Progress from NNPDF

The 12th Workshop on Hadron Physics and Opportunities Worldwide

Emanuele R. Nocera

Università degli Studi di Torino and INFN, Torino

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The NNPDF4.0 family

09/2021	NNPDF4.0 (release)	[EPJ C82 (2022) 428]
09/2021	NNPDF4.0 (code)	[EPJ C81 (2021) 958]
08/2022	Intrinsic charm	[Nature 608 (2022) 7923 483]
09/2022	PDFs and BSM searches	[EPJ C82 (2022) 1160]
11/2023	Intrinsic charm asymmetry	[PRD 109 (2024) 9 L091501]
01/2024	NNPDF4.0 QED	[EPJ C84 (2024) 540]
01/2024	NNPDF4.0 MHOU	[EPJ C84 (2024) 517]
02/2024	NNPDF4.0 aN^{3}LO	[EPJ C84 (2024) 659]
06/2024	NNPDF4.0 QED&MHOU&aN^{3}LO	[arXiv:2406.01779]
06/2024	NNPDF4.0 for MC event generators	[arXiv:2406.12961]
4Q 2024	Implications of NNPDF4.0 for LHC	[in preparation]
4Q 2024	Closure test with inconsistencies	[in preparation]
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4Q 2024	NNPDFpol2.0 (helicity PDFs)	[in preparation]
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See `https://nnpdf.mi.infn.it/` and `https://github.com/NNPDF/`

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1. Charm in the proton

[Nature **608** (2022) 7923 483; Phys.Rev. **D109** (2024) L091501]

How intrinsic charm is determined in NNPDF

4FNS Charm PDF constrained by experimental data for $Q > Q_0$

• NNPDF4.0 dataset • NNLO QCD calculations

↑

QCD evolution

4FNS Charm PDF parametrised at Q_0

• Deep-learning parametrisation • Monte Carlo representation of uncertainties

QCD evolution

↓

4FNS to 3FNS transformation

NNLO or N^{3}LO matching conditions

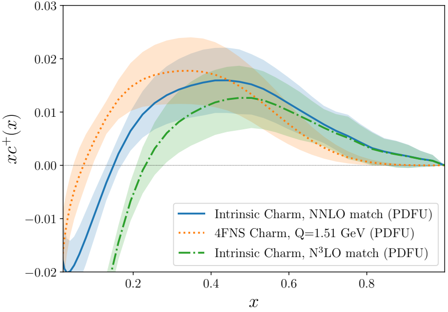
↓

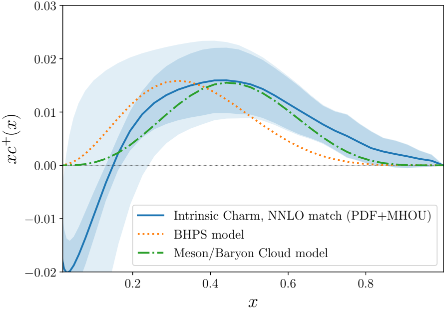
Intrinsic (3FNS) Charm

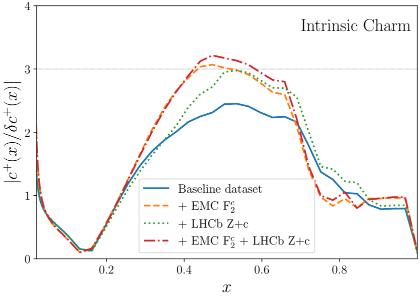
• Scale-independent • PDF and MHO uncertainties

$Q_0 = 1.65$ GeV $> m_c = 1.51$ GeV

Total intrinsic charm







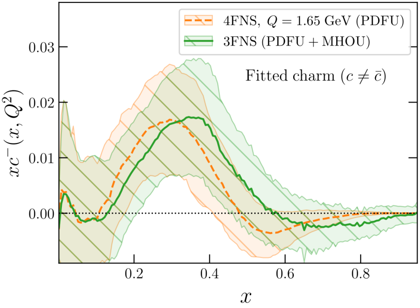
Small but nonzero
valence-like intrinsic charm (3FNS)

