Towards NNPDF4.0: The Structure of the Proton to One-Percent Accuracy

PDF4LHC meeting

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on behalf of the NNPDF Collaboration

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From NNPDF3.1 to NNPDF4.0

Collaborative progress towards extending data, theory and methodology

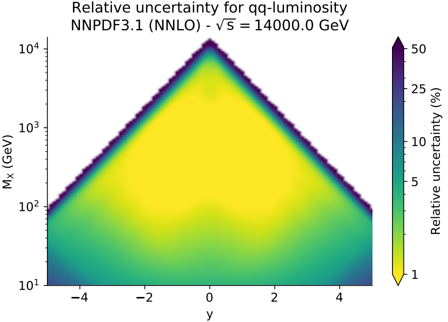
06/2017	**NNPDF3.1**	[EPJ C77 (2017) 663]
10/2017	NNPDF3.1sx: PDFs with small-x resummation	[EPJ C78 (2018) 321]
12/2017	NNPDF3.1luxQED: consistent photon PDF à la luxQED	[SciPost Phys. 5 (2018) 008]
02/2018	NNPDF3.1+ATLASphoton: inclusion of direct photon data	[EPJ C78 (2018) 470]
12/2018	NNPDF3.1alphas: α_s from a correlated-replica method	[EPJ C78 (2018) 408]
12/2018	NNPDF3.1nuc: heavy ion nuclear uncertainties in a fit	[EPJ C79 (2019) 282]
05/2019	NNPDF3.1th: missing higher-order uncertainties in a fit	[EPJ C79 (2019) 838; ibid. 931]
07/2019	Gradient descent and hyperoptimisation in PDF fits	[EPJ C79 (2019) 676]
12/2019	NNPDF3.1singletop: inclusion of single top t-channel data	[JHEP 05 (2020) 067]
05/2020	NNPDF3.1dijets: comparative study of single- and di-jets	[EPJ C80 (2020) 797]
06/2020	Positivity of $\overline{\mathrm{MS}}$ PDFs	[JHEP 11 (2020) 129]
08/2020	PineAPPL: fast evaluation of EW$\times$QCD corrections	[JHEP 12 (2020) 108]
08/2020	NNPDF3.1strangeness: assessment of strange-sensitive data	[EPJ C80 (2020) 1168]
11/2020	NNPDF3.1deu: deuteron uncertainties in a fit	[EPJ C81 (2021) 37]
03/2021	Future tests	[arXiv:2103.08606]
2021	**NNPDF4.0**	[to appear]

From NNPDF3.1 to NNPDF4.0

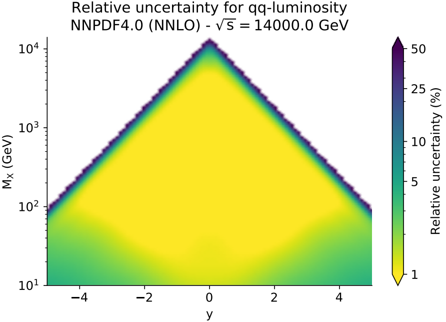
$$\mathcal{L}_{ij}(M_X, y, \sqrt{s}) = \frac{1}{s} \sum_{i,j} f_i\left(\frac{M_X e^{y}}{\sqrt{s}}, M_X\right) f_j\left(\frac{M_X e^{-y}}{\sqrt{s}}, M_X\right)$$

SINGLET

NNPDF3.1 (NNLO)



NNPDF4.0 (NNLO)



Steady progress towards 1% relative uncertainties on $\mathcal{L}_{ij}$ on a broad kinematic range

How are we getting there?

From NNPDF3.1 to NNPDF4.0

$$\mathcal{L}_{ij}(M_X, y, \sqrt{s}) = \frac{1}{s}\sum_{i,j} f_i\left(\frac{M_X e^{y}}{\sqrt{s}}, M_X\right) f_j\left(\frac{M_X e^{-y}}{\sqrt{s}}, M_X\right)$$

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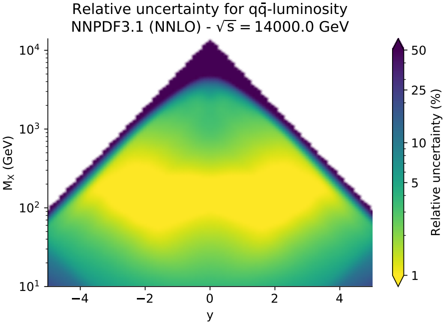

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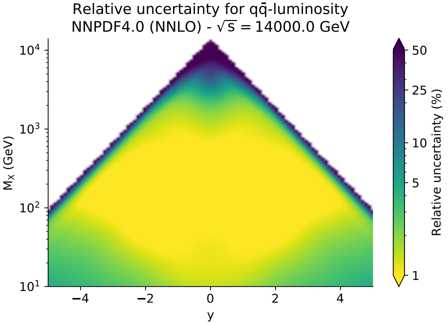

