EW Corrections in PDFs

Christopher Schwan

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Where do EW correction enter PDF fits?

PDF fitting in a nutshell: theory predictions

$$\text{MC} \to \left\{\sigma_{ab}(x_1, x_2, Q^2)\right\}_{a,b,x_1,x_2,Q^2} \xrightarrow{\text{DGLAP}} \left\{\tilde{\sigma}_{ab}(x_1, x_2, Q_0^2)\right\}_{a,b,x_1,x_2} \to \text{fit } \left\{f_a(x, Q_0^2)\right\}_{a,x}$$

EW corrections concern 3 points:

1. evolution equations: QED corrections/full EW corrections in DGLAP
2. parton definition: photon, leptons, massive gauge bosons, top quark, . . . in the hadron
3. fixed-order corrections: NLO EW + NNLO QCD for Drell–Yan W/Z, . . .

$$\sigma_{\mathrm{pp}\to X} = \sum_{a,b} \int \mathrm{d}x_1 \mathrm{d}x_2 \mathrm{d}Q^2 f_a(x_1, Q^2) f_b(x_2, Q^2) \sigma_{ab}(x_1, x_2, Q^2)$$

$$= \sum_{a,b} \int \mathrm{d}x_1 \mathrm{d}x_2 \quad f_a(x_1, Q_0^2) f_b(x_2, Q_0^2) \tilde{\sigma}_{ab}(x_1, x_2, Q_0^2)$$

$$\sigma_{ab}(x_1, x_2, Q^2) = \sum_{n,m} \alpha_s^n(Q^2) \alpha^m \sigma_{ab}^{n,m}(x_1, x_2, Q^2)$$

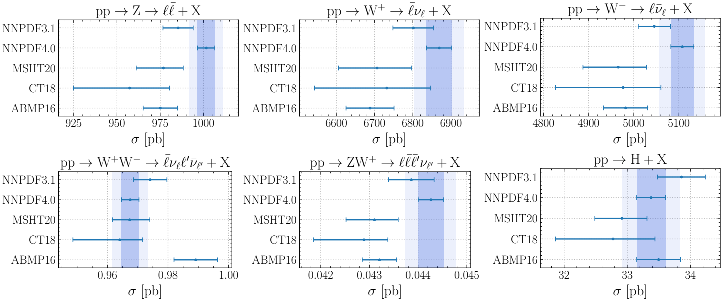
Why do we need EW corrections in PDFs?

→ PDFs are becoming more and more precise, due to

- more data (LHC 7, 8, 13 TeV),
- more precise measurements,
- better methodologies, ...

- but we (mostly) neglect EW corrections. Impact with EW corrections?
  - enlarged phase space: large $M_{\ell\bar{\ell}}$ in DY
  - impact of observables affected by large EW corrections? large x?
  - PDF uncertainties?

A few (NLO) integrated cross section with PDF uncertainties for LHC @ 14 TeV:

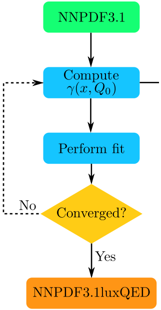


Status quo: global PDF sets with QED corrections and photon PDF

- "LO EW" PDFs with QED in DGLAP + photon PDF:
  - CT18qed/lux [K. Xie, T.J. Hobbs, T.-J. Hou, C. Schmidt, M. Yan, C.-P. Yuan]
  - MSHT20qed [T. Cridge, L.A. Harland-Lang, A.D. Martin, R.S. Thorne]
  - NNPDF3.1luxQED [V. Bertone, S. Carrazza, N.P. Hartland, J. Rojo]

DGLAP:

- $\mathcal{O}(\alpha)$
- $\mathcal{O}(\alpha_s \alpha)$ [D. de Florian et al.]
- $\mathcal{O}(\alpha^2)$ [D. de Florian et al.]



LUXqed [A. Manohar] [A. Manohar et al.]:

$$x\gamma(x, Q_0^2) = \frac{1}{2\pi\alpha(\mu)} \int_x^1 \frac{\mathrm{d}z}{z} \left\{ \int_{m_\mathrm{p}^2 x^2/(1-z)}^{\mu^2/(1-z)} \frac{\mathrm{d}Q^2}{Q^2} \alpha^2(Q^2) \left[-zF_\mathrm{L}(x/z, Q^2) + \left(zP_{\gamma\mathrm{q}}(z) + \frac{2x^2 m_\mathrm{p}}{Q^2} \right) F_2(x/z, Q^2) \right] - \alpha^2(\mu) z^2 F_2(x/z, \mu^2) \right\} + \mathcal{O}(\alpha_s \alpha, \alpha^2)$$

or similar formulae for variants of it [L.A. Harland-Lang et al.]

