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Full NLO electroweak corrections to diphoton production

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Abstract

Precise predictions for diphoton production are essential for Higgs studies and new-physics searches at the LHC. Hence, in this study it has been employed `DYTurbo` and `OpenLoops` codes to investigate real next-to-leading-order electroweak (NLO EW) corrections into the invariant mass distribution, aiming to reproduce the most accurate theoretical predictions for diphoton achieved to date.

1 Introduction

Diphoton production is a fundamental process in particle physics, particularly in the context of high-energy hadronic collisions such as those occurring at the Large Hadron Collider (LHC). It is an electroweak process that proceeds mainly through second-order interactions within the Standard Model and provides a clean, precise signal for studying a variety of background phenomena as well as possible new physics.

The two photons can be produced via several mechanisms, such as quark–antiquark annihilation processes $q\bar{q} \to \gamma\gamma$, or gluon–gluon scattering through internal particle loops $gg \to \gamma\gamma$, the latter appearing only at higher perturbative orders. The motivation for studying these corrections, currently estimated to lie in the range 15–30% across the invariant-mass scale $M_{\gamma\gamma}$, stems from forthcoming measurements of this process by the ATLAS experiment. The smaller the theoretical uncertainties, the more closely the predictions must match the experimental results, so that any small discrepancies between theory and data can point to additional, previously unaccounted-for effects, i.e. new physics. Thus, pushing the theoretical predictions to their highest precision can serve as an indicator of new physics.

At present, the state of the art includes QCD corrections at next-to-next-to-leading order (NNLO) [1]; these calculations carry theoretical uncertainties expected to be of order 8% [1, 2]. By contrast, as far as electroweak corrections are concerned, only the purely NLO QED contributions [3] have been examined so far or LO pure virtual EW corrections [4]. Because the photon is massless, the loop integrals that arise in these corrections become divergent, in contrast to the situation for purely weak corrections mediated by the Z and $W^\pm$ massive bosons.

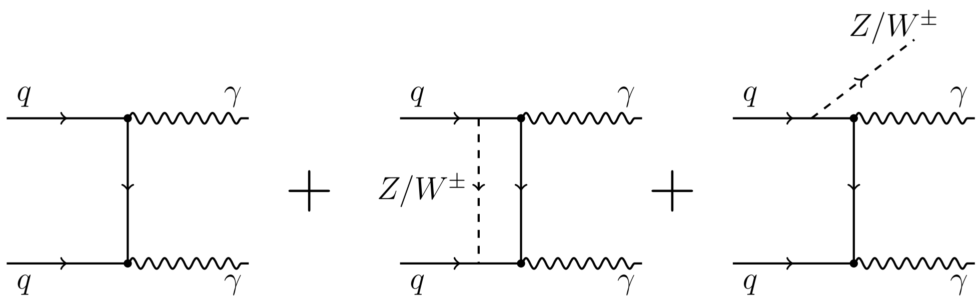

Figure 1: Representative Feynman diagrams for diphoton production up to NLO EW: The first diagram represent the contribution at tree-level (Born), the diagram at the center encodes the NLO correction with virtual $Z/W^\pm$, while the last diagram represents the NLO real $Z/W^\pm$ correction.

In order to obtain the electroweak corrections at NLO, one must include the contributions from processes involving a real $Z/W^\pm$ boson (three particles in the final state) as well as its virtual counterpart (loop), as illustrated in Fig.1. The virtual correction, the loop diagram, was first introduced in Ref. [4]. The main objective of this work is therefore to study the necessary physics to reproduce the NLO cross section of the process with real $Z/W^\pm$ bosons also, with the goal of incorporating this contribution into universal codes for high-energy process calculations. The NLO theoretical predictions have been obtained with two open-source codes to reproduce the numerical results for this process: `DYTurbo` and `OpenLoops`.