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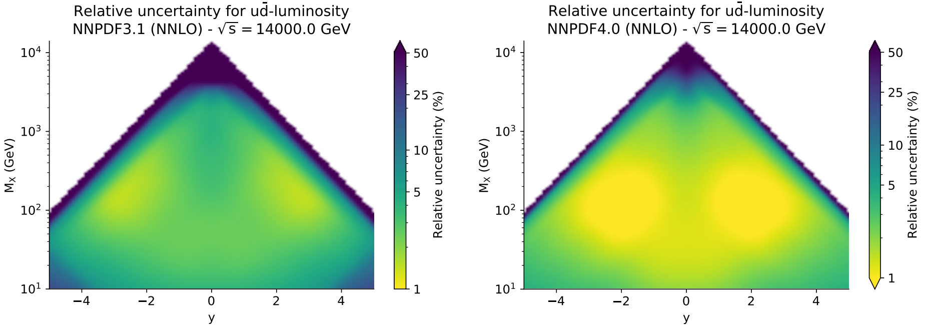
FLAVOURS

NNPDF3.1 (NNLO) NNPDF4.0 (NNLO)



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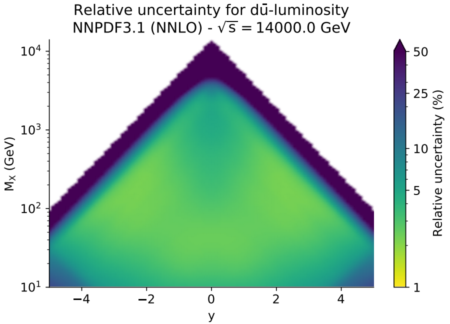
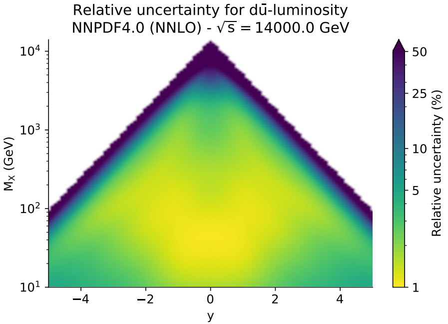


NNPDF4.0 (NNLO)



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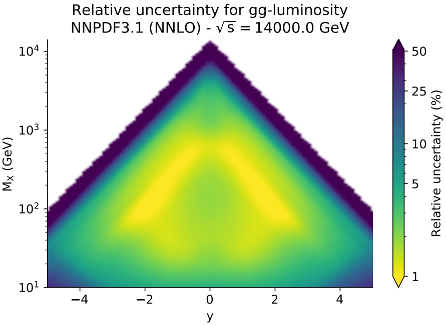
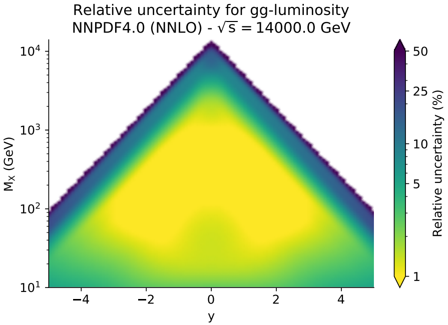
GLUON

NNPDF3.1 (NNLO)



NNPDF4.0 (NNLO)



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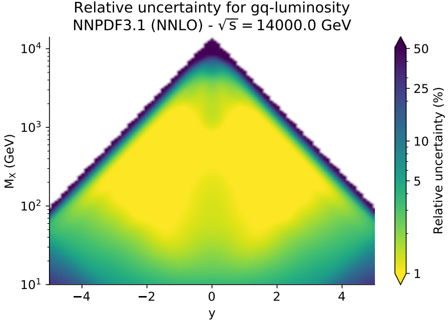
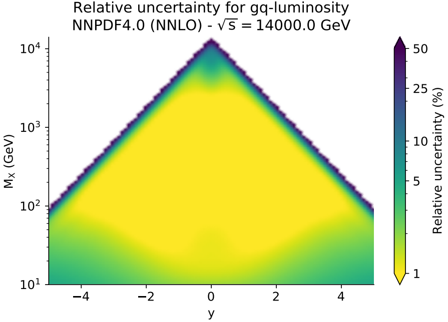


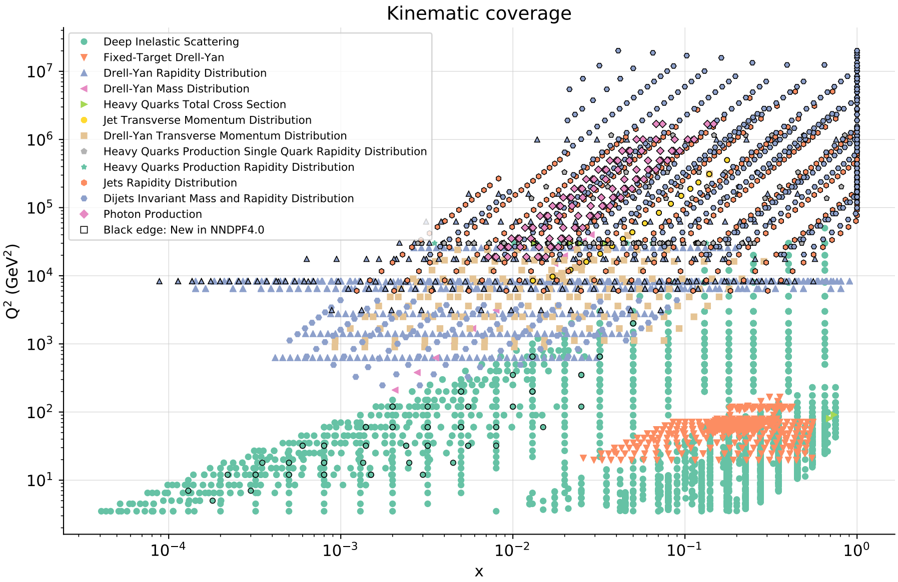
NNPDF4.0 (NNLO)



