Extended Higgs models

→ Symplest case, DM inspired is the inert Higgs doublet model, where a second Higgs doublet is added, odd under a parity $\mathbb{Z}_2$, i.e.

$$P_{\mathbb{Z}_2}(H_1) = H_1$$
$$P_{\mathbb{Z}_2}(H_2) = -H_2$$

& requiring that only H_1 obtains a v.e.v. in order to keep H_2 stable & any Higgs mixing. Then the most general potential is

$$V(H_1, H_2) = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + \lambda_1 (|H_1|^4 + \lambda_2 |H_2|^2 + \lambda_3 |H_1|^2 |H_2| + \lambda_4 H_1^+ H_2 H_2^+ H_1 + [\lambda_5 (H_1^+ H_2)^2 + h.c.]$$

To avoid ~~CP~~ keep λ_5 real.

We can then parametrize the fields as

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + i G^0) \end{pmatrix} \quad H_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(H + iA) \\ \| \\ H_2^0 \end{pmatrix}$$

where G^+, G^0 are the Goldstone bosons after ~~EW~~. So in the unitary gauge

$$H_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$$ as in the SM

but 4 additional d.o.f. appear, i.e.

$H^\pm$, H & A (last pseudoscalar)

We can substitute in the potential & obtain the mass matrices:

$$V(h, H_2) = \frac{\mu_1^2}{2}(v+h)^2 + \frac{\lambda_1}{4}(v+h)^4 +$$

$$+ \mu_2^2\left(|H_2^0|^2 + |H_2^+|^2\right) + \lambda_2\left(|H_2^0|^2 + |H_2^+|^2\right)^2$$

$$+\frac{\lambda_3}{2}(v+h)^2\left(|H_2^0|^2+|H_2^+|^2\right)+$$

$$+\frac{\lambda_4}{2}(v+h)^2|H_2^0|^2+\frac{\lambda_5}{2}(v+h)^2\left((H_2^0)^2+\text{h.c.}\right)$$

where only the last line differentiate H_2^0 & H_2^+

We have

$$(H_2^0)^2=\frac{1}{2}\left(H^2-A^2+2iHA\right)$$

$$\Rightarrow (H_2^0)^2+\text{h.c.}=H^2-A^2$$ no mixing among fields!

So we have simply

$$m_H^2=\mu_2^2+\frac{1}{2}v^2(\lambda_3+\lambda_4+\lambda_5)$$

$$m_A^2=\mu_2^2+\frac{1}{2}v^2(\lambda_3+\lambda_4-\lambda_5)$$

$$m_{H_2^\pm}^2=\mu_2^2+\frac{1}{2}v^2\lambda_3$$

so with sufficiently negative (positive) λ_5 the

lightest state is neutral & either H or A

Apart from the scalar potential, there are the $SU(2)$ gauge interactions, but not a direct coupling to fermions thanks to the $\mathbb{Z}_2$ symmetry assume SM to be even

