Pseudoscalar Higgs Boson Decays into W and Z Bosons

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Introduction

- The search for spin-zero resonances is among the major goals of present day collider physics.
- $H \to WW, ZZ$ decays can yield relatively clean signals.
- For a sufficiently heavy H they can be the dominant decay modes.
- Non-standard Higgs sectors may also contain pseudoscalar particles.

Pseudoscalar Higgs Decays

- In models without Higgs sector CP violation, there are no tree-level couplings between pseudoscalar Higgses A and vector bosons.
- The bosonic sectors of most SM extensions conserve parity.
  - $\Rightarrow$ AWW and AZZ couplings must be induced trough fermion loops.
  - $\Rightarrow$ The branching ratios are usually expected to be small.
- Higgs-fermion couplings can be enhanced by large fermion masses and other model parameters.

$\Rightarrow$ Can the $A \to WW, ZZ$ branching ratios get be of comparable size as the H branching ratios? In what models?

The Two Higgs Doublet Model

Consider a type-II two-Higgs doublet model with a CP invariant tree-level Higgs potential.

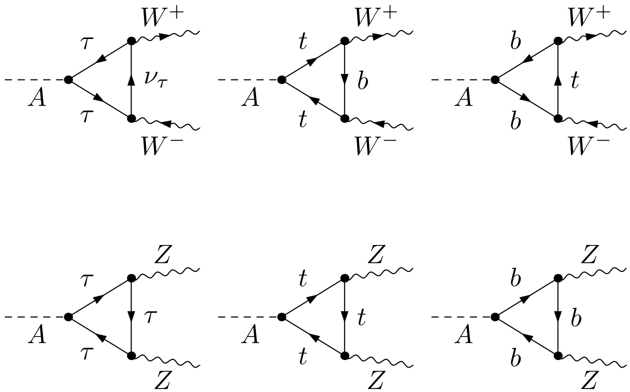
Spin zero particle content:

- two neutral scalar Higgses h, H.
- one neutral pseudoscalar Higgs A.
- one charged Higgs $H^{\pm}$.

Parameters:

- $\tan\beta$ (ratio of the two VEVs).
- Scalar Higgs mixing angle α.

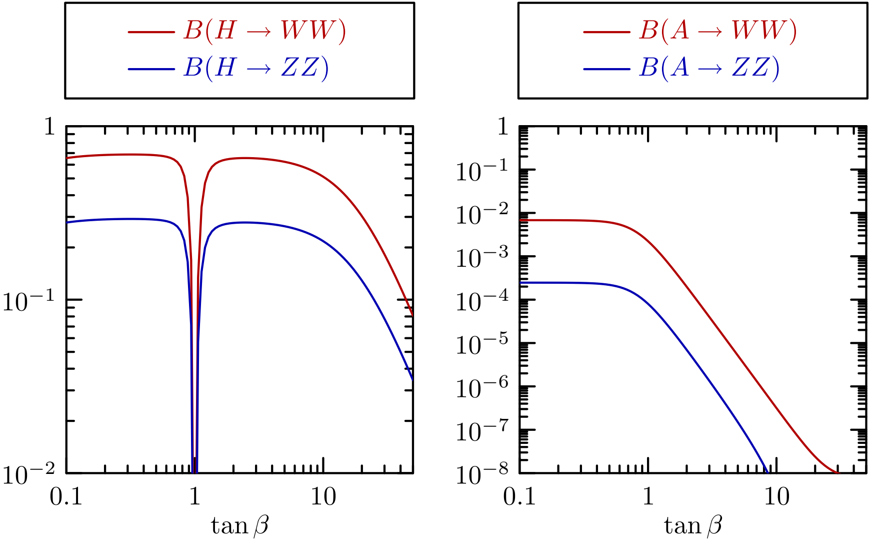
Decays



Other decay channels:

