# Recommendations for PDF usage in LHC predictions $\rightarrow$ A critical appraisal and evaluation of modern PDFs

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

**mainly on the basis of**
**EPJC 76 (2016) 471 [arXiv:1603.08906]**

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# Outline

* Introduction
* light quark PDFs
* heavy quark treatment
* gluon PDFs
* $\alpha_S$
* Recommendations for PDF usage at LHC

# QCD factorization theorem

∗ Standard collinear factorization formalism (Catani-Soper-Sterman):

$$\sigma_{H_1 H_2 \to X}(S) \;=\; \sum_{i,j} \int dx_1 dx_2 f_{i/H_1}(x_i, \mu_F) f_{j/H_2}(x_j, \mu_F) \hat{\sigma}_{ij \to X}(x_i p_1, x_j p_2, \hat{s}; \alpha_S, \mu_R, \mu_F, M_X)$$

where

$x_i = p_{z,i}/p_{z,H_1}$ = Bjorken variable

$\mu_F$ = factorization scale: separates long-distance physics (non-perturbative QCD) from short-distance physics (perturbative QCD).

$f_{i/H_1}(x_i, \mu_F)$ = PDFs (long-distance physics) reabsorb infrared collinear singularities uncancelled within the hard-scattering and are universal (process independent). At a given scale, they are non-perturbative objects, but their evolution with $\mu_F$ is governed by perturbation theory (DGLAP equations).

List of publicly available PDFs:
∗ **CJ15** (up to NLO),
∗ **ABM12, CT14, HERAPDF2.0, JR14, MMHT14, NNPDF3.0** (up to NNLO).
+ variants (ABMP16, PROSA,....) under developments

# Differences between different PDF fits

Differences between different PDF fits come mainly from:

* theory input
  (to calculate quantities to be compared to experimental data)
* experimental data used in the fits
* PDF parameterization
* best fit criterium and statistical uncertainty treatment
* theory uncertainties considered
* heavy-flavour treatment
* $\alpha_S$ treatment
* treatment of nuclear corrections

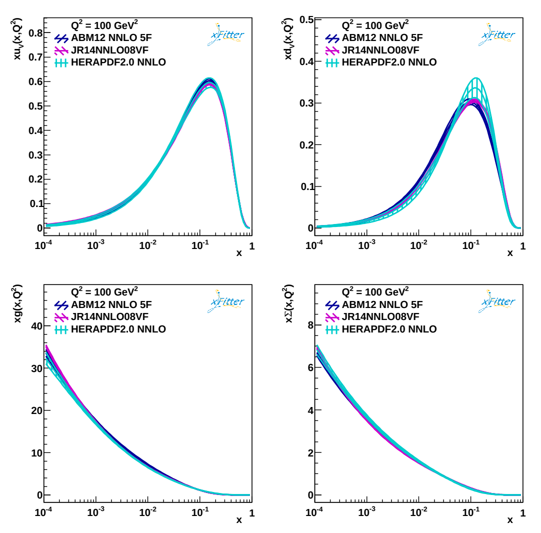
# Experimental data used in PDF fits

| PDF sets | $\Delta\chi^2$ criterion | data sets used in analysis |
|---|---|---|
| ABM12 | 1 | incl. DIS, DIS charm, DY |
| CJ15 | 1 | incl. DIS, DY (incl. $p\bar{p} \to W^{\pm}X$), $p\bar{p}$ jets, $\gamma$+jet |
| CT14 | 100 | incl. DIS, DIS charm, DY, $p\bar{p}$ jets, $pp$ jets |
| HERAPDF2.0 | 1 | incl. DIS, DIS charm, DIS jets [only HERA data] |
| JR14 | 1 | incl. DIS, DIS charm, DY, $p\bar{p}$ jets, DIS jets |
| MMHT14 | $2.3 \ldots 42.3$ (dynamical) | incl. DIS, DIS charm, DY, $p\bar{p}$ jets, $pp$ jets, $t\bar{t}$ |
| NNPDF3.0 | n.a. | incl. DIS, DIS charm, DY, $p\bar{p}$ jets, $pp$ jets, $t\bar{t}$, $W+$c |