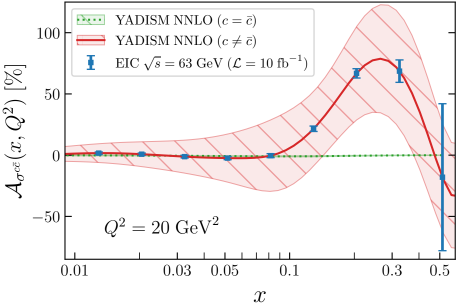
Stable upon inclusion of MHOUs
(estimated as the difference between
NNLO and N^{3}LO matching conditions)

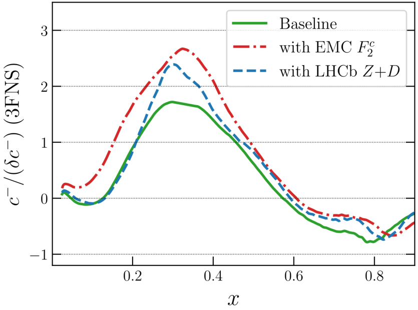
Consistence with model predicitons

2.5σ significance for baseline
3.0σ with LHCb $Z + c$ and/or EMC F_2^c

Intrinsic charm-anticharm asymmetry







Small but nonzero charm-anticharm asymmetry (3FNS)

MHOUs estimated as the difference between NNLO and N^{3}LO matching conditions

1.5σ significance for baseline
2.5σ with LHCb $Z + c$ and/or EMC F_2^c

Can be significantly improved at the EIC

$$\mathcal{A}_{\sigma^{c\bar{c}}}(x, Q^2) \equiv \frac{\sigma^{c}_{\rm red}(x,Q^2) - \sigma^{\bar{c}}_{\rm red}(x,Q^2)}{\sigma^{c\bar{c}}_{\rm red}(x,Q^2)}$$

2. Theory uncertainties in PDF determination

[Eur.Phys.J. **C84** (2024) 517]

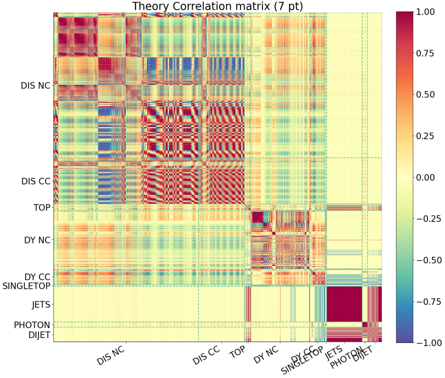
A theory covariance matrix

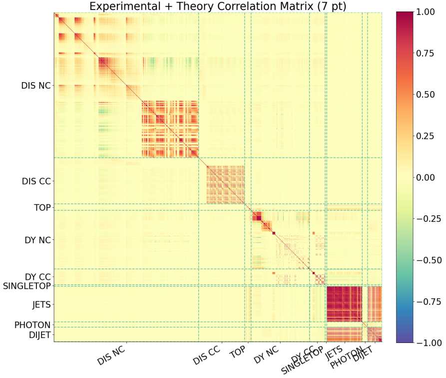
Assuming that theory uncertainties are (a) Gaussian and (b) independent from experimental uncertainties, modify the figure of merit to account for theory errors

$$\chi^2 = \sum_{i,j}^{N_{\rm dat}} (D_i - T_i)(\mathrm{cov}_{\rm exp} + \mathrm{cov}_{\rm th})^{-1}_{ij}(D_j - T_j);\ (\mathrm{cov}_{\rm th})_{ij} = \frac{1}{N}\sum_k^N \Delta_i^{(k)}\Delta_j^{(k)};\ \Delta_i^{(k)} \equiv T_i^{(k)} - T_i$$

Problem reduced to estimate the th. cov. matrix, *e.g.* in terms of nuisance parameters

$$\Delta_i^{(k)} = T_i(\mu_R, \mu_F) - T_i(\mu_{R,0}, \mu_{F,0});\ \text{vary scales in } \frac{1}{2} \leq \frac{\mu_F}{\mu_{F,0}}, \frac{\mu_R}{\mu_{R,0}} \leq 2$$





