Fenomenology of the Higgs Real Singlet Extension of the Standard Model

UNIVERSIDAD DE CANTABRIA

Author: Alain Verduras
Director: Sven Heinemeyer
Codirector: Jónatan Piedra

Real Singlet Extension I

Potential

$$V(\phi, S) = -m^2\phi^\dagger\phi \boxed{- \mu^2 S^2} + \lambda_1(\phi^\dagger\phi)^2 + \boxed{\lambda_2 S^4} + \boxed{\lambda_3\phi^\dagger\phi S^2}$$

Doublet

$$\phi = \begin{pmatrix} 0 \\ \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix}$$

Singlet

$$S = \frac{h' + x}{\sqrt{2}}$$

Mixing matrix

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \bar{h} \\ h' \end{pmatrix}$$

Real Singlet Extension II

Field mixing

$$h = \bar{h}\cos\alpha - h'\sin\alpha$$
$$H = \bar{h}\sin\alpha + h'\cos\alpha$$

Cross section

$$\sigma(e^+e^- \to Zh) = \sigma_{\mathrm{SM}} \cdot \cos^2\alpha$$
$$\sigma(e^+e^- \to ZH) = \sigma_{\mathrm{SM}} \cdot \sin^2\alpha$$

Couplings

$$g_h = g_{\mathrm{SM}} \cdot \cos\alpha$$
$$g_H = g_{\mathrm{SM}} \cdot \sin\alpha$$

Branching ratio

$$BR_{H_i}^{\mathrm{HxSM}} = \frac{\Gamma_{H_i}^{\mathrm{SM}}\sin^2\alpha}{\Gamma_{H_{\mathrm{tot}}}^{\mathrm{SM}} \cdot \sin^2\alpha + \Gamma_{H\to hh}}$$

Objetives I

$$m_h = 125 \text{ GeV} \qquad m_H \in [130, 160] \text{ GeV}$$

- Calculate the **relative experimental uncertainty of the couplings** of the new Higgs boson with the SM particles in the ILC250.

- Calculate **how much of the allowed parameter space** can be measured in the ILC250.

- Calculate the **triple Higgs couplings** of the new model and determine whether this model could help with the solution of the matter-antimatter asymmetry problem.

Objetives II

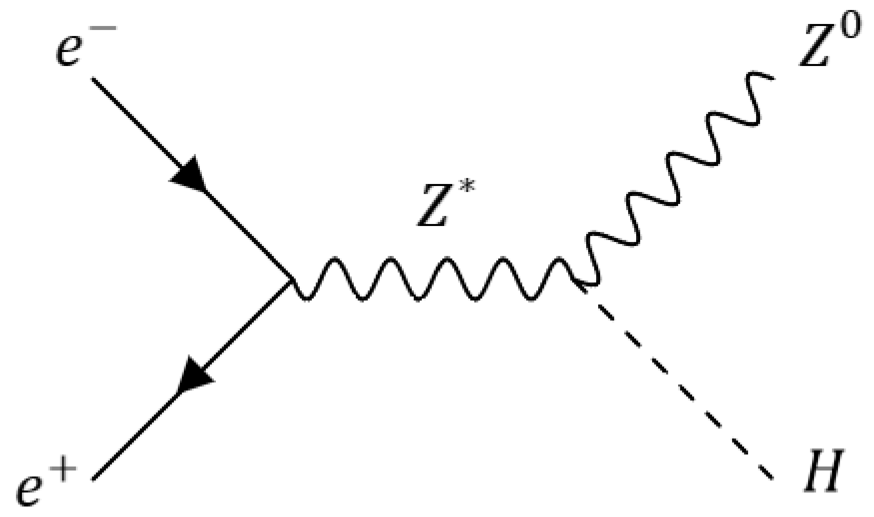
$$m_h \in [10, 60] \text{ GeV} \qquad m_H = 125 \text{ GeV}$$

- Calculate the **cross section** of the process $e^+e^- \to hhZ$ in the ILC250 and its dependence on the triple Higgs coupling constants.

- Determine whether any **triple Higgs couplings** of the new model can be measured in the ILC250.

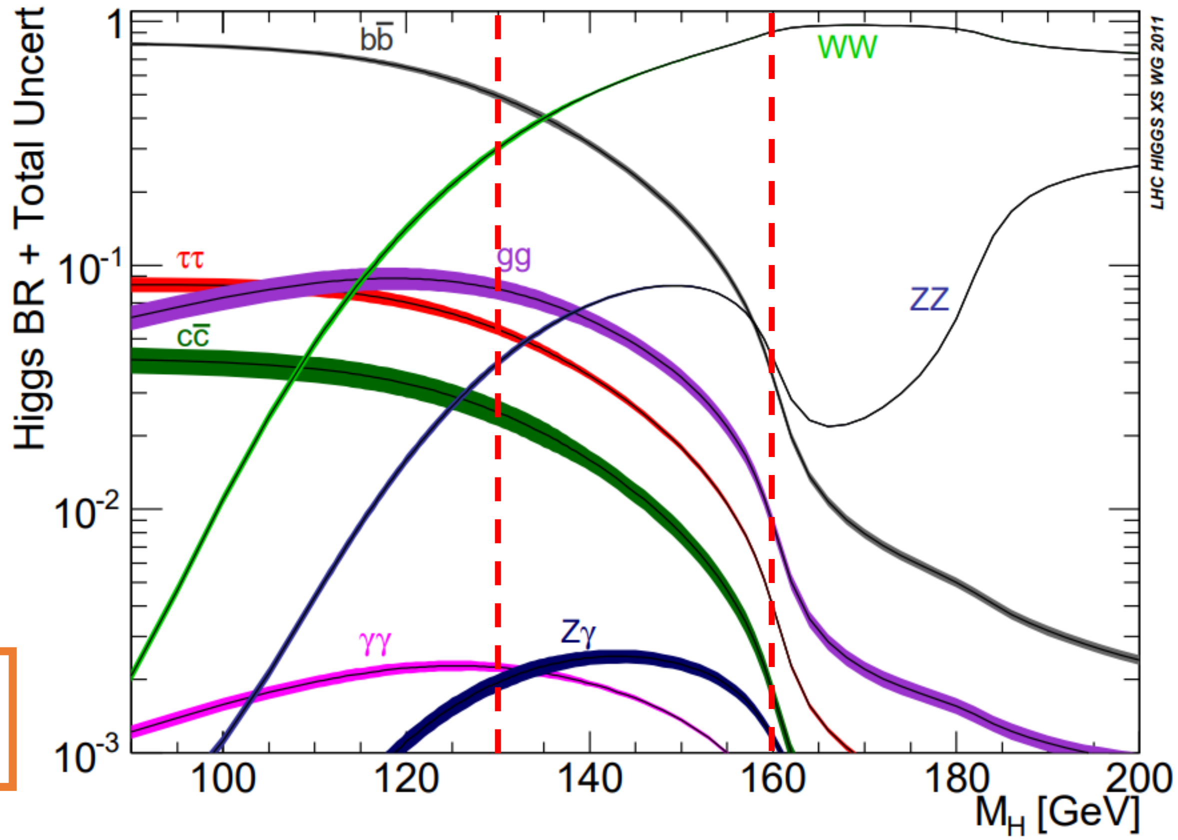
Study process I

Production process



$$m_h = 125 \text{ GeV} \qquad m_H \in [130, 160] \text{ GeV}$$

Decay channels

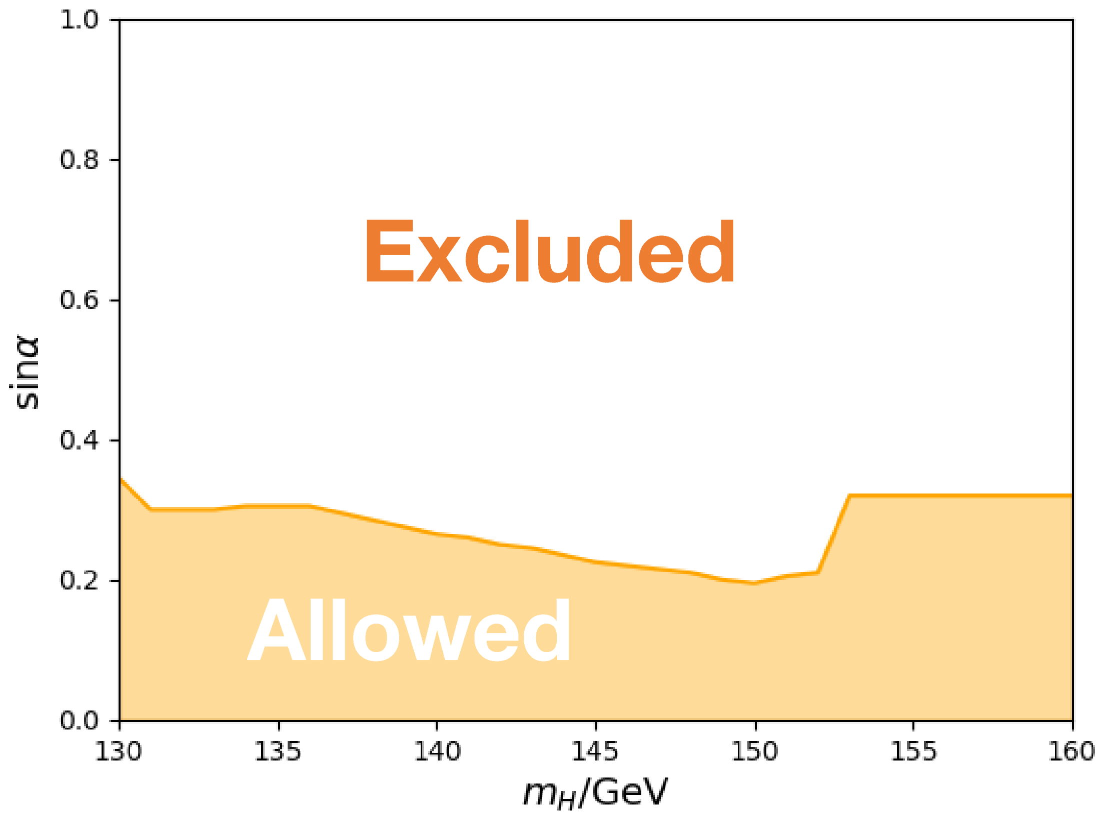


Ref: Denner, A. and Heinemeyer, S. and Puljak, I. and Rebuzzi, D. and Spira M. (sep, 2011). Standard model Higgs-boson branching ratios with uncertainties. The European Physical Journal C. 71, 9.

