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Higgs production in two-photon process and transition form factor

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ABSTRACT

The Higgs production in the two-photon fusion process is investigated where one of the photons is off-shell while the other one is on-shell. This process is realized in either electron–positron collision or electron–photon collision where the scattered electron or positron is detected (single tagging) and described by the transition form factor. We calculate the contributions to the transition form factor of the Higgs boson coming from top-quark loops and W-boson loops. We then study the Q^2 dependence of each contribution to the total transition form factor and also of the differential cross section for the Higgs production.

1. Introduction

There has been much interest in the diphoton decay of the Higgs boson discovered at LHC experiments [1], since its coupling to the photon is connected with the question whether it is really a Standard Model (SM) Higgs boson or the one beyond SM, such as in the minimal supersymmetric standard model (MSSM) or in composite models. It would be intriguing to investigate the properties of the SM Higgs boson through the production process in the two-photon fusion: $2\gamma \to H$, which might be realized at ILC [2] and is just the opposite reaction of the diphoton decay mode of the Higgs boson: $H \to 2\gamma$. The Higgs diphoton decay goes through charged fermion loops and W-boson loops as discussed in Refs. [3–9] and the references therein.

Here we are particularly interested in the virtual and real two-photon processes (i) the electron–positron collision in Fig. 1, where one of the scattered electrons (or positrons) is detected (single tagging), and (ii) the electron–photon collision $e\gamma \to eH$ shown in Fig. 2 where we observe the scattered electron. From these processes we can measure the so-called "transition form factor" of the Higgs boson as a function of the virtual photon mass squared.[1]

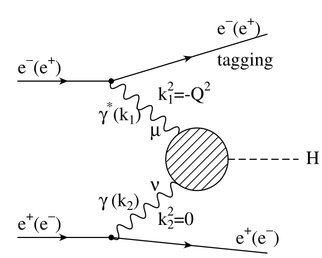

Fig. 1. e^+e^- two-photon fusion process for the Higgs production.

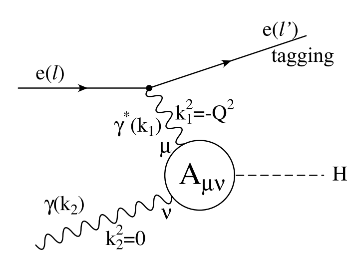

Fig. 2. $e\gamma$ two-photon fusion process for the Higgs production.

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[1] The $\gamma^*\gamma \to \pi^0$ transition form factor was first investigated in QCD [10]. The recent experimental data were given in Refs. [11,12].

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In this Letter we investigate the SM Higgs boson production in the virtual and real two-photon fusion $\gamma^*\gamma \to H$ shown in Figs. 1 and 2 and calculate the transition form factor of the Higgs boson at one-loop level. First we examine the tensor structure of the transition amplitude for $\gamma^*\gamma \to H$ which respects gauge invariance. We then evaluate the contributions to the amplitude from charged fermion loops and W-boson loops.

2. Higgs production and transition amplitude

The transition amplitude for $\gamma^*\gamma \to H$ extracted from the process in Fig. 2 is given by

$$M \equiv \langle H|T|\gamma^*(k_1)\gamma(k_2)\rangle = \epsilon^{\mu}(k_1)\epsilon^{\nu}(k_2)\, A_{\mu\nu}(k_1,k_2), \tag{1}$$

where $\epsilon^{\mu}(k_1)$ $(\epsilon^{\nu}(k_2))$ is the polarization vector of the incident virtual (real) photon, $k_1^2 = -Q^2 < 0$ and $k_2^2 = 0$. Due to the electromagnetic gauge invariance, the tensor $A_{\mu\nu}$ can be decomposed as

$$A_{\mu\nu}(k_1,k_2) = \big(g_{\mu\nu}(k_1\cdot k_2) - k_{2\mu}k_{1\nu}\big)S_1\big(m^2, Q^2, m_H^2\big) + \left(k_{1\mu}k_{2\nu} - \frac{k_1^2}{k_1\cdot k_2}k_{2\mu}k_{2\nu}\right)S_2\big(m^2, Q^2, m_H^2\big), \tag{2}$$

where m_H is the Higgs boson mass satisfying $(k_1+k_2)^2 = m_H^2$ and the intermediate particle masses in the loop are collectively denoted by m. Since $k_2^{\nu}\epsilon_{\nu}(k_2) = 0$, the transition amplitude reads

$$M = \big[g^{\mu\nu}(k_1\cdot k_2) - k_2^{\mu}k_1^{\nu}\big]S_1\big(m^2, Q^2, m_H^2\big)\epsilon_{\mu}(k_1)\epsilon_{\nu}(k_2). \tag{3}$$