Momentum sum rule:

$$\int \mathrm{d}x \left(\Sigma(x, Q_0^2) + g(x, Q_0^2) + \gamma(x, Q_0^2) \right) = 1$$

- MSHT20 [S. Bailey et al.]: NLO EW K-factors for some processes
- LUXlep [L. Buonocore et al.]: leptons in the proton

What is left to do?

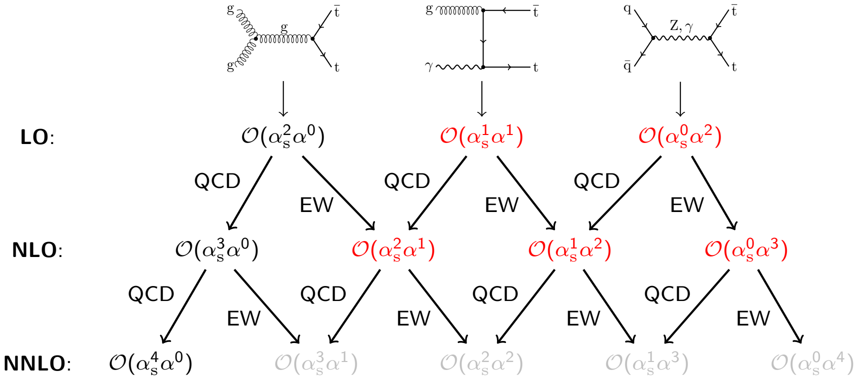
→ PDF fit with NLO EW corrections for all/most PDF processes

- fully differential predictions or K factors?

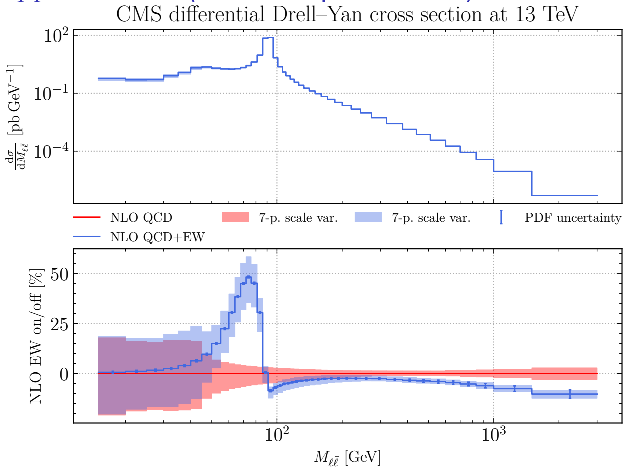
→ Use measurements matching our predictions

  - Born- vs. dressed lepton observables
  - Other subtractions from data

- Data selection: how much inconsistency do we tolerate?



NLO EW for $\mathrm{pp} \to \ell\bar{\ell} + X$ ("Z-boson production")

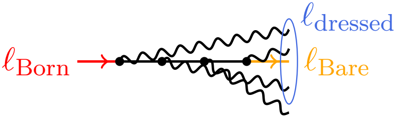


- predictions for CMS 13 TeV $L = 2.8\,\mathrm{fb}^{-1}$ [CMS Collaboration]
- very large FSR (QED) corrections around M_Z due to very small bins
- photon shower needed?
- weak correction in the tail
- uncertainty band increases for $M_{\ell\bar{\ell}} \lessapprox M_Z$ with NLO EW → PDF + theory uncertainties

FSR: Born- vs. dressed-lepton observables

large FSR effects in DY, but in purely QCD corrections not covered

1. either predict extra photon radiation in theory → dressed-leptons, post-FSR observables,
2. or "remove" photon radiation in data → Born-leptons, pre-FSR observables.



- Only charged object is the lepton: bare lepton
- Add photons around some ΔR of the lepton: dressed lepton
- Lepton before it radiates: Born lepton

→ predictions must match measurements:

1. either purely strong corrections and Born-leptons,
2. or QCD+EW corrections and dressed-leptons (preferred option here),
3. or QCD+purely weak corrections and Born-leptons,
4. or a double-counting problem
5. or throw measurements away!

. . . more double-counting problems (backup slides):

- $\gamma\gamma$ subtraction in DY,
- t-channel single top-quark production,
- DIS and EW corrections, . . .

→ find a compromise between consistency and data size!

K factors vs. interpolation grids

Should one use K factors or interpolation grids in PDF fits?