Parameter space

Parameters allowed by the constraints given by the theory, by the direct searches for the Higgs boson and by measurements

$$m_h = 125 \text{ GeV}$$
$$m_H \in [130, 160] \text{ GeV}$$



Data provided by Tania Robens

Couplings relative uncertainty

Decay channel:

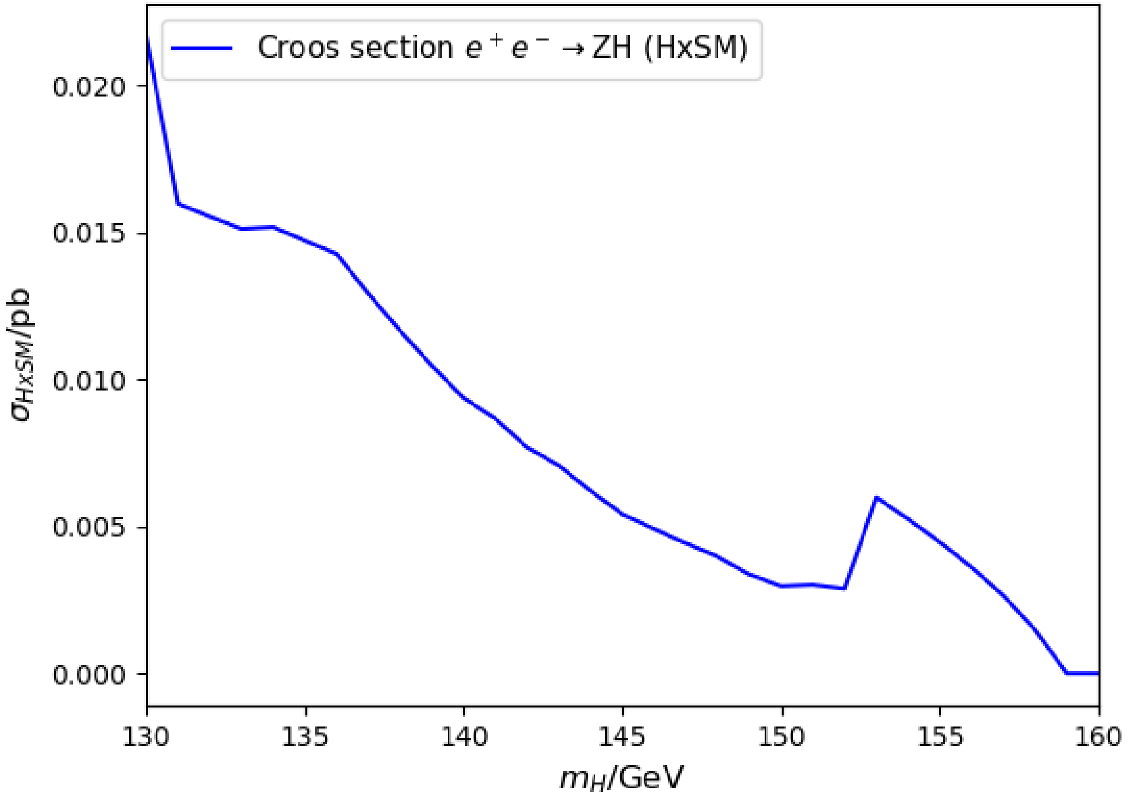
$$\frac{\left(\frac{\Delta g_x}{g_x}\right)_H}{\left(\frac{\Delta g_x}{g_x}\right)_{h_{SM}}} = \sqrt{\frac{D+f_x}{1+f_x}}\sqrt{\frac{\sigma(e^+e^- \to Zh_{SM})}{\sigma(e^+e^- \to ZH)}}\sqrt{\frac{BR(h_{SM} \to xx)}{BR(H \to xx)}\frac{1-BR(h_{SM} \to xx)}{1-BR(H \to xx)}}$$

Production channel:

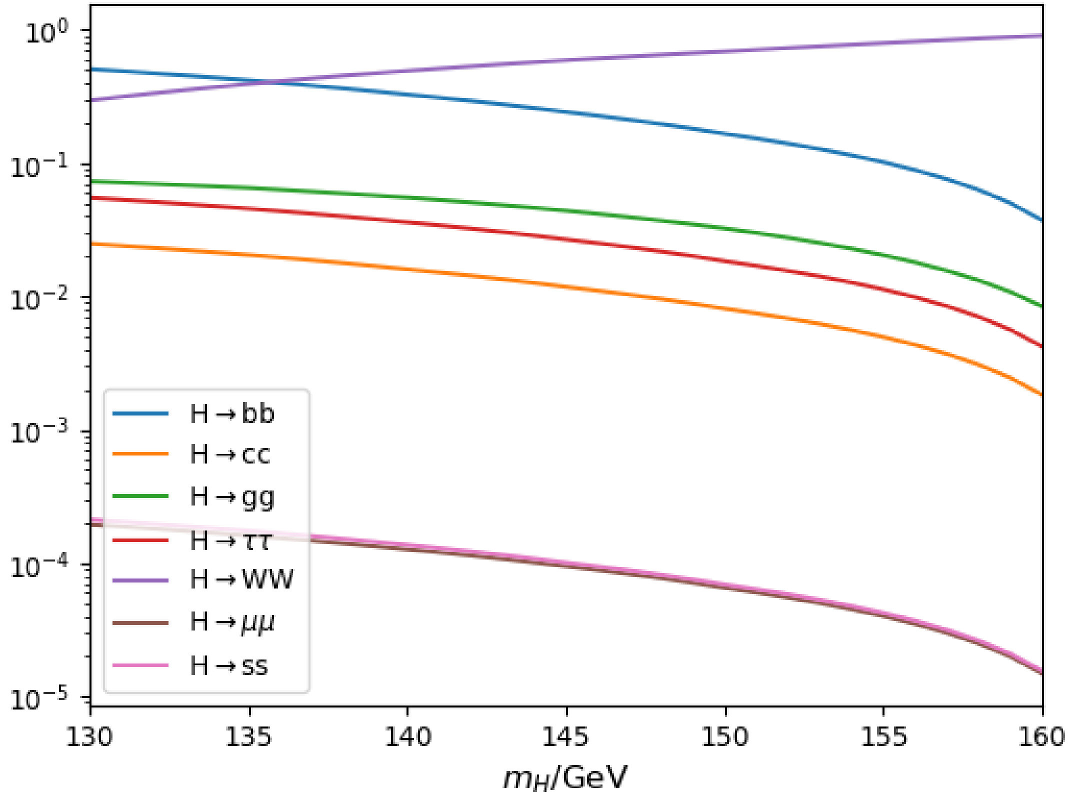
$$\frac{\left(\frac{\Delta g_Z}{g_Z}\right)_H}{\left(\frac{\Delta g_Z}{g_Z}\right)_{h_{SM}}} = \sqrt{\frac{\sigma(e^+e^- \to Zh_{SM})}{\sigma(e^+e^- \to ZH)}}$$

Expresiones obtenidas de: Heinemeyer, S., Li, C., Lika, F., Moortgat-Pick, G., Paasch, S. (2021). A 96 GeV Higgs Boson in the 2HDM plus Singlet. ArXiv: 2112.11958

Cross section



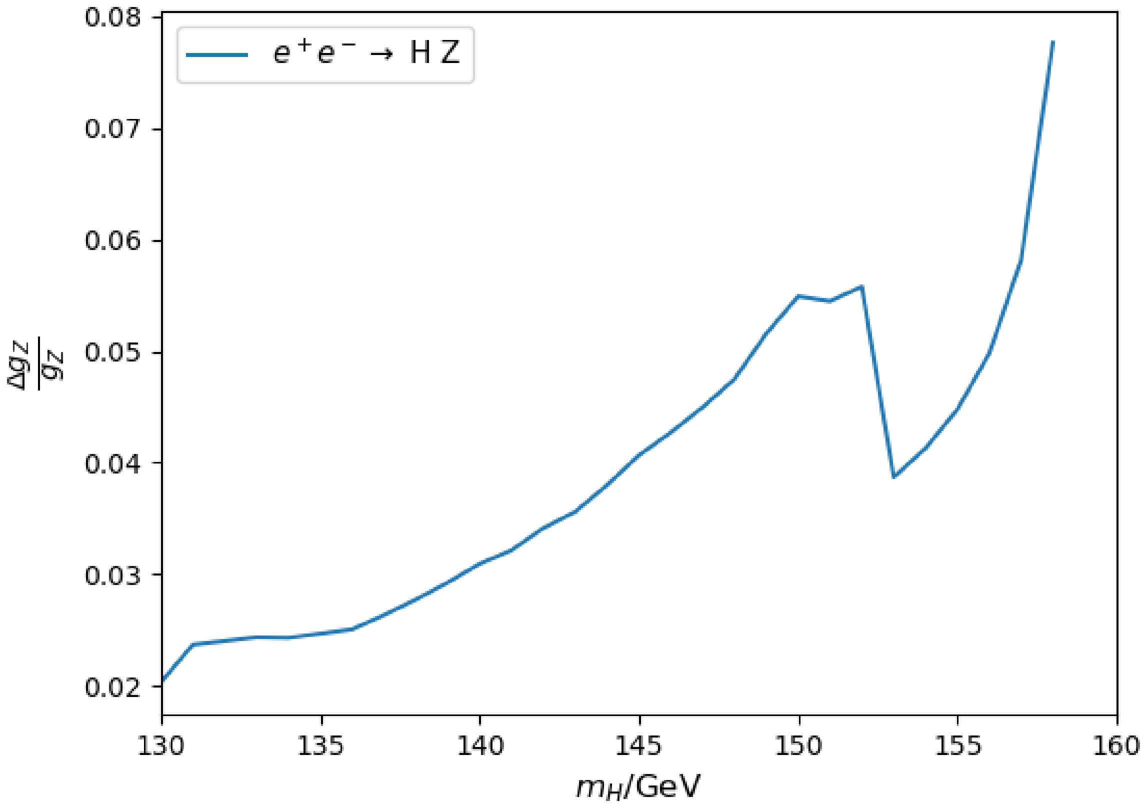
Branching ratio



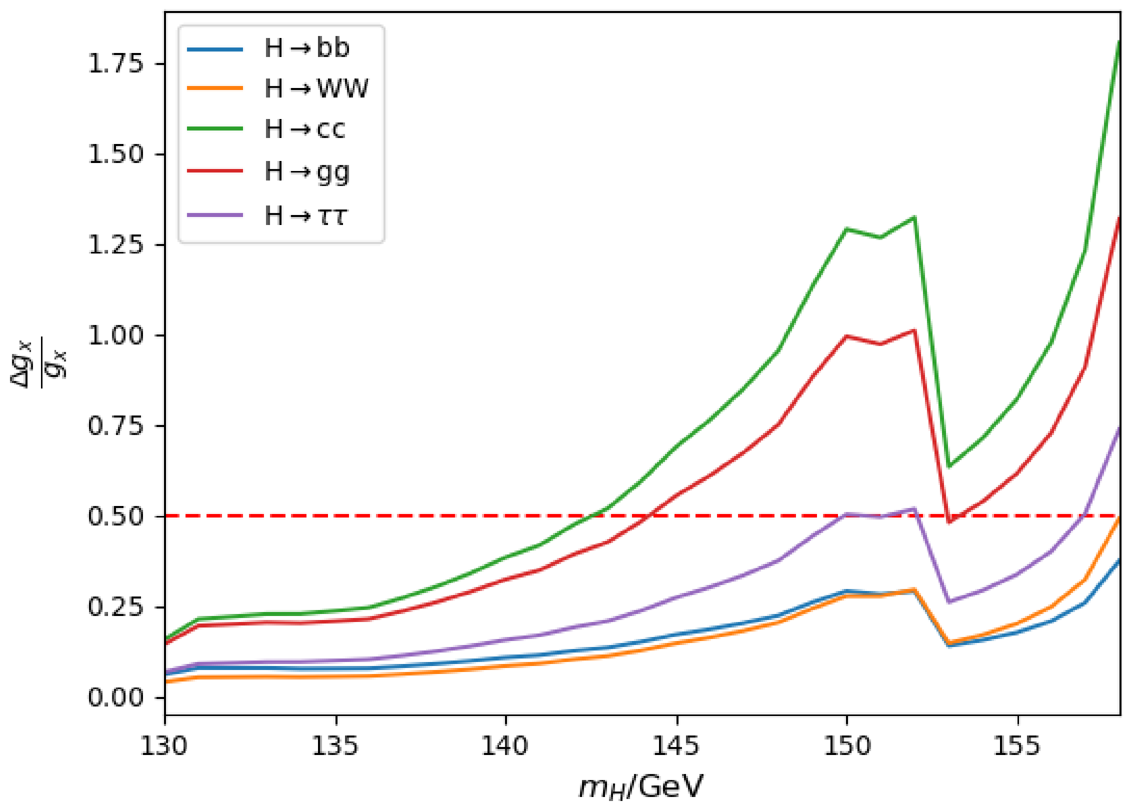
Couplings relative uncertainty: Best case

