Collinear Parton Distribution Functions: Precision, Accuracy, and Quarkonia

Synergies between LHC and EIC for quarkonium physics

Emanuele R. Nocera

Università degli Studi di Torino and INFN, Torino

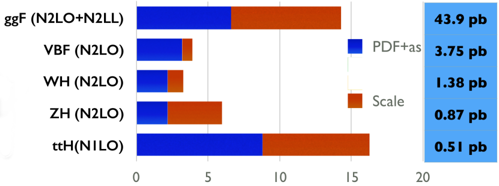
8 July 2024

PDFs at the LHC

$$\sigma(Q^2,\tau,\mathbf{k}) = \sum_{ij}\int_\tau^1 \frac{dz}{z}\mathcal{L}_{ij}(z,Q^2)\hat{\sigma}_{ij}\left(\frac{\tau}{z},\alpha_s(Q^2),\mathbf{k}\right) \qquad \mathcal{L}_{ij}(z,Q^2) = (f_i^{h_1}\otimes f_j^{h_2})(z,Q^2)$$

PDF uncertainty is often the dominant source of uncertainty in LHC cross sections

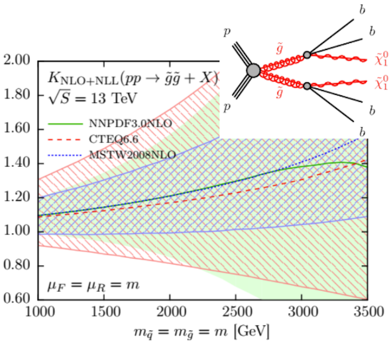
Precision



Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

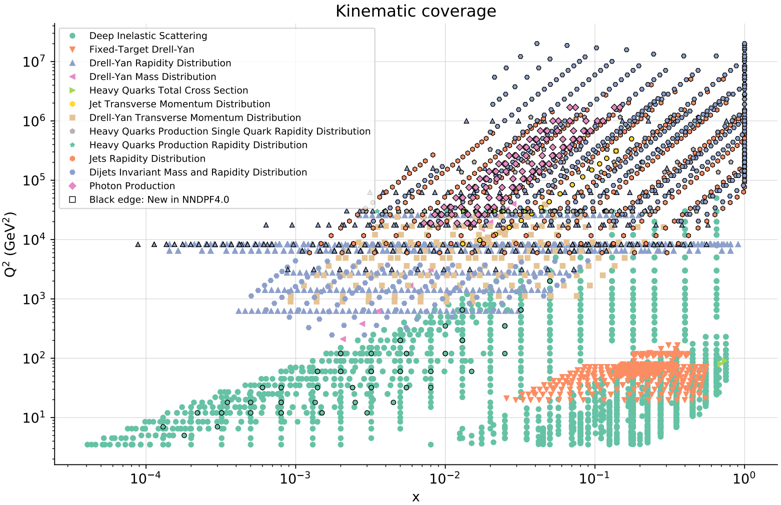
[Plot from the CERN Yellow Report 2016]

Discovery



[EPJC 76 (2016) 53]

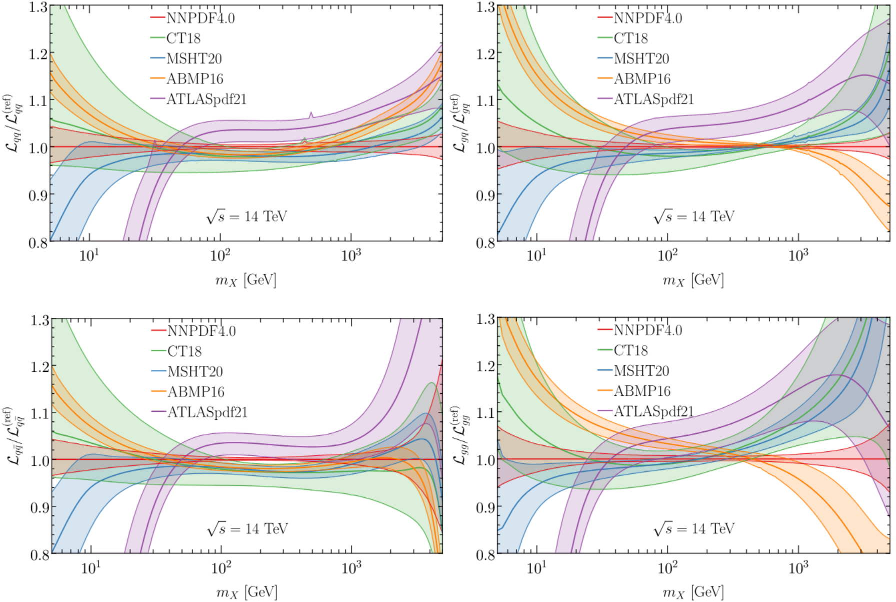
Experimental data



The inverse problem of PDF determination is addressed by parametric regression

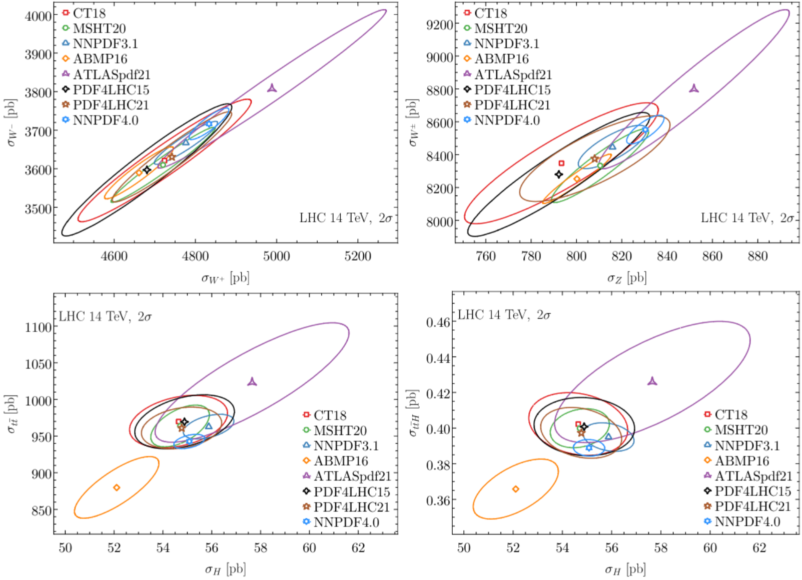
NNPDF4.0 (NNLO) $\quad N_{\rm dat} = 4618 \quad \chi^2/N_{\rm dat} = 1.16$