Steady progress towards 1% relative uncertainties on $\mathcal{L}_{ij}$ on a broad kinematic range

How are we getting there?

NNPDF4.0: data set extension



$\mathcal{O}(50)$ data sets investigated; $\mathcal{O}(400)$ data points more in NNPDF4.0 than in NNPDF3.1

New data sets in NNPDF4.0

Process	Experiment	Description	Reference
DIS	HERA	Combined reduced c and b cross sections	[EPJ C78 (2018) 473]
	NOMAD*	$\mathcal{R}_{\mu\mu}(E) = \sigma_{\mu\mu}(E)/\sigma_{CC}(E)$	[NPB 876 (2013) 339]
DY	ATLAS	W, Z central/forward rapidity distr., **7 TeV**	[EPJ C77 (2017) 367]
	ATLAS	$\{m_{\ell\ell}, \|y_{\ell\ell}\|\}$ high-mass distribution, **8 TeV**	[JHEP 08 (2016) 009]
	ATLAS	W and Z total cross section, **13 TeV**	[PLB 759 (2016) 601]
	LHCb	y_Z distribution, $2e$ and 2μ, **13 TeV**	[JHEP 09 (2016) 136]
W+c	ATLAS†	$\|\eta^\ell\|$ distribution **7 TeV**	[JHEP 05 (2014) 068]
	CMS†	$\|\eta^\mu\|$ distribution **13 TeV**	[EPJ C79 (2019) 269]
single-jet	ATLAS	$\{p_T, \|y\|\}$ distribution, **8 TeV**	[JHEP 09 (2017) 020]
$t\bar{t}$	ATLAS	normalised $y_{t\bar{t}}$ distribution, 2ℓ, **8 TeV**	[PRD 94 (2016) 092003]
	CMS	total inclusive cross section, **5 TeV**	[JHEP 03 (2018) 115]
	CMS	normalised $\{m_{t\bar{t}}, y_t\}$ distribution, **8 TeV**	[EPJ C77 (2017) 459]
	CMS	normalised y_t distribution (dilepton), **13 TeV**	[JHEP 02 (2019) 149]
	CMS	normalised y_t distribution (lepton+jet), **13 TeV**	[PRD 97 (2018) 112003]
single top	ATLAS	R_t **7, 8, 13 TeV**	[JHEP 04 (2017) 086]
	ATLAS	normalised y_t and $y_{\bar{t}}$ distributions, **7, 8 TeV**	[PRD 90 (2014) 112006; EPJ C77 (2017) 531]
	CMS	$t + \bar{t}$ cross section, **7 TeV**	[JHEP 12 (2012) 035]
	CMS	R_t **8, 13 TeV**	[JHEP 06 (2014) 090; PLB 772 (2017) 752]
W+jet	ATLAS	p_T distribution, **8 TeV**	[JHEP 05 (2018) 077]
isolated photon	ATLAS	$\{E_T^\gamma, \|\eta^\gamma\|\}$ distribution, **13 TeV**	[PLB 770 (2017) 473]
di-jets	ATLAS	$\{m_{12}, y^*\}$ distribution **7 TeV**	[JHEP 05 (2014) 059]
	CMS	$\{m_{12}, \|y_{\max}\|\}$ distribution **7 TeV**	[PRD 87 (2013) 112002]
	CMS	$\{p_{T,\mathrm{avg}}, y_b, y^*\}$ distribution **8 TeV**	[EPJ C77 (2017) 746]
DIS+jets	H1*	Single- and di-jet differential distributions	[EPJ C75 (2015) 65; C77 (2017) 215]

* Not in baseline fit; studied via reweighting

† Only NLO fit

Processes highlighted in red correspond to processes NOT in NNPDF3.1

Selection of data sets based on weighted fits (see Z. Kassabov)

