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Combining NNPDF3.0 and NNPDF2.3QED through the APFEL evolution code

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We present sets of parton distribution functions (PDFs), based on the NNPDF3.0 family, which include the photon PDF from the NNPDF2.3QED sets, and leading-order QED contributions to the DGLAP evolution as implemented in the public code APFEL. The aim is to combine our state-of-the-art determination of quark and gluon PDFs with the so far only direct determination of the photon PDF from LHC data. In addition, the use of APFEL allowed us to employ a solution of the DGLAP equation that, differently from that used for the NNPDF2.3QED sets, includes QED corrections in a more accurate way. We briefly discuss how these sets are constructed and investigate the effect of the inclusion of the QED corrections on PDFs and parton luminosities. Finally, we compare the resulting sets, which we dubbed NNPDF3.0QED, to the older NNPDF2.3QED sets and to all presently available PDF sets that include QED corrections, namely CT14QED and MRST2004QED.

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Introduction It has been shown in many contexts that the inclusion of electroweak (EW) corrections is a crucial requirement for precision phenomenology at the LHC and at the Future Circular Collider (FCC) (see *e.g.* Refs. [1, 2]). As a consequence, a huge effort is being put in the computation of EW corrections to hard matrix elements. However, a consistent inclusion of such corrections at the level of physical predictions requires the use of PDF sets which incorporate QED effects. This in particular implies the inclusion of QED corrections to the perturbative DGLAP evolution, and thus the presence of a photon PDF.

Presently, several collaborations provide sets with QED corrections. Historically, the very first PDF set that implemented QED corrections was the pioneering MRST2004QED set [3] whose photon content was determined by assuming that the respective distribution at the initial scale is obtained by one-photon collinear emission off valence quarks, such that the only parameters of this model are the masses of the *up* and *down* quarks. The MRST2004QED set provides two estimates of the photon PDF based on two different assumptions for the *up* and *down* quark masses ("current" and "constituent") but no experimental uncertainty on the respective distributions is given.

The next PDF set in chronological order to contain a photon PDF was the NNPDF2.3QED set [4]. Differently from MRST2004QED, the NNPDF2.3QED photon PDF was parametrized on the same footing as all other partons and no theoretical assumption on its functional form was made. The photon PDF was determined by a direct fit to DIS data and by reweighting on LHC Drell-Yan data. As a consequence, the resulting photon PDF was delivered with an experimental uncertainty. It is worth noticing that the QED corrections to the DGLAP evolution in NNPDF2.3QED were implemented in a different way with respect to the MRST2004QED set. The difference stems from the fact that in the former the QCD and the QED factorization scales are taken to be independent and the evolution with respect to each scale is done successively, while in the latter these scales coincide and the respective evolutions are done simultaneously.

More recently the CT14QED set [6] was made public. In this set the photon PDF is determined employing the same theoretical ansatz of the MRST2004QED set. Again, no real fit of the photon PDF is done but, differently from the MRST2004QED set, the ansatz for the photon PDF has one single parameter identified with the momentum fraction carried by the photon at the initial scale p_0^γ. This parameter is estimated by comparison with DIS data for isolated photon production from the ZEUS experiment [7], resulting in the constraint $0\% < p_0^\gamma < 0.14\%$ at the 90% confidence level (CL).

The NNPDF3.0QED set The purpose of this contribution is to document a new set of PDFs with QED corrections. This new set is based on the recent NNPDF3.0 global analysis [8] and incorporates the photon PDF from the NNPDF2.3QED analysis, employing the `APFEL` code for the QED-corrected DGLAP evolution: we dubbed it NNPDF3.0QED.

As already pointed out, the evolution of the NNPDF2.3QED sets is such that the subtraction of the QCD and QED collinear divergences is done separately. This implies the introduction of two different factorization scales, $\mu_{F,\mathrm{QCD}}$ and $\mu_{F,\mathrm{QED}}$, and the DGLAP evolution with respect to each of them is done sequentially and independently. This approach, as compared to the more common procedure adopted in the MRST2014QED and CT14QED sets in which QCD and QED factorization scales are identified, leads to a suppression of the photon PDF at large scales and small values of the Bjorken x [6, 1]. In order to construct the NNPDF3.0QED sets we have dropped the distinction between QCD and QED factorization scales and, in line with the other collaborations, we have adopted the so-called QCD⊗QED *unified* solution of the DGLAP equation as implemented in the public code APFEL [5] in which QCD and QED evolutions are done simultaneously ensuring a better accuracy.