Comparing PDF sets



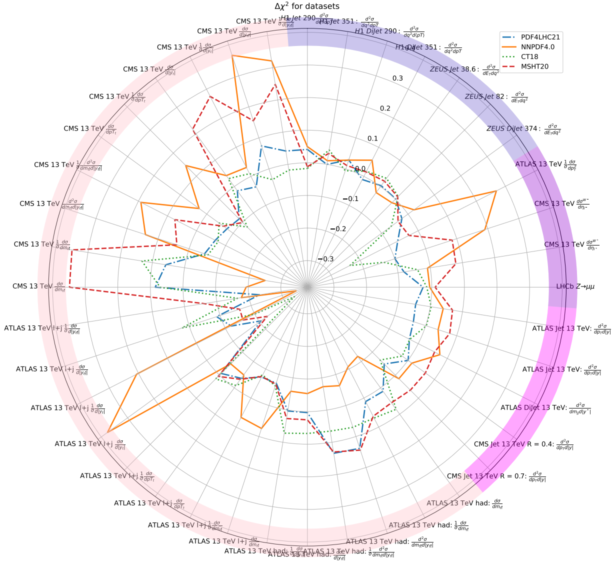
[Acta Phys.Polon.B 53 (2022) 12]

Making predictions with PDFs



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

Are all PDF sets equally accurate? [NNPDF, in preparation]

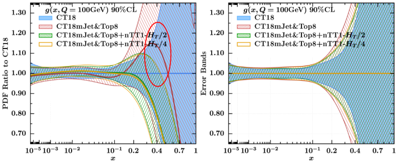


$$\Delta\chi^2 = \frac{\chi^{2,(i)}_{\rm exp+mho+pdf} - \left\langle \chi^2_{\rm exp+mho+pdf} \right\rangle}{\left\langle \chi^2_{\rm exp+mho+pdf} \right\rangle}$$

1. Precision

Gluon

Global fit without jet and $t\bar{t}$ data vs CT18NNLO



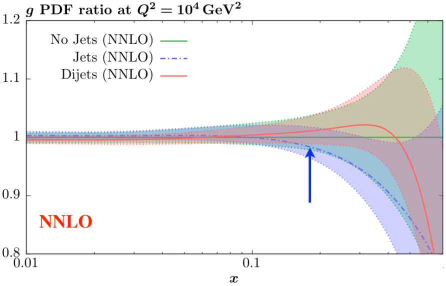
[M. Guzzi, PDF4LHC Nov. 2023]

Various processes (included in all PDF sets)
Z p_T, jets, di-jets, $t\bar{t}$

Largest impact of jets/di-jets at large x

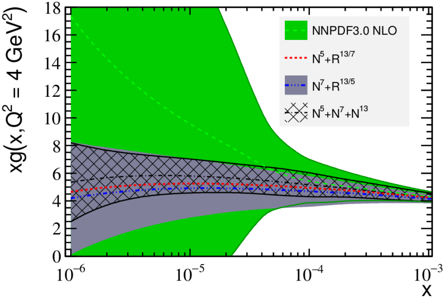
Di-jets preferred over single-inclusive jets

Forward charm production impacts small x
potentially crucial for UHE neutrino-nucleus
cross section measurements



[L. Harland-Lang, PDF4LHC Nov. 2023]

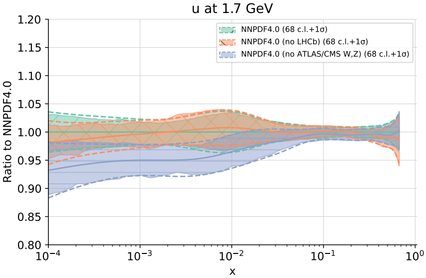
[See also EPJ C80 (2020) 797]

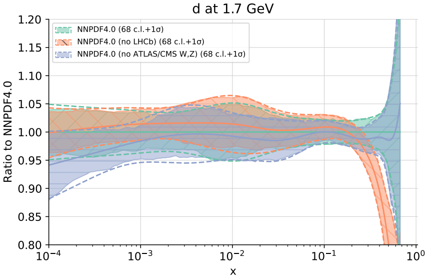


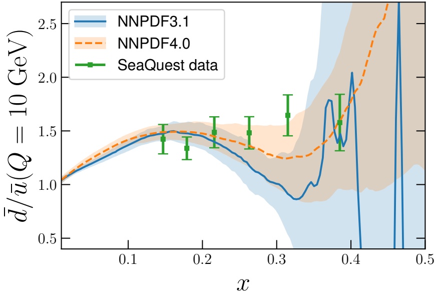
[PRL 118 (2017) 072001]

[See also arXiv:2303.13607]

Quark flavour separation







Relative impact of ATLAS/CMS/LHCb gauge boson production

LHCb is at forward rapidity

New constraint on $\bar{d}/\bar{u}$ ratio from SeaQuest

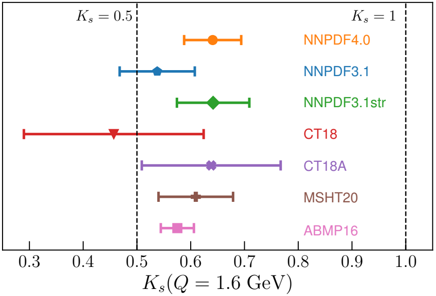
[Nature 590 (2021) 561]

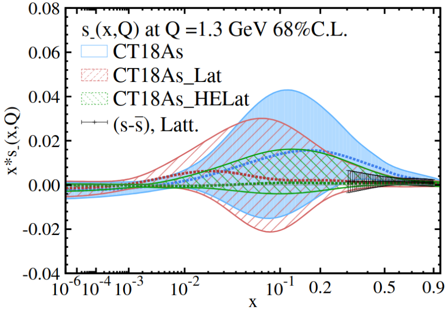
Studied by CT, MSHT, NNPDF, ABMP
Some tension with NuSea found