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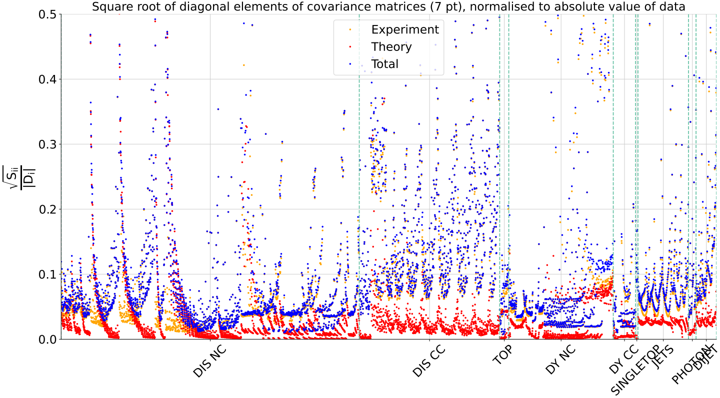

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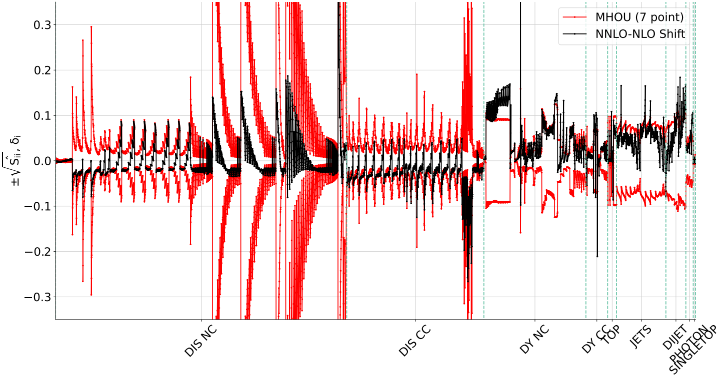
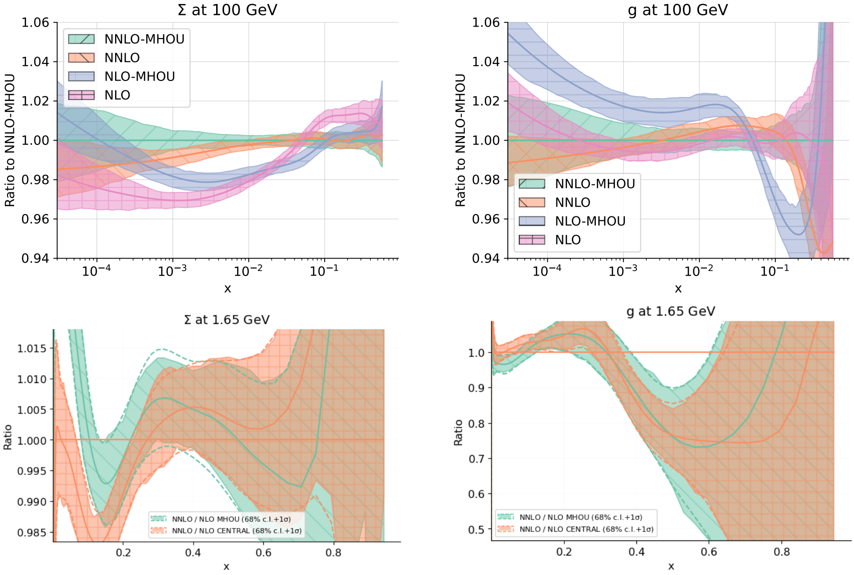


