A Suppression Mechanism for Neutrino Masses in the Higgs Triplet Model with Dark Matter

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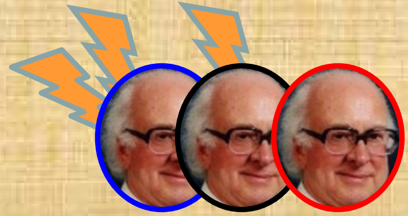
based on ‘S. Kanemura, HS, arXiv:1202.xxxx’

Higgs Triplet Model



Higgs potential

$\Delta : \mathrm{SU}(2)_L$ triplet, $Y = 1$, $\mathrm{L}\# = -2$

$$V = -m_\Phi^2(\Phi^\dagger\Phi) + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left\{\mu(\Phi^T i\sigma_2 \Delta^\dagger \Phi) + \mathrm{h.c}\right\} + (\text{quartic terms})$$

$v_\Delta \equiv \sqrt{2}\langle\Delta^0\rangle \simeq \dfrac{\mu\, v^2}{\sqrt{2}\, m_\Delta^2}$: explicit breaking of $\mathrm{L}\#$ ⟶ no NG-boson for ~~$\mathrm{L}\#$~~ ("Majoron")

Yukawa interaction with a complex Higgs triplet

$$h_{\ell\ell'}\left(-\overline{(\ell_L)^c}, \overline{(\nu_{\ell L})^c}\right)\begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}\begin{pmatrix} \nu_{\ell' L} \\ \ell'_L \end{pmatrix} + \mathrm{h.c.}$$

$$\Downarrow \quad v_\Delta \equiv \sqrt{2}\langle\Delta^0\rangle \simeq \frac{\mu\, v^2}{\sqrt{2}\, m_\Delta^2}$$

$$\frac{1}{2}\sqrt{2}\, v_\Delta h_{\ell\ell'}\, \overline{(\nu_{\ell L})^c}\nu_{\ell' L} + \mathrm{h.c.} + \cdots$$

Majorana ν_L mass matrix

$$(m_\nu)_{\ell\ell'} = \sqrt{2}\, v_\Delta\, h_{\ell\ell'} \simeq \frac{\mu v^2}{m_\Delta^2} h_{\ell\ell'}$$

Motivations

Small $(m_\nu)_{\ell\ell'} \simeq \frac{\mu v^2}{m_\Delta^2} h_{\ell\ell'}$ $\Leftrightarrow$ { Heavy triplet mass M or Small Yukawa couplings $h_{\alpha\beta}$ or Small breaking parameter μ of $L\#$ }

Small μ option seems charming

$\Rightarrow$

New particles can be light (ex. $m_{H^{\pm\pm}} \simeq m_\Delta < \mathrm{TeV}$)

(cf. GUT scale ν_R in the seesaw model)

$\longrightarrow$ Interesting phenomenology at the LHC

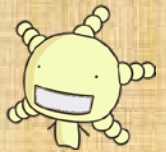
See e.g., A.G. Akeroyd, HS, M. Aoki, PRD**77**, 075010

New coupling constants can be large (ex. $|h_{\ell\ell'}| \lesssim 10^{-2}$)

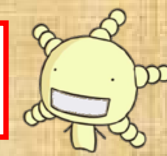
(cf. Dirac ν Yukawa coupling $\lesssim 10^{-11}$)

$\longrightarrow$ Exotic decays of charged leptons

We want to suppress μ



We want to supply the dark matter to the HTM



Our Model

HTM

SM

	L	Φ	Δ	s_1^0	s_2^0	η
$SU(2)_L$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$
$U(1)_Y$	$1/2$	$1/2$	1	0	0	$1/2$
$L\#$	1	0	-2	-1	0	-1
Z_2	$+$	$+$	$+$	$+$	$-$	$-$

Only scalar sector is extended.