**Table :** Summary of major hard processes used in the various PDF analyses and the confidence level criteria employed.

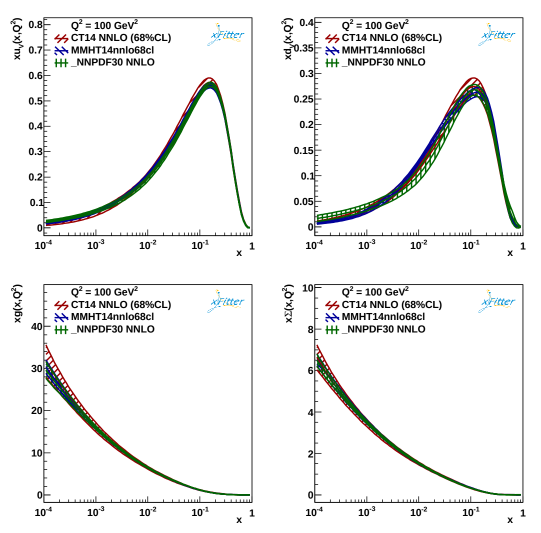
**Different PDF fits differ for the use of different data sets.**

# Examples of modern PDFs behaviour at varying $x$




*from A. Accardi et al., [arXiv:1603.08096]*

# Examples of modern PDFs behaviour at varying $x$




*from A. Accardi et al., [arXiv:1603.08096]*

# Light quark PDFs and Drell-Yan data

| Experiment | | ATLAS | | CMS | | D0 | |
|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ (TeV) | | 7 | 13 | 7 | 8 | 1.96 | |
| Final states | | $W^+ \to l^+\nu$ <br> $W^- \to l^-\nu$ <br> $Z \to l^+l^-$ | $W^+ \to l^+\nu$ <br> $W^- \to l^-\nu$ <br> $Z \to l^+l^-$ | $W^+ \to \mu^+\nu$ <br> $W^- \to \mu^-\nu$ | $W^+ \to \mu^+\nu$ <br> $W^- \to \mu^-\nu$ | $W^+ \to \mu^+\nu$ <br> $W^- \to \mu^-\nu$ | $W^+ \to e^+\nu$ <br> $W^- \to e^-\nu$ |
| Cut on the lepton $P_T$ | | $P_T^l > 20$ GeV | $P_T^l > 25$ GeV | $P_T^\mu > 25$ GeV | $P_T^\mu > 25$ GeV | $P_T^\mu > 25$ GeV | $P_T^e > 25$ GeV |
| *NDP* | | 30 | 6 | 11 | 22 | 10 | 13 |
| $\chi^2$ | ABMP16 | 31.0 | 9.2 | 22.4 | 16.5 | 17.6 | 19.0 |
| | CJ15 | – | – | – | – | 20 | 29 |
| | CT14 | 42 | – | – | – | – | 34.7 |
| | JR14 | – | – | – | – | – | – |
| | HERAPDF | – | – | – | – | 13 | 19 |
| | MMHT14 | 39 | – | – | – | 21 | – |
| | NNPDF3.0 | 35.4 | – | 18.9 | – | – | – |

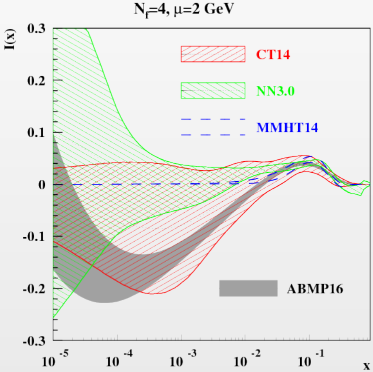
The data on $W$- and $Z$-production in $pp$ and $\bar{p}p$ collisions and the $\chi^2$ values obtained for these data sets in different PDF fits.

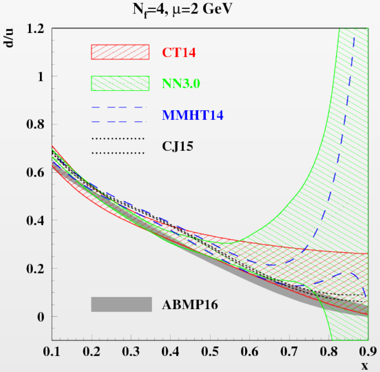
* Exp. data on $e$ and $\mu$ charge asymmetries as a function of $e$ and $\mu$ pseudorapidity.
* Exp. statistical accuracy (ranging from a few per mill to $\sim 1\%$) challenges the accuracy of numerical integration in theoretical predictions.
* $\chi^2$ sensitive to the theoretical approximation:
  NNLO / NNLL / NLO + NNLO K-factors.....