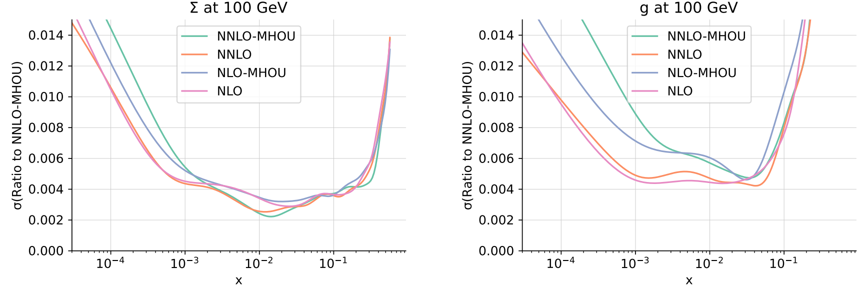
Impact on parton distributions



Faster perturbative convergence when MHOU are incorporated into PDFs

[EPJ C79 (2019) 838; ibid. 931; EPJ C84 (2024) 517]

Impact on uncertainties and fit quality



Dataset	$N_{\rm dat}$	NLO no MHOU	NLO MHOU	NNLO no MHOU	NNLO MHOU
DIS NC	2100	1.30	1.22	1.23	1.20
DIS CC	989	0.92	0.87	0.90	0.90
DY NC	736	2.01	1.71	1.20	1.15
DY CC	157	1.48	1.42	1.48	1.37
Top pairs	64	2.08	1.24	1.21	1.43
Single-inclusive jets	356	0.84	0.82	0.96	0.81
Dijets	144	1.52	1.84	2.04	1.71
Prompt photons	53	0.59	0.49	0.75	0.67
Single top	17	0.36	0.35	0.36	0.38
Total	4616	1.34	1.23	1.17	1.13

Overall (rather small) variation of uncertainties. Tensions relieved: improvement in χ^2

[EPJ C79 (2019) 838; ibid. 931; EPJ C84 (2024) 517]

3. Parton distributions at aN^{3}LO

[Eur.Phys.J. **C84** (2024) 659]

N^3LO QCD corrections in PDF determination

Splitting Functions (information is partial)

Singlet (P_{qq}, P_{gg}, P_{gq}, P_{qg})

– large-n_f limit [NPB 915 (2017) 335; arXiv:2308.07958]

– small-x limit [JHEP 06 (2018) 145]

– large-x limit [NPB 832 (2010) 152; JHEP 04 (2020) 018; JHEP 09 (2022) 155]

– 5 (10) lowest Mellin moments [PLB 825 (2022) 136853; ibid. 842 (2023) 137944; ibid. 846 (2023) 138215]

Non-singlet ($P_{NS,v}$, $P_{NS,+}$, $P_{NS,-}$)

– large-n_f limit [NPB 915 (2017) 335; arXiv:2308.07958]

– small-x limit [JHEP 08 (2022) 135]

– large-x limit [JHEP 10 (2017) 041]

– 8 lowest Mellin moments [JHEP 06 (2018) 073]

DIS structure functions (F_L, F_2, F_3)

– DIS NC (massless) [NPB 492 (1997) 338; PLB 606 (2005) 123; NPB 724 (2005) 3]

– DIS CC (massless) [Nucl.Phys.B 813 (2009) 220]

– massive from parametrisation combining known limits and damping functions [NPB 864 (2012) 399]

PDF matching conditions

– all known except for $a^3_{H,g}$ [NPB 820 (2009) 417; NPB 886 (2014) 733; JHEP 12 (2022) 134]

Coefficient functions for other processes

– DY (inclusive) [JHEP 11 (2020) 143]; DY (y differential) [PRL 128 (2022) 052001]

Incomplete Higher-Order Uncertainties

- We construct an ensemble of $\widetilde{N}_{ij}$ different approximations to $\gamma_{ij}^{(3)}(N)$ as interpolation functions that satisfy the known limits
- We approximate its best estimate with the average

$$\gamma_{ij}^{(3)}(N) = \frac{1}{\widetilde{N}_{ij}} \sum_{k=1}^{\widetilde{N}_{ij}} \gamma_{ij}^{(3),\,(k)}(N)\,.$$