Dark matter

Z_2 odd particles :

$$\left.\begin{array}{c} s_2^0 \\ \mathrm{Re}(\eta^0) \end{array}\right\} \longrightarrow \left\{\begin{array}{c} \mathcal{H}_1^0 \\ \mathcal{H}_2^0 \end{array}\right.$$

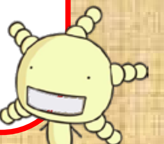
$$\mathrm{Im}(\eta^0) \longrightarrow \mathcal{A}^0$$

$$\eta^\pm \longrightarrow \mathcal{H}^\pm$$

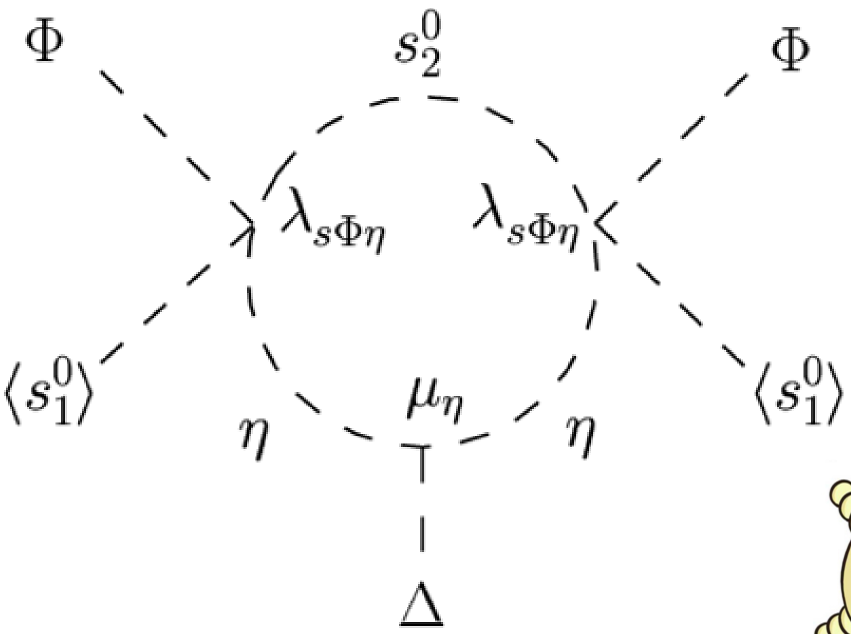
$$m_{\mathcal{H}_1^0} < m_{\mathcal{H}^\pm}$$

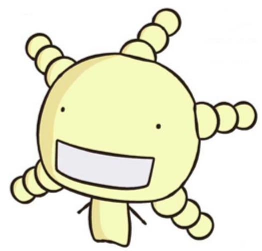
$$\Downarrow$$

$\mathcal{H}_1^0$ is DM candidate



Suppression of μ by utilizing DM candidate





"A. Oryzae diagram" ©Moyashimon

$\mu(\Phi^T i\sigma_2 \Delta^\dagger \Phi)$ at tree level is forbidden by $L\#$ conservation.

$\frac{1}{\Lambda}(s_1^0)^2(\Phi^T i\sigma_2 \Delta^\dagger \Phi)$ at 1-loop level

	Δ	s_1^0	s_2^0	η
$SU(2)_L$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$
$U(1)_Y$	1	0	0	1/2
$L\#$	-2	-1	0	-1
Z_2	+	+	−	−

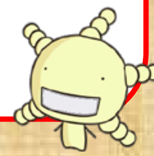
$$\mu = \frac{\lambda_{s\Phi\eta}^2\,\mu_\eta v_s^2}{64\pi^2\{(\mathcal{M}_0)^2_{ss} - (\mathcal{M}_0)^2_{\eta\eta}\}}\left\{1 - \frac{(\mathcal{M}_0)^2_{ss}}{(\mathcal{M}_0)^2_{ss} - (\mathcal{M}_0)^2_{\eta\eta}}\ln\frac{(\mathcal{M}_0)^2_{ss}}{(\mathcal{M}_0)^2_{\eta\eta}}\right\}$$

Estimation of Suppression of μ

Case of $\mathcal{H}_1^0 \simeq \mathrm{Re}(\eta^0)$ (inert doublet DM)

$$\frac{\mu}{\mu_\eta} \sim \frac{m_{\mathcal{A}^0}^2 - m_{\mathcal{H}_1^0}^2}{32\pi^2 v^2}$$