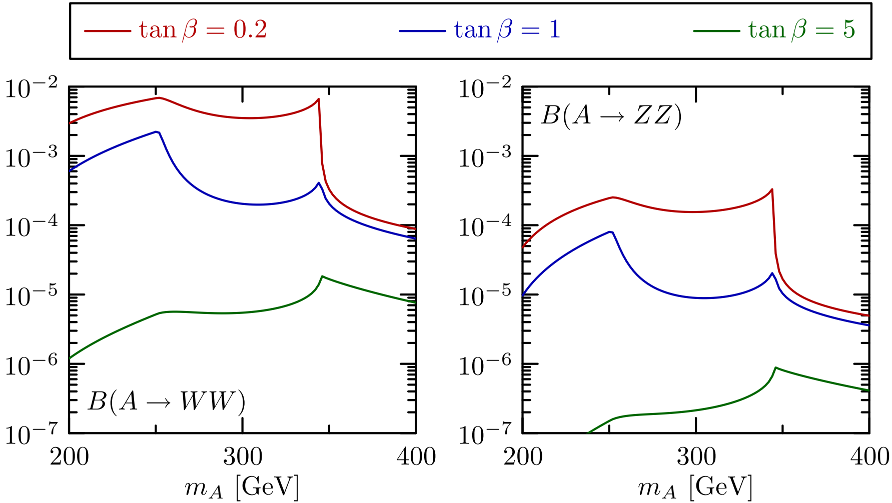
$$H \to hh,\ b\bar{b},\ \tau\bar{\tau},\ t\bar{t},\ gg\ ,$$
$$A \to Zh,\ b\bar{b},\ \tau\bar{\tau},\ t\bar{t},\ gg\ .$$

Branching Ratios



$m_H = m_A = 250\,\text{GeV},\ m_h = 160\,\text{GeV},\ \alpha = \pi/4.$

Mass dependence



$m_h = 160\,\mathrm{GeV}$.

A 4th Generation of Fermions

- The existence of a 4th generation of heavy chiral fermions (u_4, d_4, ν_4, ℓ_4) is not excluded yet.
- The mass bounds from direct searches at LEP and TEVATRON are

$$m_{u_4} > 311\,\mathrm{GeV}\ ,\ m_{d_4} > 190\,\mathrm{GeV}\ ,$$
$$m_{\nu_4} > 90\,\mathrm{GeV}\ ,\ m_{\ell_4} > 100\,\mathrm{GeV}\ .$$

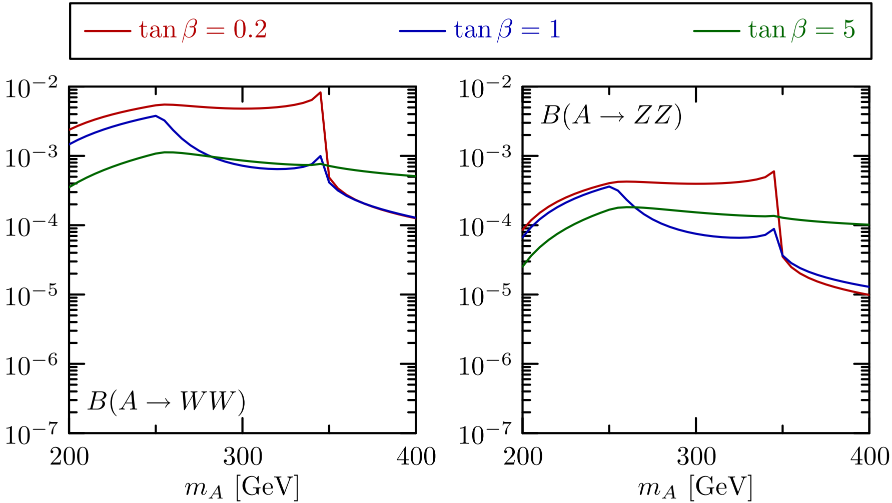
- Experimental limits on ΔS and ΔT require moderate mass splittings and

$$m_{u_4} > m_{d_4}\ ,\ m_{\ell_4} > m_{\nu_4}\ .$$

$\Rightarrow$ We add a 4th generatrion with Dirac neutrinos and

$$m_{u_4} = 320\,\mathrm{GeV}\ ,\ m_{d_4} = 200\,\mathrm{GeV}\ ,$$
$$m_{\nu_4} = 180\,\mathrm{GeV}\ ,\ m_{\ell_4} = 220\,\mathrm{GeV}\ .$$

Branching Ratios



$m_h = 160\,\mathrm{GeV}$.

Vector-like Quarks

- Another possible extension are vector-like quarks, whose left- and right-chiral components have equal gauge charges.
- They are predicted by extra dimensional models with bulk fermions and Little Higgs models.
- They only suffer very weak constraints from electroweak precision observables.

