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Electroweak corrections at the LHC: the contribution of photons

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Abstract
In this talk I review the photon contribution to the electroweak corrections for some of the most relevant processes at the LHC, namely, the Drell–Yan, VV, $t\bar{t}$ and dijet production. In the discussion I focus on two dominant effects: photon radiation from final-state light particles and the impact of the photon PDF.

Keywords
EW corrections; Final-State-Radiation; photon PDF

1 Introduction

In order to match the current and especially the future precision in the measurements of Standard Model (SM) processes at the LHC, both higher-order QCD and electroweak (EW) corrections have to be taken into account in theory predictions. Whenever NNLO QCD corrections are relevant, NLO EW corrections cannot be neglected, since they are expected to have similar sizes: $\alpha_s^2 \sim \alpha$. Moreover, in the boosted regime EW corrections are enhanced by the so-called Sudakov logarithms, with leading terms that are negative and proportional to $\log^2\left(\frac{Q^2}{m_W^2}\right)$, being Q the typical scale of the boosted regime considered. Although Sudakov effects are of purely weak origin, so they do not depend on photon (QED) effects, they can contribute in the same phase-space regions where QED corrections are large and positive, leading to cancellations. This is particular relevant in our discussion since nowadays QED and purely weak corrections are typically computed together within complete NLO EW calculations. Moreover, in the recent years, completely automated NLO EW calculations have been performed for several processes.

In the following I will discuss photon effects from the EW corrections to the cross section of the Drell–Yan, VV, $t\bar{t}$ and dijet production processes. In particular I will focus on two dominant effects:

- the impact of photon Final-State-Radiation (FSR) from light particles (typically leptons) in sufficiently exclusive observables,
- the impact of photon-initiated processes, which thus depend on the photon PDF.

When a lepton is present in a final state, FSR induces large corrections due to the collinear enhancement in the $\ell \to \ell\gamma$ splitting. The recombination of photons with leptons (dressed leptons), which is mandatory for the case of electrons only, reduces the impact of these effects, introducing a dependence on the radius R of the recombination. Unless it is explicitly specified (bare muons), we will refer always to dressed leptons.

Regarding the photon PDF it is important to keep in mind two aspects. First, the dependence on the photon PDF is entering at different perturbative orders, depending on the processes. While for neutral-current Drell–Yan and WW production it appears already at LO, for, e.g., WZ, ZZ, HV production it appears only in the NLO EW corrections. Moreover, for processes such as $t\bar{t}$ and dijet production, it appears and give its dominant contribution at $\mathcal{O}(\alpha_s\alpha)$, i.e., a tree-level contribution that is suppressed w.r.t. the dominant LO, which is of $\mathcal{O}(\alpha_s^2)$. Second, many NLO EW calculations have been performed in the recent years by using NNPDF2.3QED [1] and NNPDF3.0QED [2] distributions, which at large Bjorken-x have large central values and especially very large uncertainties. On the contrary, very recently, a new method for the determination of the photon PDF has been proposed and included in the set LUXQED PDF set [3, 4]. This new photon PDF determination has a much smaller uncertainty and

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also a considerably smaller central value for large Bjorken-x. Unless differently specified, results reviewed in the following have been calculated with an NNPDF photon distribution. The enhancements due to a specific kinematic effect in photon-induced process are in general present also with different PDF parametrizations (including also MRST2004QED [5] and CTEQ14QED [6]), whereas large effects due to solely the PDF luminosity are strongly suppressed with LUXQED, which is considered at the moment the most accurate one.

We invite the interested readers to directly look into the works cited in the following for the details of the calculation set-ups, such as definitions of cuts and input parameters, which will not be in general described here. A few details on the issue of isolated photons and NLO EW corrections will be given in Sec. 2.4.

2 Processes

2.1 Drell–Yan: W and Z

We start with the case of $pp \to \ell^+\ell^-$, referring to the results that have been presented in Ref. [7]. The invariant mass $m(\ell^+\ell^-)$ distribution receives large positive corrections just below the value $m(\ell^+\ell^-) = m_Z$ due to the FSR. Indeed, the emission of a photon from a lepton reduces the value of $m(\ell^+\ell^-)$ in the events, which mostly populate the region around the Z resonance. This effect is particularly large for bare muons (80 %), but also for dressed leptons (40 %), where quasi-collinear photons are recombined. This leads to the necessity of taking into account the effects due to the multiple emission of photons, which amount to a few percents in the aforementioned phase-space region. At LO also the $\gamma\gamma \to \ell^+\ell^-$ is present and does not include s-channel diagrams. Thus, the contribution of the photon PDF is sizable at large values of $m(\ell^+\ell^-)$, but it strongly depends on the PDF parametrization used [8].

In the case of $pp \to \ell\nu_\ell$ production FSR effects are also sizable in the distributions for the transverse mass of the lepton-neutrino pair and $p_T(\ell)$, see, e.g., Ref. [9]. These observables are particularly relevant since they can be exploited for the measurement of m_W at hadron colliders. For this purpose, also the effects of multiple emission of photons have to be taken into account, since permille accuracy is necessary in the theory predictions in order to achieve an accuracy $\sim 10-20$ MeV for the value of m_W, as it has been discussed in detail in Ref. [10].