Example: $m_{\mathcal{H}_1^0} \simeq 75\,\mathrm{GeV},\ m_{\mathcal{A}^0} \simeq 125\,\mathrm{GeV} \quad \Rightarrow \quad \frac{\mu}{\mu_\eta} \sim 10^{-4}$



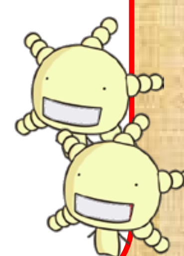
$m_{\mathcal{H}_1^0},\ m_{\mathcal{A}^0}$ satisfy LEP-II and WMAP

E. Lundstrom *et al*., PRD**79**, 035013 (2009)

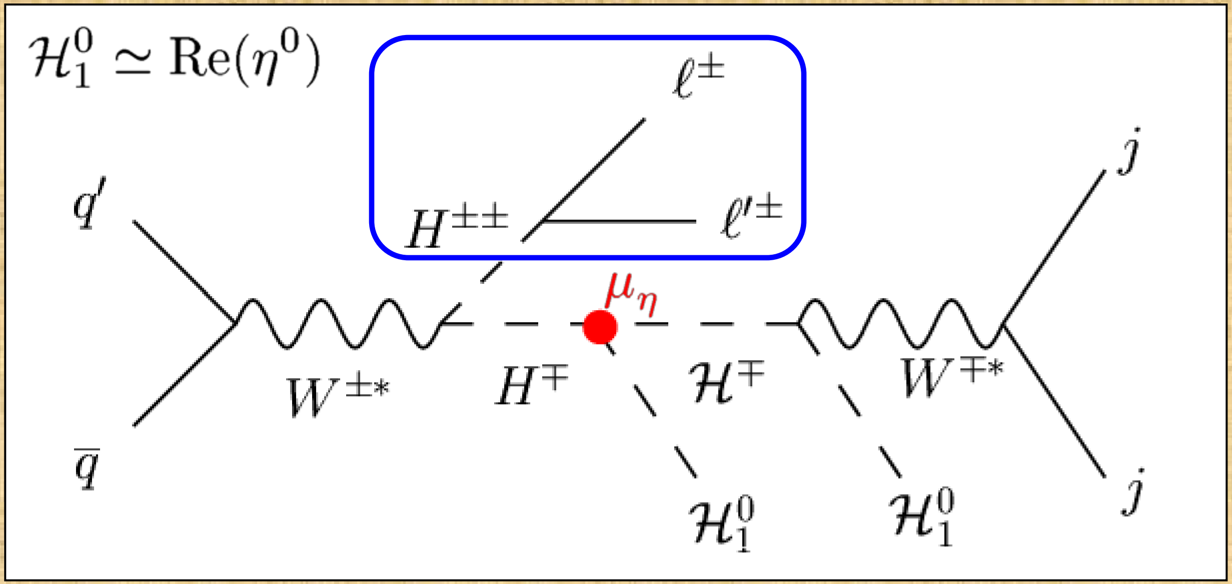
Case of $\mathcal{H}_1^0 \simeq s_2^0$ (inert singlet DM)

$$\frac{\mu}{\mu_\eta} \sim \frac{\lambda_{s\Phi\eta}^2 v_s^2}{64\pi^2 m_{\mathcal{A}^0}^2}$$

Example: $m_{\mathcal{A}^0} \sim v_s \sim 1\,\mathrm{TeV},\ \lambda_{s\Phi\eta} \sim 10^{-2} \quad \Rightarrow \quad \frac{\mu}{\mu_\eta} \sim 10^{-7}$



Hopeful Probe of μ_η at the LHC : $\ell\ell jj \not{E}_T$



$H^{\pm\pm} \to \ell^\pm \ell'^\pm$ **: The most interesting decay because of** $(m_\nu)_{\ell\ell'} = \sqrt{2}\, v_\Delta\, h_{\ell\ell'}$