α maximum

Production channel



Decay channels

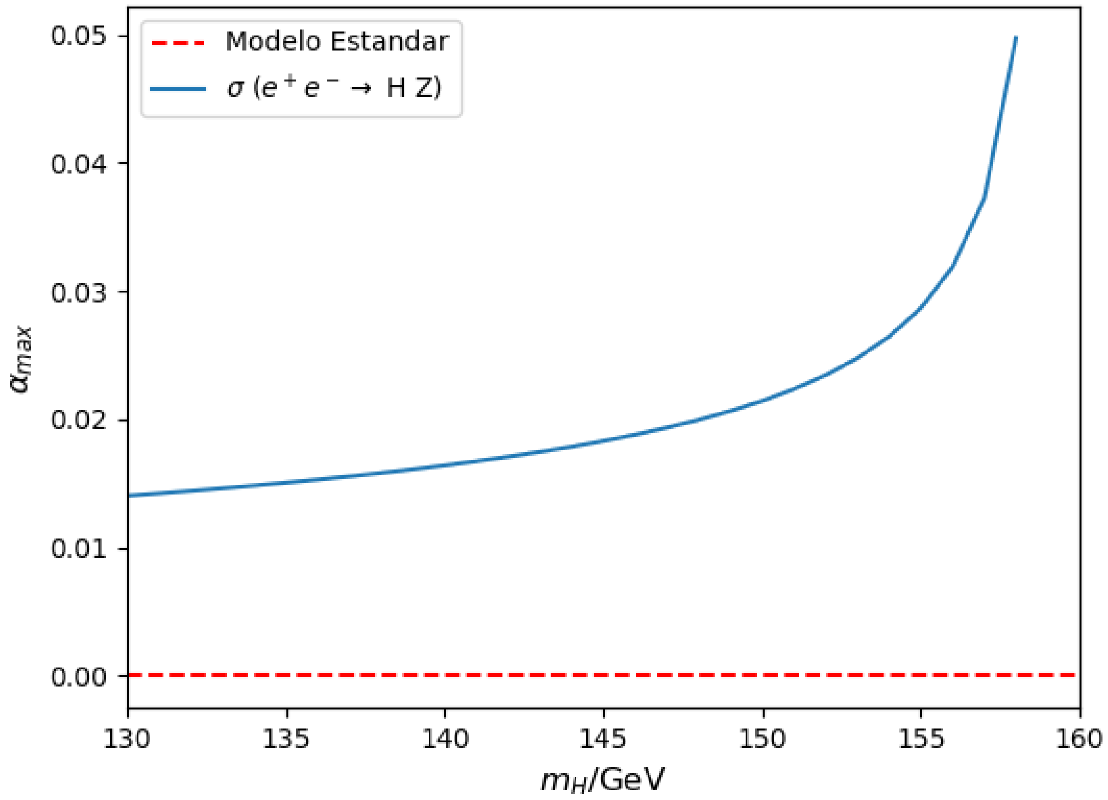


Worst case: $g - 2\Delta g = 0$

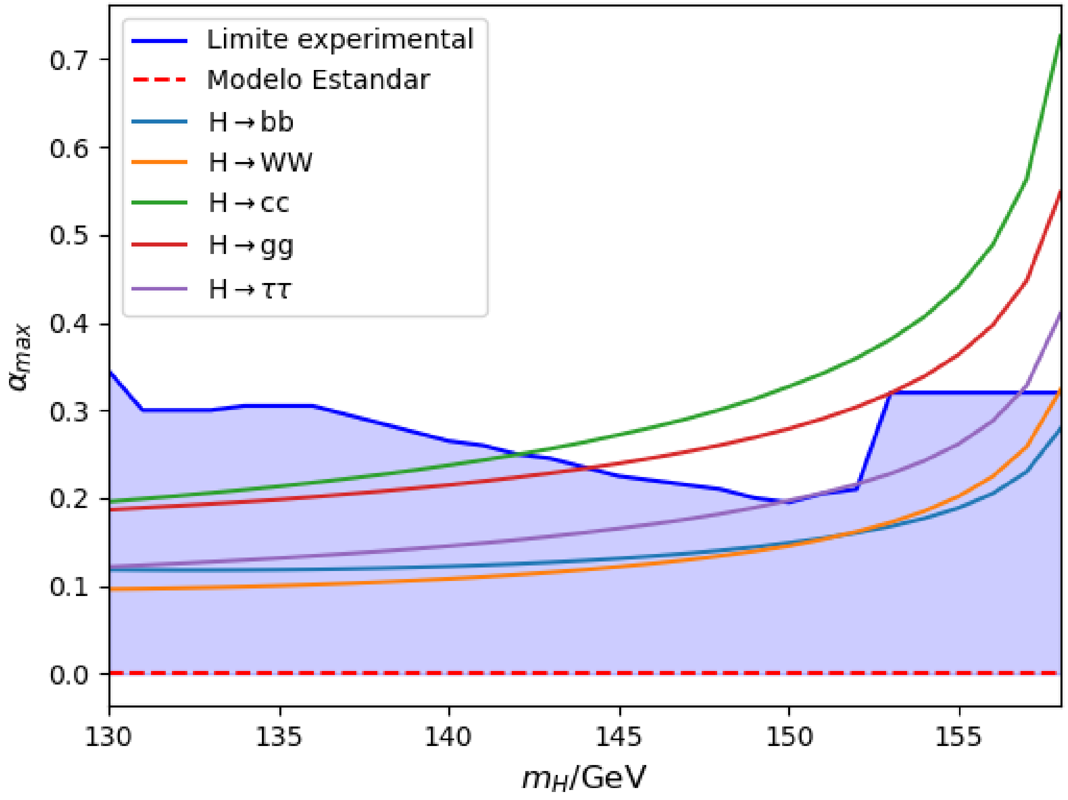
Couplings relative uncertainty: Worst case

$$2\Delta g = g$$

Production channel



Decay channels



Mixing angle precision

Production channel

$$\alpha = \sin^{-1}\left(\sqrt{\frac{\sigma(e^+e^- \to Zh_{SM})}{\sigma_{SM}(e^+e^- \to ZH)}}\left(\frac{g_Z}{\Delta g_Z}\right)_H \left(\frac{\Delta g_Z}{g_Z}\right)_{h_{SM}}\right)$$

$$c = \sqrt{\frac{\sigma(e^+e^- \to Zh_{SM})}{\sigma_{SM}(e^+e^- \to ZH)}}\left(\frac{\Delta g_Z}{g_Z}\right)_{h_{SM}}$$

$$\Delta\alpha = \frac{c}{\sqrt{1-\frac{c^2}{g^2}}}$$

Decay channels

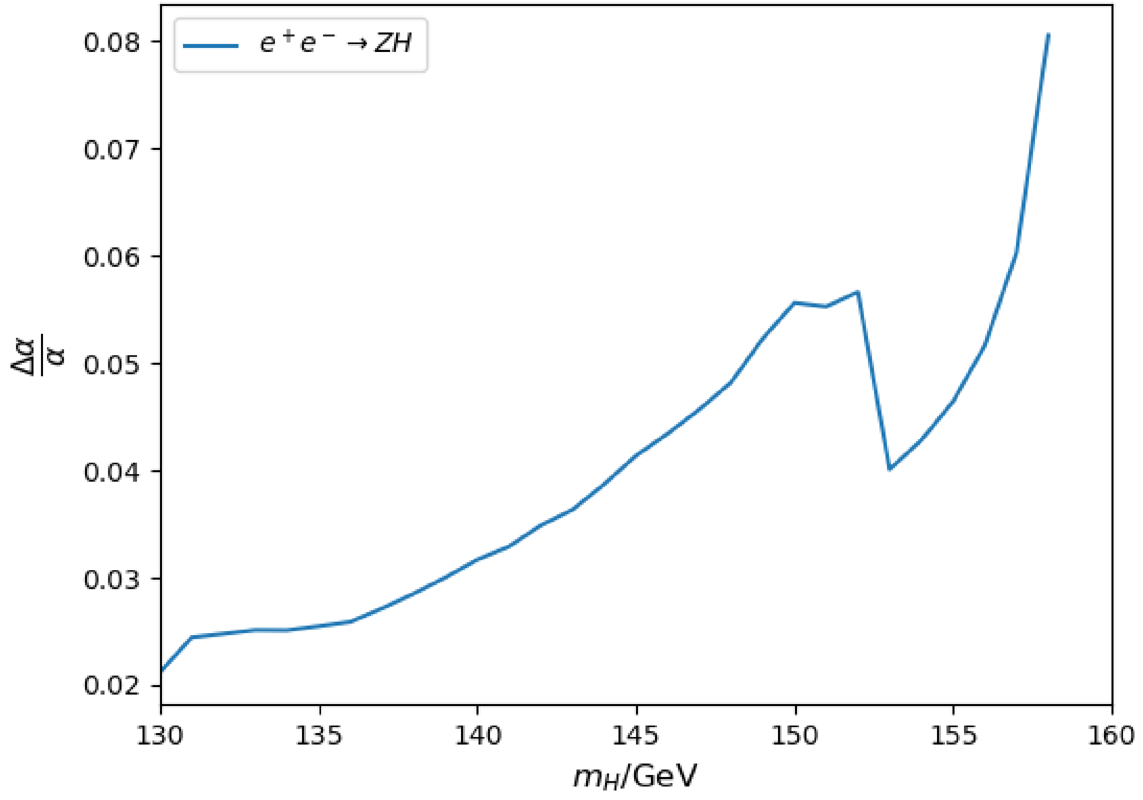
$$g_x = g_x^{SM} \cdot \sin\alpha \to \alpha = \sin^{-1}\left(\frac{g_x}{g_x^{SM}}\right)$$

$$\Delta\alpha = \frac{\Delta g_x}{g_x^{SM}\sqrt{1-\frac{g_x^2}{(g_x^{SM})^2}}}$$

