Probing Two Higgs Doublet Models with Higgs Precison Measurements

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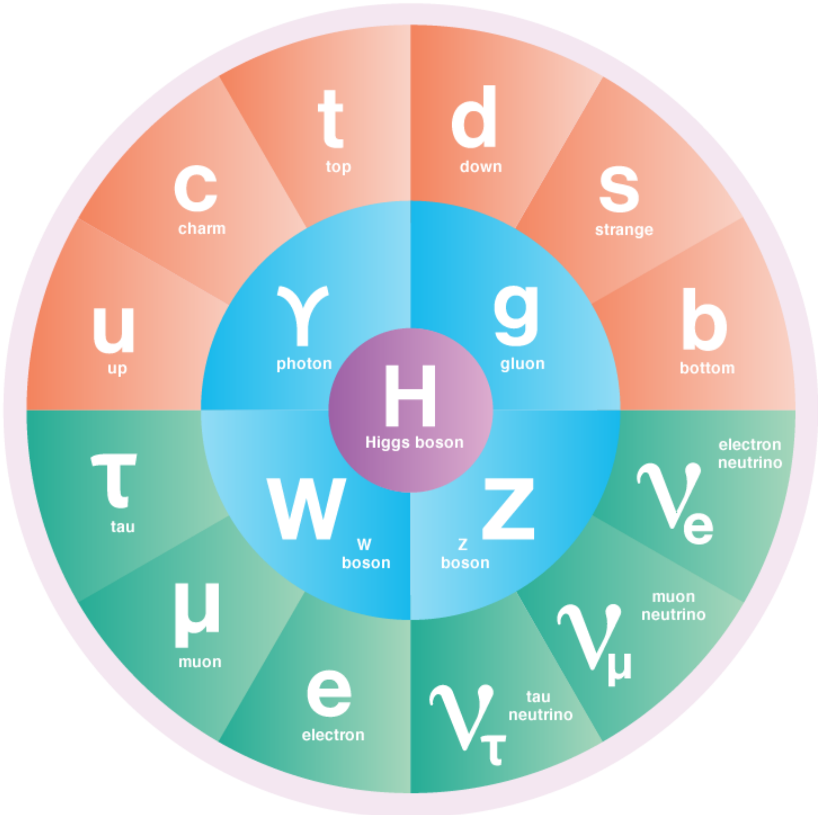
Take Home Message

If you have a light Z' that mixes with the Z the precise measurements on the Higgs properties may lead to the strongest bound on the Z-Z' mass mixing

SM works fine with one Higgs doublet

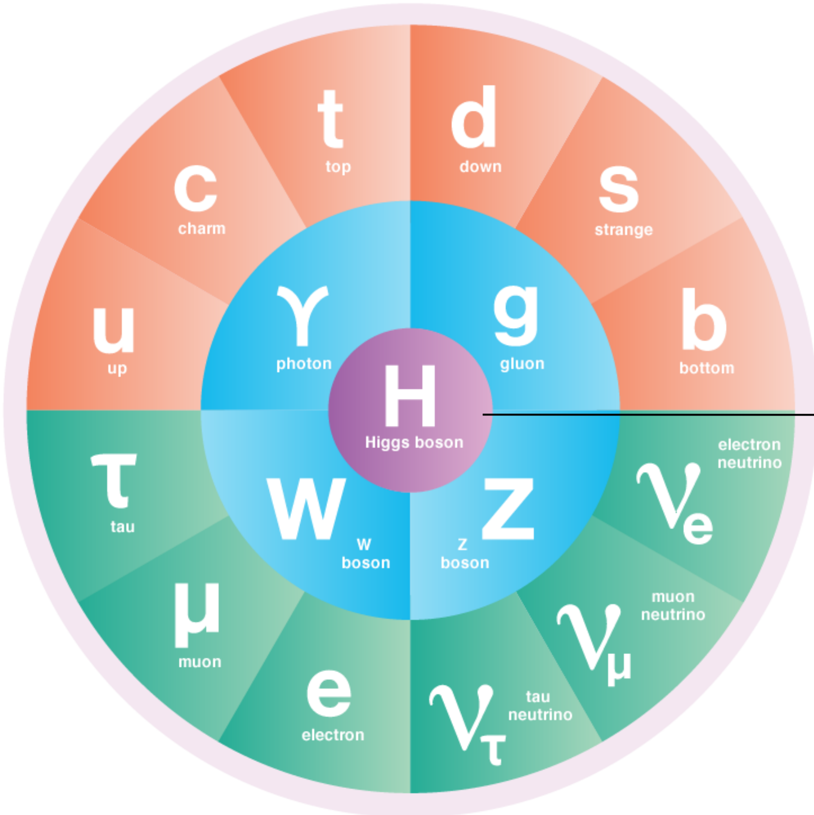
But, what if there is another higgs doublet in nature...