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \sum_{a,b} \int \mathrm{d}x_1 \int \mathrm{d}x_2 \int \mathrm{d}Q^2 \, f_a(x_1, Q^2) f_b(x_2, Q^2) \frac{\mathrm{d}\sigma_{ab}}{\mathrm{d}\mathcal{O}}(x_1, x_2, Q^2)$$

$$\approx \sum_{a,b} \sum_{i,j,k} f_a\left(x_1^i, Q_k^2\right) f_b\left(x_2^j, Q_k^2\right) \frac{\mathrm{d}\sigma_{ab}}{\mathrm{d}\mathcal{O}} \left(x_1^i, x_2^j, Q_k^2\right)$$

$$\frac{\mathrm{d}\sigma_{ab}}{\mathrm{d}\mathcal{O}}\left(x_1^i, x_2^j, Q_k^2\right) = \sum_{n,m} \alpha_\mathrm{s}^n(Q_k^2) \alpha^m \frac{\mathrm{d}\sigma_{ab}^{n,m}}{\mathrm{d}\mathcal{O}} \approx K \sum_{n',m'} \alpha_\mathrm{s}^{n'}(Q_k^2) \alpha^{m'} \frac{\mathrm{d}\sigma_{ab}^{n',m'}}{\mathrm{d}\mathcal{O}}$$

Advantages of interpolation grids:

- fully differential: correct channel (a, b) dependence
- truly PDF independent
- correct scale variation easy to get
- K factors can be calculated from grids

Disadvantages:

- interpolation code for arbitrary FO calculation in $\alpha_\mathrm{s}^n \alpha^m$ needed

K factors vs. interpolation grids—CMS DY 13 TeV

→ Are EW corrections channel dependent?

CMS DY 13 TeV (as show before):

- last invariant-mass bin: $M_{\ell\bar{\ell}} \in [1500, 3000]$GeV with NNPDF3.1luxQED, $\mu = M_{\ell\bar{\ell}}$
- total $K_{\mathrm{EW}} = \mathcal{O}(\alpha^3)/\mathcal{O}(\alpha^2) = -12\,\%$

Channel	NLO fraction	K_{EW}
$\mathrm{u\bar{u} + c\bar{c}}$	74 %	−14 %
$\mathrm{d\bar{d} + s\bar{s}}$	24 %	−9 %
$\gamma\gamma$	5.8 %	2.5 %
$\mathrm{ug + cg}$	−3 %	0 %
⋮	⋮	⋮

- $\mathrm{ug + cg}$: non-zero at $\mathcal{O}(\alpha_{\mathrm{s}}\alpha^2)$ → zero $\mathcal{O}(\alpha^3)$ correction
- K factor strongly channel-dependent
- might be an extreme case
- whether this is significant depends on experimental uncertainties, . . .

→ interpolation grids are the safe choice, developed PineAPPL [S. Carazza, E.R. Nocera, C.S., M. Zaro]

Summary

NLO EW for PDF processes:

- size of EW corrections can be large, e.g. in DY
- in DY strongly dependent on the bin sizes

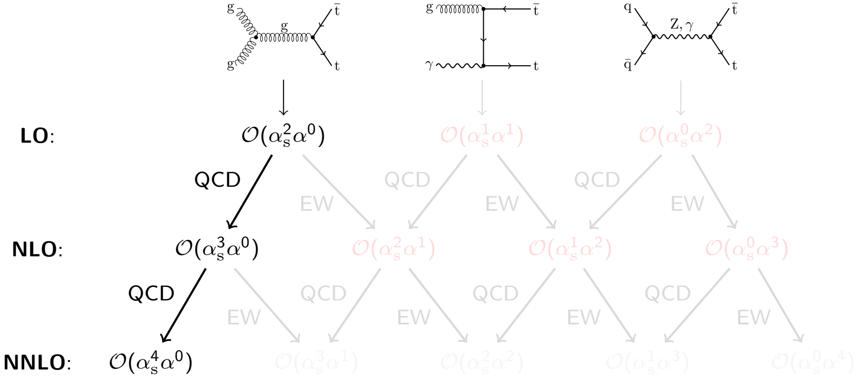
Data and theory issues:

- Born-lepton and dressed-lepton observables in purely QCD and QCD+EW fits, respectively: otherwise double counting
- proper observable definitions: $\gamma\gamma$-initiated contributions, single-top production, ...
- realistic fit: compromise between correctness and dataset size (DIS and EW corrections)

Tools:

- PineAPPL: interpolation grids for any FO calculation
- toolchain for producing theory predictions available: `https://github.com/NNPDF/runcards`
- calculated corrections for all LHC processes (see backup slides)
- we'll publish all of our grids at some point