- We include the uncertainty on the average with the theory covariance matrix formalism (each instance $\gamma_{ij}^{(3),\,(k)}$ is seen as a nuisance parameter)

$$\Delta_m(ij,k) = T_m(ij,k) - \bar{T}_m \qquad \mathrm{cov}_{mn}^{(ij)} = \frac{1}{\widetilde{N}_{ij} - 1} \sum_{k=1}^{\widetilde{N}_{ij}} \Delta_m(ij,k)\Delta_n(ij,k)\,.$$

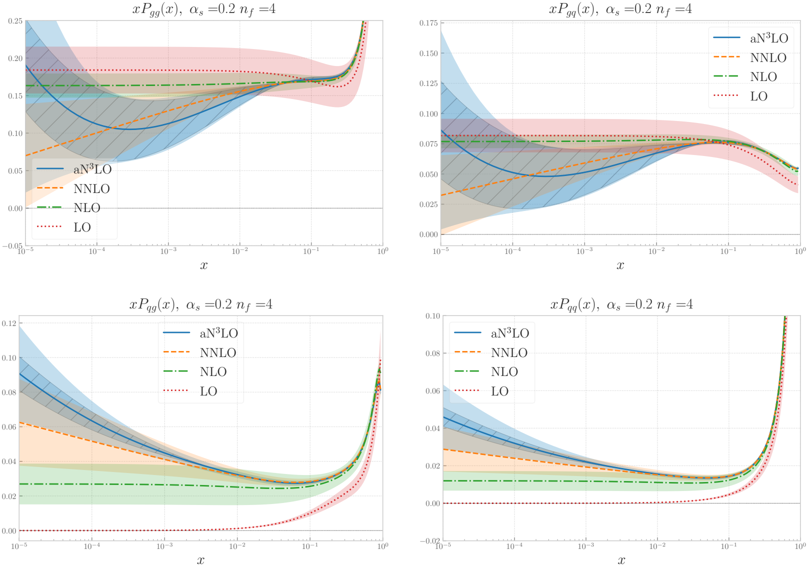
- The total contribution to the theory covariance matrix is

$$\mathrm{cov}_{mn}^{\mathrm{IHOU}} = \mathrm{cov}_{mn}^{(gg)} + \mathrm{cov}_{mn}^{(gq)} + \mathrm{cov}_{mn}^{(qg)} + \mathrm{cov}_{mn}^{(qq)}$$

- The total theory uncertainty is the sum in quadrature of the IHOU and MHOU

$$\mathrm{cov}_{mn}^{\mathrm{tot}} = \mathrm{cov}_{mn}^{\mathrm{IHOU}} + \mathrm{cov}_{mn}^{\mathrm{MHOU}}$$

Splitting functions: singlet



Excellent perturbative convergence (see benchmark [arXiv:2406.16188])

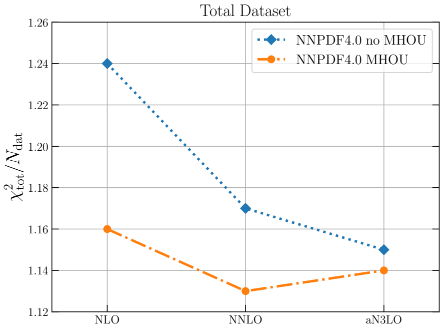
Fit quality

Dataset	$N_{\rm dat}$	NLO no MHOU	NLO MHOU	$N_{\rm dat}$	NNLO no MHOU	NNLO MHOU	$N_{\rm dat}$	aN^{3}LO no MHOU	aN^{3}LO MHOU
DIS NC	1980	1.30	1.22	2100	1.22	1.20	2100	1.22	1.20
DIS CC	988	0.92	0.87	989	0.90	0.90	989	0.91	0.92
DY NC	667	1.49	1.32	736	1.20	1.15	736	1.17	1.16
DY CC	193	1.31	1.27	157	1.45	1.37	157	1.37	1.36
Top pairs	64	1.90	1.24	64	1.27	1.43	64	1.23	1.41
Single-inclusive jets	356	0.86	0.82	356	0.94	0.81	356	0.84	0.83
Dijets	144	1.55	1.81	144	2.01	1.71	144	1.78	1.67
Prompt photons	53	0.58	0.47	53	0.76	0.67	53	0.72	0.68
Single top	17	0.35	0.34	17	0.36	0.38	17	0.35	0.36
Total	4462	1.24	1.16	4616	1.17	1.13	4616	1.15	1.14