The W and Z masses limit the type of higgs doublets in nature

$$\rho = \frac{\sum_{i=1}^{n}\left[I_i\left(I_i+1\right)-\frac{1}{4}Y_i^2\right]v_i}{\sum_{i=1}^{n}\frac{1}{2}Y_i^2 v_i} \longrightarrow Y = \pm 1$$

SM works fine with one Higgs doublet



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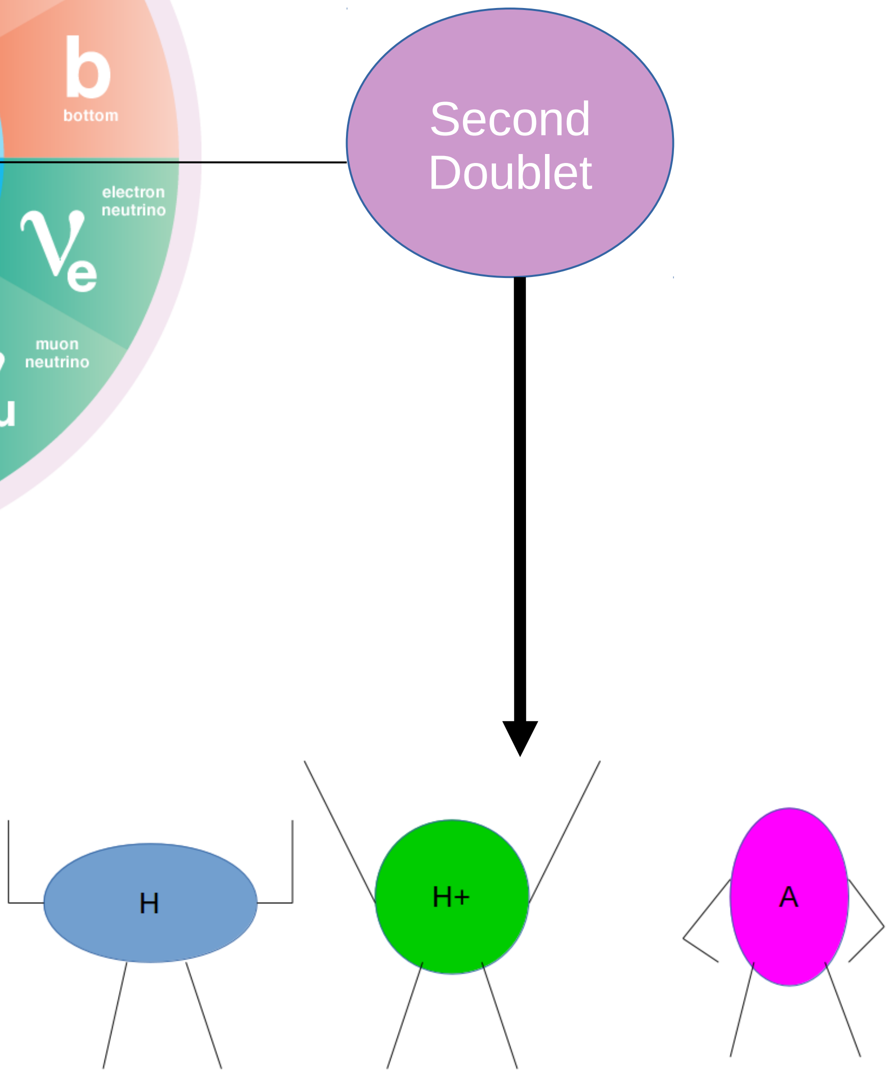


