Decay Channels of the Standard Higgs Boson¹

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Abstract—In this paper, we review the results of studies on the decay channels of the standard Higgs boson: $H \to f + \bar{f}$, $H \to Z + f + \bar{f}$, $H \to W + f + \bar{f}$, $H \to \gamma + \gamma$, $H \to \gamma + Z$, and $H \to g + g$. Here $ff'$ or $f\bar{f}'$ are the fundamental fermions pair (leptons, quarks). Within the framework of the Standard Model analytical expressions for the partial widths of the indicated decays were obtained and their dependence on the mass of the Higgs boson was studied.

Keywords: standard model, Higgs boson, left and right coupling constants, helicity, Weinberg parameter, decay width.

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INTRODUCTION

The standard model (SM), based on local gauge symmetry $SU_C(3) \times SU_L(2) \times U_Y(1)$, describes well the physics of strong and electroweak interactions between leptons and quarks [1–6]. The theory introduces a doublet of scalar fields $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, a neutral component, which has nonzero vacuum-wise value. As a result of spontaneous symmetry breaking, a new Higgs boson particle appears due to quantum excitations of the scalar field, and due to interaction with this field, gauge bosons ($W^\pm$ - and $Z^0$), charged leptons and quarks acquire mass. This mechanism of mass generation of fundamental particles is known as the mechanism of spontaneous symmetry breaking of the Brout—Englert—Higgs symmetry [7–10]. However, until recently, the Higgs boson was not experimentally discovered. The search program for the scalar Higgs boson was one of the main tasks at the Large Hadron Collider (LHC) in CERN. The discovery of the Higgs boson with the characteristics corresponding to the SM predictions was carried out by the ATLAS and CMS collaborations in 2012 [11, 12] (see also the reviews [13–15]). The missing elementary particle in the SM building was found, by the discovery of a Higgs boson with a mass of 125 GeV and this is the beginning of new studies to elucidate the nature of this particle. In this connection, the theoretical interest in the various channels of decay and the production of the Higgs boson has greatly increased. Various properties of the Higgs boson have been studied in [2, 16–21].

In this paper we review our studies on the decay channels of the Higgs boson:

\begin{align}
H & \to f + \bar{f}, \\
H & \to Z + f + \bar{f}, \\
H & \to W + f + \bar{f}, \\
H & \to \gamma + \gamma, \\
H & \to \gamma + Z, \\
H & \to g + g,
\end{align}

where $ff'$ or $f\bar{f}'$ are pairs of fundamental fermions (leptons or quarks).

We note that the various decay channels of the Higgs boson were earlier studied by a number of authors [22–32]; some preliminary results were obtained by us in [33, 34]. However, these papers do not take into account the polarization states of finite particles. Below, our analysis shows that studying the polarization characteristics of particles can provide valuable information about the nature of the Higgs boson.

1. THE DECAY OF THE HIGGS BOSON INTO LEPTONS (QUARKS)

Let us first consider the decay of the Higgs boson into a fermion-antifermion pair (1). This process is
Suppose that the fermion-antifermion pair is polarized transversely \((\xi_1 = \eta_1, \xi_2 = \eta_2, \eta_1\) and \(\eta_2\) are the transverse components of the spin vectors of the fermions):

\[
(\eta_1, n) = (\eta_1, n) = (0, (\eta_1, \eta_2)) = \eta_1\eta_2 \cos \varphi,
\]

\[
(n(\eta_1, \eta_2)) = \eta_1\eta_2 \sin \varphi,
\]

\(\varphi\) is the angle between the spin vectors \(\eta_1\) and \(\eta_2\). In this case, the decay width \(\Phi \to f + \bar{f}\) is:

\[
\frac{d\Gamma(\Phi = \eta_1, \eta_2)}{d\Omega} = \frac{N_C\beta_f m_f^2}{128\pi^2} \sqrt{2}G_F M_{\Phi} \times |\eta_1^2| \eta_2^2 (l + \eta_1\eta_2 \cos \varphi) + |\eta_2|^2 \times (1 - \eta_1\eta_2 \cos \varphi) + 2\Re(ab^*)|\beta_f| \eta_1\eta_2 \sin \varphi |. \tag{9}
\]

It follows that, if the transverse polarizations of the fermion and the antifermion are parallel \((\varphi = 0)\), then for a complete transverse polarization of the fermions \((\eta_1 = \eta_2 = 1)\), the decay of the \(\Phi\)-boson can occur only due to the CP-even interaction:

\[
\frac{d\Gamma(\Phi = \eta_1, \eta_2)}{d\Omega} \sim \beta_f |a|^2.
\]

The decay of the \(\Phi\)-boson of the CP-odd interaction occurs only for anti-parallel transverse polarizations of the fermion-antifermion pair \((\varphi = \pi)\):

\[
\frac{d\Gamma(\Phi = \eta_1, \eta_2)}{d\Omega} \sim \beta_f |b|^2.
\]

If the \(\Phi\)-boson is a mixture of the CP-even and CP-odd states, then the asymmetry

\[
\frac{d\Gamma(\Phi = \pi/2) - d\Gamma(\Phi = -\pi/2)}{d\Omega} = \frac{d\Gamma(\Phi = \pi) - d\Gamma(\Phi = -\pi/2)}{d\Omega} = 2\eta_1\eta_2 |ab^*| \frac{\Im(ab^*)}{|a|^2 + |b|^2} \tag{10}
\]

will differ from zero and this asymmetry can reach values of the order of 1 (for complete transverse polarization of the fermions \(\eta_1 = \eta_2 = 1\) and if they \(a\) and \(b\) are of the same order of magnitude).

For a pure CP-state, one of the coefficients \(a\) and \(b\) is equal to zero and another asymmetry

\[
\frac{d\Gamma(\Phi = 0) - d\Gamma(\Phi = \pi)}{d\Omega} = \frac{d\Gamma(\Phi = 0) - d\Gamma(\Phi = \pi)}{d\Omega} = \eta_1\eta_2 |ab^*| \frac{\Re(ab^*)}{|a|^2 + |b|^2} \tag{11}
\]

will be either +1 or -1, depending on whether the Higgs boson is a CP-even or CP-odd state.

The aforementioned asymmetries \(A_1\) and \(A_2\) are more favorable to study in the decay channel of the Higgs boson \(H \to \tau^- + \tau^+\). This is due to the fact that