The (N)NLO tower for $pp \to t\bar{t}$ / $pp \to jj$

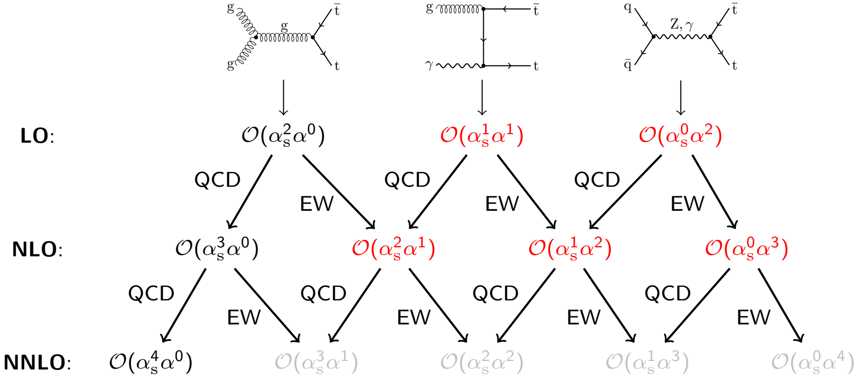


- include NNLO QCD corrections in predictions for PDF fits

→ but also higher-order α contributions: mixed LOs, NLO EW, NLO QCD–EW, ...

- for all PDF processes
- study the impact of all of these new contributions/corrections
- if we have them, use them
- importance of individual orders very much process/observable dependent

The (N)NLO tower for $pp \to t\bar{t}$ / $pp \to jj$



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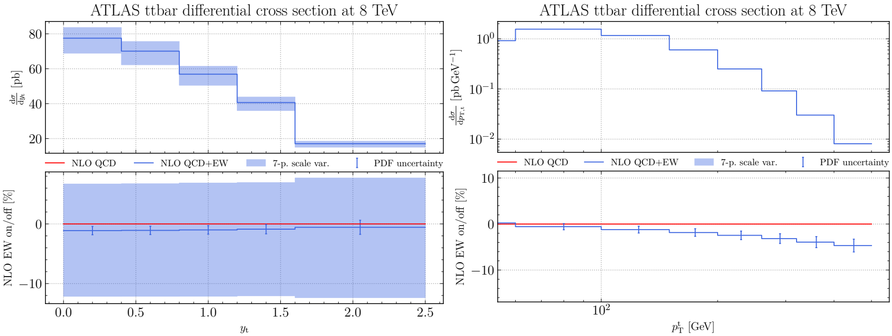
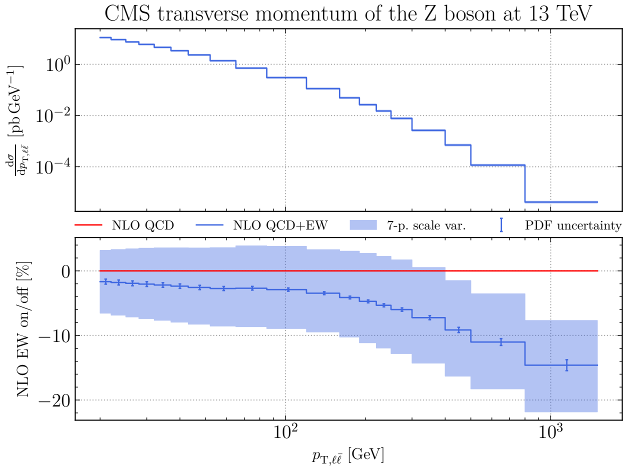
NLO EW for $\mathrm{pp} \to \mathrm{t\bar{t}} + X$



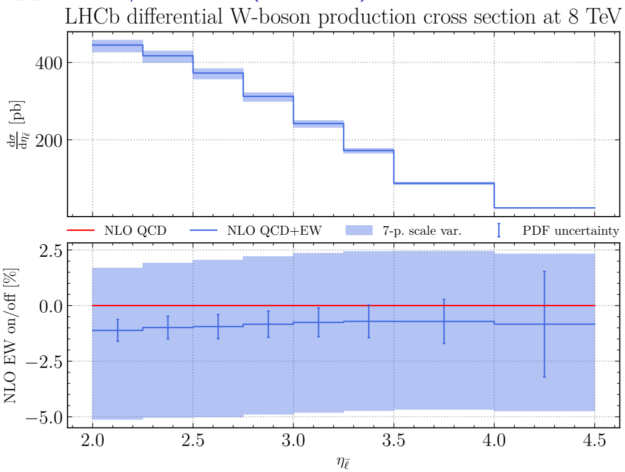
- predictions for ATLAS 8 TeV lepton–jet [ATLAS Collaboration]
- $|y_\mathrm{t}|$ included in CT18, MSHT20 and NNPDF4.0
- NLO EW $= \mathcal{O}(\alpha_\mathrm{s}\alpha) + \mathcal{O}(\alpha_\mathrm{s}^2\alpha)$
- up to $-5\,\%$ corrections for p_T^t

NLO EW for $pp \to \ell\bar{\ell} + j + X$ (Z + j)



