Full angular and mass distribution of the Higgs boson decay into two off-mass-shell Z bosons

Taras Zagoskin

V.N. Karazin Kharkov National University, Ukraine

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Introduction

- The ATLAS and CMS collaborations at the LHC recently observed a new boson h with the mass around 125 GeV with statistical significance of about five standard deviations. However clarification of properties of this particle requires more data and time.

$$S_h = 0 \ or \ S_h = 2$$

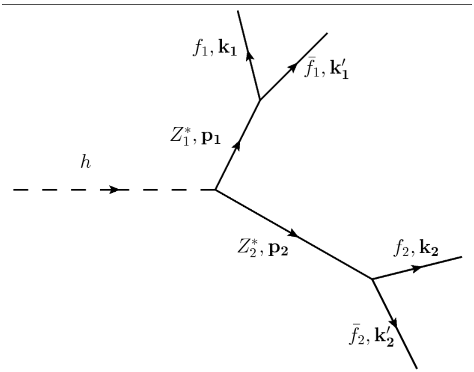
$$CP_h = ?$$

- In the SM $S_h = 0$, $C_h = P_h = 1$, but there are plenty of extensions of the SM, which contain many Higgs bosons, some of which may not have definite CP parity.

Plan of the investigation

In order to clarify the CP properties of the Higgs boson the following way has been chosen.

- We consider a decay $h \to Z_1^* Z_2^* \to f_1 \bar{f}_1 f_2 \bar{f}_2$, which matrix element is written for arbitrary CP parity of the Higgs boson.



Plan of the investigation

$$A_{h\to Z_1^* Z_2^*} = 2\sqrt{\sqrt{2}G_F}\, m_Z^2 \Big(a(e_1^*\cdot e_2^*) + \frac{b}{m_h^2}(e_1^*\cdot(p_1+p_2))(e_2^*\cdot(p_1+p_2)) +$$

$$+ i\frac{c}{m_h^2}\varepsilon_{\mu\nu\rho\sigma}(p_1^\mu + p_2^\mu)(p_1^\nu - p_2^\nu)e_1^{*\rho}e_2^{*\sigma}\Big)$$

G_F is the Fermi constant,
m_Z is the mass of the Z boson,
a, b, c are constants describing the CP-properties of the Higgs boson,
e_1 and e_2 are polarization 4-vectors of Z_1^* and Z_2^* respectively,
m_h is the mass of the Higgs boson.
In the SM $a = 1$, $b = c = 0$.

- We derive the full angular and mass distribution of this decay.
- Experimentalists measure an experimental full angular and mass distribution of this decay.
- Comparing the theoretical and experimental distributions, experimentalists get constraints on the values of a, b, c.

Obtaining the distribution

The total width Γ of the decay is

$$\Gamma = \frac{1}{2m_h}\int_\infty d^3k_1 \frac{1}{2\cdot(2\pi)^3\sqrt{k_1^2+m_{f_1}^2}}\int_\infty d^3k_1' \frac{1}{2\cdot(2\pi)^3\sqrt{(k_1')^2+m_{f_1}^2}}\int_\infty d^3k_2 \frac{1}{2\cdot(2\pi)^3\sqrt{k_2^2+m_{f_2}^2}}\times$$
$$\times\int_\infty d^3k_2' \frac{1}{2\cdot(2\pi)^3\sqrt{(k_2')^2+m_{f_2}^2}}\,\delta\left(m_h-\sqrt{k_1^2+m_{f_1}^2}-\sqrt{(k_1')^2+m_{f_1}^2}-\sqrt{k_2^2+m_{f_2}^2}-\sqrt{(k_2')^2+m_{f_2}^2}\right)\times$$
$$\times\,\delta_3(\mathbf{k_1}+\mathbf{k_1'}+\mathbf{k_2}+\mathbf{k_2'})\,(2\pi)^4 <|M|^2>,$$

where M is the matrix element of this decay and in the SM, according to the Feynman rules,