NNPDF4.0: theoretical and methodological features

Mostly covered in the previous NNPDF talk; here I summarise the main points

- Refined theoretical framework
  $\rightarrow$ nuclear uncertainties for both deuteron and heavy nuclei included by default
  $\rightarrow$ NNLO charm-quark massive corrections implemented (a bug in the NLO corrected)
  $\rightarrow$ EW corrections not included to ensure consistency with data, but carefully checked
  $\rightarrow$ charm PDF parametrised on the same footing as other PDFs
- Improved implementation of PDF properties
  $\rightarrow$ extended positivity constraints for light quark/antiquark and gluon PDFs
  $\rightarrow$ extended integrability constraints of non-singlet light quark PDF combinations
- New PDF parametrisation and optimisation
  $\rightarrow$ single neural network to parametrise eight independent PDF combinations
  $\rightarrow$ check of the independence of the results from the chosen parametrisation basis
  $\rightarrow$ new optimisation strategy based on gradient descent rather than genetic algorithms
  $\rightarrow$ scan of the hyperparameter space to find the optimal minimisation settings
- Complete statistical validation of PDF uncertainties
  $\rightarrow$ (multi-)closure tests to validate PDF uncertainties in the data region
  $\rightarrow$ future tests to check the sensibleness of PDF uncertainties in extrapolation regions
- More efficient compression tool for PDF set delivery

NNPDF4.0: Fit quality – NNLO

Data set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Fixed-target DIS	1881	1.10
HERA	1208	1.21
σ_c	37	2.11
σ_b	26	1.48
Fixed-target Drell-Yan	189	1.00
CDF	28	1.31
D0	37	1.00
ATLAS	621	1.18
Drell-Yan, 7, 8, 13 TeV	153	1.32
W+jet, 8 TeV	32	1.15
single top, 7, 8, 13 TeV	14	0.36
di-jets, 7 TeV	90	1.93
jets, 8 TeV	171	0.61
top pair, 7, 8, 13 TeV	16	2.30
Zp_T, 8 TeV	92	0.86
direct photon, 13 TeV	53	0.72
CMS	411	1.40
Drell-Yan, 7, 8 TeV	154	1.34
single top, 7, 8, 13 TeV	3	0.43
di-jets, 7 TeV	54	1.67
di-jets, 8 TeV	122	1.50
top pair, 5, 7, 8 TeV	29	0.84
top pair, 13 TeV	21	0.67
Zp_T, 8 TeV	28	1.42
LHCb	116	1.53
Total	4491	1.17

Overall good description of the data sets

Two exceptions:
HERA σ_c and ATLAS top pair

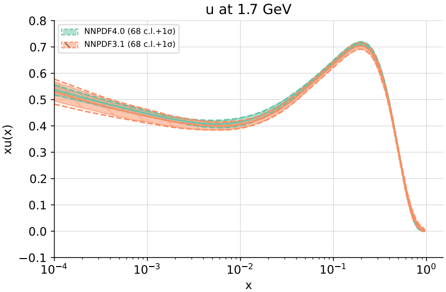
Weighted fits analysis:
in case of HERA σ_c:
lack of small-x resummation

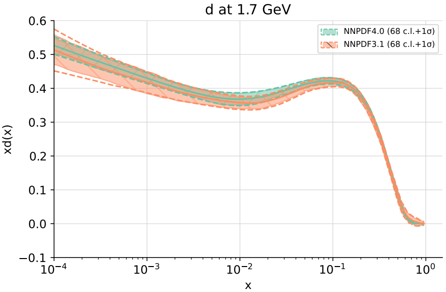
in case of ATLAS top pair:
slight tension with (di-jet) data sets
poor fit if all distributions are included
normalised rapidity distributions retained
although their $\chi^2/N_{\rm dat}$ of order 3
CMS top pair data almost insensitive to all this

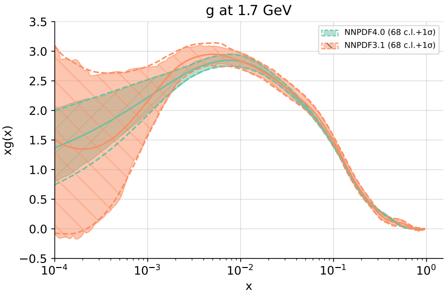
General remark:
as statistical uncertainties become smaller
a good control of systematic uncertainties
and their correlations becomes fundamental
to interpret the sensibleness of the fit

All results in the sequel are obtained at NNLO

From NNPDF3.1 to NNPDF4.0







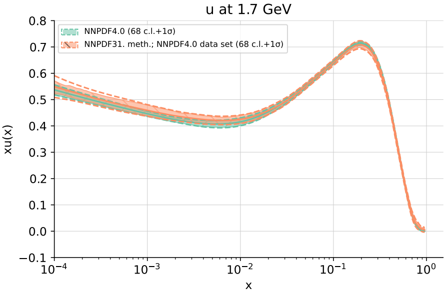
data set ($N_{\rm dat}$) \ methodology	NNPDF3.1	NNPDF4.0
NNPDF3.1 (4093)	**1.19**	1.12
NNPDF4.0 (4491)	1.25	**1.17**