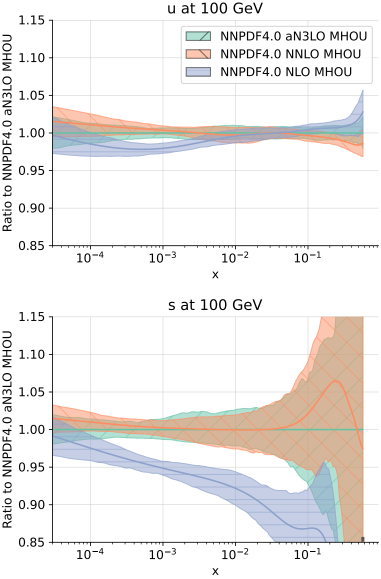
Fit quality improves with perturbative order

Fit quality almost independent from perturbative order when MHOU are included

Data whose theoretical description is affected by large scale uncertainties are deweighted in favour of more perturbatively stable data

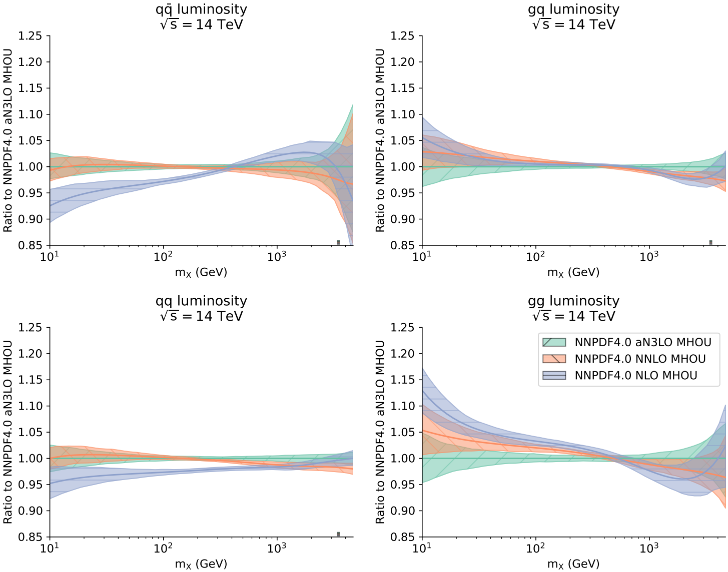


Perturbative dependence of PDFs



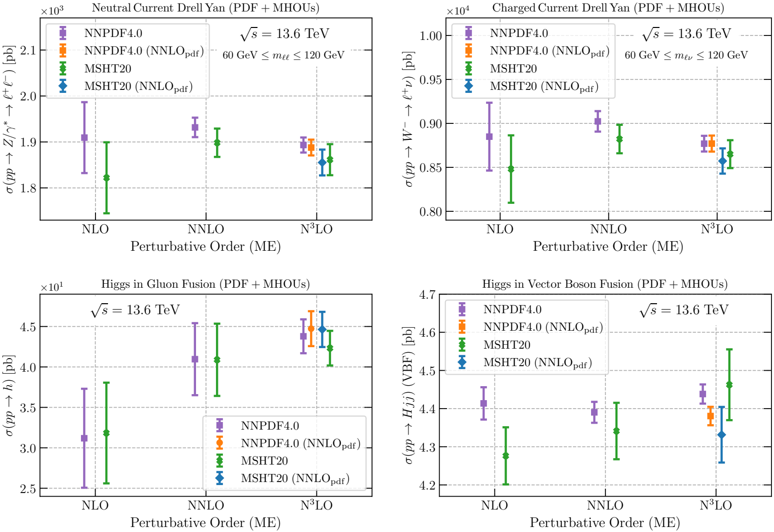
aN^{3}LO corrections suppress the gluon PDF by 2-3% at $x \sim 0.01$ w.r.t. NNLO