2.2 VV production, $V = W, Z$

Considering VV production with stable vector bosons V, FSR effects are absent due to presence of only massive particles in the final state. The dominant effect from NLO EW corrections is given by Sudakov logarithms, which, e.g., can reach a relative size of order $\sim -40\%$ for $p_T(V_2) \sim 800$ GeV, where V_2 is the softest vector boson, see Ref. [11]. However, this effect can be partially compensated by quark radiation via the $\gamma q \to VVq^{(\prime)}$, which is part of the NLO EW corrections and depends on the photon PDF. Very similarly to the case of the QCD giant K-factors these effects arise from configurations displaying $\gamma q \to Vq$ production plus a collinear $q \to Vq^{(\prime)}$ splitting, thus growing for large $p_T(V)$. Moreover, if one of the two vector bosons is a W, the initial state photon can couple directly to it, leading to further enhancements. Results computed with the MRST2004QED PDF set are available in Ref. [12]; an almost complete cancellation of Sudakov logarithms and γq-induced effects for WZ and WW production is found. The latter process, as already said, includes also $\gamma\gamma$ initial-state contributions, which give large corrections for large values of $m(WW)$, see also Ref. [13].

Similarly to the case of the large QCD corrections, enhancements due to the quark radiation can be avoided by directly vetoing jets. This procedure has been studied in Ref. [14] where one of the leptonic signatures of WW production has been considered, namely the $pp \to \nu_\mu\mu^+e^-\bar{\nu}_e$ process. Off-shell effects and non-resonant contributions are consistently included in the calculation. It is found that indeed the impact of the photon PDF in NLO EW corrections in $p_T(e^-)$ distributions is reduced by imposing a jet veto. On the other hand, with the inclusion of leptonic W decays, FSR effects are relevant, especially

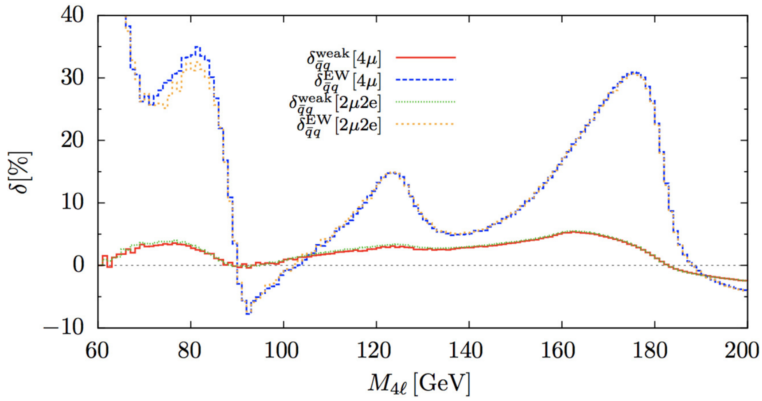

Fig. 1: Plot taken from Ref. [15] and adapted for this proceeding. In the text we refer to the blue long-dashed and yellow short-dashed lines.

in the case of bare muons.

FSR effects are particularly important in the case of the leptonic signatures of ZZ production. In Ref. [15] both the $pp \to \mu^+\mu^-e^+e^-$ as well $pp \to \mu^+\mu^-\mu^+\mu^-$ processes have been considered and the distribution of the invariant mass of the four leptons $m(4\ell)$ exhibits different regions where NLO EW corrections are large due to FSR effects, as can be seen from Fig. 1. Similarly to the Drell–Yan case, just below $m(4\ell) = m_Z$ there is an enhancement due to the migration of events from the peak associated to kinematic configurations with only one on-shell Z to smaller values of $m(4\ell)$. Analogously, the same effects is present below $m(4\ell) = 2m_Z$, which corresponds to the threshold for the production of two on-shell Z bosons, and also at $m(4\ell) = m_Z + 2p_{T,\mathrm{min}}$, where $p_{T,\mathrm{min}}$ =15 GeV is the cut on the transverse momentum of each lepton that has been used in the calculation.

Additional studies have been performed in Ref. [16] for again the $pp \to \nu_\mu\mu^+e^-\bar{\nu}_e$ signature as well as the $pp \to e^+e^-\nu\bar{\nu}$ one, which can emerge from WW, ZZ and $Z\gamma^*$ production. The impact of photon PDFs from different distributions is analysed and found to be in general non-negligible. Moreover, first attempts towards the matching of NLO EW corrections and photon showers are discussed. In particular, different approximations for the multiple emission of photons and their accuracy in reproducing hard radiation is scrutinised; reasonably accurate results are found.

NLO EW corrections have been calculated also for WWW production [17]. The contribution of γq initial states is in general large, but its value strongly depends on the PDF set used in the calculation and it is reduced by imposing a jet veto.