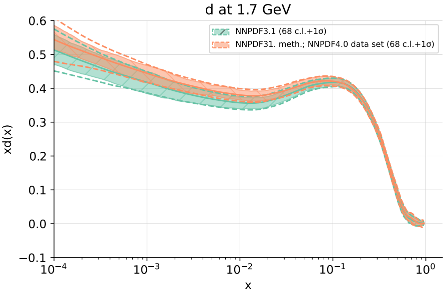
Consistency between PDF sets

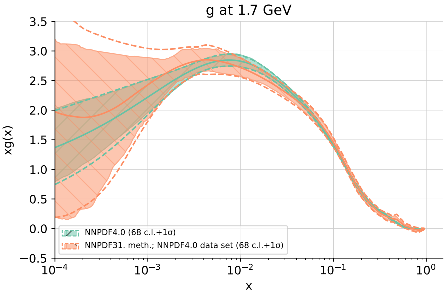
NNPDF4.0 more precise
(combination of data set and methodology)

NNPDF4.0 more accurate
(superiority of the NNPDF4.0 methodology)

From NNPDF3.1 to NNPDF4.0







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Consistency between PDF sets

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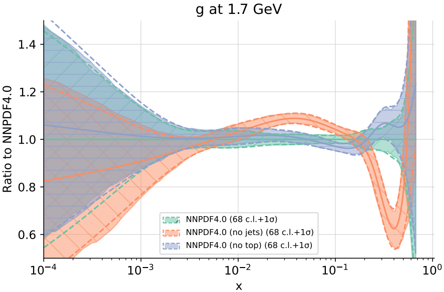
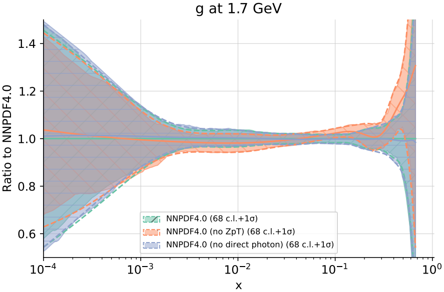
The gluon PDF: impact of data

jet and $t\bar{t}$ data



Zp_T and direct photon data



Hierarchical impact of different data sets in the fit

jet measurements have the largest pull: suppression for $0.01 \lesssim x \lesssim 0.1$, enhancement otherwise

$t\bar{t}$ and Zp_T measurements have a comparatively small pull, which is consistent with the global fit

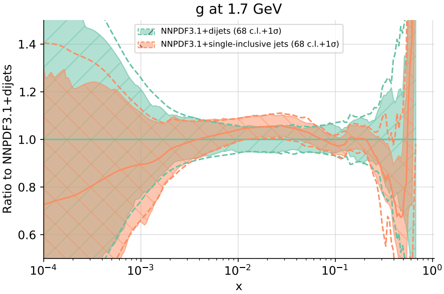
direct photon measurements have an almost immaterial pull

fit \ data set	ATLAS jets	CMS jets	ATLAS top	CMS top	ATLAS Zp_T	CMS Zp_T	ATLAS dir. phot.	total
NNPDF4.0	1.06	1.55	2.30	0.77	0.86	1.41	0.71	1.17
(no jets)	[1.71]	[3.70]	1.54	1.00	0.86	1.35	0.72	1.14
(no top)	1.08	1.57	[3.51]	[0.91]	0.86	1.43	0.74	1.18
(no Zp_T)	1.08	1.57	2.30	0.76	[0.99]	[1.81]	0.69	1.14
(no dir. phot.)	1.06	1.55	2.30	0.77	0.86	1.42	[0.71]	1.18

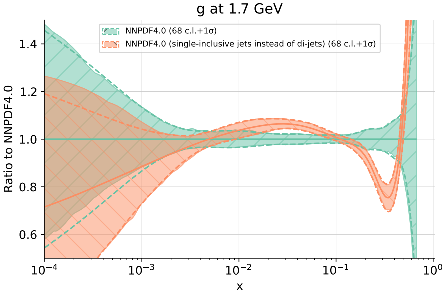
The gluon PDF: single-inclusive jet vs di-jet data

Inclusion of di-jet measurements is preferred over single-inclusive jet measurements given their greater theoretical accuracy and the avoidance of decorrelation models based on an extensive study in the framework of the NNPDF3.1 methodology [EPJ C80 (2020) 8]

NNPDF3.1



NNPDF4.0



Similar relative effect of single-inclusive vs di-jet data in NNPDF3.1 and NNPDF4.0

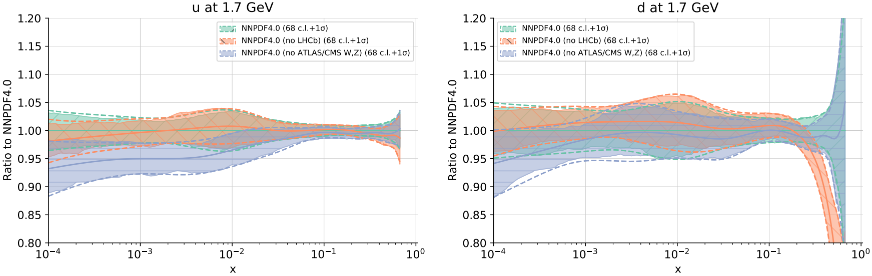
Effect enhanced within the reduced NNPDF4.0 uncertainties

fit \ data set	ATLAS 2j	CMS 2j	ATLAS 1j (7 TeV)	ATLAS 1j (8 TeV)	CMS 1j	Zp_T	top	total
NNPDF4.0	1.93	1.56	[1.28] [3.42]*	0.61 [2.82]*	[1.31]	0.99	1.17	1.17
(single-jets instead of di-jets)	[2.41]	[2.68]	1.23 [3.36]*	0.85 [3.10]*	1.07	0.99	1.19	1.14