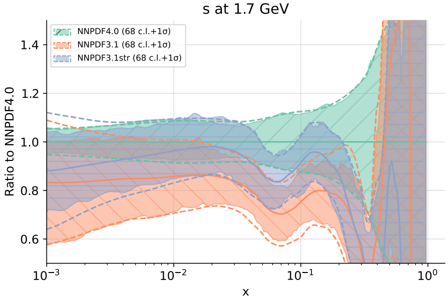
Further constraints at large x from the EIC

[PRD 103 (2021) 096005]

Strange







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

ATLAS W, Z and W+jet data enhance s

NOMAD data reduce uncertainties

nuclear uncertainties accommodate data sets

Further constraints from the FPF

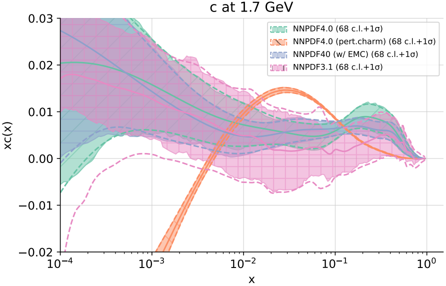
[EPJ C84 (2024) 369]

Useful input from lattice QCD

[EPJ C80 (2020) 1168; PRD 107 (2023) 076018]

[See also PRD 91 (2015) 094002]

Charm



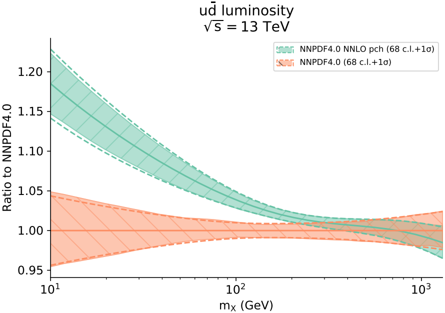
Perturbative charm alters the flavour decomposition and deteriorates the fit

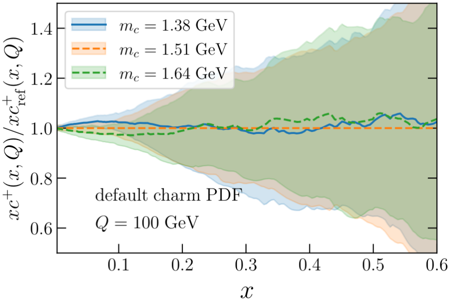
$$\chi^2_{\text{fitted charm}} = 1.17 \rightarrow \chi^2_{\text{pert. charm}} = 1.19$$

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

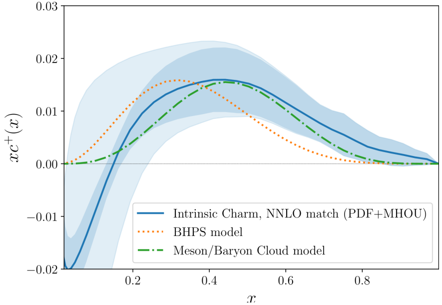
fitting charm reduces the dependence from m_c

[EPJ C76 (2016) 647; C77 (2017) 663; C82 (2022) 428]





Intrinsic Charm



Evolve results backwards (below m_c) with N^{3}LO matching

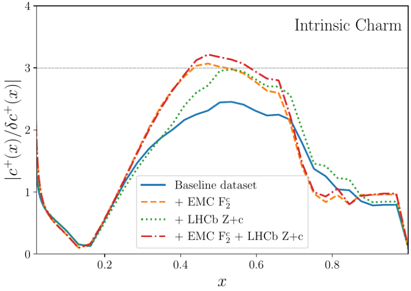
Evidence of intrinsic charm and of $c - \bar{c}$ shape compatible with models

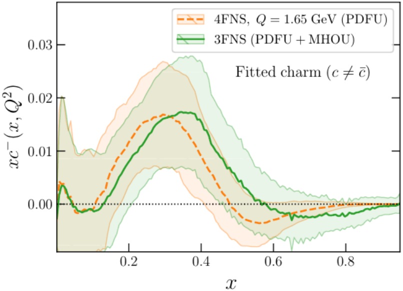
[Nature 608 (2022) 483; PRD 109 (2024) L091501]

Evidence enhanced by EMC F_2^c and $Z + D$

Challenged by CT18 [PLB 843 (2023) 137975]

Further constraints from the EIC (also on $c - \bar{c}$) [PRD 109 (2024) L091501]





2. Accuracy

Perturbative accuracy

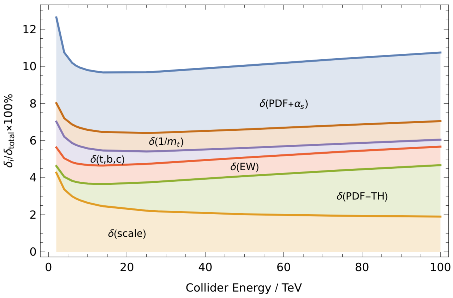
NNLO is the precision frontier for PDF determination

N3LO is the precision frontier for partonic cross sections

Mismatch between perturbative order of partonic cross sections and accuracy of PDFs is becoming a significant source of uncertainty

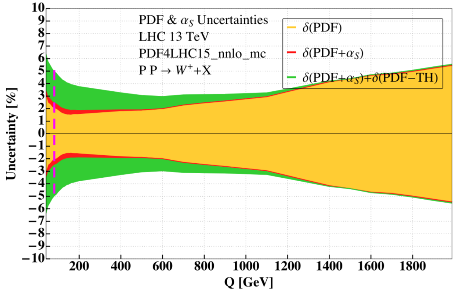
$$\hat{\sigma} = \alpha_s^p \hat{\sigma}_0 + \alpha_s^{p+1} \hat{\sigma}_1 + \alpha_s^{p+2} \hat{\sigma}_2 + \mathcal{O}(\alpha_s^{p+3}) \qquad \delta(\mathrm{PDF} - \mathrm{TH}) = \frac{1}{2} \left| \frac{\sigma^{(2)}_{\mathrm{NNLO-PDFs}} - \sigma^{(2)}_{\mathrm{NLO-PDFs}}}{\sigma^{(2)}_{\mathrm{NNLO-PDFs}}} \right|$$

Higgs production in gluon-gluon fusion



[CERN Yellow Rep.Monogr. 7 (2019) 221]

W^+ boson production in CC Drell-Yan



[JHEP 11 (2020) 143]