*S. Alekhin et al., [arXiv:1609.03327]*

# Light quark PDFs: $u/d$ ratio at large $x$ and sea isospin asymmetry

Drell-Yan (+ HERA DIS + fixed-target DIS) data allow to separate contributions of $u$ and $d$ quarks for $x \in [10^{-4}$ - $0.9]$ and to extract $d$ distribution at large $x$, eliminating the uncertainties due to deuteron DIS data.



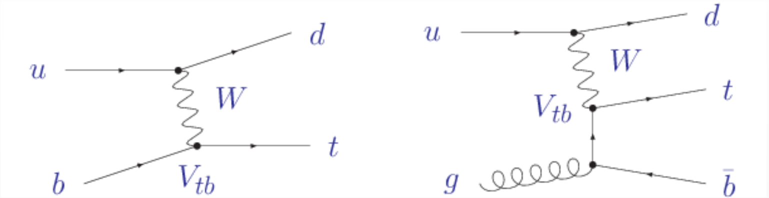



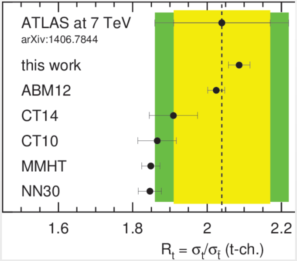

sea isospin asymmetry $I(x) = x[\bar{d}(x) - \bar{u}(x)]$
$\neq 0$ even for $x \sim 10^{-4}$

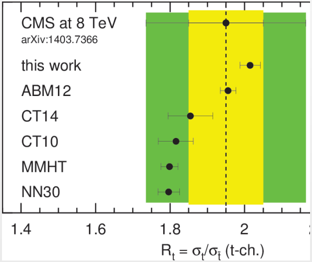
*S. Alekhin et al., [arXiv:1609.03327]*

# Light quark PDFs and single-top hadroproduction

## (t-channel)




* Systematical uncertainties largely cancel in ratios $\sigma_t/\sigma_{\bar{t}}$.
* $R_t$ theory predictons sensitive to ratio $d/u$ in PDFs.

*S. Alekhin et al., [arXiv:1508.07923]*

# Heavy-quark $\sigma$'s and FNS: FFNS vs VFNS

$*$ FFNS: heavy-quark assumed to be massive at all energy scales.
Good: power corrections $Q^2/m_h^2$ included.
Bad: potential large logarithms $\alpha_S^l \, ln^k(Q^2/m_h^2)$ with $1 \leq k \leq l$ at large $Q^2$.

$*$ GM-VFNS: effectively resums the logs by a transition in the number of active flavours $n_f \rightarrow n_f + 1$ above a given threshold. Different implementations of the transition possible:

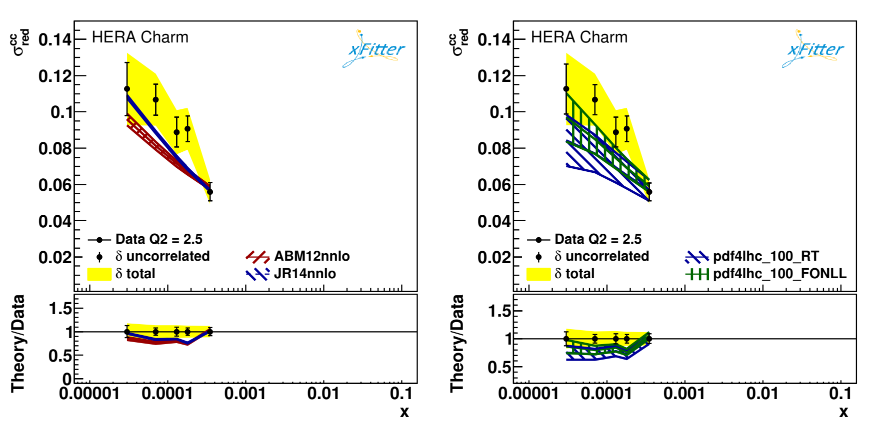
- BSMN prescription for $F_2^h$:

$$F_2^{h,BMSN}(n_f+1, x, Q^2) = F_2^{h,exact}(n_f, x, Q^2) + \{\mathrm{F}_2^{h,ZM-VFNS}(n_f, x, Q^2) - F_2^{h,asymp}(n_f, x, Q^2)\}$$