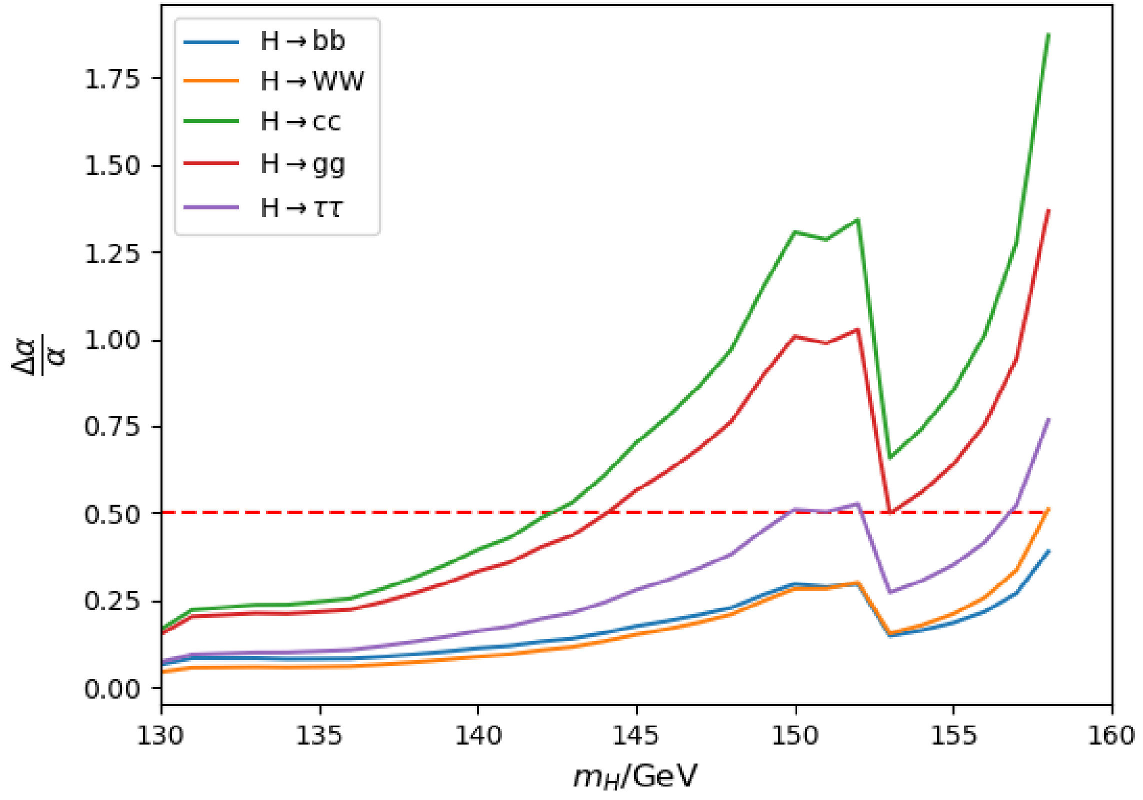
Mixing angle precision: Best case

α maximum

Production channel



Decay channels

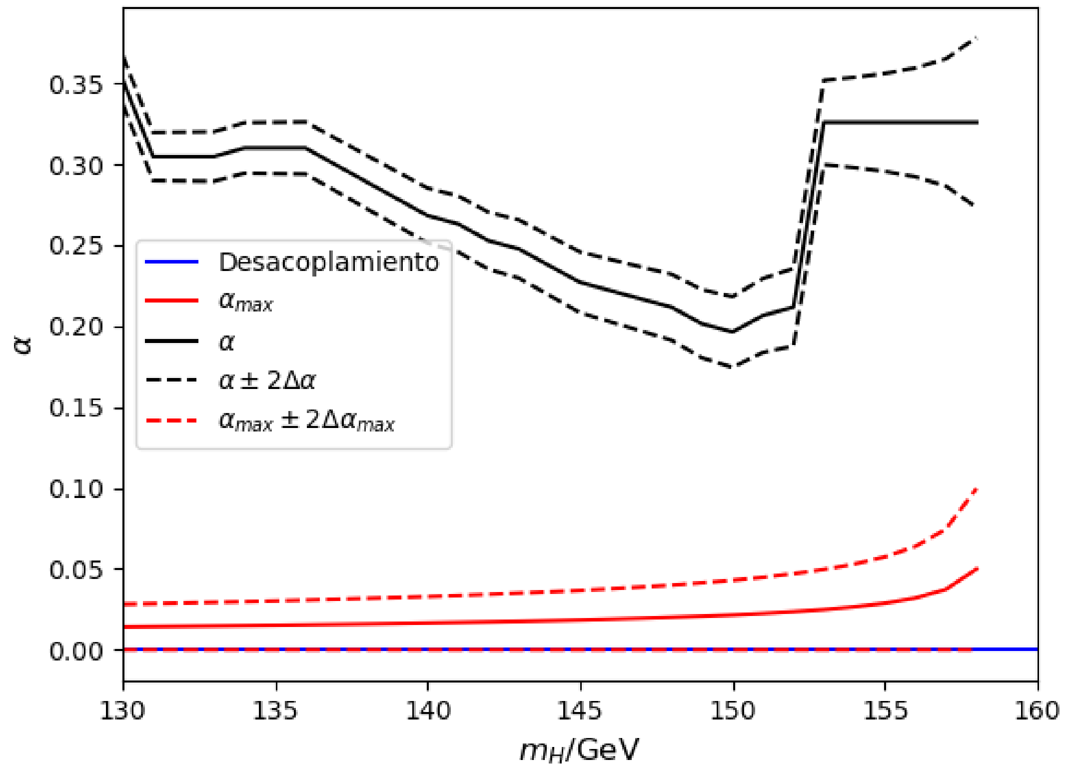


Worst case: $g - 2\Delta g = 0$

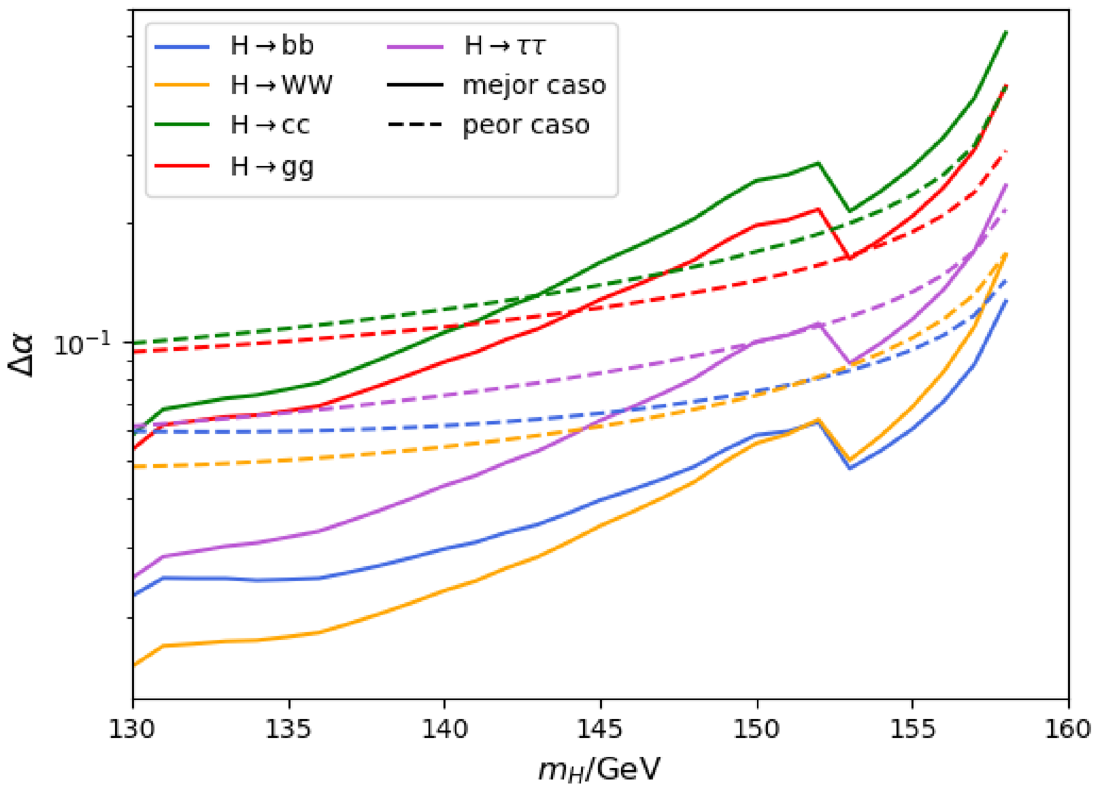
Mixing angle precision: Worst case

$$2\Delta g = g$$

Production channel



Decay channels



Mass limits

- **Charm:** $142.3\ \mathrm{GeV}$
- **Gluon:** $144.0\ \mathrm{GeV}$
- **Tau:** $[149.8, 152.1]\ \mathrm{GeV}$ $156.5\ \mathrm{GeV}$
- **Bottom:** All masses
- **W boson:** All masses
- **Z boson (production channel):** All masses

Triple Higgs couplings

$$V(\phi, S) = \ldots + \boxed{\lambda_{hhh}}\, hhh + \ldots + \boxed{\lambda_{Hhh}}\, Hhh + \ldots$$

$$\lambda_{hhh} = \frac{1}{2v}[2\lambda_1 v \cos^3\alpha - 2\lambda_2 x \sin^3\alpha + \lambda_3(v\cos\alpha\sin^2\alpha - x\sin\alpha\cos^2\alpha)]$$

$$\lambda_{Hhh} = \frac{1}{2v}[6\lambda_1 v \sin\alpha\cos^2\alpha + 6\lambda_2 x\cos\alpha\sin^2\alpha + \lambda_3(x\cos^3\alpha + v\sin^3\alpha - 2v\cos^2\alpha\sin\alpha - 2x\sin^2\alpha\cos\alpha)]$$

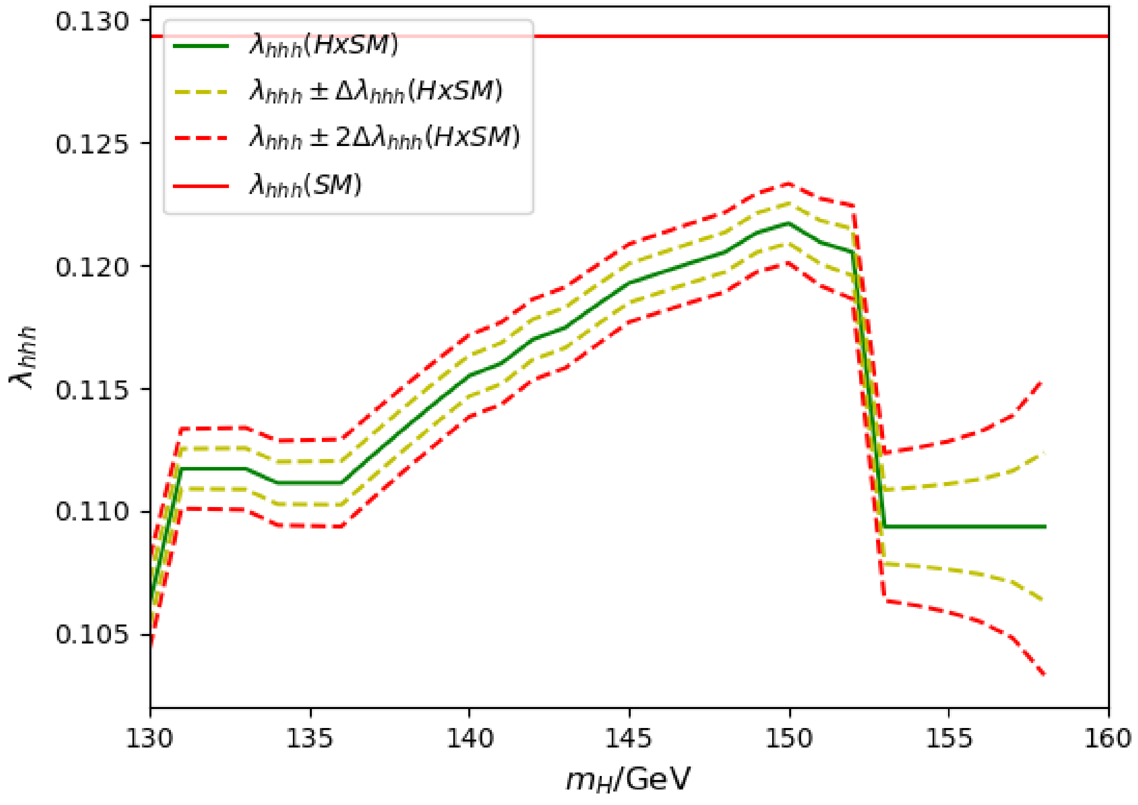
$$\lambda_{HHh} = \frac{1}{2v}[6\lambda_1 v \cos\alpha\sin^2\alpha - 6\lambda_2 x\sin\alpha\cos^2\alpha + \lambda_3(2x\cos^2\alpha\sin\alpha + 2v\cos\alpha\sin^2\alpha - x\sin^3\alpha + v\cos^3\alpha)]$$

$$\lambda_{HHH} = \frac{1}{2v}[2\lambda_1 v \sin^3\alpha + 2\lambda_2 x\cos^3\alpha + \lambda_3(x\cos\alpha\sin^2\alpha + v\sin\alpha\cos^2\alpha)]$$