The NNPDF3.0QED sets are constructed by combining the QCD partons, *i.e.* gluon and quark PDFs, from the NNPDF3.0 sets with the photon PDF from the NNPDF2.3QED sets. On the one hand, the NNPDF3.0 sets provide a state-of-the-art determinations of quark and gluon PDFs. On the other hand, the photon PDF extracted in the NNPDF2.3QED analysis is currently the only determination entirely based on fits to DIS and LHC data without the assumption of any model. Although the combination of PDFs extracted from different analyses introduces a potential inconsistency, the low level of correlation between the photon and the other PDFs guarantees that no large inaccuracy is introduced. In addition, as we will show in the following, the smallness of the photon PDF ensures that the momentum sum rule (MSR) is not significantly violated.

The combination of the NNPDF3.0 QCD partons with the NNPDF2.3QED photon is done at the scale $Q = \sqrt{2} \simeq 1.414$ GeV and the resulting sets of PDFs are then evolved using the QCD⊗QED unified solution provided by APFEL. This procedure is applied both at NLO and NNLO in QCD, while the QED corrections are always accounted to LO. It is worth mentioning that all NNPDF sets implement the so-called *truncated* solution of the DGLAP equation [9] in which the evolution operator is expanded in powers of the strong coupling α_s and truncated to the required order. This particular solution is implemented in APFEL and it has been used to produce the NNPDF3.0QED sets[1].

In Fig. 1 we compare the gluon, up, down, and strange distributions from the NNPDF3.0QED set at NNLO to the respective distributions from the NNPDF3.0 set at $Q = 100$ GeV. The plots, presented as ratios to NNPDF3.0, show that the effect of the QED corrections to the DGLAP evolution on the QCD partons is very small. It is interesting to observe that, although the deviations are very limited everywhere, the up PDF is the relatively most affected of the quark distributions. This is consistent with the fact that the QED coupling is proportional to the squared charge e_q^2 of the quark and thus the up-type quarks are more affected than the down-type ones. Similar results are obtained at NLO.

Fig. 2 shows the comparison between NNPDF3.0 and NNPDF3.0QED at NNLO for the gluon-gluon and the quark-antiquark parton luminosities at the center of mass energy $\sqrt{s} = 13$ TeV as functions of the final state in variant mass M_X. The plots are presented as ratios to NNPDF3.0. As expected, the introduction of the QED corrections has a relatively small impact also on the parton luminosities. In particular, the gluon-gluon luminosity is essentially unaffected, while the quark-antiquark luminosity from NNPDF3.0QED presents a suppression with respect to that of the NNPDF3.0 set for large values of M_X. This is the consequence of the change in the quark PDFs for large values of x shown in Fig. 1. The effect is however well within uncertainties.

We now turn to consider the photon PDF of the NNPDF3.0QED sets. As a first step we check that the inclusion of the photon PDF to the NNPDF3.0 sets does not lead to any significant violation

[1] In the NNPDF sets also the evolution of the strong coupling α_s is implemented by means of an iterative analytic solution of the RG equation based on a perturbative expansion in powers of α_s (see *e.g.* Ref. [10]).