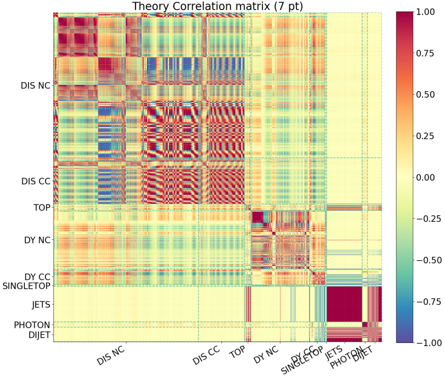
Theory uncertainties in PDF determination

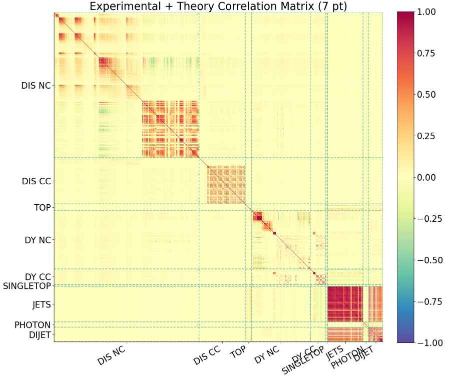
Assuming that theory uncertainties are (a) Gaussian and (b) independent from experimental uncertainties, modify the figure of merit to account for theory errors

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

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

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





The procedure is general and can be used to incorporate, *e.g.* nuclear uncertainties

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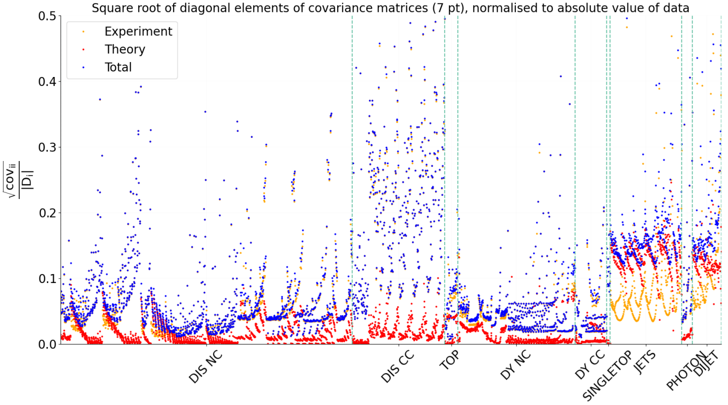

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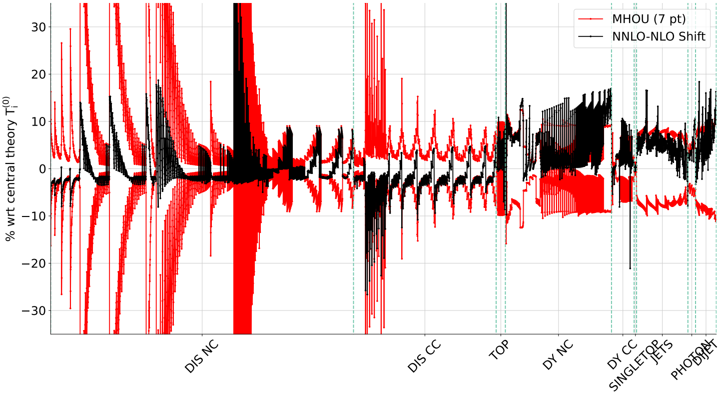
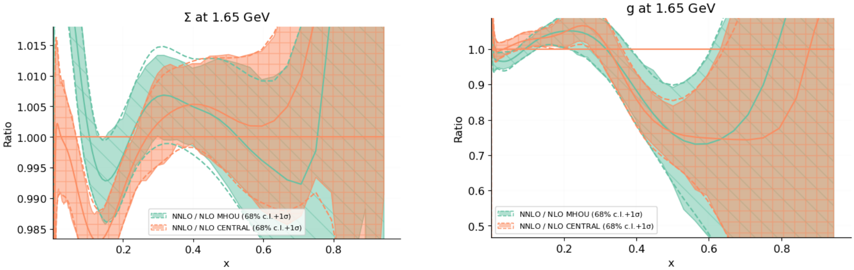


Theory uncertainties in PDF determination



Faster perturbative convergence when MHOU are incorporated into PDFs

Overall (rather small) increase in uncertainties

Increase in PDF uncertainties due to replica generation
is counteracted by extra correlations in fitting minimisation

Tensions relieved: improvement in χ^2
exp only: $\chi^2/N_{\rm dat} = 1.17$ exp+th: $\chi^2/N_{\rm dat} = 1.13$

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

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

What happens at N3LO?

N^3LO QCD corrections in PDF determination

Splitting Functions

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]

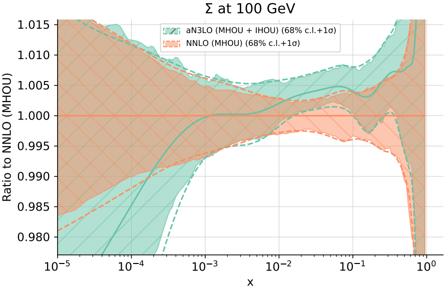
PDF matching conditions

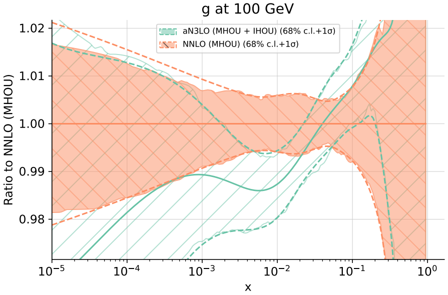
– all known except for $a^3_{H,g}$ [NPB 820 (2009) 417; NPB 886 (2014) 733; JHEP 12 (2022) 134]

Coefficient functions for other processes

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

aN^{3}LO PDFs [EPJ C84 (2024) 659]





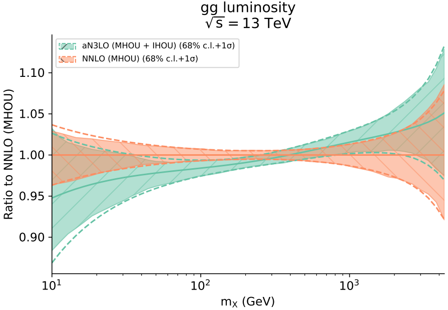
IHOU incorporated into
an independent covariance matrix
where nuisance parameters are averaged
over parametrisation variations