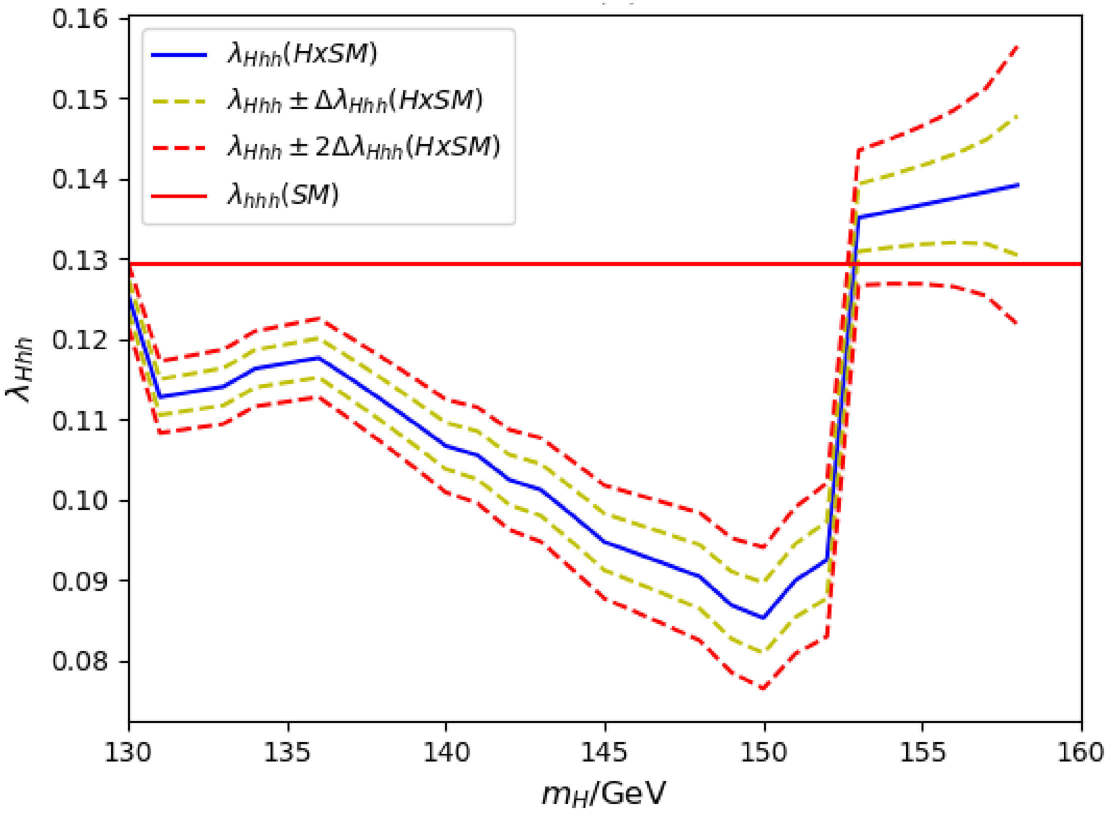
Triple Higgs couplings

α maximum

λ_{hhh} coupling



λ_{Hhh} coupling



Objetives II

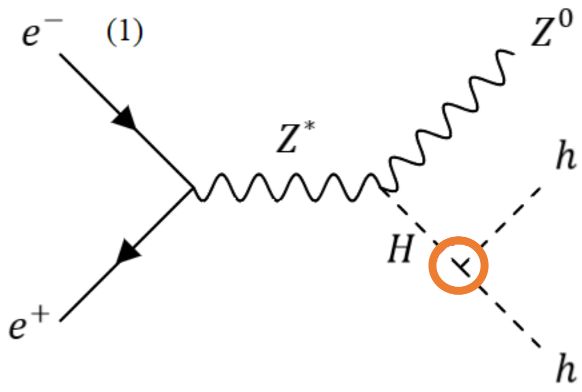
$$m_h \in [10, 60] \text{ GeV} \qquad m_H = 125 \text{ GeV}$$

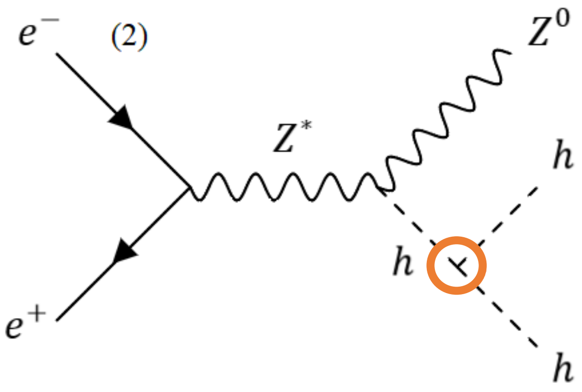
- Calculate the **cross section** of the process $e^+e^- \to hhZ$ in the ILC250 and its dependence on the triple Higgs coupling constants.

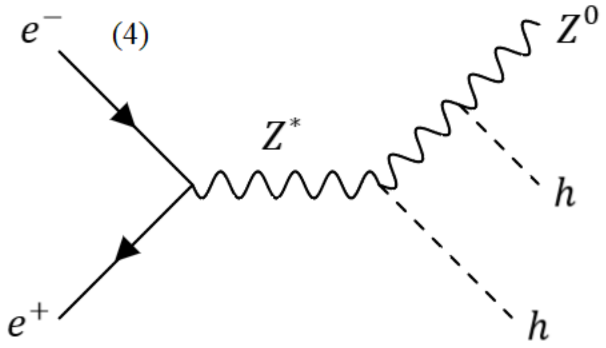
- Determine whether any **triple Higgs couplings** of the new model can be measured in the ILC250.

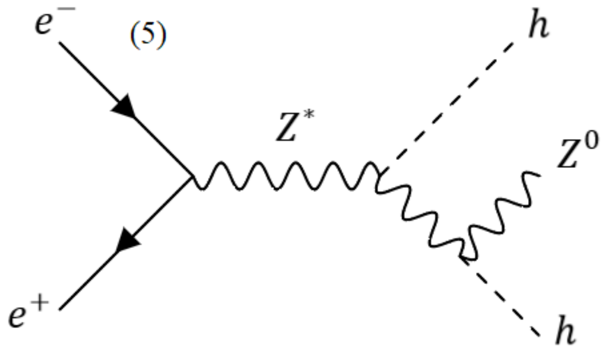
Study process II

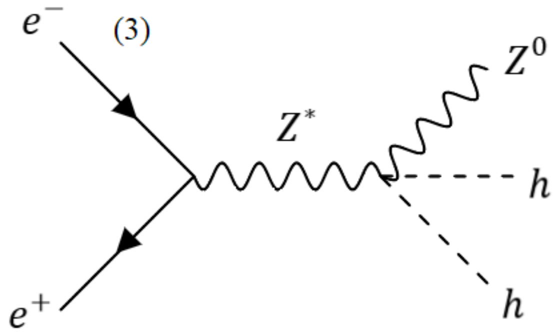
$$e^+e^- \to hhZ$$











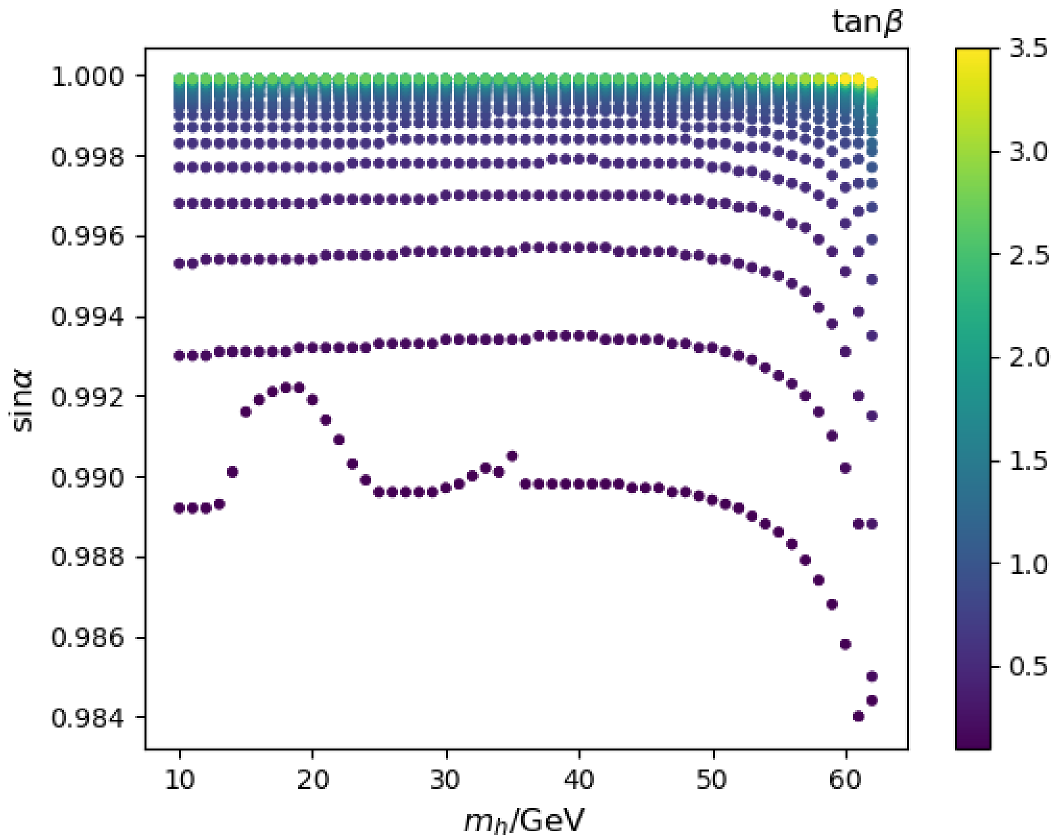
$$m_h \in [10, 60]\ \text{GeV} \qquad m_H = 125\ \text{GeV}$$

Parameter space II

The maximum values allowed by the restrictions of $\tan\beta$ for each allowable value of $\sin\alpha$ are observed.

$$\tan\beta = \frac{v}{x}$$

$$m_h \in [10, 60]\ \mathrm{GeV}$$
$$m_H = 125\ \mathrm{GeV}$$



Data provided by Tania Robens

Cálculo de la cross section

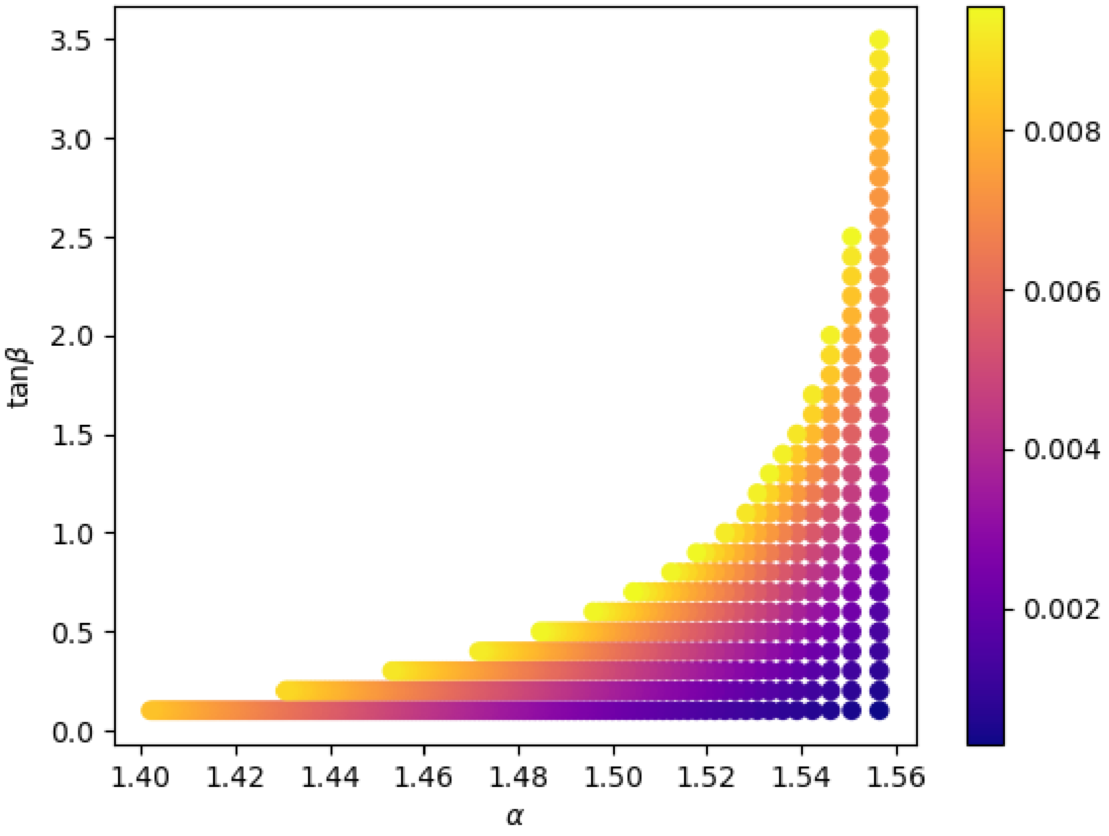
The SARAH and MadGraph5_aMC@NLO programs have been used to calculate the cross section.