$$iM = 2i\sqrt{\sqrt{2}G_F}m_Z^2 g^{\mu\nu}\times$$
$$i\frac{-g_{\mu\rho}+\frac{p_{1\mu}p_{1\rho}}{m_Z^2}}{a_1-m_Z^2+im_Z\Gamma_Z}\bar{u}(m_{f_1},\lambda_{f_1},\mathbf{k_1})(-i)\sqrt{\sqrt{2}G_F}m_Z\gamma^\rho(v_{f_1}-a_{f_1}\gamma^5)v(m_{f_1},\lambda_{\bar{f}_1},\mathbf{k_1'})\times$$
$$i\frac{-g_{\nu\sigma}+\frac{p_{2\nu}p_{2\sigma}}{m_Z^2}}{a_2-m_Z^2+im_Z\Gamma_Z}\bar{u}(m_{f_2},\lambda_{f_2},\mathbf{k_2})(-i)\sqrt{\sqrt{2}G_F}m_Z\gamma^\sigma(v_{f_2}-a_{f_2}\gamma^5)v(m_{f_2},\lambda_{\bar{f}_2},\mathbf{k_2'}).$$

a_1 is the mass of Z_1^* squared, a_2 is the mass of Z_2^* squared,
Γ_Z is the total width of the Z boson,
v_f and a_f are constants depending on the fermion f.

Obtaining the distribution

By definition,

$$< |M|^2 >= \sum_{\lambda_{f_1}=-\frac{1}{2}}^{\frac{1}{2}} \sum_{\lambda_{\bar{f}_1}=-\frac{1}{2}}^{\frac{1}{2}} \sum_{\lambda_{f_2}=-\frac{1}{2}}^{\frac{1}{2}} \sum_{\lambda_{\bar{f}_2}=-\frac{1}{2}}^{\frac{1}{2}} |M|^2.$$

We can divide the expression of Γ into three parts:

$$\Gamma = \frac{1}{(2\pi)^8 \cdot 2m_h} \int_{4m_{f_1}^2}^{(m_h-2m_{f_2})^2} da_1 \int_{4m_{f_2}^2}^{(m_h-\sqrt{a_1})^2} da_2$$

$$\underbrace{\int_\infty d^3p_1 \frac{1}{2\sqrt{p_1^2+a_1}} \int_\infty d^3p_2 \frac{1}{2\sqrt{p_2^2+a_2}} \delta(m_h - \sqrt{p_1^2+a_1} - \sqrt{p_2^2+a_2})\delta_3(\mathbf{p_1}+\mathbf{p_2})}_{h\to Z_1^* Z_2^*}$$

$$\underbrace{\int_\infty d^3k_1 \frac{1}{2\sqrt{k_1^2+m_{f_1}^2}} \int_\infty d^3k_1' \frac{1}{2\sqrt{(k_1')^2+m_{f_1}^2}} \delta(\sqrt{p_1^2+a_1} - \sqrt{k_1^2+m_{f_1}^2} - \sqrt{(k_1')^2+m_{f_1}^2})\delta_3(\mathbf{p_1}-\mathbf{k_1}-\mathbf{k_1'})}_{Z_1^*\to f_1\bar{f}_1}$$

$$\underbrace{\int_\infty d^3k_2 \frac{1}{2\sqrt{k_2^2+m_{f_2}^2}} \int_\infty d^3k_2' \frac{1}{2\sqrt{(k_2')^2+m_{f_2}^2}} \delta(\sqrt{p_2^2+a_2} - \sqrt{k_2^2+m_{f_2}^2} - \sqrt{(k_2')^2+m_{f_2}^2})\delta_3(\mathbf{p_2}-\mathbf{k_2}-\mathbf{k_2'})}_{Z_2^*\to f_2\bar{f}_2} < |M|^2 >$$