General Scalar Potential

$$
\begin{aligned}
V\left(\Phi_1,\Phi_2\right) =& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 \\
&+ \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\
&+ \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \lambda_6\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_1^\dagger\Phi_2\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + h.c.\right]
\end{aligned}
$$

General Yukawa Lagrangian

$$
\begin{aligned}
-\mathcal{L}_{Y_{2\mathrm{HDM}}} =& \, y^{1d}\bar{Q}_L\Phi_1 d_R + y^{1u}\bar{Q}_L\widetilde{\Phi}_1 u_R + y^{1e}\bar{L}_L\Phi_1 e_R \\
&+ y^{2d}\bar{Q}_L\Phi_2 d_R + y^{2u}\bar{Q}_L\widetilde{\Phi}_2 u_R + y^{2e}\bar{L}_L\Phi_2 e_R + h.c.,
\end{aligned}
$$

$$\boxed{\Phi_1 \to -\Phi_1, \; \Phi_2 \to +\Phi_2}$$

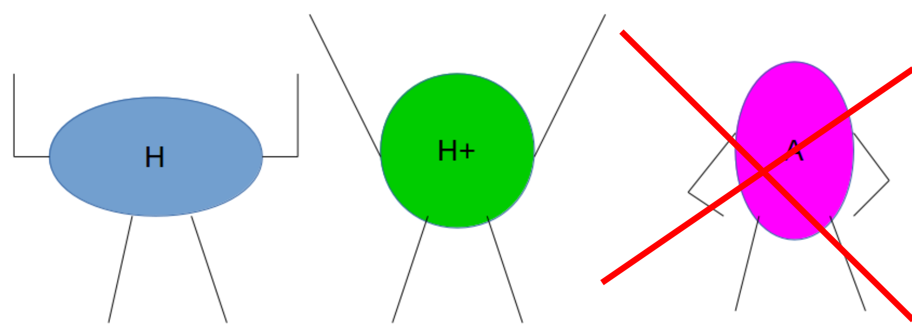
Ad hoc: to suppress flavor changing Interactions

Neutrino masses and absence of FCNI in the 2HDM from Gauge Principles

2HDM + U(1) gauge symmetry

Two Higgs Doublet Models free from FCNI

Fields	u_R	d_R	Q_L	L_L	e_R	N_R	Φ_2	Φ_1
Charges	u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	$\frac{5u}{2}+\frac{7d}{2}$
$U(1)_A$	1	-1	0	0	-1	1	1	-1
$U(1)_B$	-1	1	0	0	1	-1	-1	1
$U(1)_C$	$1/2$	-1	$-1/4$	$3/4$	0	$3/2$	$3/4$	$9/4$
$U(1)_D$	1	0	$1/2$	$-3/2$	-2	-1	$1/2$	$5/2$
$U(1)_E$	0	1	$1/2$	$-3/2$	-1	-2	$7/2$	$-1/2$
$U(1)_F$	$4/3$	$2/3$	1	-3	-4	$-8/3$	$1/3$	$17/3$
$U(1)_G$	$-1/3$	$2/3$	$1/6$	$-1/2$	0	-1	$-1/2$	$-3/2$
$U(1)_{B-L}$	$1/3$	$1/3$	$1/3$	-1	-1	-1	0	2
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$-1/2$	-1		$1/2$	$\neq h_2$
$U(1)_N$	0	0	0	0	0		0	$\neq h_2$



Neutrino masses and absence of FCNI in the 2HDM from Gauge Principles

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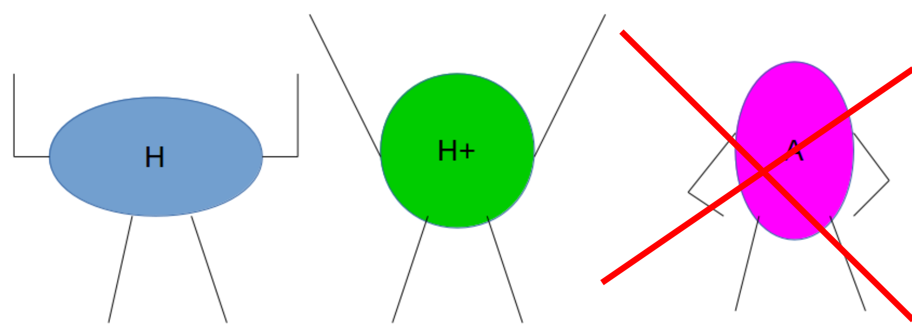
This 2HDM has no pseudoscalar!