Difference in $\{\}$ has to vanish at threshold ($Q^2 \sim m_h^2$):

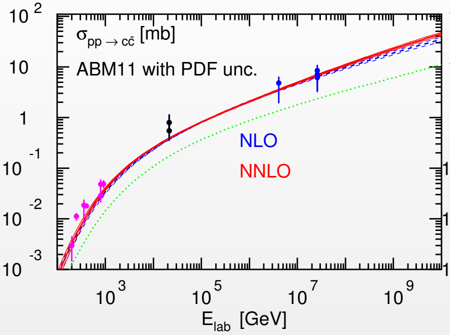
- ACOT: S-ACOT-$\chi$ slow rescaling $x \rightarrow \chi(x) = x(1 + 4m_h^2/Q^2)$
- FONLL: suppression of $\{\}$ by damping factor $(1 + m_h^2/Q^2)$
- RT: continuity of physical observables at threshold
- .....

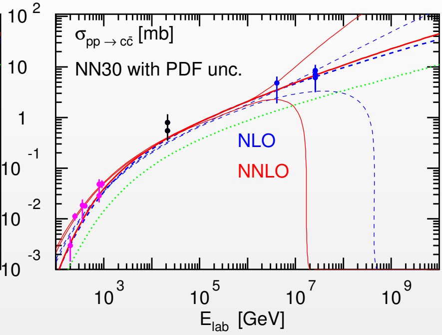
# charm DIS $\sigma_{red}^{cc}$: FFNS vs VFNS




* FFNS does not behave worse than GM-VFNS.
* PDF4LHC mixes PDFs derived with different GM-VFNS (ACOT, FONNL and RT).
* extraction of $m_{charm}$ value depends on the FNS scheme.

# $\sigma(pp \to c\bar{c})$: PDFs and their behaviour at low Bjorken $x$

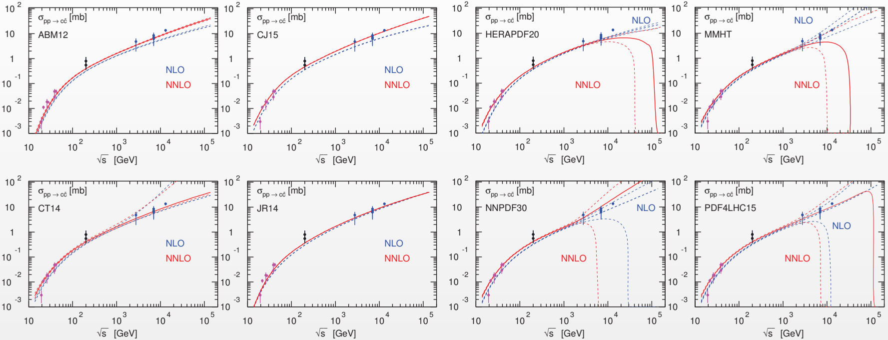



$*$ Probing higher energies allows to probe smaller $x$ region, down to values where no data constrain PDFs yet (at least at present).

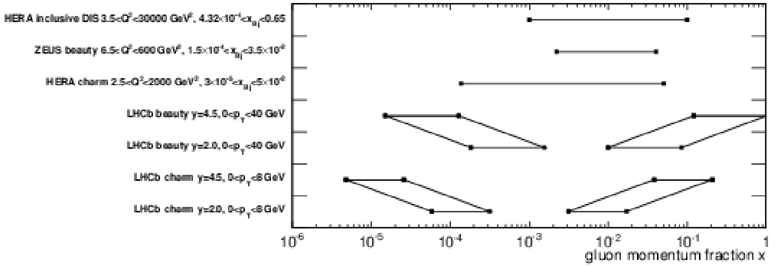
$*$ Different behaviour of different PDF parameterizations:
- ABM parameterization + $F_L$ data constrains PDFs at low $x$;
- NNPDF parameterization in LHAPDF reflects the absence of constraints from experimental data at low $x$.