Full angular and mass distribution

Using the approximations $m_{f_1} \approx 0$, $m_{f_2} \approx 0$, it can be derived that

$$\Gamma \approx \int_0^{m_h^2} da_1 \int_0^{(m_h-\sqrt{a_1})^2} da_2 \int_0^{\pi} d\theta_1 \sin\theta_1 \int_0^{\pi} d\theta_2 \sin\theta_2 \int_0^{2\pi} d\varphi$$

$$\frac{\sqrt{2} G_F^3 m_Z^8}{(4\pi)^6 \cdot m_h^3} \cdot \frac{\lambda^{\frac{1}{2}}(m_h^2, a_1, a_2) a_1 a_2}{((a_1 - m_Z^2)^2 + (m_Z\Gamma_Z)^2)((a_2 - m_Z^2)^2 + (m_Z\Gamma_Z)^2)} \times$$
$$\times \left[(a_{f_1}^2 + v_{f_1}^2)(a_{f_2}^2 + v_{f_2}^2)(2((1+c_1^2)(1+c_2^2) + s_1^2 s_2^2 \cos(2\varphi)) - 4f(a_1,a_2)s_1c_1s_2c_2\cos\varphi +\right.$$
$$\left.+ f^2(a_1,a_2)s_1^2 s_2^2) + 16 a_{f_1} v_{f_1} a_{f_2} v_{f_2}(2c_1c_2 - f(a_1,a_2)s_1s_2\cos\varphi)\right].$$

θ_1 is the angle between the momentum of Z_1 in the h rest frame and the momentum of f_1 in the Z_1 rest frame,
θ_2 is the angle between the momentum of Z_2 in the h rest frame and the momentum of f_2 in the Z_2 rest frame,
φ is the angle between the planes of the decays $Z_1 \to f_1\bar{f}_1$ and $Z_2 \to f_2\bar{f}_2$.
By definition,

$$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz,$$
$$s_1 = \sin\theta_1, c_1 = \cos\theta_1, s_2 = \sin\theta_2, c_2 = \cos\theta_2,$$
$$f(a_1,a_2) = \frac{m_h^2 - a_1 - a_2}{\sqrt{a_1 a_2}}.$$

φ and mass distribution

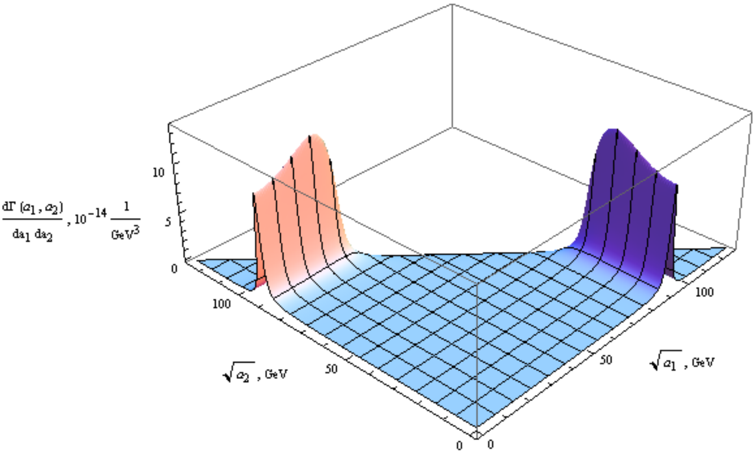
$$\frac{d\Gamma}{da_1 da_2 d\varphi} \approx \frac{\sqrt{2} G_F^3 m_Z^8}{9\pi \cdot (4\pi)^5 m_h^3} \cdot \frac{\lambda^{\frac{1}{2}}(m_h^2, a_1, a_2) a_1 a_2}{((a_1 - m_Z^2)^2 + (m_Z \Gamma_Z)^2)((a_2 - m_Z^2)^2 + (m_Z \Gamma_Z)^2)} \times$$

$$\times \left[4(a_{f_1}^2 + v_{f_1}^2)(a_{f_2}^2 + v_{f_2}^2)\left(\frac{\lambda(m_h^2, a_1, a_2)}{a_1 a_2} + 12 + 2\cos(2\varphi)\right) - 9\pi^2 a_{f_1} v_{f_1} a_{f_2} v_{f_2} f(a_1, a_2) \cos\varphi\right]$$

$$\Gamma \approx \int_0^{m_h^2} da_1 \int_0^{(m_h - \sqrt{a_1})^2} da_2 \int_0^{2\pi} d\varphi \frac{d\Gamma}{da_1 da_2 d\varphi}$$