This is a key distinction to the canonical 2HDM



2HDM + U(1) gauge symmetry

$$m_s^2 = \lambda_s v_s^2,$$

$$m_h^2 = \frac{1}{2}\left(\lambda_1 v_1^2 + \lambda_2 v_2^2 - \sqrt{(\lambda_1 v_1^2 - \lambda_2 v_2^2)^2 + 4(\lambda_3 + \lambda_4)^2 v_1^2 v_2^2}\right) \longrightarrow$$

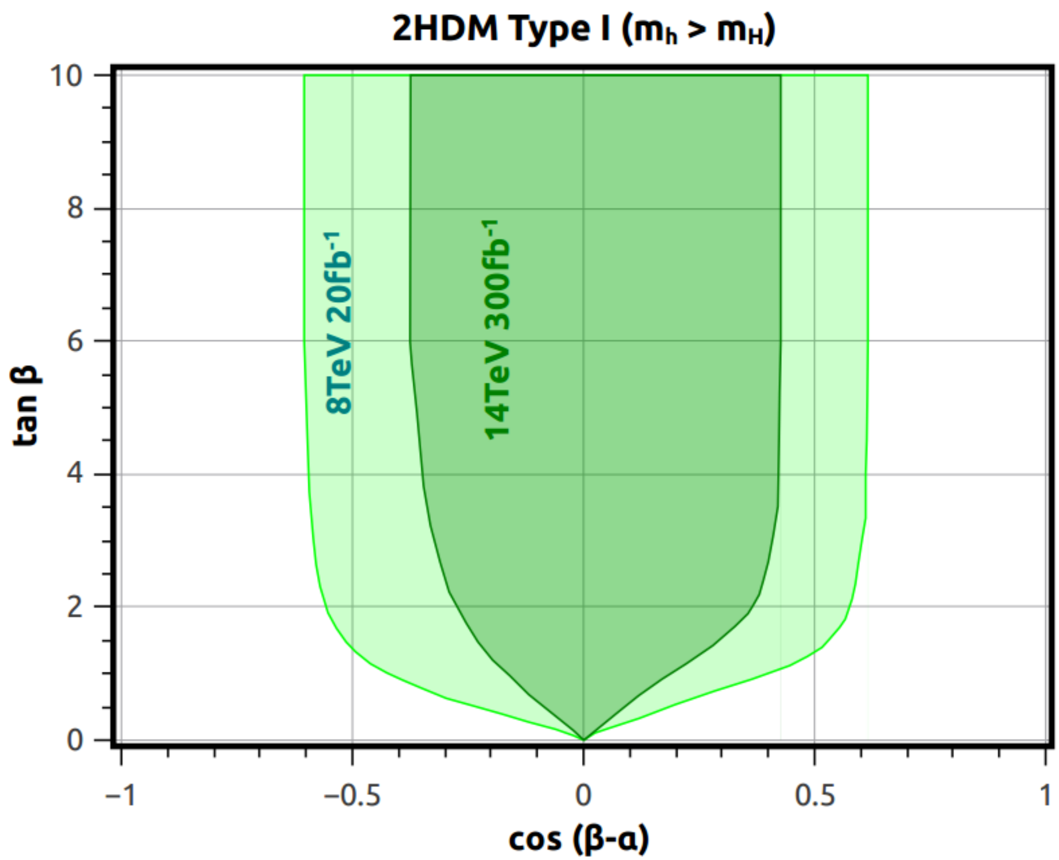
New light scalar lighter than 125GeV

$$m_H^2 = \frac{1}{2}\left(\lambda_1 v_1^2 + \lambda_2 v_2^2 + \sqrt{(\lambda_1 v_1^2 - \lambda_2 v_2^2)^2 + 4(\lambda_3 + \lambda_4)^2 v_1^2 v_2^2}\right) \longrightarrow$$

SM Higgs is the heavy scalar!