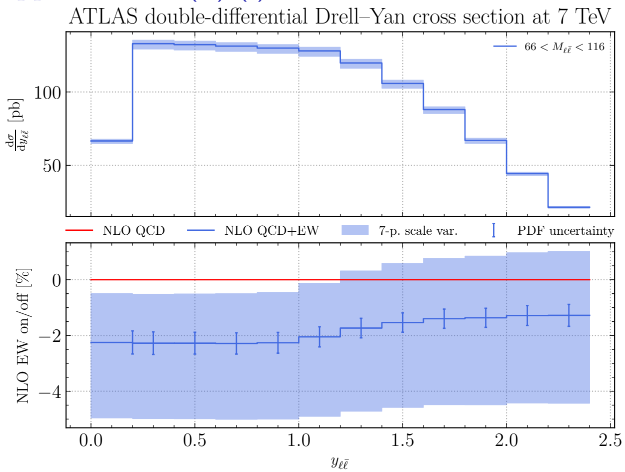
- predictions for CMS 13 TeV L = 35.9 fb^{-1} [CMS Collaboration]
- NLO EW = $\mathcal{O}(\alpha^3) + \mathcal{O}(\alpha_s \alpha^3)$
- up to −14 % corrections

NLO EW for pp $\to \ell\bar{\nu}_\ell/\bar{\ell}\nu_\ell + X$ (DY W$^\pm$)



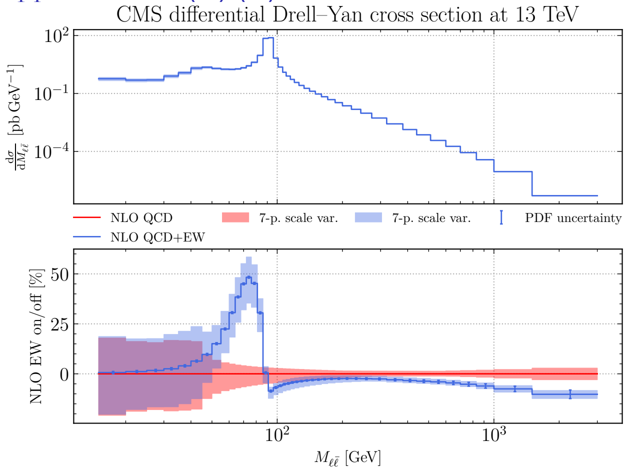
- predictions for LHCb 8 TeV [LHCb Collaboration]
- included in ABMP16, CT18, MSHT20, NNPDF4.0
- very small corrections

NLO EW for $\mathrm{pp} \to \ell\bar{\ell} + X$ (Z) (I)



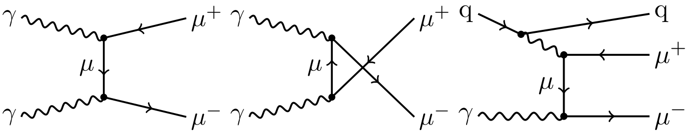
- predictions for ATLAS 7 TeV central-central [ATLAS Collaboration]
- included in C18A/Z, MSHT20, NNPDF4.0
- small corrections because of symmetric bin limits around M_Z

NLO EW for $\mathrm{pp} \to \ell\bar{\ell} + X$ (Z) (II)



- predictions for CMS 13 TeV $L = 2.8\,\mathrm{fb}^{-1}$ [CMS Collaboration]
- very large FSR (QED) corrections around M_Z due to very small bins
- higher order correction? photon shower?
- uncertainty band increases in the vicinity of $M_{\ell\bar{\ell}} \lessapprox M_\mathrm{Z}$ upon inclusion of NLO EW

Subtraction of photon–photon contributions

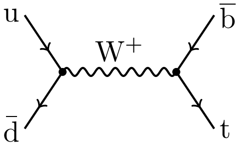


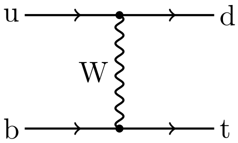
- For ATLAS and CMS it seems to be standard procedure to subtract $\gamma\gamma$-induced contributions:
- not considered part of "Drell–Yan lepton pair production"
- but: proton contains photons, should be counted towards signal!
- Subtracted in data (using photon-PDF), original data most likely lost
- Size of the LO contribution can become significant in large-invariant-mass bins (3 % to 6 %) depending on the used PDF

t-channel single-top production

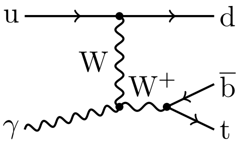
Not properly/easily definable at NLO EW (see also [R. Frederix, D. Pagani, I. Tsinikos]):