Partonic luminositites



aN^{3}LO corrections suppress the gg luminosity by 1-2% at $m_X \sim 100$ GeV w.r.t. NNLO

Inclusive cross sections



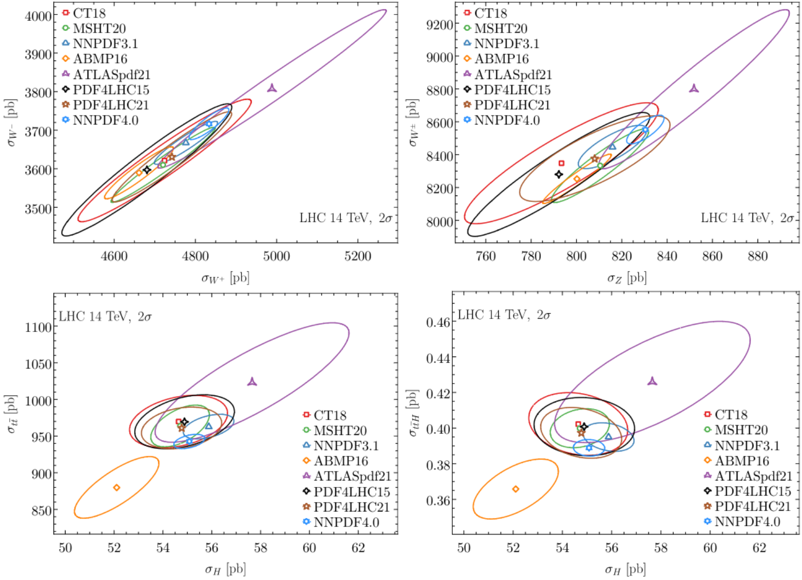
Effect of using aN^{3}LO PDFs instead of NNLO PDFs in N^{3}LO predictions is small

Good consistency with MSHT20 [EPJ C83 (2023) 185]

4. Implications of NNPDF4.0 for LHC data

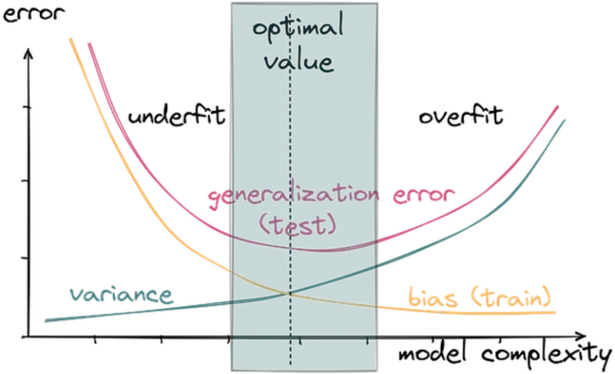
[NNPDF, in preparation]

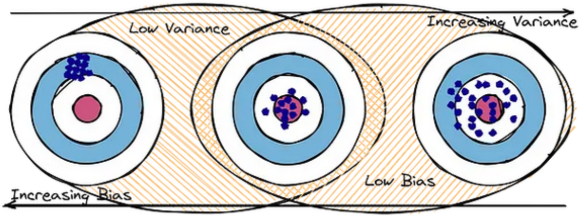
Making predictions with PDFs



[Acta Phys.Polon.B 53 (2022) 12]

Accuracy vs precision or bias vs variance





Validation of PDF uncertainties

Data region: closure tests

Fit PDFs to pseudodata generated assuming a known underlying law

Define bias and variance

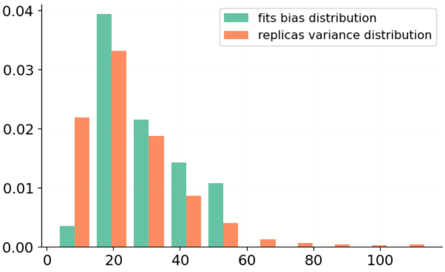
bias difference of central prediction and truth