$\chi^2/N_{\rm dat} = 1.13$ (NNLO (MHOU))
$\chi^2/N_{\rm dat} = 1.13$ (aN^{3}LO (MHOU+IHOU))

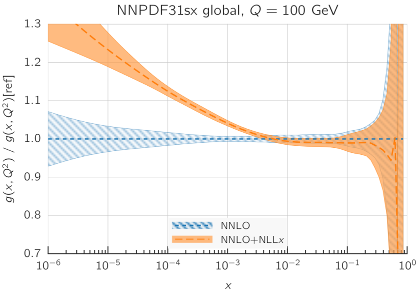
PDFs only affected at small x

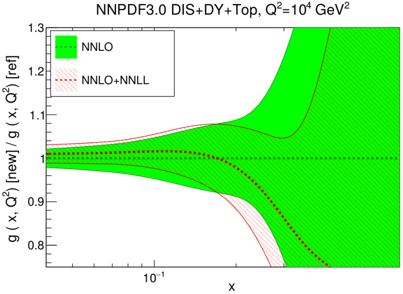
largest effect: 2% suppression in $\mathcal{L}_{gg}$
around the Higgs mass

[MSHT: EPJ C83 (2023) 185; benchmark arXiv:2406.16188]



Beyond fixed-order accuracy





small x: $\frac{1}{x}\ln^k x$
high-energy gluon emission: single logs

large x: $\left(\frac{\ln^k(1-x)}{(1-x)}\right)_+$
soft gluon emission: double logs

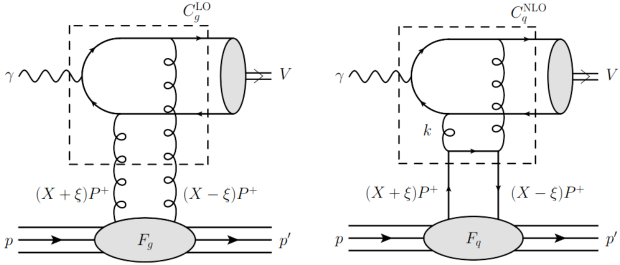
Large logs $\alpha_s \ln \sim 1$ spoil the convergence of the perturbative series

PDFs with threshold resummation [JHEP 1509 (2015) 191] (only DIS, DY Z/γ, total $t\bar{t}$ + evol.)
suppression in PDFs partially or totally compensates enhancements in partonic cross-sections
accuracy of the resummed fit competitive with the fixed-order fit, except for the large-x gluon

PDFs with high-energy (BFKL) resummation [EPJ C78 (2018) 321] (only DIS + evol.)
Resummed PDFs enhanced at small x, uncertainties reduced, fit quality improves
Large effects for future colliders, or b production at LHC
High-density effects modelled in CT18X; similar outcome on PDFs and fit quality

3. Quarkonia [See also C. Flett's talk on Thursday]

J/Ψ photoproduction



$$A = \frac{4\pi\sqrt{4\pi\alpha}e_q(\epsilon_V^*\cdot\epsilon_\gamma)}{N_c}\left(\frac{\langle O_1\rangle_V}{m_c^3}\right)^{1/2}\int_{-1}^{+1}\frac{dX}{X}\left[C_g(X,\xi)F_g(X,\xi)+C_q(X,\xi)F_q(X,\xi)\right]$$

$$\xi = \frac{p^+-p'^+}{p^++p'^+} = \frac{M_\psi^2}{2W^2-M_\psi^2} \qquad P = \frac{p+p'}{2}$$

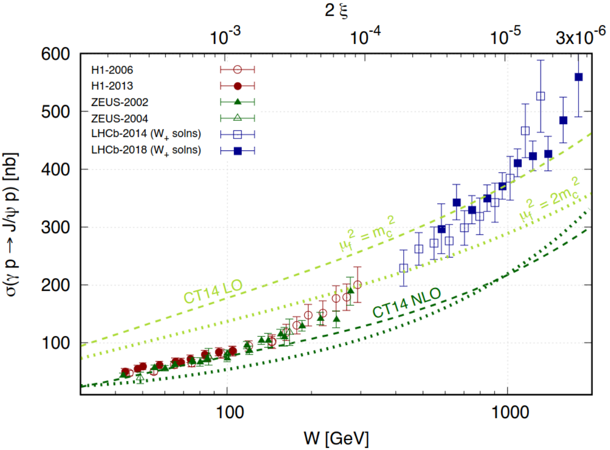
For $\xi < 10^{-3}$, GPDs can be related to PDFs via the Shuvaev transform [PRD 60 (1999) 014015]

Subtract the low $k_t < Q_0$ contribution from the NLO coefficient functions to avoid double counting of logs in the NLO coefficient function and in the PDF

$$A(\mu_F) = C^{\mathrm{LO}} \otimes GPD(\mu_F) + C^{\mathrm{NLO}}_{\mathrm{rem}} \otimes GPD(\mu_F)$$

With $\mu_F = M_\psi/2$, $C^{\mathrm{NLO}}_{\mathrm{rem}}(\mu_F)$ does not contain terms enhanced by $\ln(1/x) \simeq \ln(1/\xi)$

Description of the J/ψ data [PRD 102 (2020) 114021]



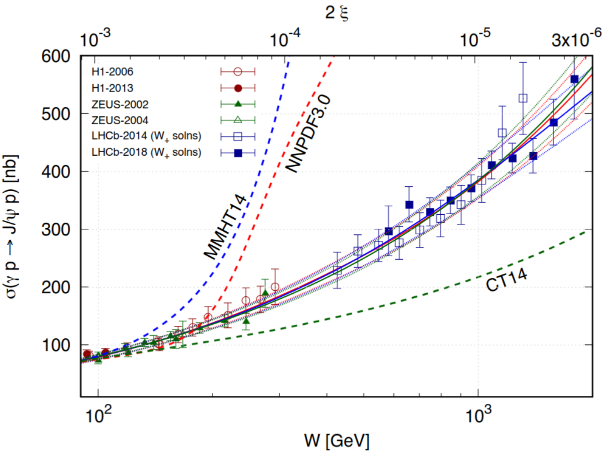
$$xg(x,\mu_0^2) = Cxg^{\rm global}(x,\mu_0^2) + (1-C)xg^{\rm new}(x,\mu_0^2) \text{ with } C = \frac{x^2}{x^2+x_0^2}$$

$$xg^{\rm new}(x,\mu_0^2) = nN_0(1-x)x^{-\lambda} \text{ and matching } x_0g^{\rm new}(x_0,\mu_0^2) = x_0g^{\rm global}(x_0,\mu_0^2)$$

$$\frac{\Re A}{\Im A} = \tan\left(\frac{\pi}{2}\frac{\partial(\ln \Im A/W^2)}{\partial(\ln W^2)}\right)$$

