The decays of a neutral particle with zero spin and arbitrary CP parity into ZZ or W^-W^+

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Introduction

- In 2012 the ATLAS and CMS collaborations observed a boson h with the mass around 126 GeV. We call this particle the Higgs boson. However, clarification of properties of the observed boson h requires more data.

$$q_h = 0$$

$$S_h = 0 \ or \ S_h = 2\,(very\ unlikely)$$

$$CP_h = ?$$

- In the SM for the Higgs boson

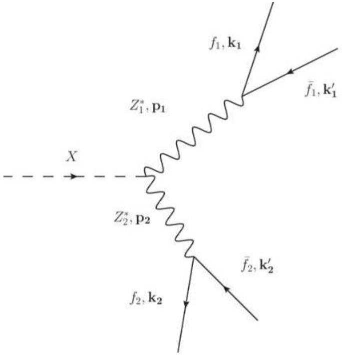
$$q = 0, S = 0, C = P = 1,$$

but some supersymmetric extensions of the SM assume existence of Higgs bosons with negative or indefinite CP parity.

Plan of the investigation

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

- We consider the decay $X \to Z_1^* Z_2^* \to f_1 \bar{f}_1 f_2 \bar{f}_2$, where X is a neutral particle with zero spin and arbitrary CP parity, $f_1 \neq f_2$.



Plan of the investigation

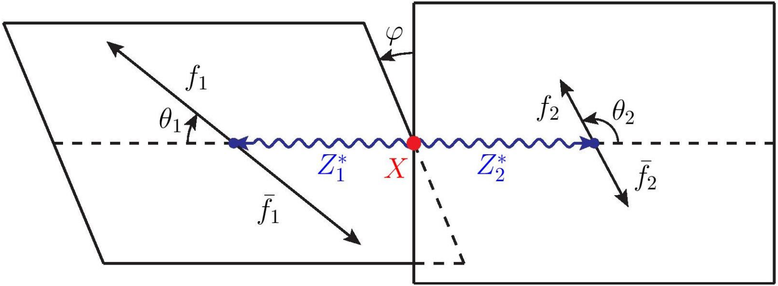
$$A_{X\to Z_1^* Z_2^*} \sim a(e_1^* \cdot e_2^*) + \frac{b}{m_X^2}(e_1^* \cdot p_2)(e_2^* \cdot p_1) + i\,\frac{c}{m_X^2}\varepsilon_{\mu\nu\rho\sigma}(p_1^\mu + p_2^\mu)(p_1^\nu - p_2^\nu)e_1^{*\rho}e_2^{*\sigma}$$

e_1 and e_2 are the polarization 4-vectors of Z_1^* and Z_2^* respectively. a, b, c are complex-valued functions of the masses of Z_1^* and Z_2^*. These functions characterize the CP properties of the boson X. At tree level

CP_X	a	b	c
1	any	any	0
1 (SM)	1	0	0
-1	0	0	$\neq 0$
indefinite	$\neq 0$	any	$\neq 0$
	any	$\neq 0$	$\neq 0$

- We derive the full distribution of the decay $X \to Z_1^* Z_2^* \to f_1 \bar{f}_1 f_2 \bar{f}_2$.
- Experimentalists measure an experimental full distribution of this decay for $X = h$.
- Comparing the theoretical and experimental distributions, one can get constraints on the values of a, b, c at various masses of Z_1^* and Z_2^*.

Definitions of θ_1, θ_2, φ



θ_1 is the angle between the momentum of Z_1^* in a rest frame of X and the momentum of f_1 in a rest frame of Z_1^*,
θ_2 is the angle between the momentum of Z_2^* in a rest frame of X and the momentum of f_2 in a rest frame of Z_2^*,
φ is the azimuthal angle between the planes of the decays $Z_1^* \to f_1 \bar{f}_1$ and $Z_2^* \to f_2 \bar{f}_2$.

Definitions of A_0, $A_\parallel$, $A_\perp$

Moreover, it is convenient to write down the fully differential width by means of the following amplitudes:

$$A_0 \equiv -\left(a\frac{m_X^2 - a_1 - a_2}{2\sqrt{a_1 a_2}} + b\frac{\lambda(m_X^2, a_1, a_2)}{4m_X^2\sqrt{a_1 a_2}} \right),$$

$$A_\parallel \equiv \sqrt{2}a,$$

$$A_\perp \equiv \sqrt{2}c\frac{\lambda^{\frac{1}{2}}(m_X^2, a_1, a_2)}{m_X^2}.$$

a_j is the mass squared of Z_j^*, i.e. the invariant mass of the pair $f_j\bar{f}_j$,
$\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$.