- **SARAH:** It has been used to build the model

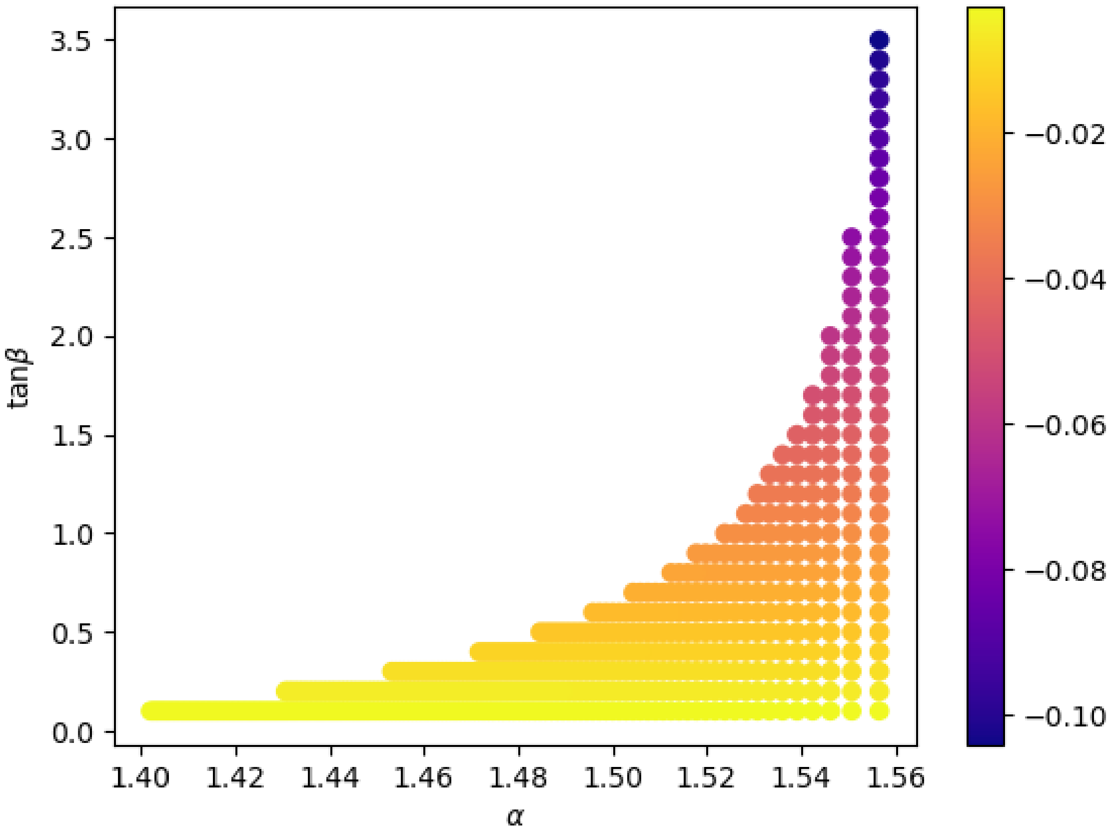
- **MadGrapg5_aMC@NLO:** Once the model was built with SARAH, it was used to perform the cross-section calculations.

Triple Higgs couplings

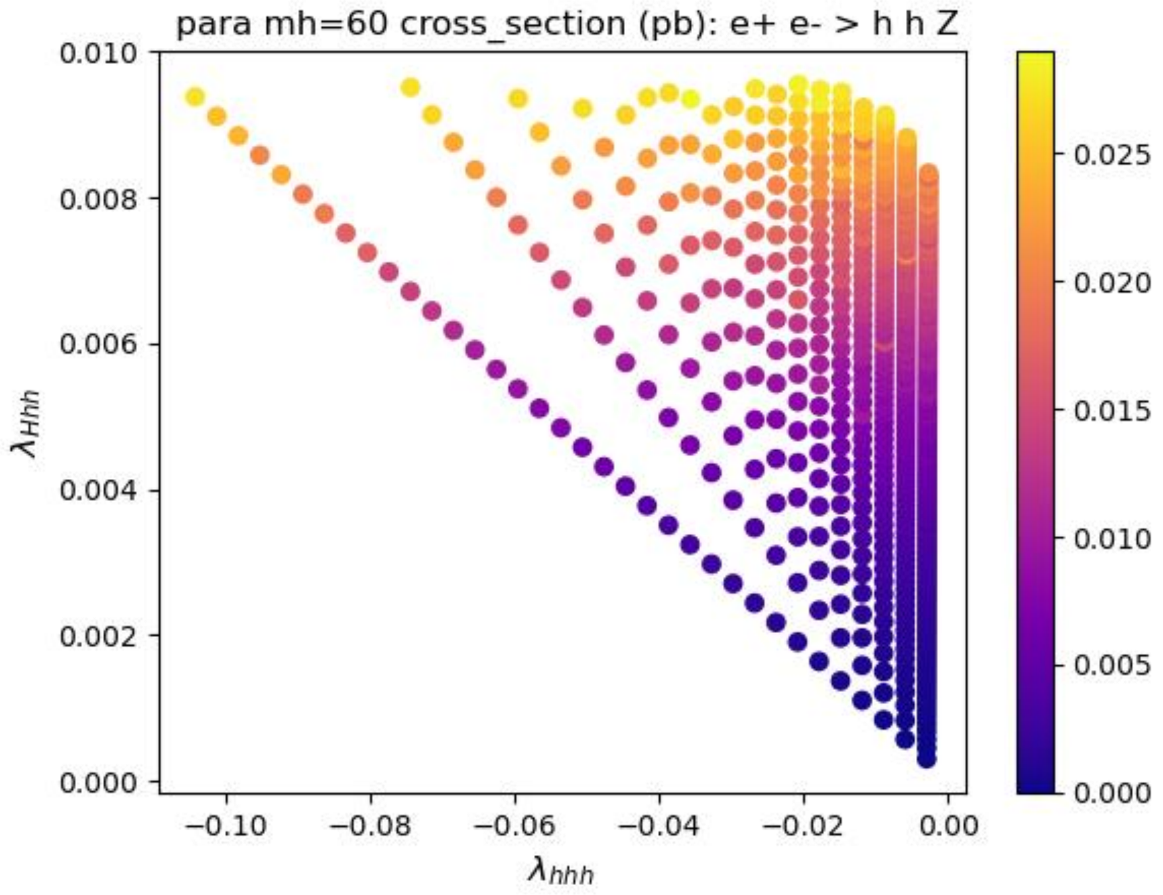
λ_{Hhh} coupling



λ_{hhh} coupling



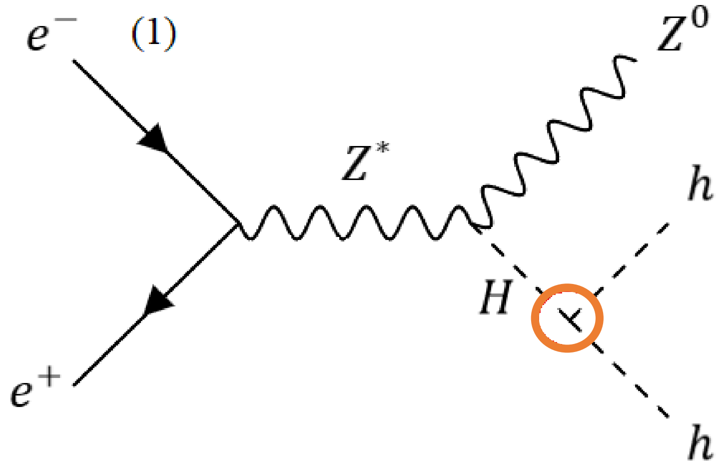
Cross section calculation



Dependency with the Hhh coupling

Higher cross section than the SM

Hhh coupling:



Conclusions

$$m_h = 125 \text{ GeV} \qquad m_H \in [130, 160] \text{ GeV}$$

- Due to the **high accuracy of the production channel** in the ILC250, most of the space allowed by the constraints can be explored to validate the model.
- This simple extension of the SM **cannot reduce the matter-antimatter asymmetry problem.**

$$m_h \in [10, 60] \text{ GeV} \qquad m_H = 125 \text{ GeV}$$

- Considering that the **Hhh coupling dominates the calculation** of the cross section and that it is sufficient to measure the process, it **seems possible to measure the Hhh coupling** constant at the ILC250 collider in the absence of an experimental study.

Thanks for your attention

Cross section

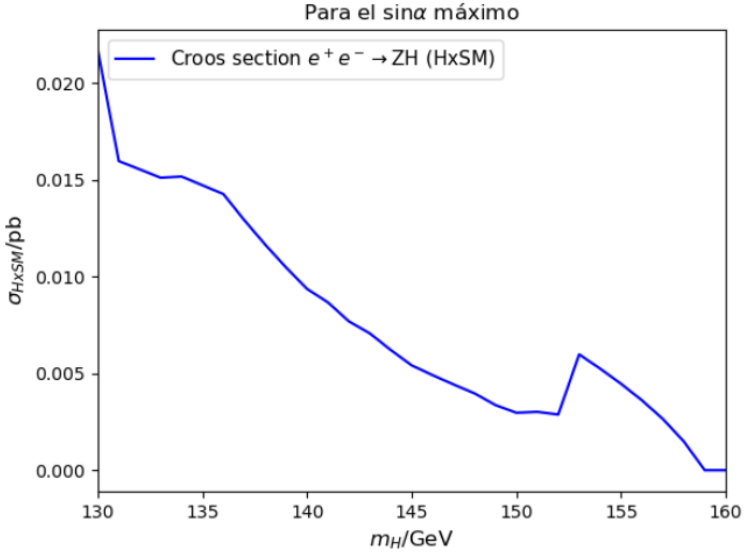


Figura 7: Cross Section del bosón de Higgs pesado para un rango de masas de $m_H \in [130, 160]$ GeV.