$\Im A$ computed at $t=0$; total cross section restored assuming an exponential t behaviour

Description of the J/ψ data [PRD 102 (2020) 114021]

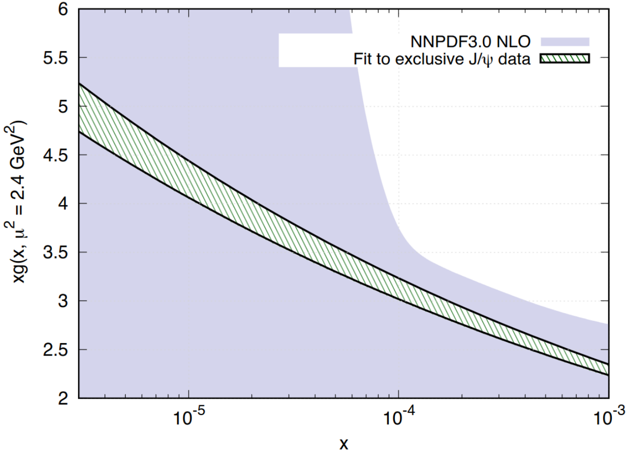


Perform a two-parameter $(\lambda; n)$ fit to the LHCb and HERA data with $x < 0.001$ using NNPDF3.0, MMHT14, and CT14

Same low-x gluon central values, with very similar χ^2

Excellent description of the J/ψ data

Impact of the J/ψ data [PRD 102 (2020) 114021]



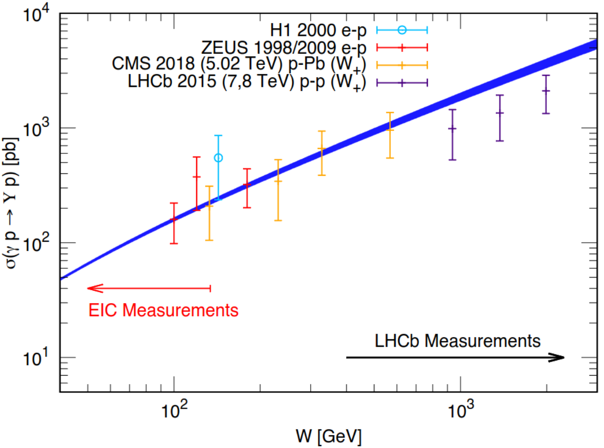
Bayesian reweighting of NNPDF3.0 NLO

Obvious reduction of gluon PDF uncertainty at small x

How well does this generalise to, say, Υ production?

Is the shape consistent with what one gets from reweighitng of D-meson data?

Predictions of exclusive Υ photoproduction [PRD 105 (2022) 034008]

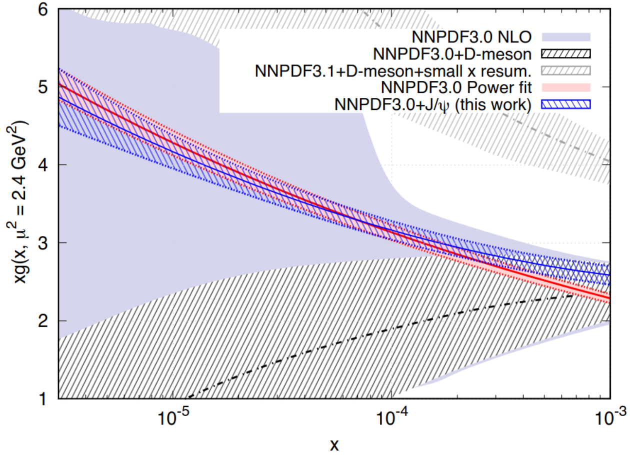


Exclusive Υ ultraperipheral photoporduction at the LHC and at the EIC

Same theoretical formalism as for exclusive J/ψ production

Very good generalisation of the small-x gluon PDF determined from J/ψ measurements and evolved to the Υ scale with standard DGLAP

Comparison with impact from D-meson data [PRD 102 (2020) 114021]



A much harder gluon is needed at small x to describe the J/ψ data

Gluon found from D meson data fails to describe the B meson distribution

Inconsistency of experimental measurements? Inaccuracy of the theory?

4. Conclusions

Summary

A precise and accurate determination of PDFs is key to Precision and Discovery

Current PDF sets may largely differ in precision, but are more or less equally accurate

Precision

LHC measurements are being instrumental to reduce PDF uncertainties to few percent

Good complementarity with other facilities (HL-LHC, EIC, FPF)

Accuracy

Refinement of the theoretical framework
(theory uncertainties, N^{3}LO corrections, resummation)

Largest effect on the gluon PDF at small/intermediate values of x

Quarkonia

Promising theoretical and phenomenological progress
towards inclusion of quarkonia in PDF determination

Need to revisit the data description in light of recent PDF determinations

Consider to extend the systematic inclusion of theory uncertainties in these studies

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Thank you

A. Additional material

Validation of PDF uncertainties

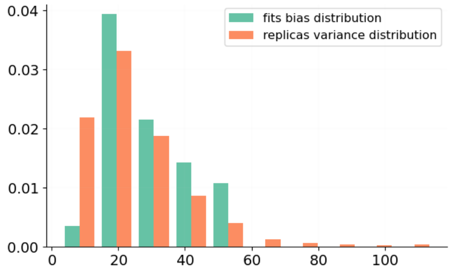
Data region: closure tests

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



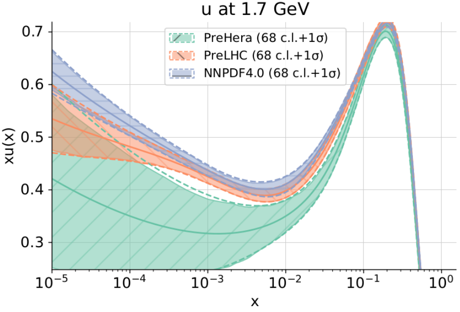
[EPJ C77 (2017) 663; EPJ C82 (2022) 330]

