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Next-to-leading-order QCD corrections to $e^+e^- \to H + \gamma$

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ABSTRACT

The associated production of Higgs boson with a hard photon at lepton collider, *i.e.*, $e^+e^- \to H\gamma$, is known to bear a rather small cross section in Standard Model, and can serve as a sensitive probe for the potential new physics signals. Similar to the loop-induced Higgs decay channels $H \to \gamma\gamma, Z\gamma$, the $e^+e^- \to H\gamma$ process also starts at one-loop order provided that the tiny electron mass is neglected. In this work, we calculate the next-to-leading-order (NLO) QCD corrections to this associated $H + \gamma$ production process, which mainly stem from the gluonic dressing to the top quark loop. The QCD corrections are found to be rather modest at lower center-of-mass energy range ($\sqrt{s} < 300$ GeV), thus of negligible impact on Higgs factory such as CEPC. Nevertheless, when the energy is boosted to the ILC energy range ($\sqrt{s} \approx 400$ GeV), QCD corrections may enhance the leading-order cross section by 20%. In any event, the $e^+e^- \to H\gamma$ process has a maximal production rate $\sigma_{\max} \approx 0.08$ fb around $\sqrt{s} = 250$ GeV, thus CEPC turns out to be the best place to look for this rare Higgs production process. In the high energy limit, the effect of NLO QCD corrections become completely negligible, which can be simply attributed to the different asymptotic scaling behaviors of the LO and NLO cross sections, where the former exhibits a milder decrement $\propto 1/s$, but the latter undergoes a much faster decrease $\propto 1/s^2$.

1. Introduction

After the historical discovery of the 125 GeV boson by the ATLAS and CMS collaborations at LHC in 2012 [1,2], a great amount of efforts have been devoted to unravelling its nature. Numerous evidences have been accumulating to indicate that this new particle is just the long-sought Higgs boson, which plays the pivotal role in mediating spontaneous electroweak symmetry breaking. To date, the measured couplings between the Higgs boson and heavy fermions/gauge bosons are compatible with the Standard Model (SM) predictions within 10%–20% accuracy [3].

One of the central goals of contemporary high-energy physics is to precisely nail down the properties of the Higgs boson, and to search for the footprint of new physics in the Higgs sector. In contrast to the hadron colliders that are plagued with enormous background events, lepton colliders appear to be much more appealing options for conducting precision measurements on Higgs properties. Three promising next-generation e^+e^- colliders, International Linear Collider (ILC) in Japan [4,5], Future Circular Collider (FCC-ee) at CERN [6] (formerly called TLEP), and Circular Electron–Positron Collider (CEPC) in China [7,8], have been proposed in recent years.

All these three e^+e^- colliders plan to operate at center-of-mass (CM) energy around 250 GeV, where the dominant Higgs production channel is via the so-called Higgsstrahlung process, $e^+e^- \to HZ$. For this reason, these e^+e^- machines are collectively referred to as Higgs factory. This golden process has been intensively studied theoretically in the past decades, *e.g.*, the leading order (LO) prediction was first given in Refs. [9–11], while the next-to-leading order (NLO) electroweak corrections were analyzed in Refs. [12–14]. Very recently, the mixed electroweak-QCD next-to-next-to-leading order (NNLO) corrections have also been investigated by two groups [15,16], which yield the state-of-the-art prediction for $\sigma(HZ)$ about 230 fb around $\sqrt{s} = 240$ GeV.

The motif of this work is to study another type of Higgs production process at future lepton colliders, the associated production

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of Higgs boson with a hard photon, that is, $e^+e^- \to H\gamma$. Owing to the exceedingly small electron Yukawa coupling and the absence of $H\gamma\gamma$, $H\gamma Z$ couplings at tree level, this process first arises at one-loop order in SM. The LO prediction to $\sigma(H\gamma)$ in SM is available long ago [17–19], which turns out to be several orders-of-magnitude smaller than that of $\sigma(HZ)$ around the Higgs factory energy.

Due to the highly suppressed production rate predicted in SM, the discovery prospect of the $e^+e^- \to H\gamma$ process appears to be rather obscure in the future e^+e^- colliders. On the other hand, this may turn into a virtue, since this rare Higgs production process can serve as a sensitive probe for new physics search. Had the couplings between the Higgs boson and the gauge bosons/top quark been notably modified by some beyond-SM models, or had some hypothesized heavy charged particles been strongly coupled to the Higgs boson, the production cross section for $\sigma(H\gamma)$ might be substantially enhanced relative to its SM value, so that the $e^+e^- \to H\gamma$ process could even possibly be observed at Higgs factory. The impact of possible new physics scenarios on this process has been extensively investigated in literatures [20–26].

Needless to say, an accurate SM account for the $e^+e^- \to H\gamma$ process is crucial and mandatory for confidently interpreting the potential experimental signal in future. The goal of this work is to conduct a detailed study on the NLO QCD corrections to this process in various energy range. In a sense, the required two-loop calculation is similar to the previous works about NLO QCD corrections to $H \to \gamma\gamma$ [27–36] and $H \to Z\gamma$ [37–39]. Nevertheless, the situation in our case is more involved than these Higgs decay processes, due to the occurrence of a new energy scale, $\sqrt{s}$. We are also interested in inferring how the effects of NLO QCD corrections vary with $\sqrt{s}$.

The rest of this paper is organized as follows. In Section 2, we establish the notations and briefly describe the procedure of our NLO calculation. Section 3 is dedicated to presenting our numerical results. Finally we present a summary and outlook in Section 4. For the convenience of the readers, the compact expressions for the LO amplitude are collected in Appendix A.