* No decorrelation model

Quark flavour decomposition: impact of data

Quarks



The bulk of the constraint on u and d comes from inclusive fixed-target and collider DIS

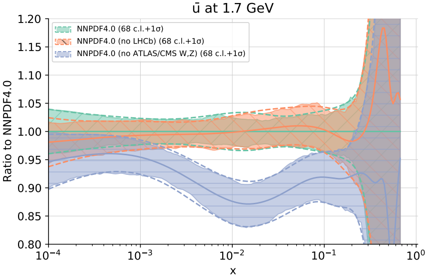
LHCb data sets affect the d PDF at large x (as in NNPDF3.1)

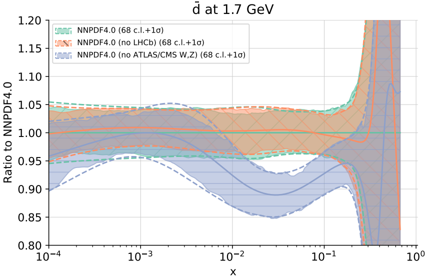
Effect of single top (not shown) is immaterial, see [JHEP 05 (2020) 067]

data set / fit	FT DIS	HERA	FT DY	Tevatron	ATLAS W, Z	CMS W, Z	LHCb	single top	total
NNPDF4.0	1.10	1.21	1.00	1.14	1.28	1.33	1.54	0.37	1.17
(no LHCb)	1.08	1.21	0.97	1.27	1.34	1.35	[2.60]	0.34	1.16
(no ATLAS/CMS W, Z)	1.05	1.20	0.85	1.02	[2.14]	[1.36]	1.39	0.37	1.11
DIS-only	1.03	1.21	[1.40]	[1.22]	[4.15]	[3.83]	[2.96]	[0.33]	1.10

Quark flavour decomposition: impact of data

Antiquarks





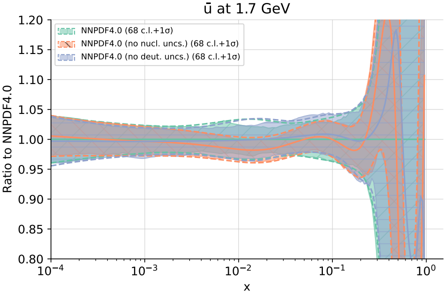
ATLAS and CMS DY data sets have a pull of about 2σ for $x \sim 0.02$ on both $\bar{u}$ and $\bar{d}$

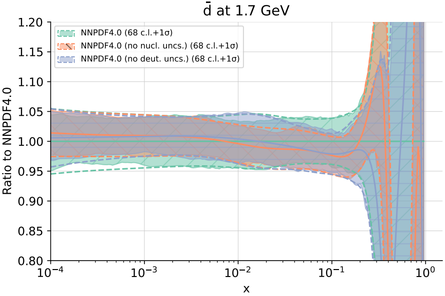
The pull is not encompassed by a corresponding increase of PDF uncertainties

Genuine effect of data, detected thanks to the new methodology and data set

fit \ data set	FT DIS	HERA	FT DY	Tevatron	ATLAS W, Z	CMS W, Z	LHCb	single top	total
NNPDF4.0	1.10	1.21	1.00	1.14	1.28	1.33	1.54	0.37	1.17
(no LHCb)	1.08	1.21	0.97	1.27	1.34	1.35	[2.60]	0.34	1.16
(no ATLAS/CMS W, Z)	1.05	1.20	0.85	1.02	[2.14]	[1.36]	1.39	0.37	1.11
DIS-only	1.03	1.21	[1.40]	[1.22]	[4.15]	[3.83]	[2.96]	[0.33]	1.10

Quark flavour separation: nuclear uncertainties





Effect of nuclear uncertainties relevant at large x

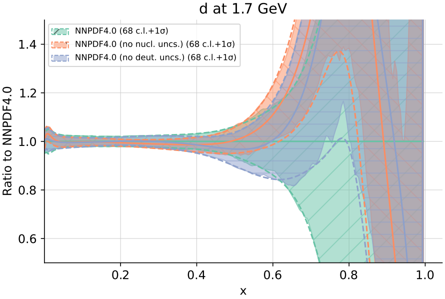
to reconcile FT DIS with LHC DY data

$\chi^2_{\rm tot} = 1.17 \rightarrow \chi^2_{\rm tot} = 1.26$ (no nucl. uncs.)