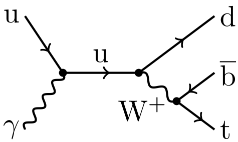
- included in ABMP16 and NNPDF4.0
- Analyses, e.g. [ATLAS collaboration], treat *s*-channels as irreducible background
- single-production at LO:





- but at NLO EW not (gauge-invariantly) separable:





$\rightarrow$ ignore these datasets

- better idea: partonic cross section with zero b jets?
- probably not too important [E.R. Nocera, M. Ubiali, C. Voisey], due to larger data uncertainty

What is PineAPPL? [S. Carrazza, E.R. Nocera, C.S., M. Zaro]

We needed

- an interpolation grid library supporting EW corrections,
- and Monte Carlo calculating them

- APPLgrid [T. Carli et al.] and fastNLO [T. Kluge, K. Rabbertz, M. Wobisch] don't support EW corrections
- we tried to extend APPLgrid and aMCfast [V. Bertone, R. Frederix, S. Frixione, J. Rojo, M. Sutton] (interface to Madgraph5)
- but we ran into memory/performance problems

Therefore we eventually developed

PineAPPL (PineAPPL Is Not an Extension of APPLgrid)

How can I use PineAPPL?

Source code, installation instructions, etc.:

https://github.com/N3PDF/pineappl

- converters available: APPLgrid/fastNLO → PineAPPL
- interfaces available for
  - Madgraph5_aMC@NLO [R. Frederix, S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro],
  - YADISM [A. Candido, F. Hekhorn, G. Magni]
  - other MCs in preparation ...
- public process (runcard) repository: https://github.com/NNPDF/runcards
  - run generators yourself
  - change parameters
  - write runcards for new processes
- soon-to-be public grid repository for PDF processes: https://github.com/NNPDF/pineapplgrids (similar to ploughshare)
- can be used to produce EW K factors
- command-line program for easy convolutions, plots, etc.
- APIs for C, Fortran, Python, Rust

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
NMC F_2^d/F_2^p	[31]	✓	✓	✗	✗	✓
NMC $\sigma^{\mathrm{NC},p}$	[32]	✓	✓	✗	✓	✓
SLAC F_2^p, F_2^d	[33, 237]	✓	✓	✓	✗	✓
BCDMS F_2^p	[34]	✓	✓	✓	✓	✓
BCDMS F_2^d	[238]	✓	✓	✗	✓	✓
BCDMS, NMC, SLAC F_L	[32, 34, 237]	✗	✗	✗	✗	✓
CHORUS $\sigma_{CC}^{\nu}, \sigma_{CC}^{\bar{\nu}}$	[35]	✓	✓	✗	✗	✓
CHORUS	[239]	✗	✗	✓	✗	✗
NuTeV F_2, F_3	[240]	✗	✗	✗	✗	✓
NuTeV/CCFR $\sigma_{CC}^{\nu}, \sigma_{CC}^{\bar{\nu}}$	[36]	✓	✓	✓	✓	✓
EMC F_2^c	[42]	(✓)	(✓)	✗	✗	✗
NOMAD	[109]	✗	(✓)	✓	✗	✗
CCFR xF_3^p	[241]	✗	✗	✗	✓	✗
CCFR F_2^p	[242]	✗	✗	✗	✓	✗
CDSHW F_2^p, xF_3^p	[243]	✗	✗	✗	✓	✗
E665 F_2^p, F_2^d	[244]	✗	✗	✗	✗	✓
HERA NC, CC	[245]	✗	✗	✗	✗	✓
HERA I+II $\sigma_{\mathrm{NC,CC}}^p$	[38]	✓	✓	✓	✓	✗
HERA I+II $\sigma_{c\bar{c}}^{\mathrm{red}}$	[145]	✗	✓	✗	(✓)	✓
HERA I+II $\sigma_{b\bar{b}}^{\mathrm{red}}$	[145]	✗	✓	✗	(✓)	✗
HERA I+II $\sigma_{c\bar{c}}^{\mathrm{red}}$	[39]	✓	✗	✓	✓	✗
H1 $F_2^{c\bar{c}}$	[246]	✗	✗	✗	✓	✗
H1 $F_2^{b\bar{b}}$	[40]	✓	✗	✓	✗	✗
ZEUS $\sigma_{b\bar{b}}^{\mathrm{red}}$	[41]	✓	✗	✓	✗	✗
H1 F_L	[247]	✗	✗	✗	✓	✓
H1 and ZEUS F_L	[248, 249]	✗	✗	✗	✗	✓
ZEUS 820 (HQ) (1j)	[110]	✗	(✓)	✗	✗	✗
ZEUS 920 (HQ) (1j)	[111]	✗	(✓)	✗	✗	✗
H1 (LQ) (1j-2j)	[113]	✗	(✓)	✗	✗	✗
H1 (HQ) (1j-2j)	[114]	✗	(✓)	✗	✗	✗
ZEUS 920 (HQ) (2j)	[112]	✗	(✓)	✗	✗	✗

Table B.1. The fixed-target and collider DIS measurements used for PDF determination. For each PDF set, a blue tick indicates that the given dataset is included and a red cross that it is not included. A parenthesized tick denotes that a dataset was investigated but not included in the baseline fit.