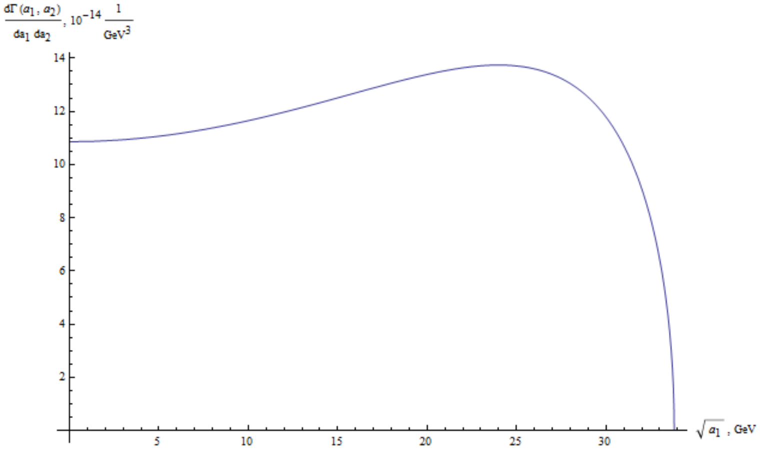
Mass distribution

Figure: $\frac{d\Gamma(a_1,a_2)}{da_1 da_2}$ of a decay $h \to Z_1^* Z_2^* \to l_1 \bar{l}_1 l_2 \bar{l}_2$ as a function of $\sqrt{a_1}$, $\sqrt{a_2}$, in the SM. $l_1 = e^-, \mu^-; l_2 = e^-, \mu^-$.



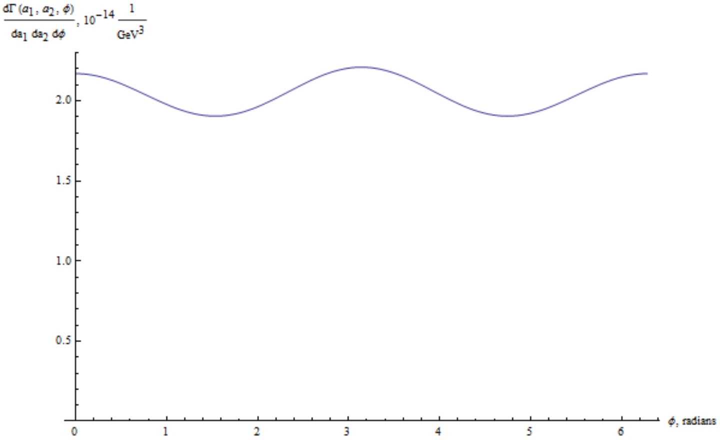
Mass distribution

Figure: $\frac{d\Gamma(a_1,a_2)}{da_1 da_2}$ of a decay $h \to Z_1^* Z_2^* \to l_1 \bar{l}_1 l_2 \bar{l}_2$ as a function of $\sqrt{a_1}$, when $\sqrt{a_2} = m_Z$, in the SM.



φ distribution

Figure: $\frac{d\Gamma(a_1,a_2,\varphi)}{da_1 da_2 d\varphi}$ of a decay $h \to Z_1^* Z_2^* \to l_1 \bar{l}_1 l_2 \bar{l}_2$ as a function of φ, when $\sqrt{a_1} = m_Z$ and $\sqrt{a_2} = \frac{m_h - m_Z}{2}$, in the SM.



Conclusions

- In order to clarify the CP properties of the Higgs boson we are to obtain the full angular and mass distribution of a decay $h \to Z_1^* Z_2^* \to f_1 \bar{f}_1 f_2 \bar{f}_2$ for arbitrary CP parity of the Higgs boson.
- We have derived the full angular and mass distribution, when $CP_h = 1$, i.e. in the SM.
- We are going to obtain the distribution for arbitrary CP parity of the Higgs boson, i.e. beyond the SM.
- We should wait for the experimental full angular and mass distribution and then compare it with the theoretical one in order to get constraints on the values of a, b, c.