Branching Ratio

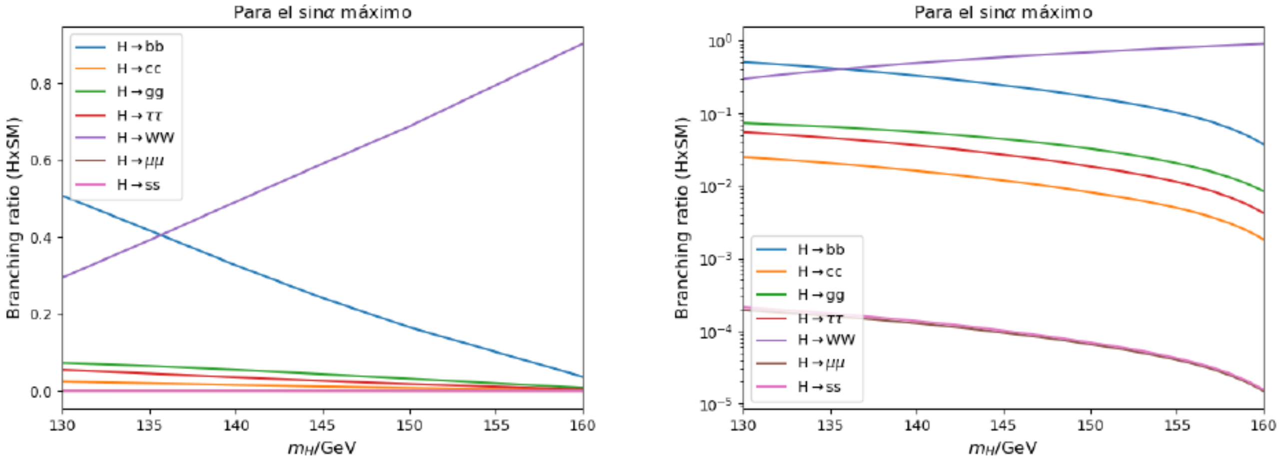
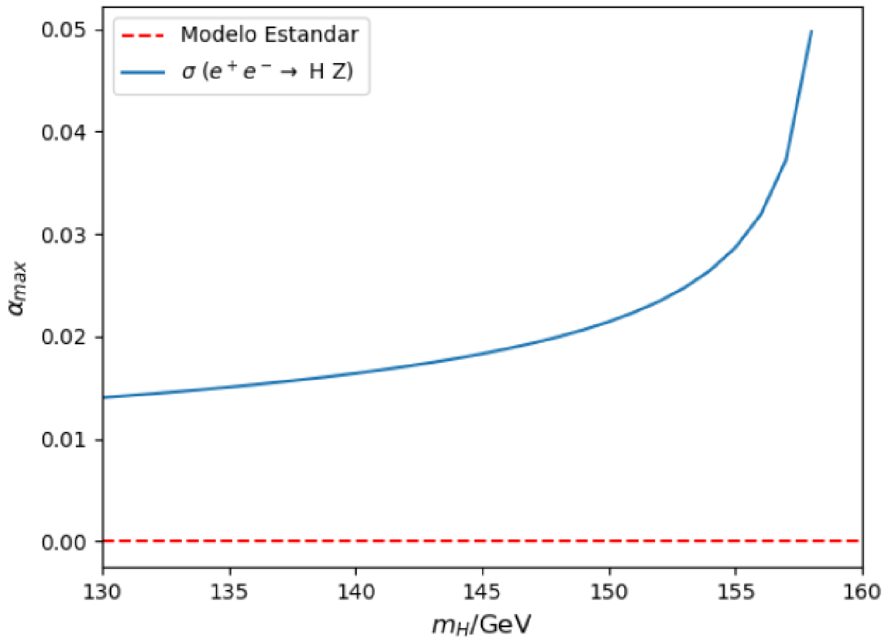
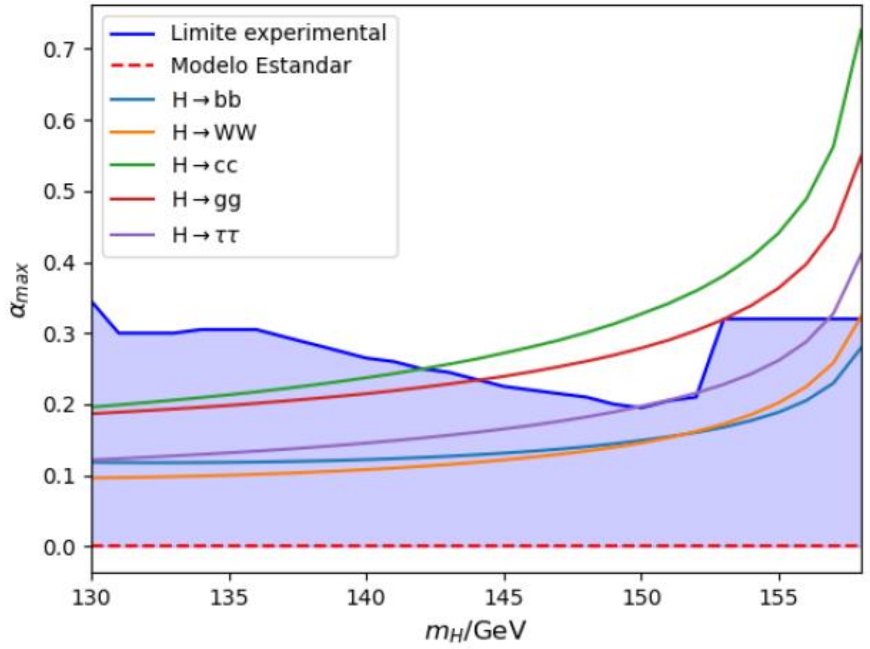


Figura 8: Branching ratios para los procesos de decaimiento principales ($H \to xx$) para el bosón de Higgs pesado en un rango de masas de $m_H \in [130, 160]$ GeV en escala decimal (izquierda) y en escala logarítmica (derecha).

Incertidumbre acoplamientos peor caso





Incertidumbre ángulo de mezcla

Mejor caso

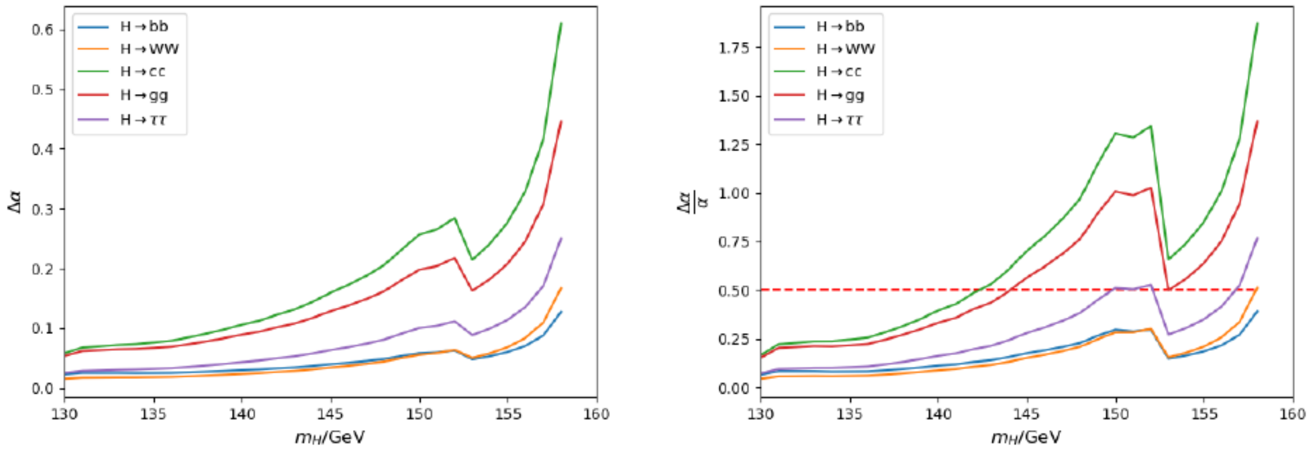


Figura 13: Valores de la incertidumbre del ángulo de mezcla α para los principales canales de desintegración en el mejor caso (izquierda). Valores de la incertidumbre relativa del ángulo de mezcla α para los principales canales de desintegración en el mejor caso (derecha).

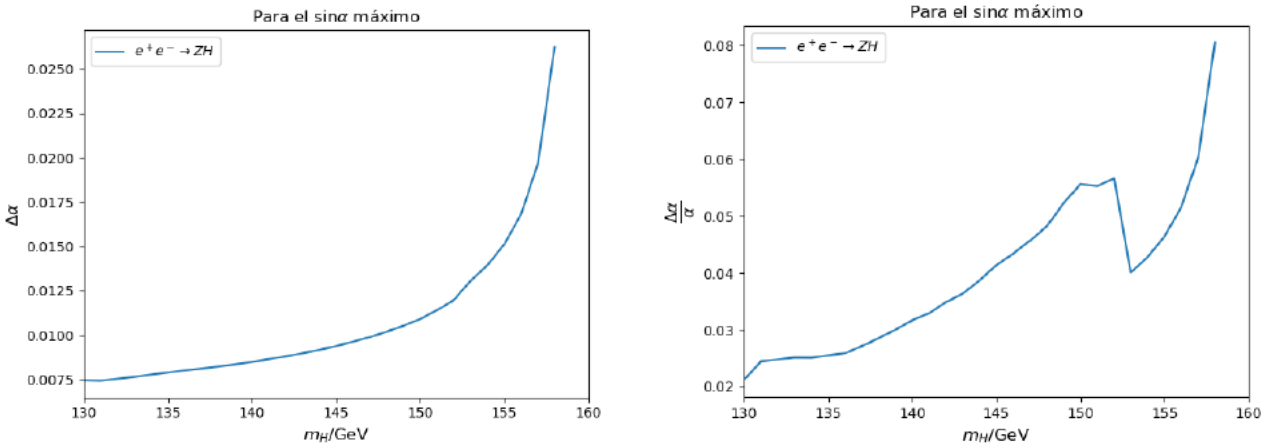


Figura 14: Valores de la incertidumbre del ángulo de mezcla α para el canal de producción ($e^+e^- \to ZH$) (izquierda). Valores de la incertidumbre relativa del ángulo de mezcla α para el canal de producción (derecha).

Incertidumbre ángulo de mezcla

Peor caso

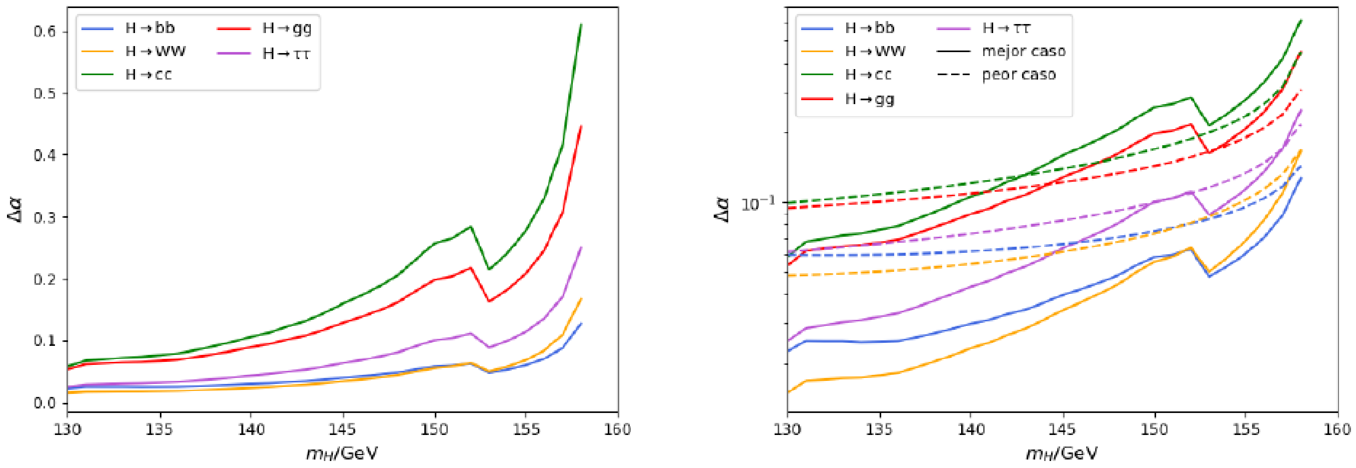


Figura 15: Valores obtenidos para la incertidumbre del ángulo de acoplamiento para los canales de desintegración en el peor caso (izquierda). Valores obtenidos para la incertidumbre del ángulo de acoplamiento para los canales de desintegración en el peor caso (línea discontinua) junto con el mejor caso (línea continua) (derecha).