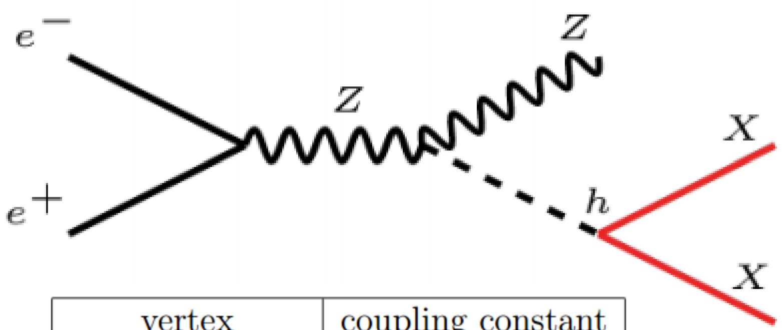
Usually bounds on 2HDM are expressed with this plot

In our model we need much more!



2HDM + U(1) gauge symmetry

Higgs Associated Production at LEP- light higgs searches



vertex	coupling constant
$H\,t\bar{t}, H\,b\bar{b}, H\,\tau\bar{\tau}$	$\frac{\sin\alpha}{\sin\beta}$
$H\,WW, H\,ZZ$	$\cos(\beta-\alpha)$
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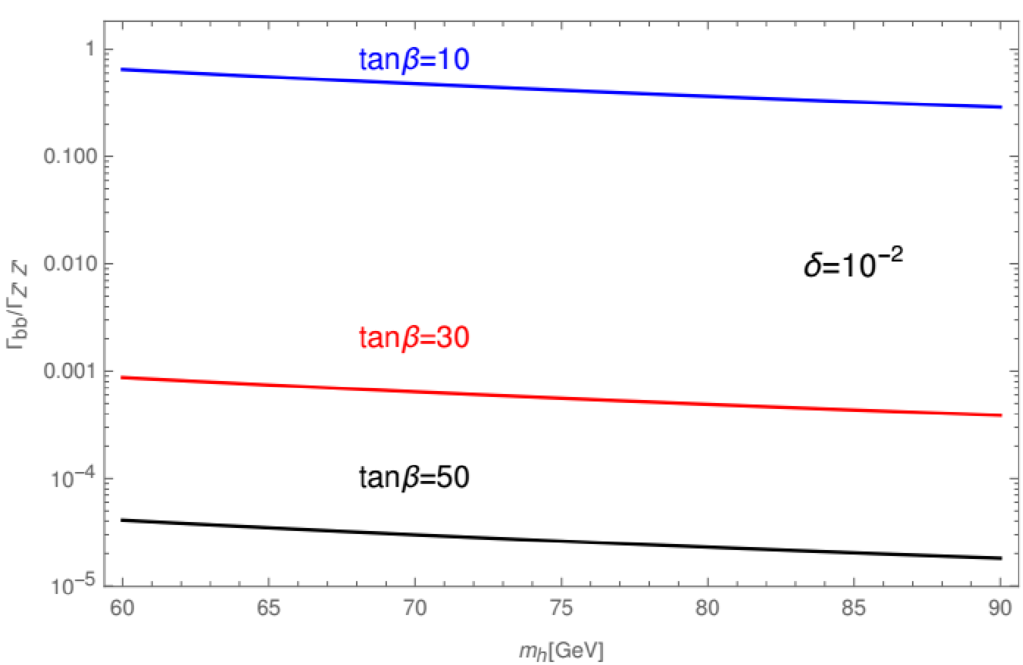
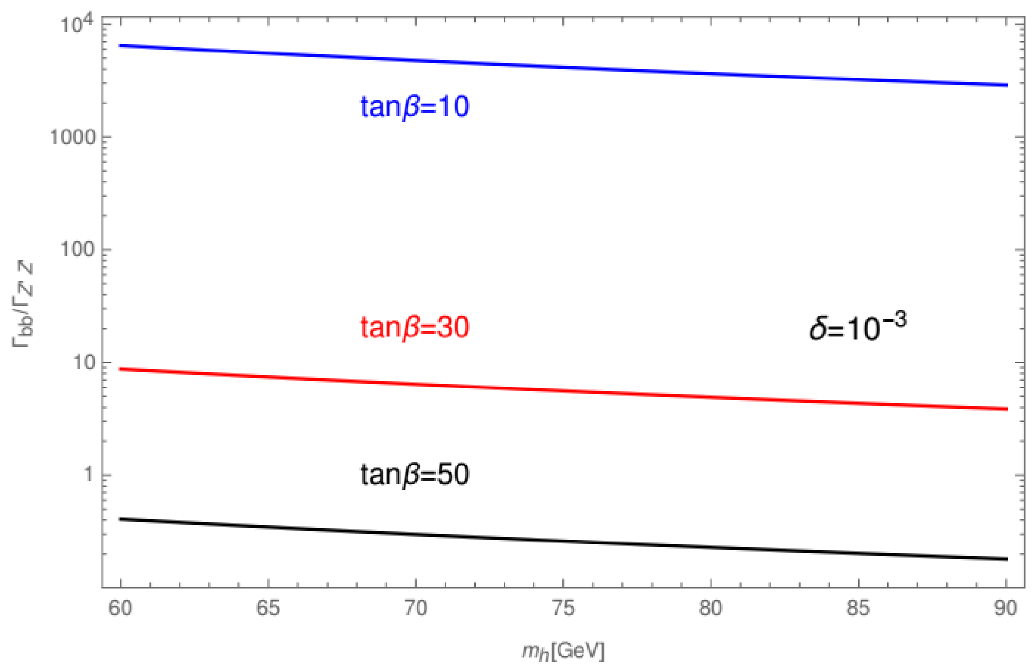
$$\Gamma_{h\to Z'Z'} = \frac{g_Z^2}{128\pi}\frac{m_h^3}{m_Z^2}(\delta\tan\beta)^4\left(\frac{\cos^3\beta\cos\alpha-\sin^3\beta\sin\alpha}{\cos\beta\sin\beta}\right)^2$$