# $\sigma(pp \to c\bar{c})$: PDFs and their behaviour at low Bjorken $x$




Some PDFs predict unphysical negative cross-sections at NNLO.

# $x$ dependence of gluon PDFs

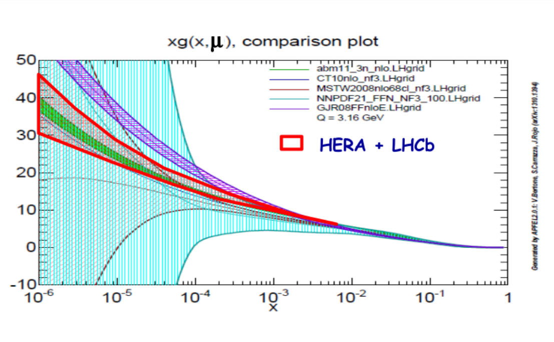



*from O. Zenaiev et al. (PROSA collaboration), [arXiv:1503.04581]*

- LHCb ($p$-$p$) acts as a complementary experiment with respect to HERA ($e$-$p$) in order to constrain PDFs.
- Additional constraints come from other LHC experiments.
- At present PDF behaviour in the "extreme" regions (low-$x$ and high-$x$) is more uncertain than in the intermediate-$x$ range.
- The higher is the energy of a hadronic collision, the higher is the probability that partons in the "extreme" regions partecipate in it.

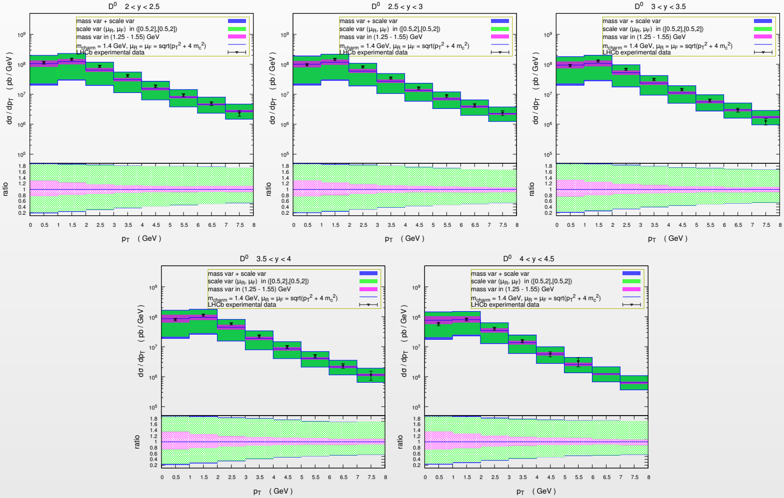
# PROSA PDF fit [O. Zenaiev, A. Geiser et al. [arXiv:1503.04585]]

First fit already including some LHCb data (charm and bottom) appeared in arXiv.




- ∗ **ABM** PDFs, although non including any info from LHCb, in agreement with **PROSA** fit → good candidates for ultra-high-energy applications.
- ∗ **CT10** PDFs in marginal agreement with PROSA fit.
- ∗ **NNPDF** PDFs: at present still the largest uncertainties, at least when looking to the public release available in LHAPDF, they have recenly worked at incorporating PROSA idea in their fit as well (Gauld et al. [arXiv:1506.08025]).