variance uncertainty of replica predictions

If PDF uncertainty faithful, then

E[bias] = variance

25 fits, 40 replicas each



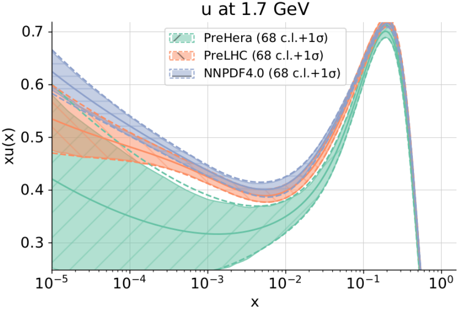
[EPJ C77 (2017) 663; EPJ C82 (2022) 330]

Extrapolation regions: future test

Test PDF uncertainties on data sets not included in a given PDF fit that cover unseen kinematic regions

Data set	NNPDF4.0	pre-LHC	pre-HERA
pre-HERA	1.09	1.01	0.90
pre-LHC	1.21	1.20	23.1
NNPDF4.0	1.29	3.30	23.1

Only exp. cov. matrix



[Acta Phys.Polon. B52 (2021) 243]

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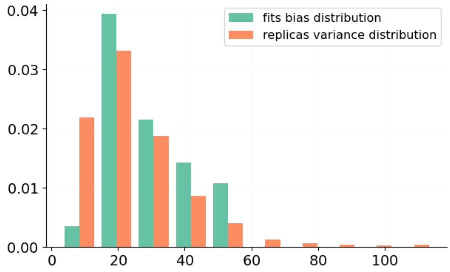

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Extrapolation regions: future test

Test PDF uncertainties on data sets
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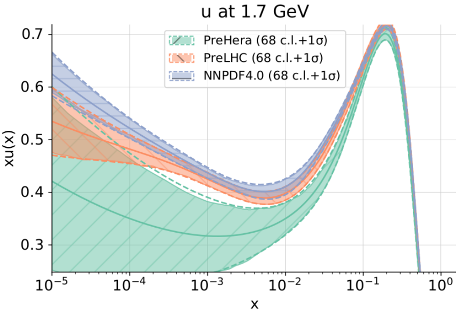
that cover unseen kinematic regions

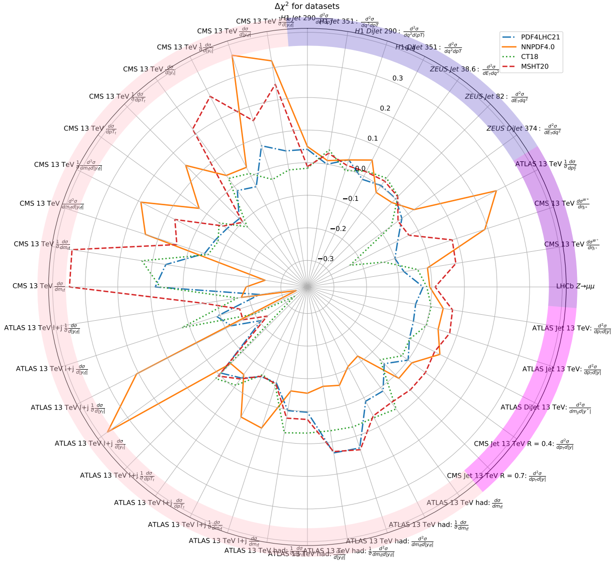
Data set	NNPDF4.0	pre-LHC	pre-HERA
pre-HERA			0.86
pre-LHC		1.17	1.22
NNPDF4.0	1.12	1.30	1.38

Exp+PDF cov. matrix



[Acta Phys.Polon. B52 (2021) 243]

Are all PDF sets equally accurate?



$$\Delta\chi^2 = \frac{\chi^{2,(i)}_{\mathrm{exp+mhou+pdf}} - \left\langle \chi^2_{\mathrm{exp+mhou+pdf}} \right\rangle}{\left\langle \chi^2_{\mathrm{exp+mho+pdf}} \right\rangle}$$

5. To conclude

Thank you

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