2.3 Top quark pair production

Similarly to the VV case, with stable top quarks FSR effects are absent. The relevance of the photon PDF for $t\bar{t}$ production has been discussed for the first time in Ref. [18] and carefully analysed in Ref. [19]. The LO cross section of $t\bar{t}$ production is $\mathcal{O}(\alpha_s^2)$; no photon-induced channel is present at this order. However, tree-level $\gamma g \to t\bar{t}$ contributions are present and contribute at $\mathcal{O}(\alpha_s\alpha)$, which we denote as LO EW. Moreover also $\gamma q \to t\bar{t}q$ contributions are present at $\mathcal{O}(\alpha_s^2\alpha)$, that is in the NLO EW corrections.

In Ref. [19] the contribution of the photon PDF has been found to be large for NNPDF2.3QED, especially at large $p_T(t)$ and $m(t\bar{t})$, with a sizable dependence on the definition of the factorization scale. The main contribution arises from the LO EW term, while the NLO EW part is in general small. Also at large values of the top-quark and top-quark-pair rapidity the impact of the photon PDF has been found to be non negligible and potentially measurable via normalized distributions for these variables. However, in Ref. [20], where a detailed study of $t\bar{t}$ distributions at NNLO QCD and NLO EW accuracy

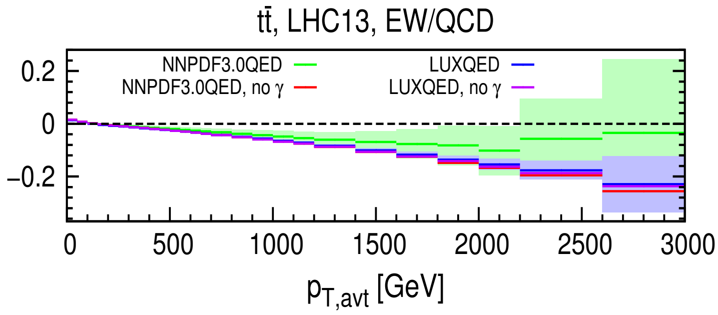

Fig. 2: Plot taken from Ref. [20]. The relative impact of EW corrections (LO EW, NLO EW and all the other fixed-order subdominant contributions) for the average transverse momentum of the top quarks at the 13 TeV LHC are displayed for four different cases. NNPDF3.0QED and LUXQED, both including or not the contribution from the photon PDF. Bands refer to the PDF uncertainties.

has been performed, it has been shown that photon-induced effects are negligible when LUXQED PDF set is used. The reason is due to the fact that no special kinematic enhancement is present in the $g\gamma$-initiated contribution and for this reason its size is completely PDF dependent, in particular very small for LUXQED as can be seen in Fig. 2.

In Ref. [21], one of the dilepton signatures of $t\bar{t}$ production has been analysed, namely the $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ process. Similarly to what has already been discussed for the Z resonance in Secs. 2.1 and 2.2, the reconstructed top mass $m(e^+\nu_e b)$ receives large corrections in the region below $m(e^+\nu_e b) = m_t$, due to FSR effects. Also, non-negligible photon-induced effects (with NNPDF photon density) have been observed for $m^2(e^+b) > m_t^2 - m_W^2$, a phase-space region that is not allowed with an on-shell top quark.

2.4 Dijet production

The first calculation including photon effects from NLO EW corrections to dijet production has been performed in Ref. [22]. As expected, photon PDF effects are important for large values of the inclusive $p_T(j)$, at least with the NNPDF parametrization. On the contrary, the impact of NLO EW corrections is in general modest. However, a few theoretical issues concerning jet and photon discrimination within the calculation of EW corrections have been addressed.

In this calculation not only the LO and NLO EW orders have been considered but also all the tree-level induced $\mathcal{O}(\alpha_s^{(2-i)}\alpha^i)$ with $0 \leq i \leq 2$ contributions and all the NLO contributions of $\mathcal{O}(\alpha_s^{(3-i)}\alpha^i)$ with $0 \leq i \leq 3$. At this level of accuracy, the only straightforward way for obtaining infrared-safe observables is the usage of democratic jets, i.e., the inclusion of photons as well leptons in the jet definitions. Nevertheless, one may want to identify the contributions of a processes with a single or two isolated photons to the dijet calculation with democratic-jet definition. While $\mathcal{O}(\alpha_s\alpha)$ and $\mathcal{O}(\alpha_s^2\alpha)$ term for single isolated-photon and $\mathcal{O}(\alpha^2)$ and $\mathcal{O}(\alpha_s\alpha^2)$ for double isolated photon can be calculated via the usage of Frixione isolation [23], subleading terms necessarily involve the usage of fragmentation functions, including the poorly known photon-to-photon one. Nevertheless, we evaluated the aformentioned contributions for which fragmentation functions are not necessary and we concluded that they represent a negligible fraction of the cross section with democratic jets, pointing to the fact that the definition of jets including photons is completely legitimate and in fact closer to the one used in experimental analyses.

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