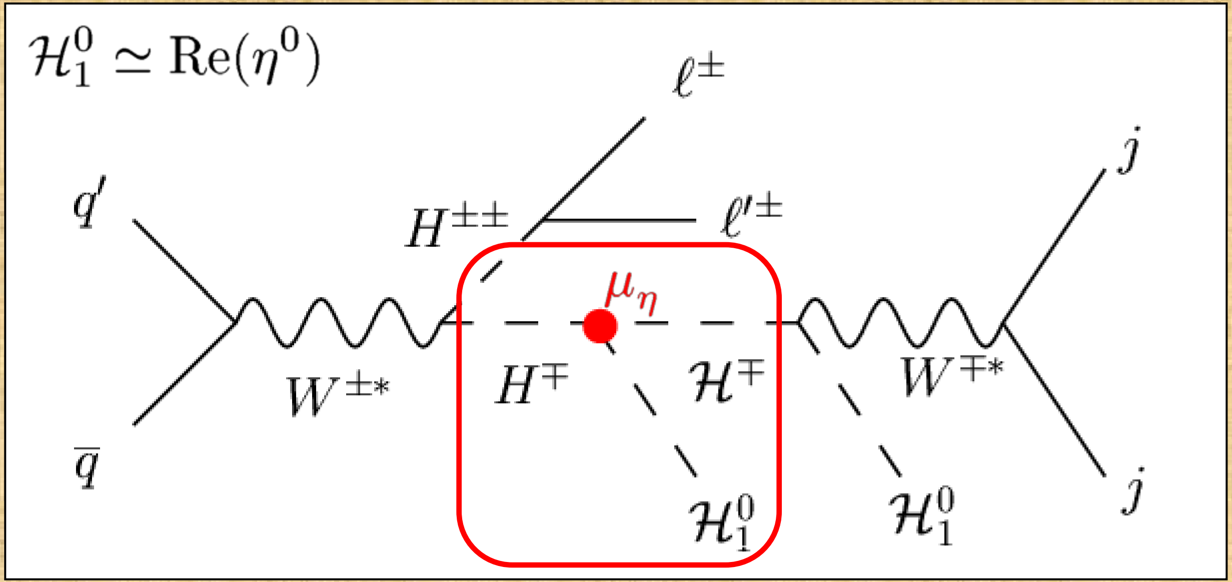
Good for BG reduction by imposing $m(\ell\ell') = m_{H^{\pm\pm}}$

$v_\Delta \ll 0.1\,\mathrm{MeV} \;\Longrightarrow$ Negligible $H^{\pm\pm} \to W^\pm W^\pm,\ (H^\pm \to W^\pm Z)$

$m_{H^{\pm\pm}} = m_{H^\pm} (= m_{H^0, A^0}) \;\Longrightarrow$ No $H^{\pm\pm} \to W^{\pm *} H^\pm,\ (H^\pm \to W^{\pm *} H^0,\ \mathrm{etc.})$

$m_{H^{\pm\pm}} \leq 2 m_{\mathcal{H}^\pm} \;\Longrightarrow$ No $H^{\pm\pm} \to \mathcal{H}^\pm \mathcal{H}^\pm$