The motivation behind this inclusion is based in the measurement procedure by the LHC collaborations. Measuring two hard photons at the LHC implies considering events in which at least two photons are measured. Therefore any other collection of particles accompanying two photons pass the selection criteria. Remove events such that $Z\gamma\gamma$ or $W^{\pm}\gamma\gamma$ even if it is physically possible, it is statistically "very expensive" and would enlarge the selection uncertainties vainly.

`DYTurbo` was originally introduced by A. Camarda, L. Cieri *et al.* in *"DYTurbo: Fast predictions for Drell–Yan processes"* [5], the `DYTurbo` code is a numerical tool developed to obtain high-precision differential distributions in hadronic-collision processes, such as Drell–Yan production, and has since been extended to study related observables with accuracy up to NNLO (next-to-next-to-leading order) in QCD and the option to include electroweak (EW) corrections [6].

`OpenLoops` was introduced in late 2011 by Fabio Cascioli, Philipp Maierhöfer, and Stefano Pozzorini, first presented in the article *"Scattering Amplitudes with Open Loops"* [7]. That work proposed a new technique for generating scattering amplitudes with one-loop corrections. By combining these open loops with loop-integral reduction methods (such as tensor techniques or OPP), the authors obtained an extremely flexible, fast, and stable one-loop amplitude generator.

2 Procedure

The first step was to understand the syntax of both codes so as to introduce the contribution with a real $Z/W^{\pm}$ boson. First, the various channels must be defined. For the process with an external Z boson, responsible for flavor-conserving weak transitions, there are five possible channels: $u\bar{u}$, $d\bar{d}$, $c\bar{c}$, $s\bar{s}$, and $b\bar{b}$. By contrast, transitions involving $W^{\pm}$ correspond to flavor-changing processes, so the allowed channels are $q\bar{q}'$ and $\bar{q}q'$, where $q = u$, c denotes the "up" sector and $q' = d$, s, b the "down" sector.

After these changes have been implemented, the code outputs a `.root` file, which can be visualized with `ROOT` and yields a histogram of $d\sigma/dM_{\gamma\gamma}$ versus $M_{\gamma\gamma}$, where $M_{\gamma\gamma}$ is the invariant mass of the diphoton system. Therefore, the differential cross section is given by

$$\frac{d\sigma}{dM_{\gamma\gamma}}(q_T, M_{\gamma\gamma}, s) = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2 f_{a/h1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) \frac{d\hat{\sigma}_{ab}}{dM_{\gamma\gamma}}(q_T, M_{\gamma\gamma}, y, \hat{s}; \mu_R^2, \mu_F^2) \tag{1}$$

where $f_{a/h1}$ and f_{b/h_2} represent the parton distribution function (PDF) of the parton a(b), with momenta fraction $x_1(x_2)$, inside the hadron $h_1(h_2)$, while μ_R and μ_F are the renormalization and factorization scales. y represents the rapidity, and s the center of mass energy squared. The kinematical cuts used in the run are, with center-of-mass energy $\sqrt{s} = 13$ TeV, given by

$$p_{T_{\gamma_1}} > 40 \text{ GeV}, \quad p_{T_{\gamma_2}} > 30 \text{ GeV}, \quad |\eta_\gamma| < 2.37\,, \tag{2}$$

where $p_{T_{\gamma_i}}$ are the transverse momenta of the photon $i = 1, 2$ and η_γ is their corresponding pseudo-rapidity.

Hence, with this procedure one is able to compute the real NLO EW corrections and compare them with the previous results in the literature, which only account for NLO virtual EW corrections. This work is based on previous results from [8, 9, 10, 11, 12, 6, 13, 14, 15, 1, 2] .

Under this considerations, in this work we are able to reproduce the must accurate prediction for the differential cross section $\frac{d\sigma}{dM_{\gamma\gamma}}$, as we have included the real contributions coming from the third group of Feynman diagrams in Figure 1. On the other hand, Jesús Sánchez Illana will focus his work on computing the cross section differential in the transverse momentum of the diphoton system q_T, whose contribution is complementary to this results, making use of the universal transverse momentum resummation formalism.