3. Transition form factor

For a virtual and real two-photon process, we define the transition form factors F_{total}, $F_{1/2}$ and F_1 as follows:

$$S_1\big(m^2, Q^2, m_H^2\big)\Big/\left(\frac{ge^2}{(4\pi)^2}\frac{1}{m_W}\right) = F_{\text{total}}\big(Q^2, m_H^2\big) = \sum_f N_c e_f^2 F_{1/2}(\rho_f, \tau_f) + F_1(\rho_W, \tau_W), \tag{4}$$

where e and g are the electromagnetic and weak gauge couplings, respectively, and m_W is the W boson mass. $F_{1/2}$ and F_1 are contributions from fermion loops and W boson loops, respectively, N_c is a color factor (1 for leptons and 3 for quarks), e_f is the electromagnetic charge of fermion in the unit of proton charge and

$$\rho_f \equiv \frac{Q^2}{4m_f^2}, \qquad \tau_f \equiv \frac{4m_f^2}{m_H^2}, \qquad \rho_W \equiv \frac{Q^2}{4m_W^2}, \qquad \tau_W \equiv \frac{4m_W^2}{m_H^2}. \tag{5}$$

3.1. Fermion loop contribution

We calculate the charged fermion triangle-loop diagrams shown in Fig. 3 and obtain

$$F_{1/2}(\rho,\tau) = -\frac{2\tau}{1+\rho\tau}\left\{1 + \left(1 - \frac{\tau}{1+\rho\tau}\right)\left(f(\tau) + \frac{1}{4}g(\rho)\right) + \frac{\tau}{1+\rho\tau}\big(2\rho\sqrt{\tau-1}\sqrt{f(\tau)} - \sqrt{\rho(\rho+1)}\sqrt{g(\rho)}\big)\right\}, \tag{6}$$

where

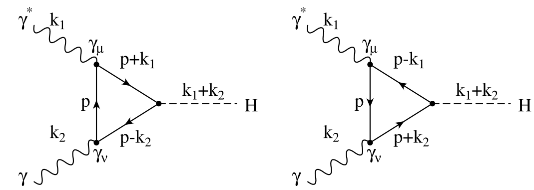

Fig. 3. Fermion triangle-loop contribution for $\gamma^*\gamma \to H$.

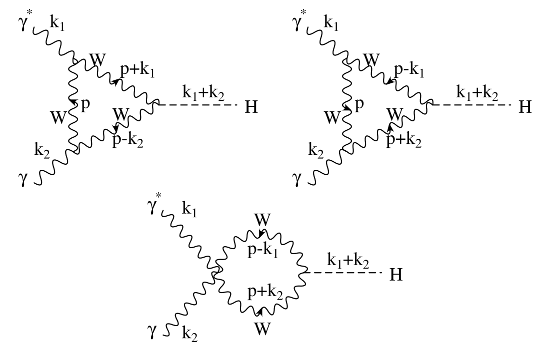

Fig. 4. W-boson loop contribution for $\gamma^*\gamma \to H$.

$$f(\tau) = \left[\sin^{-1}\sqrt{\frac{1}{\tau}}\right]^2, \quad \text{for } \tau \geqslant 1, \tag{7}$$

$$= -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2, \quad \text{for } \tau < 1, \tag{8}$$

$$g(\rho) = \left[\log\frac{\sqrt{\rho+1}+\sqrt{\rho}}{\sqrt{\rho+1}-\sqrt{\rho}}\right]^2. \tag{9}$$

Eq. (6) shows that the fermion loop contribution $F_{1/2}$ is proportional to τ_f, i.e., the fermion mass squared m_f^2. Thus the contributions to the transition form factor from leptons and light-flavor (u, d, s, c and b) quarks are negligibly small compared to the one from top quark. Therefore, from now on, we consider only the top-quark loop contribution for $F_{1/2}$.

3.2. W-boson loop contribution

Next we calculate the W-boson loop diagrams in unitary gauge shown in Fig. 4 and obtain

$$F_1(\rho,\tau) = \frac{1}{1+\rho\tau}\left\{\frac{\tau}{1+\rho\tau}\big(4\rho + 8\rho^2\tau + 6(1+\rho\tau) - 3\tau\big) \times \left(f(\tau) + \frac{1}{4}g(\rho)\right) + \big(4\rho + 2(1+\rho\tau) + 3\tau\big) \times \left(1 + \frac{2\rho\tau}{1+\rho\tau}\sqrt{\tau-1}\sqrt{f(\tau)} - \frac{\tau}{1+\rho\tau}\sqrt{\rho(\rho+1)}\sqrt{g(\rho)}\right)\right\}, \tag{10}$$

where the expressions of $f(\tau)$ and $g(\rho)$ are given in Eqs. (7) and (9), respectively.

It is noted that $f(\tau)$ and $g(\rho)$ appear in the expressions of $F_{1/2}(\rho,\tau)$ in Eq. (6) and $F_1(\rho,\tau)$ in Eq. (10) as the following combinations,

$$f(\tau) + \frac{1}{4}g(\rho) \quad \text{and} \quad 2\rho\sqrt{\tau-1}\sqrt{f(\tau)} - \sqrt{\rho(\rho+1)}\sqrt{g(\rho)}, \tag{11}$$