2. Descriptions of the NLO calculation

Owing to the Lorentz covariance and electromagnetic current conservation, the amplitude for $e^+e^- \to H\gamma$ can be decomposed into the linear combination of four distinct Lorentz structures [19]:

$$\mathcal{M} = \sum_{i=1,2;\,\alpha=\pm} C_i^\alpha \Lambda_i^\alpha, \tag{1}$$

where $C_{1,2}^{\pm}$ are scalar coefficients, and

$$\Lambda_1^{\pm} = \bar{v}(p_+)(1\pm\gamma_5)(\not\varepsilon_\gamma^* p_\gamma\cdot p_- - \not p_\gamma \varepsilon_\gamma^*\cdot p_-)u(p_-), \tag{2a}$$

$$\Lambda_2^{\pm} = \bar{v}(p_+)(1\pm\gamma_5)(\not\varepsilon_\gamma^* p_\gamma\cdot p_+ - \not p_\gamma \varepsilon_\gamma^*\cdot p_+)u(p_-), \tag{2b}$$

where p_+ and p_- signify the momenta of the incoming positron and electron, p_γ and p_H signify the momenta of the outgoing photon and Higgs boson, and ε_γ denotes the photon polarization vector. For simplicity, we shall neglect the tiny electron mass throughout this work.

Substituting (2) into (1), squaring, averaging upon the $e^\pm$ spins and summing over photon helicity, we can express the unpolarized differential cross section for $e^+e^- \to H\gamma$ as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{2s}\frac{s-m_H^2}{16\pi s}\frac{1}{4}\sum_{\rm pol}|\mathcal{M}|^2$$
$$= \frac{s-m_H^2}{64\pi s}\left[t^2\left(|C_1^+|^2+|C_1^-|^2\right) + u^2\left(|C_2^+|^2+|C_2^-|^2\right)\right], \tag{3}$$

where θ denotes the polar angle between the the outgoing Higgs and the incoming positron, and m_H represents the Higgs boson mass. $s=(p_++p_-)^2$, $t=(p_H-p_+)^2$, and $u=(p_H-p_-)^2$ are standard Mandelstam's variables.

This process first occurs at one-loop order in SM, with some typical diagrams shown in Fig. 1. The calculation of the LO amplitude has been comprehensively described in Refs. [17–19].

To assess the impact of the NLO QCD corrections, it is convenient to expand the scalar form factors $C_{1,2}^{\pm}$ in powers of the strong coupling constant:

$$C_{1,2}^{\pm} = C_{1,2}^{\pm(0)} + \frac{\alpha_s}{\pi}C_{1,2}^{\pm(1)} + \cdots, \tag{4}$$

where $C_{1,2}^{\pm(0)}$ designate the LO contributions, and $C_{1,2}^{\pm(1)}$ encode the relative order-α_s corrections.

Substituting (4) back into (3), employing $|C_{1,2}^{\pm}|^2 \approx |C_{1,2}^{\pm(0)}|^2 + 2\frac{\alpha_s}{\pi}\,{\rm Re}\left[C_{1,2}^{\pm(0)}C_{1,2}^{\pm(1)*}\right]$, one then readily identifies the NLO QCD corrections to the differential cross section. The LO expressions for $C_{1,2}^{\pm(0)}$ are well recorded in literatures [17–19]. The central challenge of this work is then to compute the four form factors $C_{1,2}^{\pm}$ through order α_s.

In our calculation, we employ the Feynman gauge in both electroweak and QCD sectors. Moreover, we adopt the dimensional regularization to regularize both UV and IR divergences. The LO and NLO Feynman diagrams and corresponding amplitudes are generated by FeynArts [40]. We use the Mathematica packages FeynCalc [41,42]/FeynCalcFormLink [43] to carry out the trace over Dirac/color matrices, and utilize the packages Apart [44] (and another private code) and the C++ package FIRE [45] to carry out the partial fraction together with the integration-by-parts (IBP) reduction for tensor integrals, finally end up with a number of master integrals (MIs).

Similar to the loop-induced processes $H \to \gamma\gamma, Z\gamma$, the LO amplitude for $e^+e^- \to H\gamma$ is also UV finite. The corresponding $C_{1,2}^{\pm(0)}$ can then be expressed in terms of the linear combinations of a number of one-loop Passarino–Veltman functions. These form factors have been presented in this format in previous work [19], while retaining a non-vanishing electron mass to regulate the potential collinear divergence (which can arise from the last diagram in Fig. 1). Of course, the ultimate amplitude is free from collinear singularity and one is allowed to take the smooth limit $m_e \to 0$ in the end. As stated before, we have set $m_e = 0$ at the outset and used dimensional regularization to regularize both UV and collinear divergences. We feel that our procedure looks simpler both conceptually and technically. For the sake of completeness, and for readers' convenience, we present our condensed expressions for $C_{1,2}^{\pm(0)}$ in the Appendix A. The involved Passarino–Veltman functions can be worked out analytically, or can be accurately evaluated by the packages LoopTools [46] and Collier [47] in a numerical manner.

We wish to describe more details about the calculation of the NLO QCD corrections. At NLO, all the two-loop diagrams have simple s-channel topology, some of which are illustrated in Fig. 2. They can simply be obtained by dressing the gluon to the top quark loop in all possible ways. For simplicity, we have suppressed the contributions from five lighter quarks, due to their much smaller Yukawa couplings. Thanks to the simple s-channel topology, the amplitude assumes a factorized form:

$$\mathcal{M}^{(1)} = e\bar{v}(p_+)\gamma_\mu\left(g_e^- P_- + g_e^+ P_+\right)u(p_-)\frac{1}{s-M_Z^2}\mathcal{T}^{\mu\nu}_{Z\gamma H}\varepsilon^*_{\gamma,\nu}$$