3 Results at fully NLO EW

Once the contributions from real $W^{\pm}/Z$ corrections had been implemented in `DYTurbo`, one can reproduce the invariant mass distribution of the real contributions at NLO Electroweak. The differential cross-section as a function of the invariant mass $M_{\gamma\gamma}$ of the two photons was evaluated in the range $M_{\gamma\gamma} \in (0,\ 2201)$ GeV.

Figure 2 displays these gauge-boson contributions: the left panel shows the cross-section arising from a real $W^{\pm}$ bosons, whereas the right panel presents the contribution of a real Z boson.

As can be seen, both NLO contributions feature a pronounced peak at $M_{\gamma\gamma} \simeq 90$ GeV, which correspond to the resonances around both $M_{W^{\pm}} = (80.3692 \pm 0.0133)$ GeV and $M_Z = (91.1880 \pm 0.0020)$ GeV in Ref. [16]. In the left-hand panel the real $W^{\pm}$ term is roughly a factor of three larger than the real Z contribution. However, for $M_{\gamma\gamma} \sim 500$ GeV, the two curves flatten out and approach comparable values $\frac{d\sigma}{dM_{\gamma\gamma}} \simeq 0$.

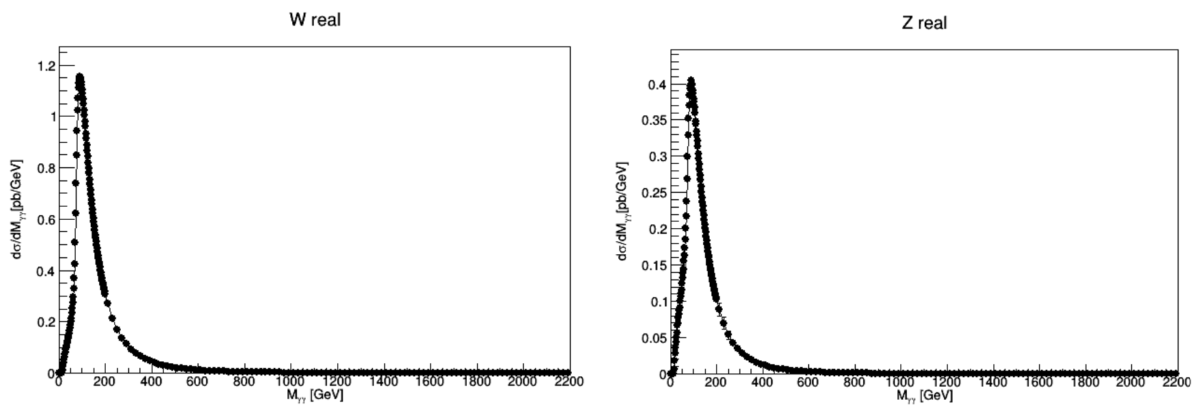

Figure 2: Contribution to the NLO differential cross section of $W^{\pm}/Z$ bosons in diphoton production. The group of Feynman diagrams considered are depicted in Fig. 1. The cross section differential in the invariant mass $M_{\gamma\gamma}$, is given the left panel for outgoing $W^{\pm}$ bosons, while the right panel present the contribution for a real outgoing Z boson.

Once the invariant-mass distributions of the real NLO electroweak contributions have been obtained, we can turn to the physical quantity of primary interest and display it: the ratio of the complete differential cross-section, including both real and virtual NLO corrections, to the LO differential cross section. This result is presented in the right-hand panel of Fig. 3.