Hopeful Probe of μ_η at the LHC : $\ell\ell jj\not{E}_T$



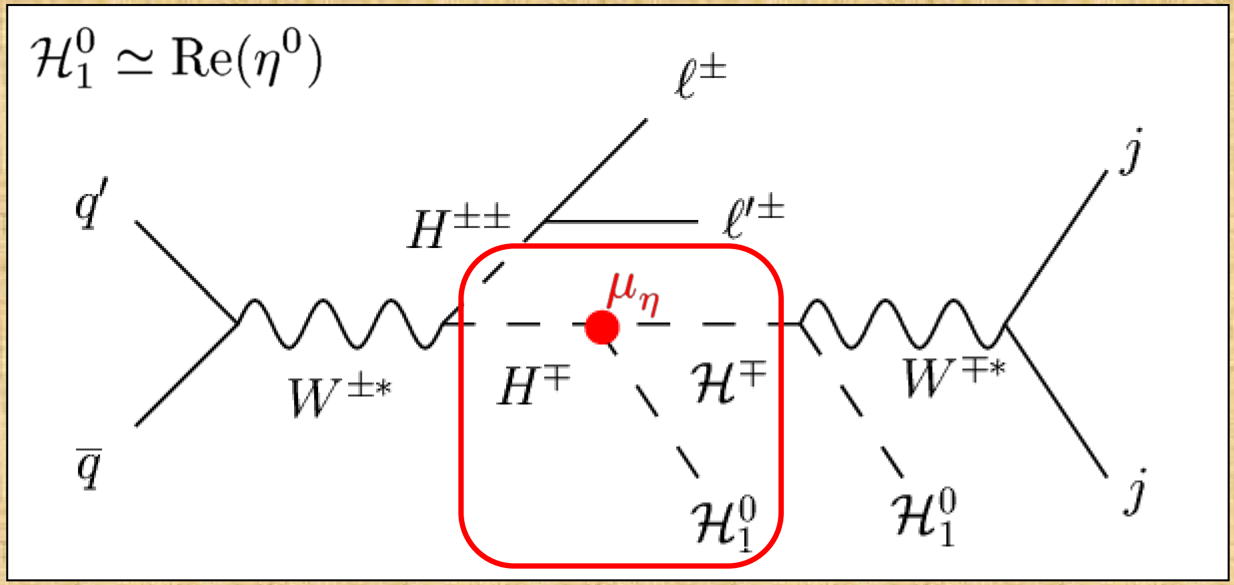
$m_{H^\pm} \geq m_{\mathcal{H}^\pm} + m_{\mathcal{H}_1^0} \Rightarrow H^\pm \to \mathcal{H}^\pm \mathcal{H}_1^0$ with $\mu_\eta(\eta^T i\sigma_2 \Delta^\dagger \eta)$

$\mu/\mu_\eta \ll 1 \longrightarrow$ Negligible contribution from $\eta^T \Delta\Delta^\dagger \eta$

$$\frac{\Gamma(H^\pm \to \ell^\pm \nu)}{\Gamma(H^\pm \to \mathcal{H}^\pm \mathcal{H}_1^0)} \sim \left(\frac{\mu}{\mu_\eta}\right)^2 \left(\frac{v}{v_\Delta}\right)^4 \left(\frac{m_\nu}{m_{H^\pm}}\right)^2$$

For example, $(10^{-4})^2 \left(\frac{100\,\mathrm{GeV}}{10\,\mathrm{keV}}\right)^4 \left(\frac{0.1\,\mathrm{eV}}{100\,\mathrm{GeV}}\right)^2 \sim 10^{-4} \longrightarrow$ Negligible

Hopeful Probe of μ_η at the LHC : $\ell\ell jj\not{E}_T$



c.f. usual HTM for the case of $H^{\pm\pm} \to \ell^\pm \ell'^\pm$

$H^- \to \ell^- \nu$

$W^{+*} H^{--}$

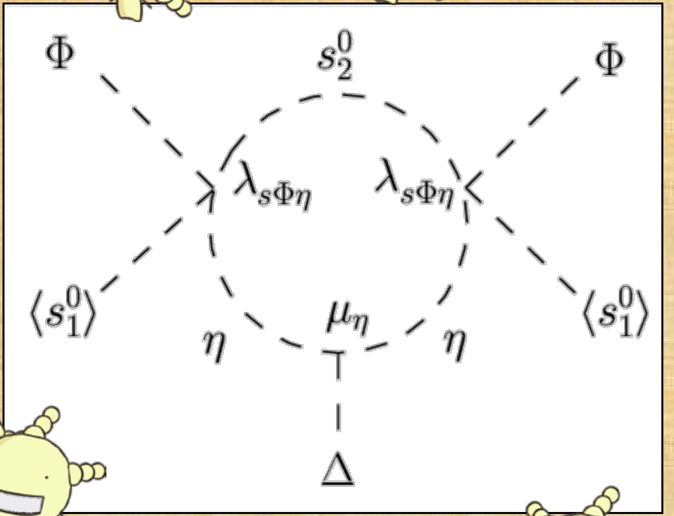
$\to \ell^- \ell'^-$

Additional leptons likely to exist.