⇒ We add an $SU(2)$ doublet $Q = (U, D)$ and two $SU(2)$ singlets U', D':

$$\begin{aligned}\mathcal{L}_{\mathsf{VQ,gauge}} = & \ \bar{Q} i \not{D} Q + \bar{U}' i \not{D} U' + \bar{D}' i \not{D} D' \\ & -M_Q \bar{Q} Q - M_U \bar{U}' U' - M_D \bar{D}' D' \quad , \\ \mathcal{L}_{\mathsf{VQ,Yuk}} = & -y_U \bar{Q}_L \Phi_u^{\mathsf{c}} U'_R - y_D \bar{Q}_L \Phi_d D'_R \\ & -\tilde{y}_U \bar{Q}_R \Phi_u^{\mathsf{c}} U'_L - \tilde{y}_D \bar{Q}_R \Phi_d D'_L + \mathsf{h.c.} \quad .\end{aligned}$$

Mass Matrices

After EWSB we get mass matrices

$$\begin{pmatrix} M_Q & y_U v_u \\ \tilde{y}_U v_u & M_U \end{pmatrix} , \begin{pmatrix} M_Q & y_D v_d \\ \tilde{y}_D v_d & M_D \end{pmatrix} ,$$

which can be diagonalised with bi-orthogonal rotations

$$\begin{pmatrix} D \\ D' \end{pmatrix}_{L,R} = \begin{pmatrix} \cos\varphi^D_{L,R} & -\sin\varphi^D_{L,R} \\ \sin\varphi^D_{L,R} & \cos\varphi^D_{L,R} \end{pmatrix} \begin{pmatrix} D_1 \\ D_2 \end{pmatrix}_{L,R} ,$$

$$\begin{pmatrix} U \\ U' \end{pmatrix}_{L,R} = \begin{pmatrix} \cos\varphi^U_{L,R} & -\sin\varphi^U_{L,R} \\ \sin\varphi^U_{L,R} & \cos\varphi^U_{L,R} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \end{pmatrix}_{L,R} ,$$

Parameters

The mixing angles must satisfy

$$t_{L-R}^{U,D} \equiv \tan(\varphi_L^{U,D} - \varphi_R^{U,D}) = \frac{v_{u,d}(\tilde{y}_{U,D} - y_{U,D})}{M_Q + M_{U,D}} \ ,$$

$$t_{L+R}^{U,D} \equiv \tan(\varphi_L^{U,D} + \varphi_R^{U,D}) = \frac{v_{u,d}(\tilde{y}_{U,D} + y_{U,D})}{M_Q - M_{U,D}} \ .$$

The mass eigenvalues are

$$m_{U_{1,2}} = \frac{1}{2}\left[\sqrt{(M_Q + M_U)^2 + v_u^2(y_U - \tilde{y}_U)^2} \pm \sqrt{(M_Q - M_U)^2 + v_u^2(y_U + \tilde{y}_U)^2}\right] \ ,$$

$$m_{D_{1,2}} = \frac{1}{2}\left[\sqrt{(M_Q + M_D)^2 + v_d^2(y_D - \tilde{y}_D)^2} \pm \sqrt{(M_Q - M_D)^2 + v_d^2(y_D + \tilde{y}_D)^2}\right] \ .$$

For the numerical analysis we choose as independent parameters

$$M_Q = 1\,\mathrm{TeV} \ , \ m_{U_2} = m_{D_2} = 320\,\mathrm{GeV} \ ,$$

$$t_{L-R}^U \ , \ t_{L+R}^U \ , \ t_{L-R}^D \ , \ t_{L+R}^D \ .$$

Results

- Large (small) values of $\tan\beta$ enhance the $AD\bar{D}$ ($AU\bar{U}$) couplings.
- For small $t_{L+R}^{U,D}$ or small $t_{L-R}^{U,D}$ the vector-quark sector becomes parity conserving and does not contribute to $A \to WW, ZZ$ decays.
- For large $t_{L\pm R}^{U,D}$ the mixing angles approach 0 or $\pm\pi/2$

  $\Rightarrow$ (most) digagrams get suppressed by factors $\sin\varphi_L^{U,D}$, $\cos\varphi_R^{U,D}$, ...
- The vector-quark contributions saturate for $t_{L\pm R}^{U,D} \gtrsim 10$.
- Only small contributions to $A \to ZZ$ decays.

$$\tan\beta = 0.2 \quad \Rightarrow \quad B(A \to WW) < 2\%$$
$$\tan\beta = 5 \quad \Rightarrow \quad B(A \to WW) < 0.12\%$$

Conclusions

- We studied the $A \to WW, ZZ$ branching ratios in the (CP conserving) 2HDM extended by different types of heavy fermions.
- We find the largest branching ratios for small $\tan\beta$:

$$B(A \to WW) \lesssim 2\% \ , \ B(A \to ZZ) \lesssim 10^{-3} \ .$$

⇒ If a spin-zero resonance decays dominantly into WW, ZZ it is most likely CP even.

⇒ If the WW and ZZ decays of a spin-zero resonance are rare it could be a pseudo-scalar.