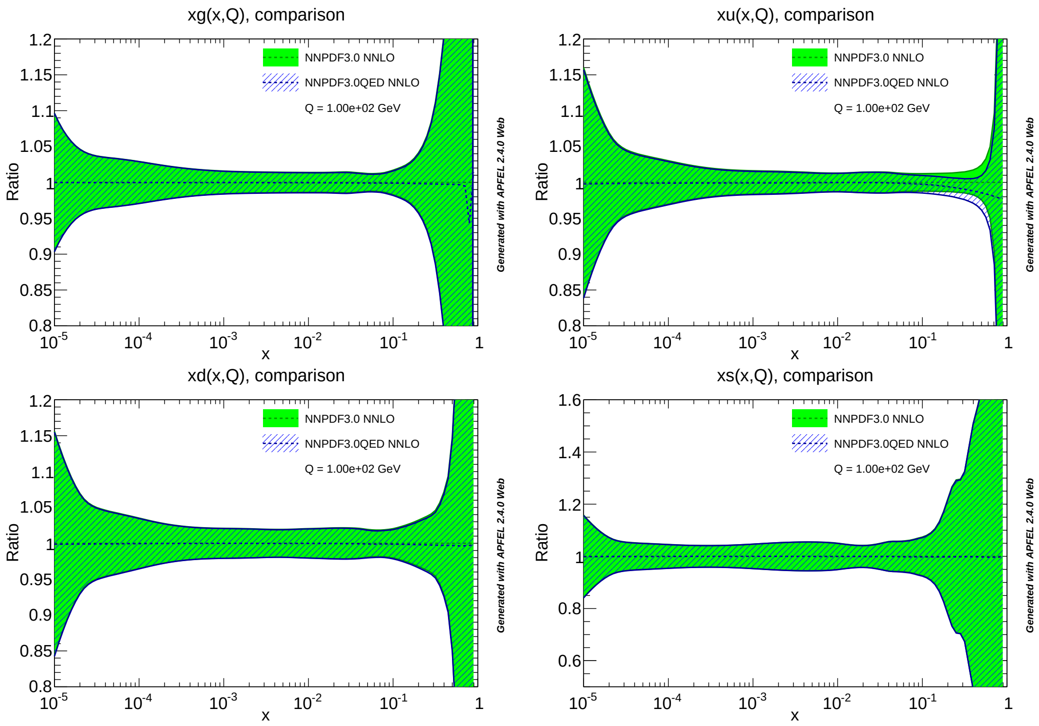

Figure 1: Comparison between NNPDF3.0 NNLO and NNPDF3.0QED NNLO for the g, u, d, and s distributions at $Q = 100$ GeV. Plots generated with `APFEL Web` [11].

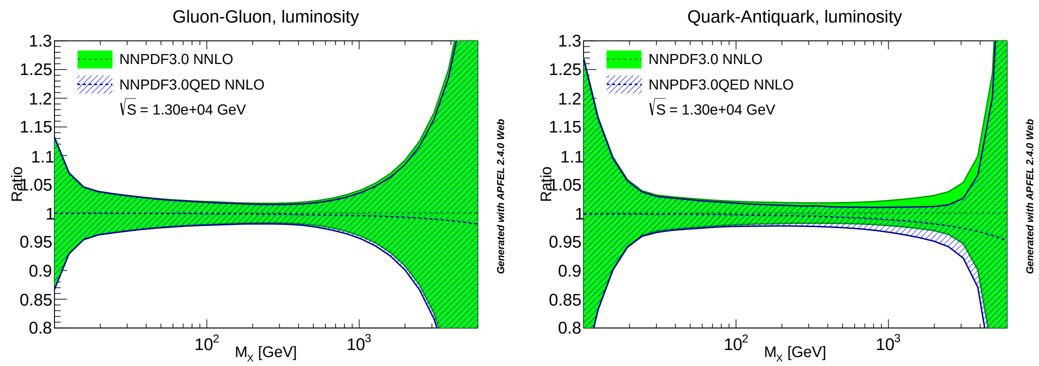

Figure 2: Comparison between NNPDF3.0 NNLO and NNPDF3.0QED NNLO for the gg and $q\bar{q}$ parton luminosities at $\sqrt{s} = 13$ TeV as functions of the final state in variant mass M_x.

of the MSR. For the NNLO sets we find:

$$\begin{aligned} \text{NNPDF3.0 NNLO:} \quad & \int_0^1 dx\,x \left[g(x,Q) + \sum_{i=1}^{6} q_i(x,Q) + \overline{q}_i(x,Q) \right] = 0.999 \pm 0.005\,, \\ \text{NNPDF3.0QED NNLO:} \quad & \int_0^1 dx\,x \left[\gamma(x,Q) + g(x,Q) + \sum_{i=1}^{6} q_i(x,Q) + \overline{q}_i(x,Q) \right] = 1.002 \pm 0.008\,, \end{aligned} \tag{1}$$

and thus the MSR is conserved within uncertainties[2]. Similar results are found at NLO. This

[2]Note that the DGLAP evolution preserves the total momentum fractions and thus the MSR is independent of the

PDF Set	$p^\gamma(Q=\sqrt{2}\text{ GeV})$	$p^\gamma(Q=10^2\text{ GeV})$	$p^\gamma(Q=10^3\text{ GeV})$
NNPDF3.0QED NLO	0.4 ± 0.4 %	0.6 ± 0.4 %	0.7 ± 0.4 %
NNPDF3.0QED NNLO	0.4 ± 0.3 %	0.6 ± 0.3 %	0.7 ± 0.3 %