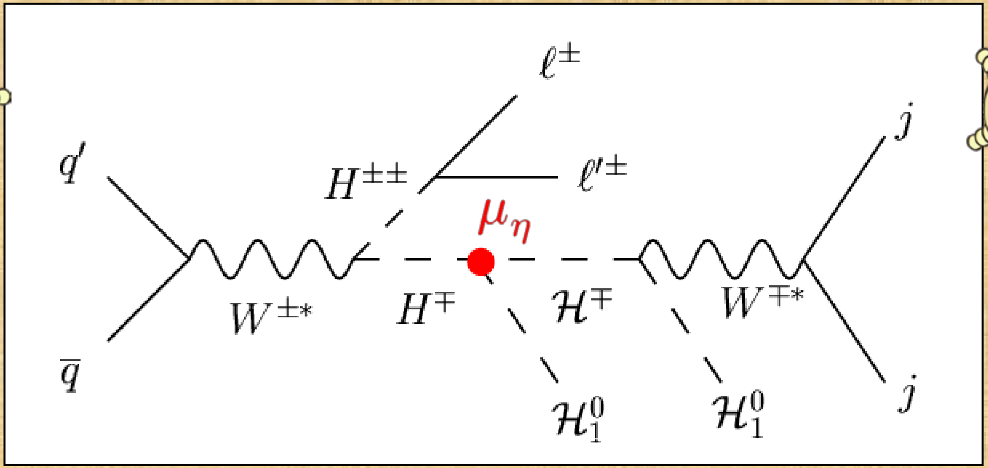
Summary

The Higgs Triplet Model is extended.

- **Dark matter** candidate
- **one-loop** $\mu(\Phi^T i\sigma_2 \Delta^\dagger \Phi)$



The model would be tested by $\ell\ell jj\not{E}_T$ at the LHC



Backup

Scalar Potential

$$V = V_2 + V_3 + V_4$$

$$V_2 \equiv -m_{s_1}^2 |s_1^0|^2 + \frac{1}{2} m_{s_2}^2 (s_2^0)^2 - m_\Phi^2 \Phi^\dagger \Phi + m_\eta^2 \eta^\dagger \eta + m_\Delta^2 \,\mathrm{tr}(\Delta^\dagger \Delta)$$

$$V_3 \equiv (\mu_\eta \eta^T i\sigma_2 \Delta^\dagger \eta) + \mathrm{h.c.}$$

$$\begin{aligned} V_4 \equiv\ & \lambda_{1\Phi} (\Phi^\dagger \Phi)^2 + \lambda_{1\eta} (\eta^\dagger \eta)^2 + \lambda_{1\Phi\Phi} (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_{1\Phi\eta} (\Phi^\dagger \eta)(\eta^\dagger \Phi) \\ & + \lambda_2 [\mathrm{tr}(\Delta^\dagger \Delta)]^2 + \lambda_3 \,\mathrm{tr}[(\Delta^\dagger \Delta)^2] \\ & + \lambda_{4\Phi} (\Phi^\dagger \Phi) \,\mathrm{tr}(\Delta^\dagger \Delta) + \lambda_{4\eta} (\eta^\dagger \eta) \,\mathrm{tr}(\Delta^\dagger \Delta) \\ & + \lambda_{5\Phi} (\Phi^\dagger \Delta^\dagger \Delta \Phi) + \lambda_{5\eta} (\eta^\dagger \Delta^\dagger \Delta \eta) \\ & + \lambda_{s1} |s_1^0|^4 + \lambda_{s2} (s_2^0)^4 + \lambda_{s3} |s_1^0|^2 (s_2^0)^2 \\ & + \lambda_{s\Phi 1} |s_1^0|^2 (\Phi^\dagger \Phi) + \lambda_{s\Phi 2} (s_2^0)^2 (\Phi^\dagger \Phi) \\ & + \lambda_{s\eta 1} |s_1^0|^2 (\eta^\dagger \eta) + \lambda_{s\eta 2} (s_2^0)^2 (\eta^\dagger \eta) + \{\lambda_{s\Phi\eta}\, s_1^0\, s_2^0\, (\eta^\dagger \Phi) + \mathrm{h.c.}\} \\ & + \lambda_{s\Delta 1} |s_1^0|^2 \mathrm{tr}(\Delta^\dagger \Delta) + \lambda_{s\Delta 2} (s_2^0)^2 \mathrm{tr}(\Delta^\dagger \Delta) \end{aligned}$$