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
DY E866 $\sigma_{\mathrm{DY}}^d/\sigma_{\mathrm{DY}}^p$ (NuSea)	[45]	✓	✓	✓	✓	✓
DY E866 σ_{DY}^p	[44]	✓	✓	✗	✓	✓
DY E605 σ_{DY}^p	[43]	✓	✓	✓	✓	✗
DY E906 $\sigma_{\mathrm{DY}}^d/\sigma_{\mathrm{DY}}^p$ (SeaQuest)	[115]	✗	✓	✗	✗	✗

Table B.2. Same as Table B.1 for fixed-target Drell–Yan data sets.

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
CDF Z rapidity	[46]	✓	✓	✗	✓	✓
CDF $W \to \ell\nu$ asymmetry (1.8 TeV)	[250]	✗	✗	✗	✓	✗
CDF $W \to e\nu$ asymmetry ($\mathcal{L} = 170$ pb^{-1})	[251]	✗	✗	✗	✓	✗
CDF $W \to e\nu$ asymmetry ($\mathcal{L} = 1$ fb^{-1})	[252]	✗	✗	✗	✗	✓
CDF k_t inclusive jets	[50]	✓	✓	✗	✗	✓
CDF cone-based inclusive jets	[253]	✗	✗	✗	✓	✗
D0 Z rapidity	[47]	✓	✓	✗	✓	✓
D0 $W \to e\nu$ asymmetry ($\mathcal{L} = 0.75$ fb^{-1})	[254]	✗	✗	✗	✗	✓
D0 $W \to e\nu$ (prod.) asymmetry ($\mathcal{L} = 9.7$ fb^{-1})	[255]	✗	✗	(✓)	✗	✓
D0 $W \to e\nu$ (prod. and decay) asymmetry ($\mathcal{L} = 9.7$ fb^{-1})	[49]	✓	(✓)	✓	✓	✗
D0 $W \to \mu\nu$ asymmetry ($\mathcal{L} = 0.3$ fb^{-1})	[256]	✗	✗	✗	✓	✗
D0 $W \to \mu\nu$ asymmetry ($\mathcal{L} = 7.3$ fb^{-1})	[48]	✓	✓	✓	✗	✓
D0 cone-based inclusive jets	[257]	✗	✗	✗	✓	✓
CDF and D0 top-pair production	[258]	✗	✗	(✓)	✗	✓
CDF and D0 single-top production	[259]	✗	✗	✓	✗	✗

Table B.3. Same as Table B.1 for Tevatron data sets.

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
ATLAS W, Z 7 TeV ($\mathcal{L} = 35$ pb^{-1})	[51]	✓	✓	✓	✓	✓
ATLAS W, Z 7 TeV ($\mathcal{L} = 4.6$ fb^{-1})	[52]	✓	✓	✗	(✓)	✓
ATLAS low-mass DY 7 TeV	[53]	✓	✓	✗	(✓)	✗
ATLAS high-mass DY 7 TeV	[54]	✓	✓	✗	(✓)	✓
ATLAS W 8 TeV	[79]	✗	(✓)	✗	✗	✓
ATLAS DY 2D 8 TeV	[78]	✗	✓	✗	✗	✓
ATLAS high-mass DY 2D 8 TeV	[77]	✗	✓	✗	(✓)	✓
ATLAS $\sigma_{W,Z}$ 13 TeV	[81]	✗	✓	✓	✗	✗
ATLAS W+jet 8 TeV	[93]	✗	✓	✗	✗	✓
ATLAS Z p_T 7 TeV	[260]	(✓)	✗	✗	(✓)	✗
ATLAS Z p_T 8 TeV	[63]	✓	✓	✗	✓	✓
ATLAS $W + c$ 7 TeV	[83]	✗	✓	✗	(✓)	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 7, 8 TeV	[65]	✓	✓	✓	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 7, 8 TeV	[261–266]	✗	✗	✓	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 13 TeV ($\mathcal{L} = 3.2$ fb^{-1})	[66]	✓	✗	✓	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 13 TeV ($\mathcal{L} = 139$ fb^{-1})	[134]	✗	✓	✗	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ and Z ratios	[267]	✗	✗	✗	✗	(✓)
ATLAS $t\bar{t}$ lepton+jets 8 TeV	[67]	✓	✓	✗	✓	✓
ATLAS $t\bar{t}$ dilepton 8 TeV	[89]	✗	✓	✗	✗	✓
ATLAS single-inclusive jets 7 TeV, R=0.6	[73]	✓	(✓)	✗	✓	✓
ATLAS single-inclusive jets 8 TeV, R=0.6	[86]	✗	✓	✗	✗	✗
ATLAS dijets 7 TeV, R=0.6	[148]	✗	✓	✗	✗	✗
ATLAS direct photon production 8 TeV	[100]	✗	(✓)	✗	✗	✗
ATLAS direct photon production 13 TeV	[101]	✗	✓	✗	✗	✗
ATLAS single top R_t 7, 8, 13 TeV	[94, 96, 98]	✗	✓	✓	✗	✗
ATLAS single top diff. 7 TeV	[94]	✗	✓	✗	✗	✗
ATLAS single top diff. 8 TeV	[96]	✗	✓	✗	✗	✗