$\Rightarrow$ Type I HDM with no FCNC

Indeed if one has instead $\tilde{H} = \varepsilon H$

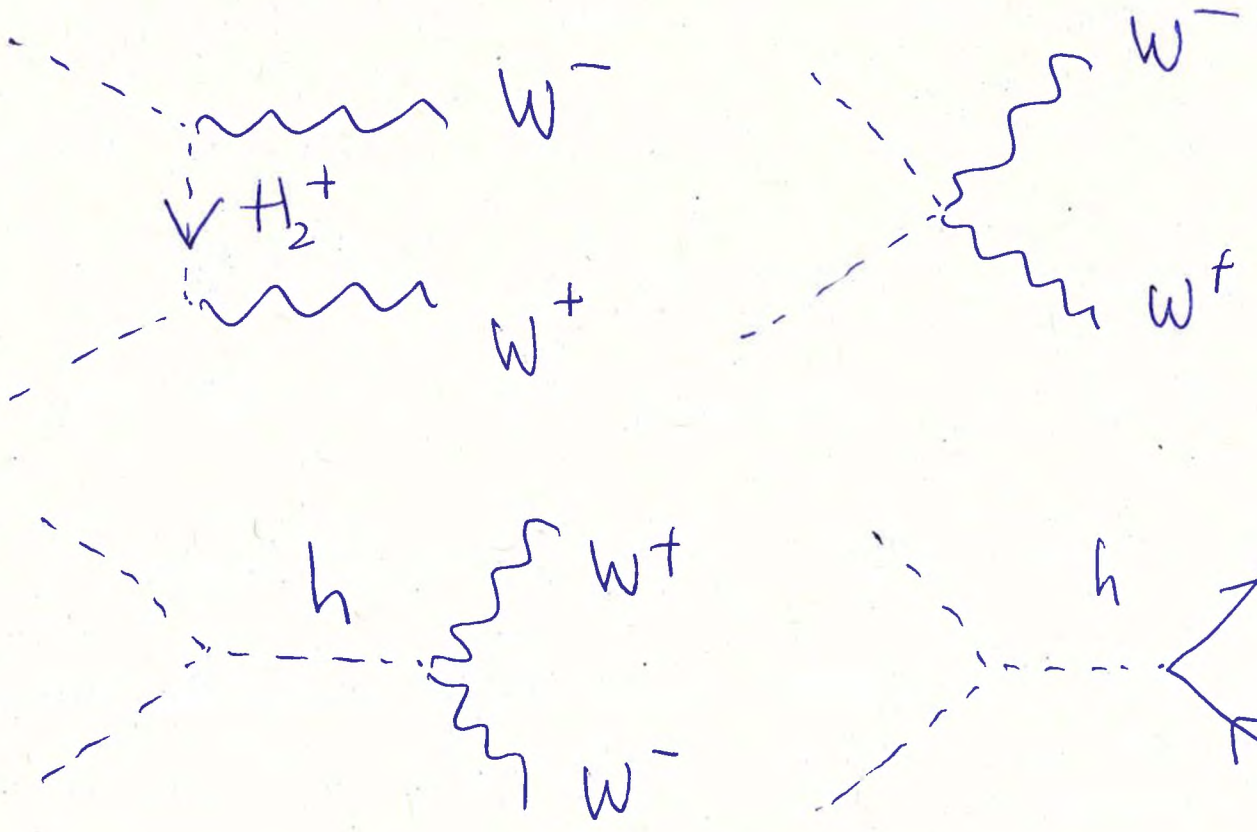
$$Y_1 \tilde{H}_1 \bar{q} u + Y_2 \tilde{H}_2 \bar{q} u$$

we have $m_u = \frac{Y_1}{\sqrt{2}} v$

& diagonalising m_u only diagonalises Y_1, but not Y_2 & so FCNC can arise from

$$Y_{2ij} \left[H_2^0 \bar{u}_i u_j - H_2^- \bar{d}_i u_j \right]$$

H/A interactions:



The lightest neutral state can be WIMP DM but its parameter space is strongly constrained, eg. at low mass by the invisible Higgs width & LEP constraints, while at larger masses often the cross-section $HH \to W^+W^-$ is too large to reproduce the DM density.

For $m_H \simeq 500-800$ GeV coannihilation among the 3 states can help to give the correct density.

Generic 2HDM models: mixings among the scalar fields & different fermionic couplings, i.e. see | Branco et al. arXiv:1106.0034

$$\begin{pmatrix} H \\ h \end{pmatrix} \simeq \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}(H_1^{(0)}) \\ \mathrm{Re}(H_2^{(0)}) \end{pmatrix}$$

$$\begin{pmatrix} G^0/G^\pm \\ A/H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} H_1^\pm/A_1^0 \\ H_2^\pm/A_2^0 \end{pmatrix}$$

where $\tan\beta = \frac{v_2}{v_1}$ ratio of v.e.v.'s, $\alpha \neq \beta$

Then the coupling to the gauge bosons & the fermions change by mixings:

$$g_h^V = \sin(\beta-\alpha) \qquad g_H^V = \cos(\beta-\alpha)$$

& the fermion coupling are

	Φ_1	Φ_2	Φ_1	Φ_2
Type I	All	None	$\cot\beta$	$\cot\beta$
Type II	u	d, e		
epton spec	u, d	e		
Flipped	u, e	d		

Etc.

Coupling only one Higgs to one type of fields avoids FCNC, otherwise need Yukawa alignment

Reviews of 2HDM : G. C. Branco et al.
Phys. Rept. 516 (2012) 1-102
1106.0034 [hep-ph]

L. Wang, J. M. Yang & Y. Zhang
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Inert Higgs: original paper

N. G. Deshpande and E. Ma
Phys. Rev. D18 (1978) 2574

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