On the one hand, the left panel shows only the ratio of cross-sections that includes the virtual electroweak (EW) contribution, that is, the first two diagrams of Fig. 1. This ratio, already reported in the literature [4], quantifies how virtual EW corrections modify the LO cross-section. For intermediate invariant-mass values, $M_{\gamma\gamma} \simeq 100$–$110$; GeV, the virtual EW piece induces a modest $\sim 2\%$ variation. However, as the invariant mass increases, the deviation grows steadily, reducing the cross-section copiously. For $M_{\gamma\gamma} \gtrsim 500$ GeV the deviation reaches the $\sim 20\%$ level, diminution given by Sudakov logarithms that arise at high energies, when the boson masses $M_{W^{\pm}}$ and M_Z tends to zero (are small enough) respect to the energy scale of the process or event. The curve we obtain reproduces exactly the published results, lending confidence to the correctness of the code used in this analysis.

On the other hand, to produce the most accurate prediction at full NLO, one may need to include the real electroweak contribution. However, in addition to the motivation related to precision, there are two other motivations, which have already been described in Sec. 1: (i) in Quantum Field Theory, there is a strong motivation to add all Feynman diagrams to a given order; otherwise, infrared divergences remain uncancelled. Something similar happens in full EW theory, even if the theory is finite (excluding the photon), since the vector bosons are massive. It is well-known in the literature that including both real and virtual corrections in full EW theory reduces the impact of large Sudakov logarithms [17]. (ii) The experimental procedure for taking data at the LHC includes any other group of particles accompanying the two photons, particularly other vector bosons.

Among the processes explained in Section 2, we have been able to introduce this contribution into the differential cross section, result which is presented in the right-hand panel of Figure 3.

As can be seen in the ratio $(LO + \text{virtual EW} + \text{real EW})/LO$, the real EW contributions soften the steep fall-off of the cross section produced by the purely virtual terms. Firstly, for invariant masses $M_{\gamma\gamma} \lesssim 100$ GeV, the NLO correction with respect to the LO prediction amounts to roughly $2-3\%$, yielding a value above the LO result. As given for the Virtual EW correction, up to $M_{\gamma\gamma} \simeq 110$ GeV, the ratio continues raising to a peak about to 5%, a growth driven mainly by the real emissions. As the virtual corrections are negative, the ratio begins to decrease. Nevertheless, because the real contributions dominate in the intermediate mass region, the overall ratio remains positive all the way up to $M_{\gamma\gamma} \simeq 2$ TeV, where it levels off at the ratio ~ 1.

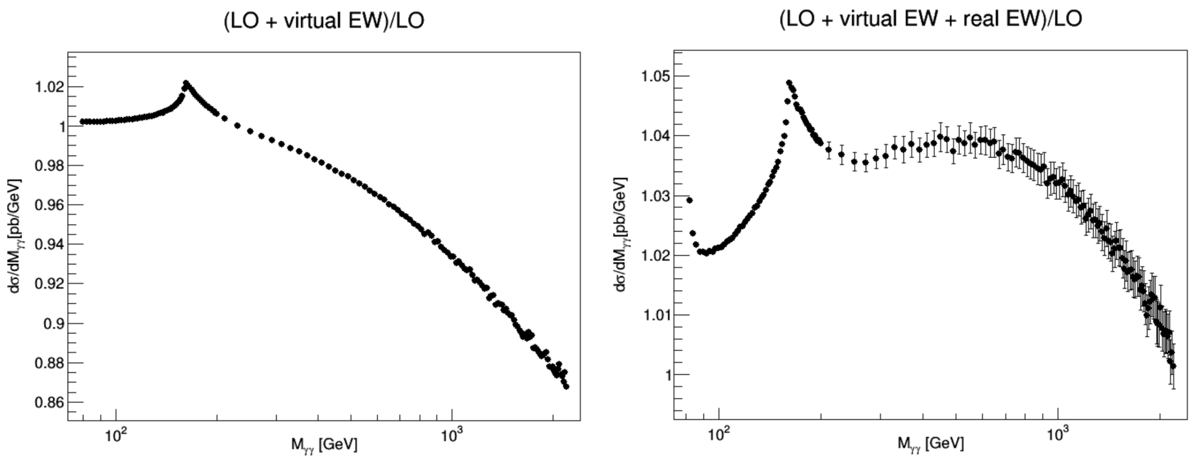

Figure 3: . Rations of the differential cross sections with respect to the LO contribution, both in terms of the invariant mass. En the left-hand panel, it is represented the virtual EW correction. In the right-handed panel, there are presented both real and virtual corrections