$$\Gamma_{h\to b\bar{b}} = \frac{3m_b^2 m_h}{8\pi v^2}\left(\frac{\cos\alpha}{\sin\beta}\right)^2 .$$

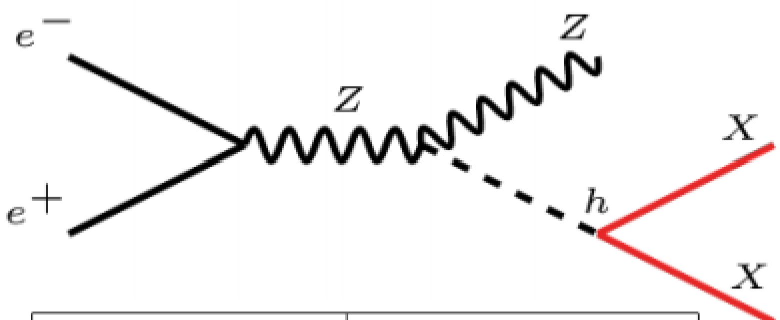
Z' is a gauge boson lighter than the Z





2HDM + U(1) gauge symmetry

Higgs Associated Production at LEP



$$\Gamma_{h\to Z'Z'} = \frac{g_Z^2}{128\pi}\frac{m_h^3}{m_Z^2}(\delta\tan\beta)^4\left(\frac{\cos^3\beta\cos\alpha - \sin^3\beta\sin\alpha}{\cos\beta\sin\beta}\right)^2$$