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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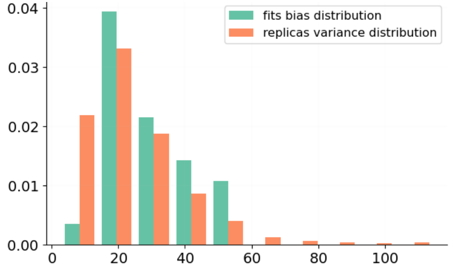


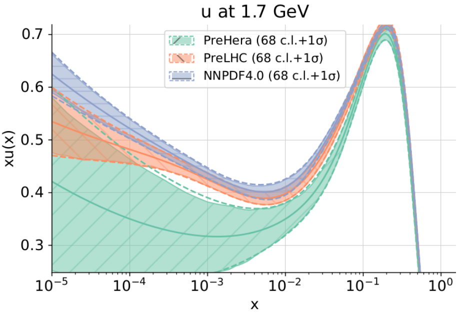
[EPJ C77 (2017) 663; EPJ C82 (2022) 330]

Extrapolation regions: future test

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

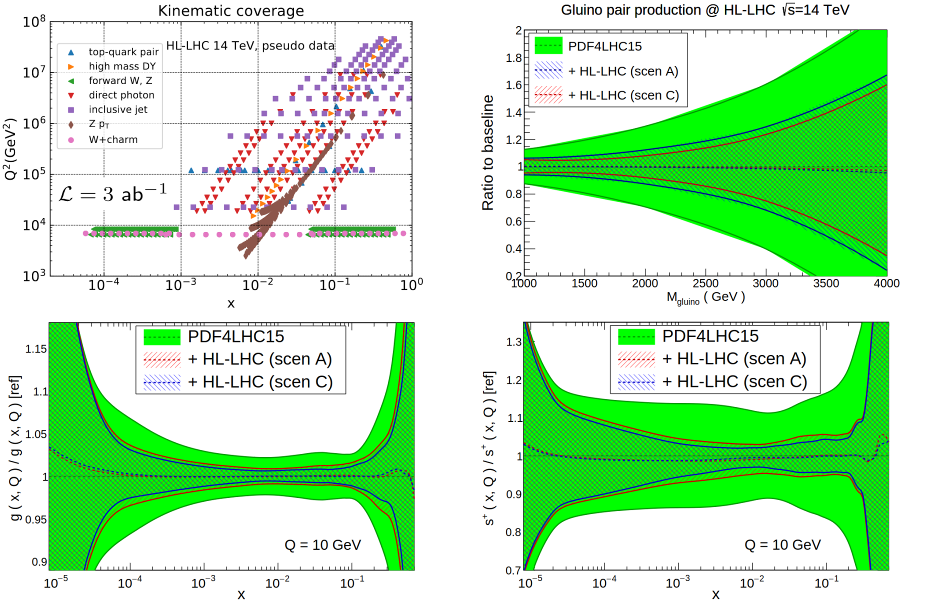
Data set	NNPDF4.0	pre-LHC	pre-HERA
pre-HERA			0.86
pre-LHC		1.17	1.22
NNPDF4.0	1.12	1.30	1.38

Exp+PDF cov. matrix



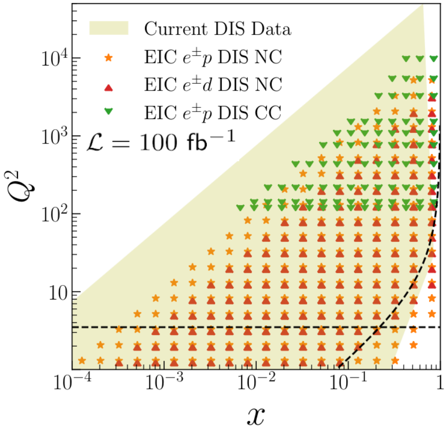
[Acta Phys.Polon. B52 (2021) 243]

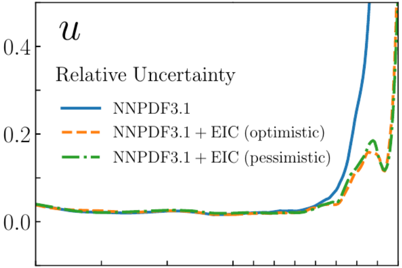
Impact of future data: HL-LHC

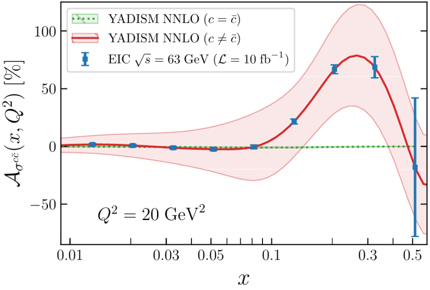


[EPJ.C 78 (2018) 962]