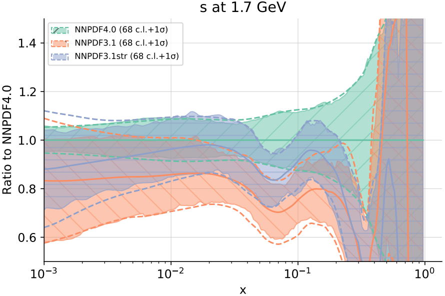
$\chi^2_{\rm LHCb} = 1.54 \rightarrow \chi^2_{\rm tot} = 1.76$ (no nucl. uncs.)

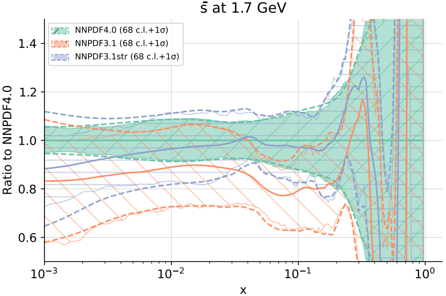
The bulk of the effect is due to nuclear uncertainties for heavy nuclei

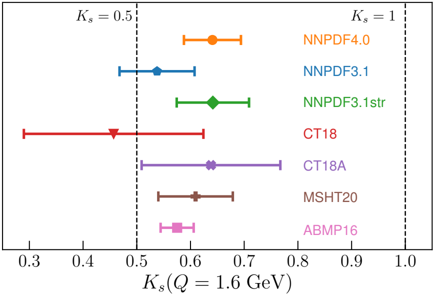
deuteron uncertainties have a comparatively smaller effect at inermediate values of x



The strange PDF: impact of data







Enhanced s and $\bar{s}$ PDFs w.r.t. NNPDF3.1
effect of ATLAS W, Z and W+jet data

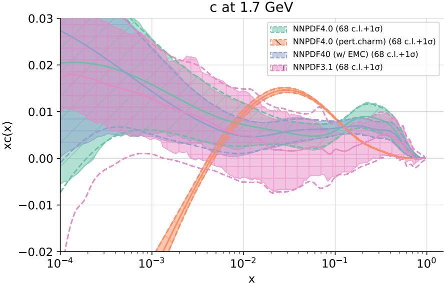
Good consistency with NNPDF3.1str
no nuclear uncertainties in NNPDF3.1str
no NOMAD nor $W + c$ data in NNPDF4.0

Good consistency of K_s across PDF sets

$$K_s(Q^2) = \frac{\int_0^1 dx[s(x,Q^2)+\bar{s}(x,Q^2)]}{\int_0^1 dx[\bar{u}(x,Q^2)+\bar{d}(x,Q^2)]}$$

See also [EPJ C80 (2020) 1168]

Impact of theory: perturbative vs fitted charm

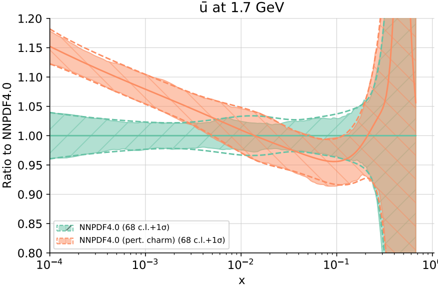


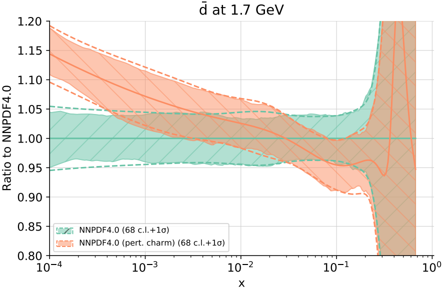
Striking evidence of intrinsic charm even w/o EMC F_2^c data

Perturbative charm alters the flavour decomposition and deteriorates the fit

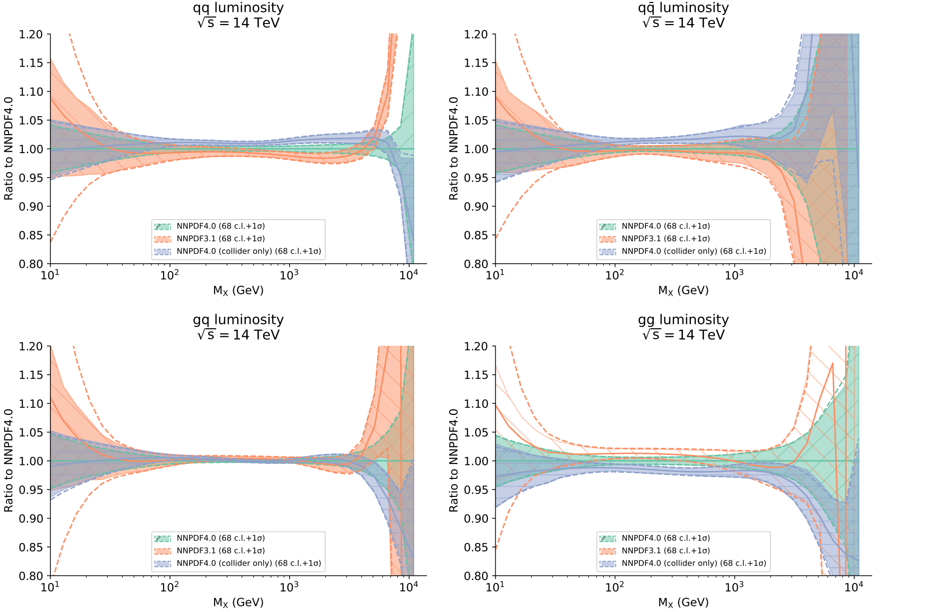
$$\chi^2_{\text{fitted charm}} = 1.17 \to \chi^2_{\text{pert. charm}} = 1.19$$