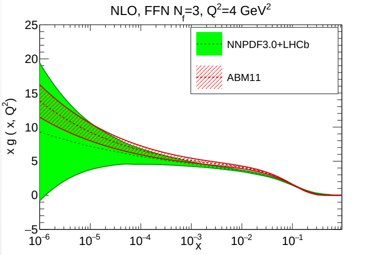
# Comparison of theoretical predictions using ABM PDFs with LHCb data on $pp \to D^0 + X$

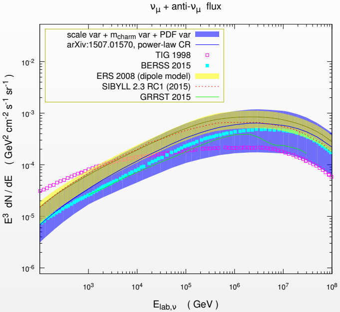


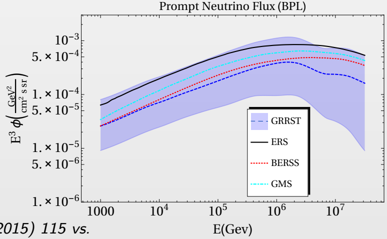

Data within theoretical uncertainties in all measured rapidity bins

(LHCb coverage : $2 < |y| < 4.5$)

# Application: prompt neutrino fluxes




*Garzelli, Moch, Sigl JHEP 1510 (2015) 115 vs.*

*Gauld, Roho, Rottoli et al. JHEP 1602 (2016) 130*

# Strong coupling constant $\alpha_S(M_Z)$

| | | |
|---|---|---|
| ABM12 | $0.11320 \pm 0.0011$ | fit at NNLO |
| CJ15 | $0.11830 \pm 0.0002$ | fit at NLO |
| CT14 | 0.118 | assumed at NNLO |
| HERAPDF2.0Jets | $0.1183 +0.0040 -0.0034$ | fit at NLO |
| JR14 | $0.11360 \pm 0.0004$<br>$0.11620 \pm 0.0006$ | dynamical fit at NNLO<br>standard fit at NNLO |
| MMHT14 | 0.118 | assumed at NNLO |
| NNPDF3.0 | $0.115 - 0.121$ | assumed at NNLO; preferred value 0.118 |
| PDF4LHC15 | 0.118 | assumed at NNLO |

Values of $\alpha_s(M_Z)$ obtained or used in the nominal PDF sets of the various groups.

$\alpha_S^{\mathrm{PDG}} = 0.1181 \pm 0.0013$

Most updated simultaneous extraction of $\alpha_S$, $m_c$, $m_b$, $m_t$, by ABM12 PDFs:

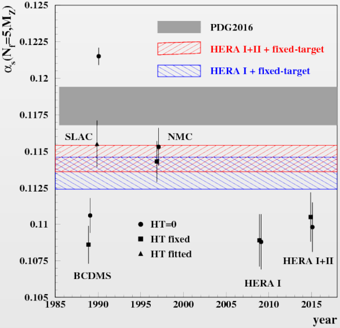
$\alpha_S = 0.1147 \pm 0.0008$

$m_c(m_c) = 1.252 \pm 0.018\,GeV$

$m_b(m_b) = 3.83 \pm 0.12\,GeV$

$m_t(m_t) = 160.9 \pm 1.1\,GeV$

*S. Alekhin et al. [arXiv:1609.07417]*



# Higgs production in $gg$ fusion

| PDF sets | $\sigma(H)^{\rm NNLO}$ [pb] nominal $\alpha_s(M_Z)$ | $\sigma(H)^{\rm NNLO}$ [pb] $\alpha_s(M_Z) = 0.115$ | $\sigma(H)^{\rm NNLO}$ [pb] $\alpha_s(M_Z) = 0.118$ |
|---|---|---|---|
| ABM12 | $39.80 \pm 0.84$ | $41.62 \pm 0.46$ | $44.70 \pm 0.50$ |
| CJ15 | $42.45 \, ^{+\,0.43}_{-\,0.18}$ | $39.48 \, ^{+\,0.40}_{-\,0.17}$ | $42.45 \, ^{+\,0.43}_{-\,0.18}$ |
| CT14 | $42.33 \, ^{+\,1.43}_{-\,1.68}$ | $39.41 \, ^{+\,1.33}_{-\,1.56}$ (40.10) | $42.33 \, ^{+\,1.43}_{-\,1.68}$ |
| HERAPDF2.0 | $42.62 \, ^{+\,0.35}_{-\,0.43}$ | $39.68 \, ^{+\,0.32}_{-\,0.40}$ (40.88) | $42.62 \, ^{+\,0.35}_{-\,0.43}$ |
| JR14 (dyn) | $38.01 \pm 0.34$ | $39.34 \pm 0.22$ | $42.25 \pm 0.24$ |
| MMHT14 | $42.36 \, ^{+\,0.56}_{-\,0.78}$ | $39.43 \, ^{+\,0.53}_{-\,0.73}$ (40.48) | $42.36 \, ^{+\,0.56}_{-\,0.78}$ |
| NNPDF3.0 | $42.59 \pm 0.80$ | $39.65 \pm 0.74$ $(40.74 \pm 0.88)$ | $42.59 \pm 0.80$ |
| PDF4LHC15 | $42.42 \pm 0.78$ | $39.49 \pm 0.73$ | $42.42 \pm 0.78$ |