Impact of future data: EIC





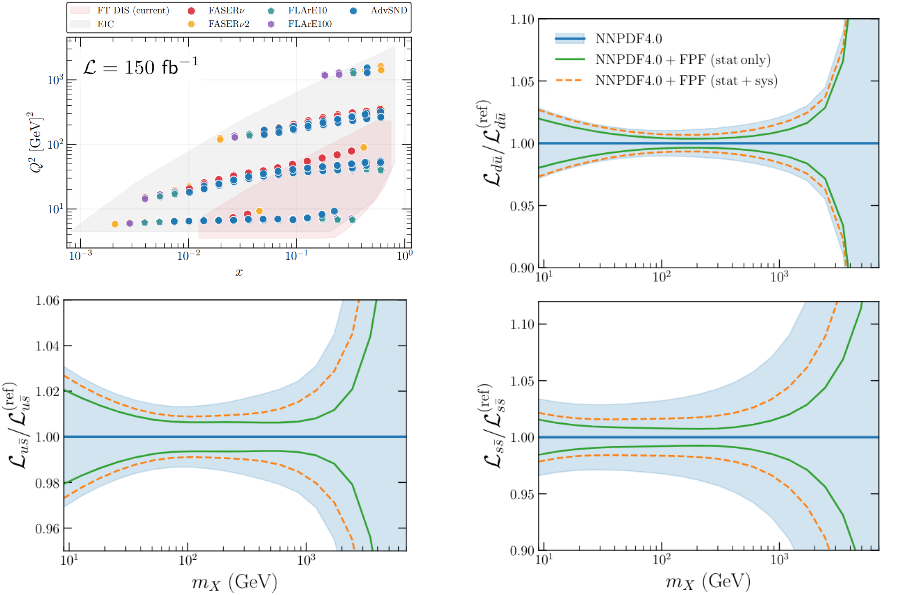


$E_\ell \times E_p$ [GeV]: 18× 275; 10× 100; 5× 100

$$\mathcal{A}_{\sigma^{c\bar{c}}} = \frac{\sigma^{c}_{\rm red} - \sigma^{\bar{c}}_{\rm red}}{\sigma^{c\bar{c}}_{\rm red}}$$

[PRD 103 (2021) 096005; see also arXiv:; arXiv:2311.00743]

Impact of future data: FPF



[arXiv:2309.09581; see T. Mäkelä's talk]

Fitting away New Physics

DIS [PRL 123 (2019) 132001]

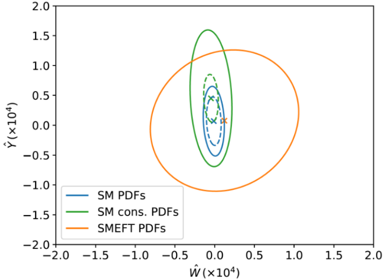
DY tails [JHEP 07 (2021) 122]

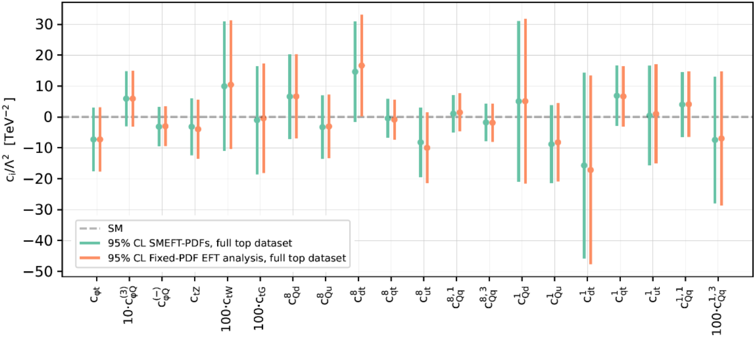
DIS/DY [JHEP 08 (2022) 088]

Jet/top [JHEP 05 (2023) 003]

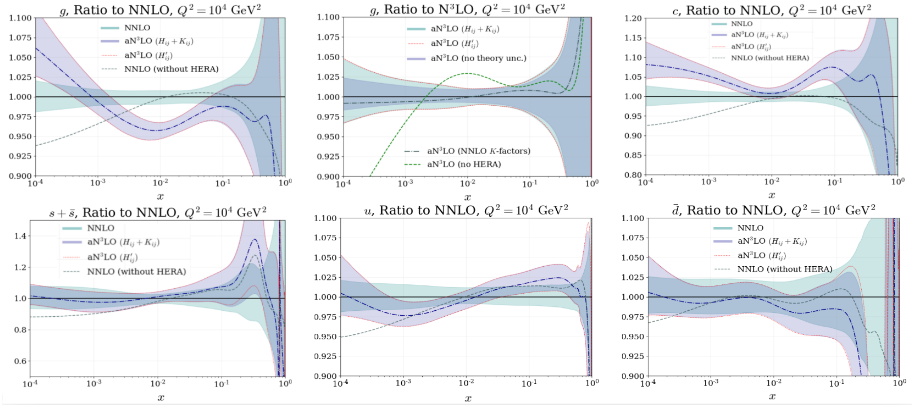
Jets [JHEP 02 (2022) 142]

Many more analyses by ATLASs, CMS, ...





aN^{3}LO PDFs — MSHT



[EPJ C83 (2023) 185; see also T. Cridge's talk]

3-5% correction on the gluon PDF at $x \sim 10^{-2}$

larger charm PDF (perturbatively generated)

inclusion of theory uncertainties may inflate PDF uncertainties at small x

inclusion of aN^{3}LO corrections generally improve the χ^2 of HERA and LHC jets

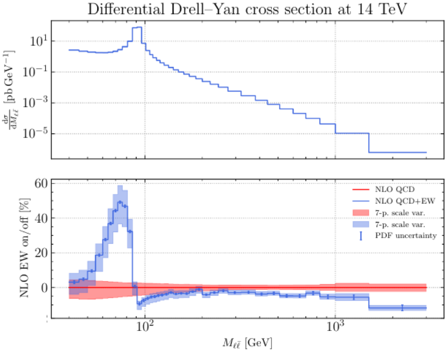
NLO EW corrections in PDF determination

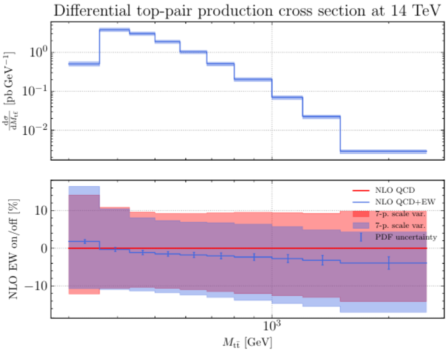
If we aim to PDF accurate to 1% NLO EW corrections do matter

especially as higher invariant mass and transverse momentum regions are accessed

Different approaches taken in general-purpose PDF fits

NLO EW K-factors (MSHT20); no NLO EW corrections by default (NNPDF4.0)





QED corrections in DGLAP evolution

[Com.Phys.Commun. 185 (2014) 1647]

Photon PDF

[PRL 117 (2016) 242002; JHEP 12 (2017) 046]

Photon PDF fits à la LuxQED

[SciPost Phys. 5 (2019) 1; JHEP 79 (2019) 10]

Automation of NLO EW corrections

[JHEP 07 (2018) 185]

Fast interpolation grids: PINEAPPL

[JHEP 12 (2020 108]

Careful scrutiny of data

(no FSR nor photon-initiated subtraction)