Table 1: Photon momentum fractions at $Q=\sqrt{2},10^2,10^3$ GeV for NNPDF3.0QED NLO and NNLO. Uncertainties are given at 68% CL symmetric around the central value.

indicates that the momentum fraction carried by the photon is very small, it is however interesting to quantify it. In Tab. 1 we report the percent photon momentum fraction defined as:

$$p^\gamma(Q) = \int_0^1 dx x\gamma(x,Q)\,, \tag{2}$$

at NLO and NNLO for three different scales. As expected, the fraction of the momentum carried by the photon grows slowly with the scale but the associated uncertainties are typically large. In particular, at low scales the photon momentum fraction is nearly compatible with zero.

Finally, in Fig. 3 we compare the photon PDF of NNPDF3.0QED to the other determinations currently available, namely NNPDF2.3QED, CT14QED, and MRST2004QED. The comparison is done at NLO because the CT14QED and MRST2004QED sets are available only at this order. In the left panel of Fig. 3 the photon PDFs are compared at $Q=\sqrt{2}$ GeV where, by definition, the NNPDF2.3QED and the NNPDF3.0QED photons are identical. At this scale all determinations are mostly compatible across the whole range in x considered, with the only exception of MRST2004QED mem=1 which tends to be a bit harder than the others for medium values of x. In the right panel of Fig. 3 the photon PDFs are compared at $Q=100$ GeV. The main observation is that, while the NNPDF2.3QED photon PDF at small values of x is substantially smaller than the others, the photon of the NNPDF3.0QED set presents the same level of agreement with CT14QED and MRST2004QED as at small scales. This is the desired effect of the QCD$\otimes$QED unified evolution implemented in `APFEL`.

The extraction of the photon PDF from a complete global analysis is in our next future plans and in this sense the NNPDF3.0QED sets are meant to be a temporary solution. Amongst other improvements, the future analysis will most likely include NLO QED corrections to the DGLAP evolution equations [13, 14] and new experimental data able to constraint the photon PDF, such as the 8 TeV high-mass Drell-Yan data from ATLAS [12].

The NNPDF3.0QED sets are available from the NNPDF `HepForge` web page:

https://nnpdf.hepforge.org/html/nnpdf30qed/nnpdf30qed.html

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scale Q.

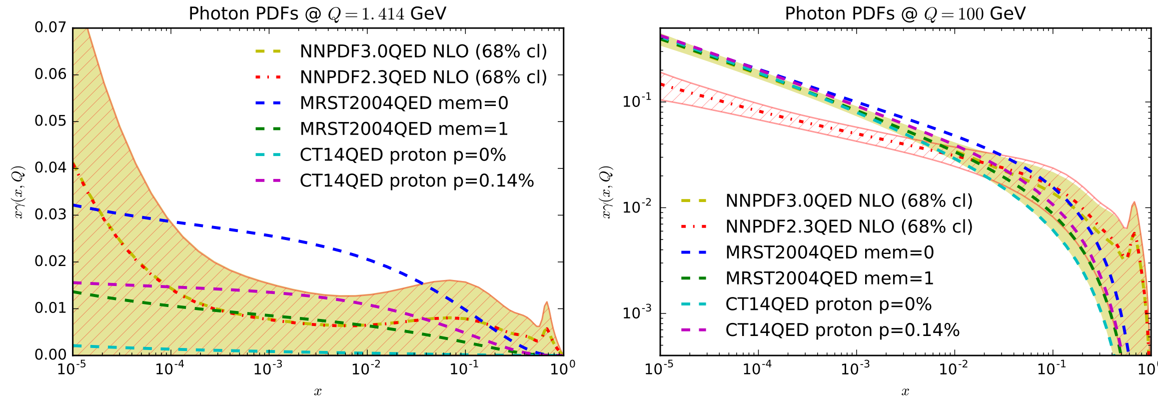

Figure 3: Comparison of the photon PDF at $Q = 1.414$ GeV (left) and $Q = 100$ GeV (right) between NNPDF3.0QED, NNPDF2.3QED, MRST2004QED with "current" (mem=0) and "constituent" (mem=1) quark masses, and CT14QED with photon momentum fractions $p_0^\gamma = 0\%$ and $p_0^\gamma = 0.14\%$. Uncertainties for NNPDF3.0QED and NNPDF2.3QED are given as 68% CL level symmetric around the central value.

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