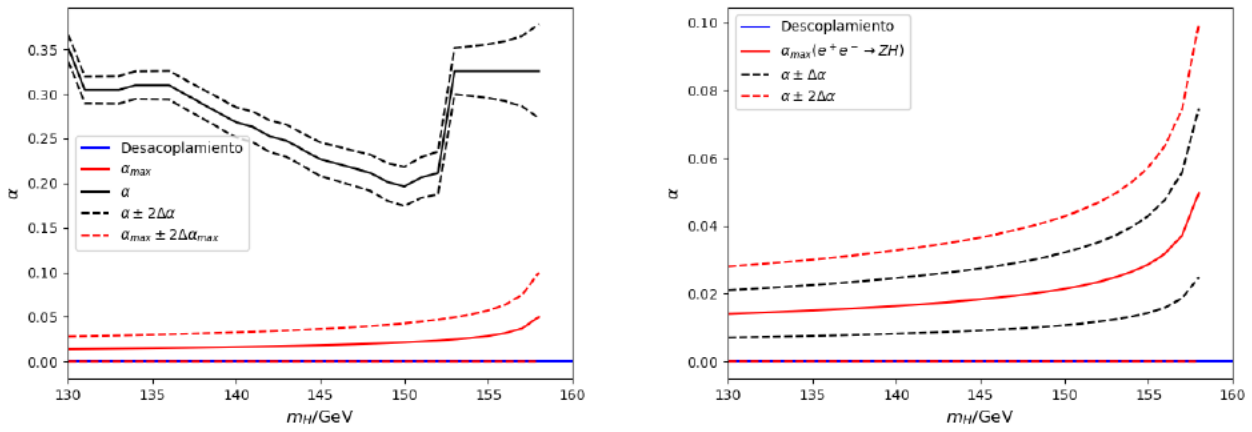


Figura 16: A la izquierda se observan los valores del ángulo de mezcla más menos dos veces la incertidumbre en negro para el mejor caso y en rojo para el peor caso calculadas a partir de la incertidumbre de la constante de acoplamiento g_Z. A la derecha se observa más en detalle el peor caso.

hhh

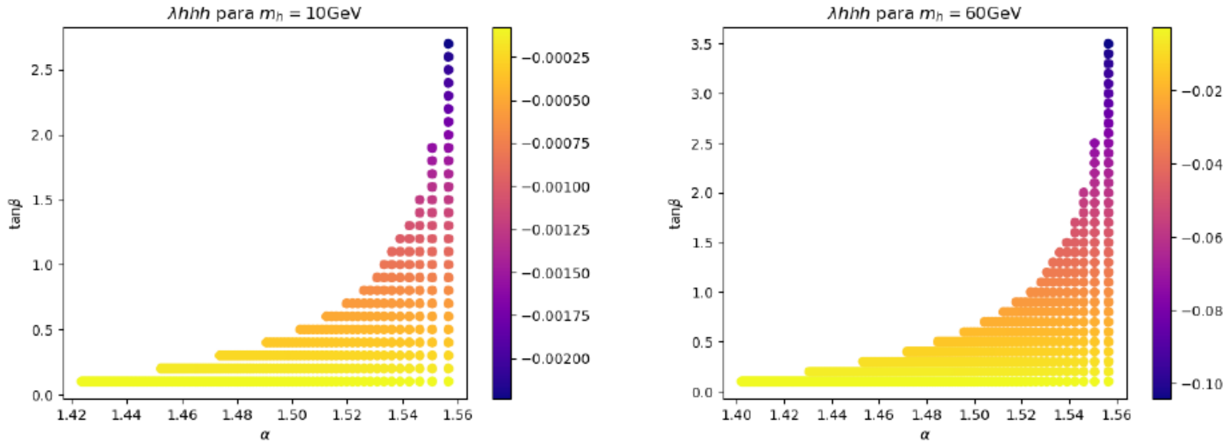


Figura 21: Valores permitidos de $\tan\beta$ frente a los valores permitidos de α junto con los valores obtenidos para la constante de acoplamiento λ_{hhh} (en el mapa de color) para $m_h = 10$ GeV (izquierda) y $m_h = 60$ GeV (derecha).

Hhh

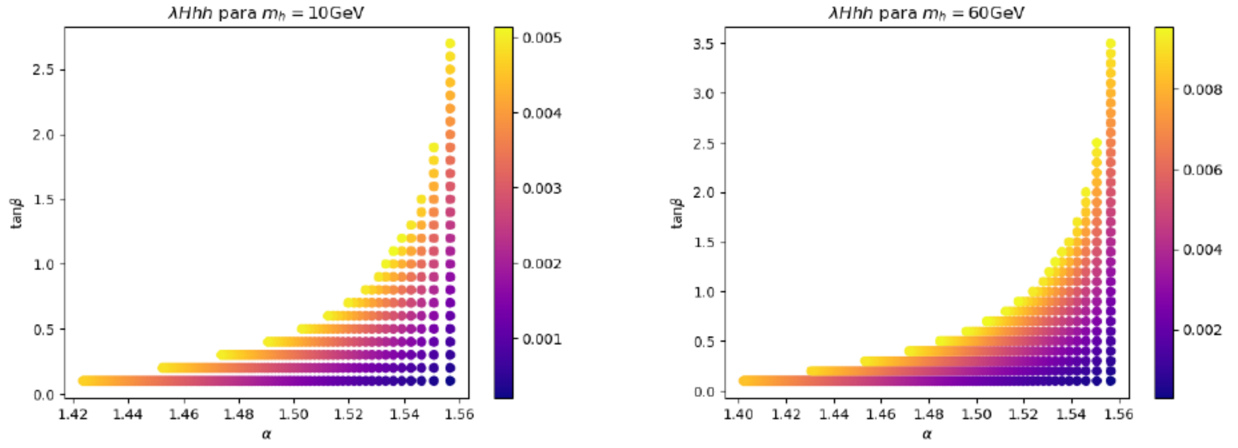
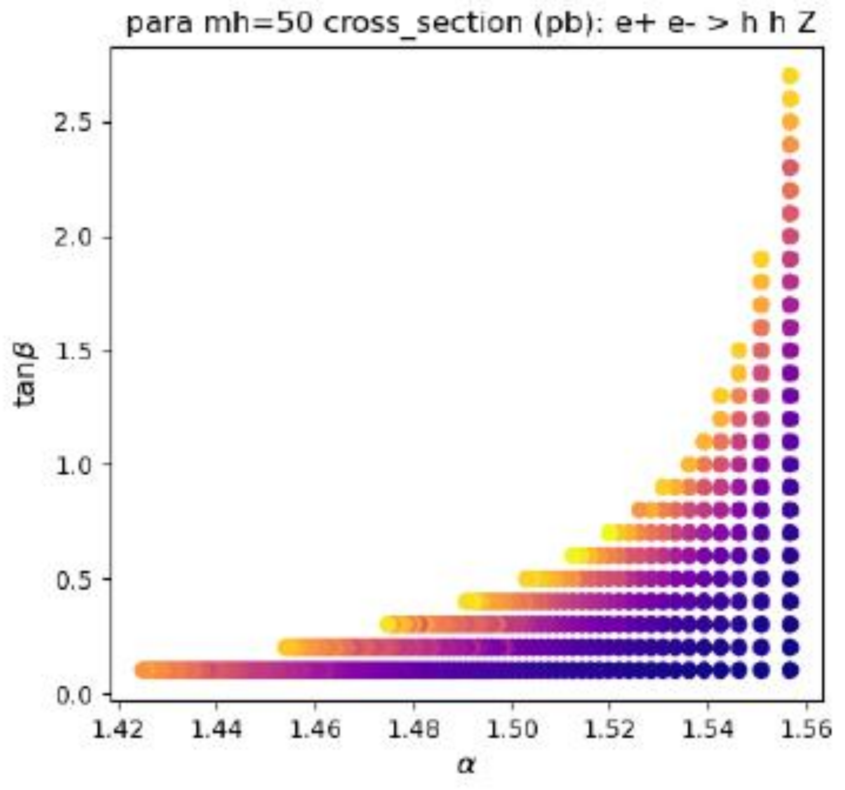
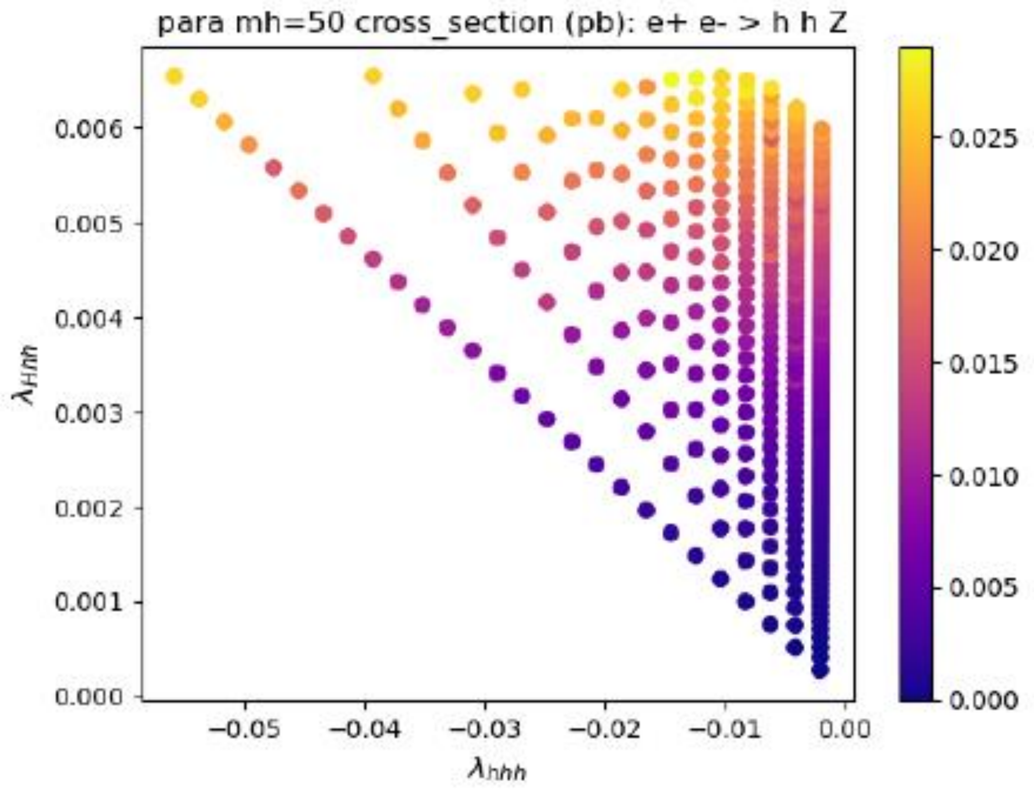


Figura 22: Valores permitidos de $\tan\beta$ frente a los valores permitidos de α junto con los valores obtenidos para la constante de acoplamiento λ_{Hhh} (en el mapa de color) para $m_h = 10$ GeV (izquierda) y $m_h = 60$ GeV (derecha).

Mh=50 GeV


para mh=50 cross_section (pb): e+ e- > h h Z
tanβ
α
2.5
2.0
1.5
1.0
0.5
0.0
1.42
1.44
1.46
1.48
1.50
1.52
1.54
1.56
0.025
0.020
0.015
0.010
0.005
0.000


para mh=50 cross_section (pb): e+ e- > h h Z
λHhh
λhhh
0.006
0.005
0.004
0.003
0.002
0.001
0.000
−0.05
−0.04
−0.03
−0.02
−0.01
0.00
0.025
0.020
0.015
0.010
0.005
0.000

Cálculos triple Higgs

$$V(\phi, S) = -m^2 \begin{pmatrix} 0 & \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 0 \\ \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix} - \mu^2 \left(\frac{h' + x}{\sqrt{2}} \right)^2 + \lambda_1 \left(\begin{pmatrix} 0 & \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 0 \\ \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix} \right)^2 + \lambda_2 \left(\frac{h' + x}{\sqrt{2}} \right)^4$$
$$+ \lambda_3 \begin{pmatrix} 0 & \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 0 \\ \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix} \left(\frac{h' + x}{\sqrt{2}} \right)^2 = -\frac{m^2}{2}(\bar{h}^2 + v^2 + 2v\bar{h}) - \frac{\mu^2}{2}(h'^2 + x^2 + 2xh')$$
$$+ \frac{\lambda_1}{4}(\bar{h}^2 + v^2 + 2v\bar{h})^2 + \frac{\lambda_2}{4}(h'^2 + x^2 + 2xh')^2 + \frac{\lambda_3}{4}(\bar{h}^2 + v^2 + 2v\bar{h})(h'^2 + x^2 + 2xh') \quad (41)$$

$$V(\phi, S) = -\frac{m^2}{2}[(h\cos\alpha + H\sin\alpha)^2 + v^2 + 2v(h\cos\alpha + H\sin\alpha)] - \frac{\mu^2}{2}[(H\cos\alpha - h\sin\alpha)^2 + x^2$$
$$+ 2x(H\cos\alpha - h\sin\alpha)] + \frac{\lambda_1}{4}[(h\cos\alpha + H\sin\alpha)^2 + v^2 + 2v(h\cos\alpha + H\sin\alpha)^2]$$
$$+ \frac{\lambda_2}{4}[(H\cos\alpha - h\sin\alpha)^2 + x^2 + 2x(H\cos\alpha - h\sin\alpha)]^2 + \frac{\lambda_3}{4}[(h\cos\alpha + H\sin\alpha)^2 + v^2$$
$$+ 2v(h\cos\alpha + H\sin\alpha)][(H\cos\alpha - h\sin\alpha)^2 + x^2 + 2x(H\cos\alpha - h\sin\alpha)] \quad (42)$$