Table B.4. Same as Table B.1 for ATLAS data sets.

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
CMS W asym. 7 TeV ($\mathcal{L} = 36$ pb^{-1})	[268]	✗	✗	✗	✗	✓
CMS Z 7 TeV ($\mathcal{L} = 36$ pb^{-1})	[269]	✗	✗	✗	✗	✓
CMS W electron asymmetry 7 TeV	[55]	✓	✓	✗	✓	✓
CMS W muon asymmetry 7 TeV	[56]	✓	✓	✓	✓	✗
CMS Drell-Yan 2D 7 TeV	[57]	✓	✓	✗	(✓)	✓
CMS Drell-Yan 2D 8 TeV	[270]	(✓)	✗	✗	✗	✗
CMS W rapidity 8 TeV	[58]	✓	✓	✓	✓	✓
CMS W, Z p_T 8 TeV ($\mathcal{L} = 18.4$ fb^{-1})	[271]	✗	✗	✗	(✓)	✗
CMS Z p_T 8 TeV	[64]	✓	✓	✗	(✓)	✗
CMS $W + c$ 7 TeV	[76]	✓	✓	✗	(✓)	✓
CMS $W + c$ 13 TeV	[84]	✗	✓	✗	✗	(✓)
CMS single-inclusive jets 2.76 TeV	[75]	✓	✗	✗	✗	✓
CMS single-inclusive jets 7 TeV	[147]	✓	(✓)	✗	✓	✓
CMS dijets 7 TeV	[74]	✗	✓	✗	✗	✗
CMS single-inclusive jets 8 TeV	[87]	✗	✓	✗	✓	✓
CMS 3D dijets 8 TeV	[149]	✗	(✓)	✗	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 5 TeV	[88]	✗	✓	✗	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 7, 8 TeV	[146]	✓	✓	✗	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 8 TeV	[272]	✗	✗	✗	✗	✓
CMS $\sigma_{tt}^{\rm tot}$ 5, 7, 8, 13 TeV	[68, 273–281]	✗	✗	✓	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 13 TeV	[69]	✓	✓	✓	✗	✗
CMS $t\bar{t}$ lepton+jets 8 TeV	[70]	✓	✓	✗	✗	✓
CMS $t\bar{t}$ 2D dilepton 8 TeV	[90]	✗	✓	✗	✓	✓
CMS $t\bar{t}$ lepton+jet 13 TeV	[91]	✗	✓	✗	✗	✗
CMS $t\bar{t}$ dilepton 13 TeV	[92]	✗	✓	✗	✗	✗
CMS single top $\sigma_t + \sigma_{\bar{t}}$ 7 TeV	[95]	✗	✓	✓	✗	✗
CMS single top R_t 8, 13 TeV	[97, 99]	✗	✓	✓	✗	✗
CMS single top 13 TeV	[282, 283]	✗	✗	✗	✗	(✓)

Table B.5. Same as Table B.1 for CMS data sets.

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
LHCb Z 7 TeV ($\mathcal{L} = 940$ pb^{-1})	[59]	✓	✓	✗	✗	✓
LHCb $Z \to ee$ 8 TeV ($\mathcal{L} = 2$ fb^{-1})	[61]	✓	✓	✓	✓	✓
LHCb W 7 TeV ($\mathcal{L} = 37$ pb^{-1})	[284]	✗	✗	✗	✗	✓
LHCb $W, Z \to \mu$ 7 TeV	[60]	✓	✓	✓	✓	✓
LHCb $W, Z \to \mu$ 8 TeV	[62]	✓	✓	✓	✓	✓
LHCb $W \to e$ 8 TeV	[80]	✗	(✓)	✗	✗	✗
LHCb $Z \to \mu\mu, ee$ 13 TeV	[82]	✗	✓	✗	✗	✗

Table B.6. Same as Table B.1 for LHCb data sets.