Based on the results displayed in the right-hand panel of Fig. 3, we see that including the real electroweak corrections improves the theoretical prediction for diphoton production: the overall NLO contribution now amounts to roughly a 5% modification of the LO cross-section. As represented, at large invariant masses the real emission term cancels partially the Sudakov logarithms carried by the virtual diagrams, so the predicted ratio settles to ~ 1.

All data used for reproducing the plots of this work are presented in the repository.

4 Conclusion

We can conclude that the study has been successful. The right-hand panel of Fig. 3 accurately reproduces the $(LO$+virtual EW$)/LO$ ratio already published in the literature, providing strong evidence that our implementation is reliable. Furthermore, Fig. 2 presents the differential cross-section for the real NLO electroweak contributions: the left panel shows that the diagram with an on-shell $W^{\pm}$ boson features a sharp peak around $M_{W^{\pm}} = (80.3692 \pm 0.0133)$ GeV with $\frac{d\sigma}{dM_{\gamma\gamma}} \simeq 1.17$ pb/GeV , followed by a rapid decrease toward zero at high invariant mass. On the other hand, the right panel reveals a similar peak near $M_Z = (91.1880 \pm 0.0020)$ GeV with $\frac{d\sigma}{dM_{\gamma\gamma}} \simeq 0.41$ pb/GeV. Both contributions almost vanishes for $M_{\gamma\gamma} \gtrsim 500$ GeV.

Finally, by adding the newly computed real EW NLO contributions to the previous LO + virtual EW results, we reproduced the full ratio $(LO +$ virtual EW + real EW$)/LO$ shown in Fig. 3. The inclusion of real emissions counteracts the Sudakov logarithms that decrease the cross-section at high energies, so the total prediction now deviates from the Born level by only $\sim 5\%$. Although the statistical uncertainty grows in the high-invariant-mass region, longer runs with more calls will reduce it, yielding more precise theoretical predictions that can serve as sensitive probes of physics beyond the Standard Model. A natural next step is to incorporate both NNLO QCD and electroweak corrections in order to obtain further improve the accuracy.

Furthermore, given the close collaboration between the LHCPHENO Theory Group and the ATLAS group at IFIC, this work is extremely timely, as the new LHC measurements on diphoton production will investigate electroweak effects in the tail of the invariant mass distribution.

In my opinion, this research done under the supervision of Leandro Javier Cieri, Distinguished Researcher of Excellence (CIDEGENT), has been very interesting and has greatly helped me realize the importance of obtaining models whose theoretical predictions match the observations as closely as possible, not only because of the need to validate the model, but also for the evidence it provides regarding the presence of new physics.

Throughout the stay In addition, I learned how a computer cluster operates and how to work on it, since these codes require a large number of cores to run. In conclusion, I think this research has been very helpful because it has enriched my knowledge about the measurement and detection of physical processes, the need to obtain theoretical predictions that are as accurate as possible, and the importance of programming in theoretical physics.

5 LHCPHENO Theory Group

The LHCPHENO Theory Group [18], founded in 1989, is world-leading group in Particle Physics Phenomenology whose main objective is the determination of the parameters of the Standard Theory with the highest possible precision, and the identification of possible signals of new physics beyond the present theoretical framework. Therefore, they focus on high-precision calculations within the framework of quantum field theory and on building models that can reveal possible hints of physics beyond the Standard Model.

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