mainly due to a worsening of the LHC W, Z and top pair data sets





NNPDF4.0: parton luminosities



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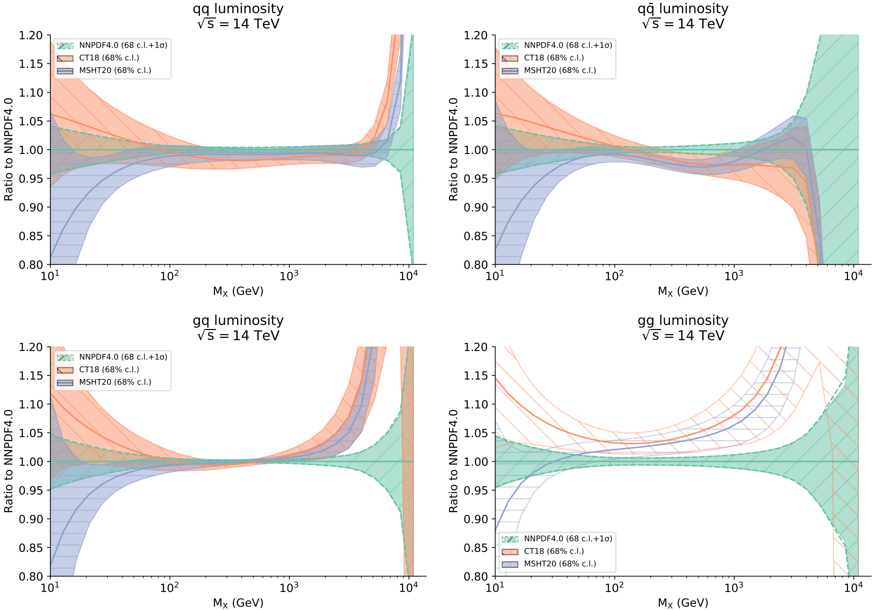
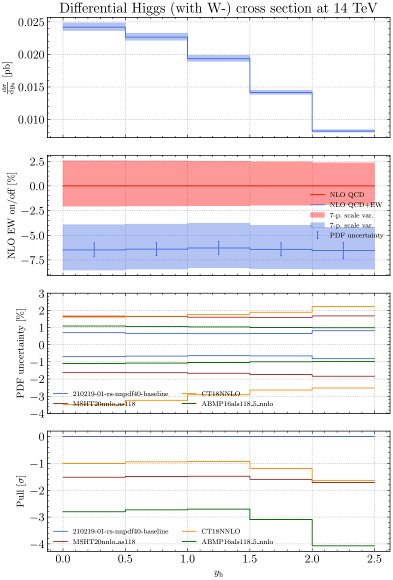
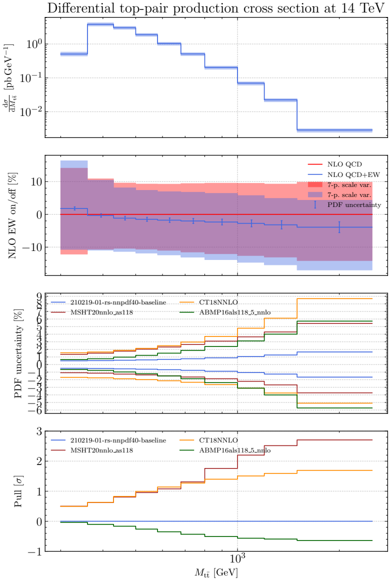


NNPDF4.0: implications for LHC phenomenology





[Plots by courtesy of C. Schwan]

Conclusions

NNPDF4.0 is the next generation parton set of the NNPDF family.

It achieves 1% accuracy in an unprecedentedly broad kinematic range by consistently improving the previous NNPDF3.1 parton set.

This result builds upon an extensive LHC data set combined with deep-learning optimisation models.

Its faithfulness in representing PDF uncertainties is completely validated by closure tests.

1% PDF uncertainties challenge the accuracy of theoretical predictions and demand an increasing effort towards the systematic inclusion in the fit of theoretical uncertainties (nuclear, higher orders, physical parameters, . . .) and higher-order QCD and EW corrections.

The **NNPDF code** used to produce the NNPDF4.0 parton set **will be made publicly available** with its documentation.

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Thank you