Masses of Z_2-Odd Scalars

$$\begin{pmatrix} \mathcal{H}_1^0 \\ \mathcal{H}_2^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_0' & -\sin\theta_0' \\ \sin\theta_0' & \cos\theta_0' \end{pmatrix} \begin{pmatrix} \eta_r^0 \\ s_2^0 \end{pmatrix}, \quad \tan 2\theta_0' = \frac{\sqrt{2}\,\lambda_{s\Phi\eta}\, v\, v_s}{(\mathcal{M}_0)^2_{ss} - (\mathcal{M}_0)^2_{\eta\eta}}$$

$$(\mathcal{M}_0)^2_{\eta\eta} \equiv m_\eta^2 + (\lambda_{1\Phi\Phi} + \lambda_{1\Phi\eta})\, v^2/2 + \lambda_{s\eta 1}\, v_s^2/2$$

$$(\mathcal{M}_0)^2_{ss} \equiv m^2_{s_2^0} + \lambda_{s3}\, v_s^2 + \lambda_{s\Phi 2}\, v^2$$

$$\begin{aligned}
m^2_{\mathcal{H}_1^0} &= \frac{1}{2}\left\{(\mathcal{M}_0)^2_{\eta\eta} + (\mathcal{M}_0)^2_{ss} - \sqrt{\left\{(\mathcal{M}_0)^2_{\eta\eta} - (\mathcal{M}_0)^2_{ss}\right\}^2 + 2\,\lambda^2_{s\Phi\eta}\, v^2\, v_s^2}\right\}, \\
m^2_{\mathcal{H}_2^0} &= \frac{1}{2}\left\{(\mathcal{M}_0)^2_{\eta\eta} + (\mathcal{M}_0)^2_{ss} + \sqrt{\left\{(\mathcal{M}_0)^2_{\eta\eta} - (\mathcal{M}_0)^2_{ss}\right\}^2 + 2\,\lambda^2_{s\Phi\eta}\, v^2\, v_s^2}\right\}, \\
m^2_{\mathcal{A}^0} &= (\mathcal{M}_0)^2_{\eta\eta}, \\
m^2_{\mathcal{H}^\pm} &= (\mathcal{M}_0)^2_{\eta\eta} - \frac{1}{2}\lambda_{1\Phi\eta}\, v^2
\end{aligned}$$

$$m_{\mathcal{H}_1^0} \le m_{\mathcal{A}^0} \le m_{\mathcal{H}_2^0}$$

Masses of Z_2-Even Scalars

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{pmatrix} \begin{pmatrix} \phi_r^0 \\ s_{1r}^0 \end{pmatrix}, \qquad \tan 2\theta_0 = \frac{\lambda_{s\Phi 1}\, v\, v_s}{\lambda_{s1} v_s^2 - \lambda_{1\Phi} v^2}$$

$$\begin{aligned}
m_{h^0}^2 &\simeq \lambda_{1\Phi} v^2 + \lambda_{s1} v_s^2 - \sqrt{(\lambda_{1\Phi} v^2 - \lambda_{s1} v_s^2)^2 + \lambda_{s\Phi 1}^2 v^2\, v_s^2}\ , \\
m_{H^0}^2 &\simeq \lambda_{1\Phi} v^2 + \lambda_{s1} v_s^2 + \sqrt{(\lambda_{1\Phi} v^2 - \lambda_{s1} v_s^2)^2 + \lambda_{s\Phi 1}^2 v^2\, v_s^2}
\end{aligned}$$

$$\begin{aligned}
m_{H_T^0}^2 \simeq m_{A_T^0}^2 &\simeq m_{H^\pm}^2 + \frac{1}{4}\lambda_{5\Phi} v^2, \\
m_{H^\pm}^2 &\simeq m_\Delta^2 + \frac{1}{4}(2\lambda_{4\Phi} + \lambda_{5\Phi}) v^2 + \frac{1}{2}\lambda_{s\Delta 1} v_s^2, \\
m_{H^{\pm\pm}}^2 &\simeq m_{H^\pm}^2 - \frac{1}{4}\lambda_{5\Phi} v^2
\end{aligned}$$