The differential width with respect to a_1, a_2, θ_1, θ_2, φ

Using approximations $m_{f_1} = m_{f_2} = 0$, we have derived that

$$\begin{aligned}\frac{d^5\Gamma}{da_1 da_2 d\theta_1 d\theta_2 d\varphi} =& |A_0|^2 f_1 + (|A_\parallel|^2 + |A_\perp|^2) f_2 + (|A_\parallel|^2 - |A_\perp|^2) f_3 \\ &+ Re(A_0^* A_\parallel) f_4 + Re(A_0^* A_\perp) f_5 + Re(A_\parallel^* A_\perp) f_6 \\ &+ Im(A_0^* A_\parallel) f_7 + Im(A_0^* A_\perp) f_8 + Im(A_\parallel^* A_\perp) f_9.\end{aligned}$$

f_1, f_2, ..., f_9 depend on a_1, a_2, θ_1, θ_2, φ, but they are independent of a, b and c.

The dependence of the fully differential width on the couplings a, b and c is concentrated in nine quadratic combinations of the amplitudes A_0, $A_\parallel$, $A_\perp$.

How many decays should be measured for obtaining a precise enough experimental full distribution of the decay?

$$d^n\Gamma \leftrightarrow 10^{n+1} \text{ decays}$$
$$d^5\Gamma \leftrightarrow 10^6 \text{ decays}$$

How many decays have been observed?

$$h \to Z_1^* Z_2^* \to e^- e^+ \mu^- \mu^+$$

26 decays (ATLAS and CMS together after about 1.5 years of measurements)

Distributions of four and less variables should be considered

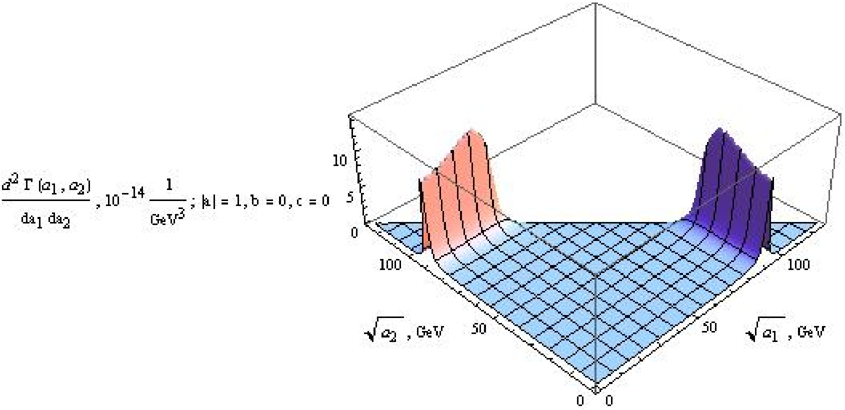
We will probably have a precise enough experimental full distribution

in 60000 years (roughly).

That is why we should try to get constraints on a, b, c by means of measuring distributions of as little a number of variables as possible.

$a_1 a_2$-differential width

Figure: $\frac{d^2\Gamma}{da_1 da_2}$ of the decay $X \to Z_1^* Z_2^* \to l_1^- l_1^+ l_2^- l_2^+$ as a function of $\sqrt{a_1}$, $\sqrt{a_2}$, if X is the SM Higgs boson and $m_X = 125.7$ GeV.
$l_1, l_2 = e, \mu, \tau, l_1 \neq l_2$.