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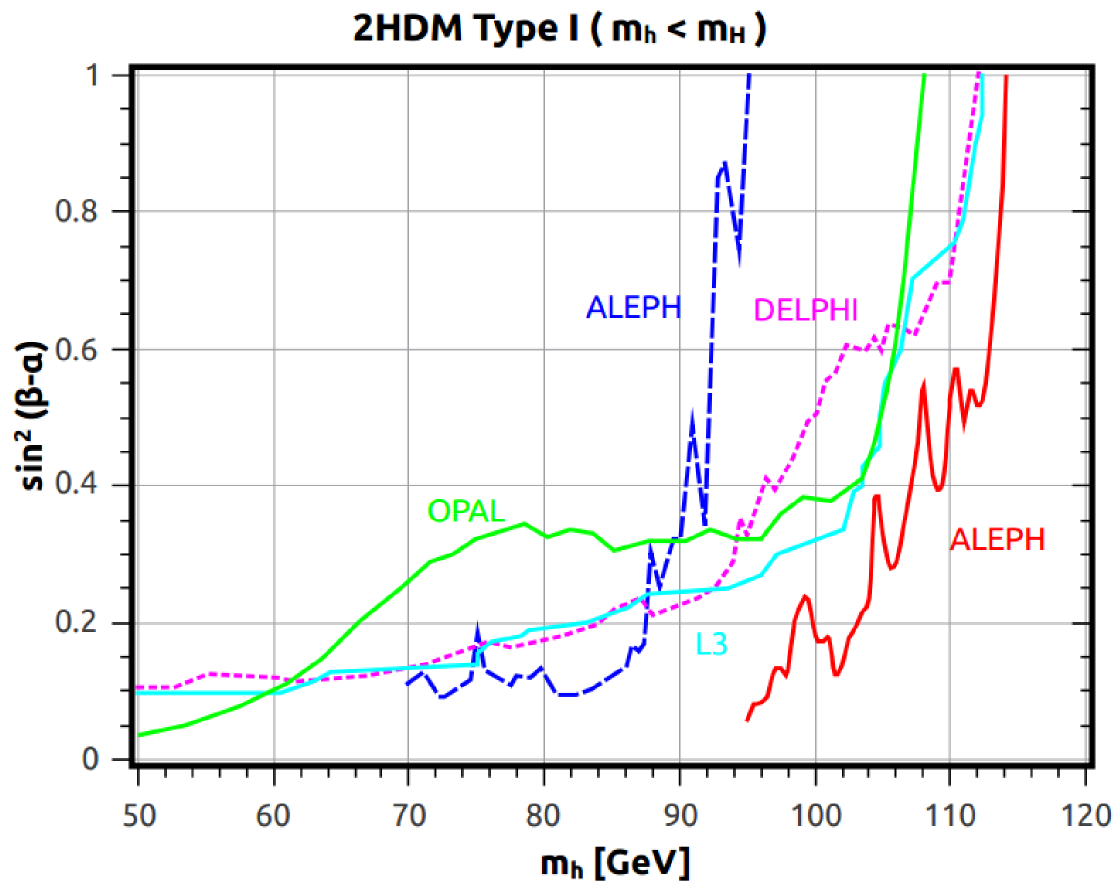
$h\,WW,\, h\,ZZ$	$\sin(\beta-\alpha)$

$$\sigma(Zh)/\sigma(ZH_{SM})BR(h\to \text{inv})$$



Higgs Properties as measured by the LHC. Thanks to Higgs Working group!

Higgs decay channel	branching ratio	error
$b\bar{b}$	5.84×10^{-1}	1.5%
$c\bar{c}$	2.89×10^{-2}	6.5%
g g	8.18×10^{-2}	4.5%
ZZ^*	2.62×10^{-1}	2%
WW^*	2.14×10^{-1}	2%
$\tau^+\tau^-$	6.27×10^{-2}	2%
$\mu^+\mu^-$	2.18×10^{-4}	2%
$\gamma\gamma$	2.27×10^{-3}	2.6%
$Z\gamma$	1.5×10^{-3}	6.7%
$ZZ^* \to 4\ell$	2.745×10^{-4}	2%
$ZZ^* \to 2\ell 2\nu$	1.05×10^{-4}	2%

$$\Gamma(H \to ZZ') = \frac{g_Z^2}{64\pi} \frac{(M_H^2 - M_Z^2)^3}{M_H^3 M_Z^2} \delta^2 \tan\beta^2 \sin^2(\beta - \alpha)$$

$$\Gamma(H \to Z'Z') = \frac{g_Z^2}{128\pi} \frac{M_H^3}{M_Z^2} \delta^4 \tan\beta^4 \left(\frac{\cos^3\beta \sin\alpha + \sin^3\beta \cos\alpha}{\cos\beta \sin\beta} \right)^2$$

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If you have a light Z' that mixes with the Z the precise measurements on the Higgs properties may lead to the strongest bound on the Z-Z' mass mixing

$$\delta^2 \leq \frac{4.6 \times 10^{-6}}{BR(Z' \to l^+ l^-) \sin^2(\beta - \alpha) \tan\beta^2}$$

The Higgs offers a powerful probe to new physics

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