**Table :** The Higgs cross section at NNLO in QCD (computed in the effective theory $m_t >> m_H$) at $\sqrt{s} = 13$ TeV for $m_H = 125.0$ GeV at the nominal scale $\mu_r = \mu_f = m_H$ with the PDF (and, if available, also $\alpha_s$) uncertainties. The columns correspond to different choices for the central value of $\alpha_s(M_Z)$ using the nominal PDF set. The numbers in parenthesis are obtained using the PDF sets `CT14nnlo_as_0115`, `HERAPDF20_NNLO_ALPHAS_115`, `MMHT2014nnlo_asmzlargerange` and `NNPDF30_nnlo_as_0115`.

**(PDF + $\alpha_S$) uncertainties $\sim \mathcal{O}(10\%)$ are larger than residual QCD uncertainty ($\sim 3\%$, with $N^3LO$ predictions available)**

# Higgs production in $gg$ fusion

| PDF sets | $m_c^{\text{pole}}$ [GeV] | $\alpha_s(M_Z)$ (fixed) | $\chi^2$/NDP (HERA DIS charm data) | $\sigma(H)^{\text{NNLO}}$ [pb] fixed $\alpha_s(M_Z)$ |
|---|---|---|---|---|
| NNPDF2.1 | $\sqrt{2}$ | 0.119 | $65/52$ | $44.18 \pm 0.49$ |
| | 1.5 | 0.119 | $78/52$ | $44.54 \pm 0.51$ |
| | 1.6 | 0.119 | $92/52$ | $44.74 \pm 0.50$ |
| | 1.7 | 0.119 | $110/52$ | $44.95 \pm 0.51$ |
| NNPDF2.3 | $\sqrt{2}$ | 0.118 | $71/52$ | $43.77 \pm 0.41$ |
| NNPDF3.0 | 1.275 | 0.118 | $67/52$ | $42.59 \pm 0.80$ |

**Table :** Values of charm-quark pole mass and $\alpha_s(M_Z)$ for various NNPDF analyses, together with the value of $^2$/NDP for the HERA DIS charm data and the Higgs cross-section at NNLO in QCD (in the limit $m_t >> m_h$) for $\sqrt{s} = 13$ TeV, and $\mu_R = \mu_F = m_H$. The values of the strong coupling $\alpha_s(M_Z)$ have been fixed in those fits. The values of $\chi^2$/NDP for the description of the HERA charm data have been determined with the FONLL-C scheme.

- NNPDF PDF fits to HERA charm data prefer small values of $m_c^{\text{pole}}$ (in contradiction with the most updated $m_c^{MSbar}(m_c)$ values quoted in the PDG).
- Higgs cross-section increases linearly with charm mass.
- Similar trend also observed for MSTW and MMHT PDFs.

# Recommendations for PDF usage at LHC

*"For precision physics at LHC, use as many different individual recent PDF sets as possible, together with the respective uncertainties for the chosen PDF set, the strong coupling constant $\alpha_S(M_Z)$, and the heavy-quark masses $m_c$, $m_b$ and $m_t$. Once a PDF set is updated, the most recent version should be used."*

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Risks of using PDF4LHC PDFs and PDF4LHC recommendations published in J. Phys. G 43 (2016) 023001:

1) do not take into account predictions of all PDF groups:
potential underestimate of the uncertainties.

2) do not take into proper account correlations between $\alpha_S(M_Z^2)$,
heavy-quark and $W$ masses and the PDF fit parameters:
these quantities have to be extracted simultaneously
when performing PDF fits.