a_2-differential width

Integrating $\frac{d^2\Gamma}{da_1 da_2}$ approximately, we derive that

$$\frac{d\Gamma}{da_2} \approx \frac{\sqrt{2} G_F^3 m_Z^9}{288\pi^4 m_X^3 \Gamma_Z} (a_{f_1}^2 + v_{f_1}^2)(a_{f_2}^2 + v_{f_2}^2) \frac{\lambda^{\frac{1}{2}}(m_X^2, m_Z^2, a_2) a_2}{(a_2 - m_Z^2)^2 + (m_Z \Gamma_Z)^2} \sum_{\lambda=0,\|,\perp} |A'_\lambda|^2$$

$$\forall a_2 \mid 2m_{f_2} < \sqrt{a_2} \leq m_X - \sqrt{m_Z^2 + 3 m_Z \Gamma_Z}.$$

a_f and v_f are constants depending on a fermion f, $A'_\lambda \equiv A_\lambda|_{a_1 = m_Z^2}$.
In several articles the formula for $\frac{d\Gamma}{da_2}$ has been used in the narrow-Z-width approximation when

$$\sqrt{a_2} \leq m_X - m_Z,$$

and their approach is inaccurate.

$m_h - \sqrt{m_Z^2 + 3 m_Z \Gamma_Z} \approx 30.8$ GeV
$m_h - m_Z \approx 34.5$ GeV

Relations between the helicity coefficients and observables

We call the ratios of the nine quadratic combinations of the fully differential width to $\sum_{\lambda=0,\|,\perp} |A_\lambda|^2$ 'the helicity coefficients'. Integrating $\frac{d^5\Gamma}{da_1 da_2 d\theta_1 d\theta_2 d\varphi}$, we can relate all the helicity coefficients to observables. For example,

$$O_1^{(1,2)}(a_2) \equiv \left(\frac{d\Gamma}{da_2}\right)^{-1} \left(\int_0^{\frac{\pi}{2}} d\theta_{1,2} \frac{d^2\Gamma}{da_2 d\theta_{1,2}} - \int_{\frac{\pi}{2}}^{\pi} d\theta_{1,2} \frac{d^2\Gamma}{da_2 d\theta_{1,2}} \right) \sim \frac{\mathrm{Re}(A_\|'^* A_\perp')}{\sum_\lambda |A_\lambda'|^2}$$

$$= \mathrm{Re}(F_\|'^* F_\perp').$$

$$F_\lambda' \equiv \frac{A_\lambda'}{\sqrt{\sum_\lambda |A_\lambda|^2}}, \ \lambda = 0, \|, \perp \, .$$

Relations between the helicity coefficients and observables

$$\left.\begin{aligned}
O_1^{(1,2)}(a_2) &\sim \mathrm{Re}(F_{\|}'^{*}F_{\perp}')\\
O_2^{(1,2)}(a_2) &\sim |F_0'|^2\\
O_3(a_2) &\sim |F_{\|}'|^2+|F_{\perp}'|^2\\
O_4(a_2) &\sim |F_{\|}'|^2-|F_{\perp}'|^2\\
O_5(a_2) &\sim \mathrm{Im}(F_{\|}'^{*}F_{\perp}')\\
O_6(a_2) &\sim \mathrm{Re}(F_0'^{*}F_{\|}')\\
O_7^{(1,2)}(a_2) &\sim \mathrm{Im}(F_0'^{*}F_{\|}')\\
O_8^{(1,2)}(a_2) &\sim \mathrm{Re}(F_0'^{*}F_{\perp}')\\
O_9(a_2) &\sim \mathrm{Im}(F_0'^{*}F_{\perp}')
\end{aligned}\right\}\rightarrow \textit{Constraints on } a,\ b,\ c$$

Conclusions

- In order to clarify the CP properties of the Higgs boson we have considered the fully mass and angular differential width of the decay $X \to Z_1^* Z_2^* \to f_1 \bar{f}_1 f_2 \bar{f}_2$, where X is a neutral particle with zero spin and arbitrary CP parity, $f_1 \neq f_2$.
- Limits of applicability of approximations used when deriving various differential widths are established.
- All the helicity coefficients are related to observables. We have also plotted the observables and determined what constraints on a, b, c can be put by them.
- We should wait for experimentalists measuring the observables $O_1^{(1,2)}$, O_2, ..., O_9 and then get constraints on a, b, c using the shown relations between F_0', $F_\parallel'$, $F_\perp'$ and $O_1^{(1,2)}$, ..., O_9.
- An analogous analysis has been carried out for the decay $X \to W^{-*} W^{+*} \to f_{1-} \bar{f}_{2-} \bar{f}_{1+} f_{2+}$.

The presentation is based on the paper *Zagoskin and Korchin, arXiv:1504.07187*.