

SUPPLEMENTARY MATERIAL FOR “ENTANGLEMENT SUPPRESSION, ENHANCED SYMMETRY AND A STANDARD-MODEL-LIKE HIGGS BOSON”

A. Derivation of Eqs. (13-15) in the main text:

Assuming that the initial state is a tensor product of two pure single particle states with no entanglement:

$$|\Phi_a\rangle = \kappa|1\rangle + \epsilon|2\rangle, \quad |\Phi_b\rangle = \gamma|1\rangle + \delta|2\rangle, \quad (1)$$

where $|i\rangle$ is the i th flavor basis state and $|\kappa|^2 + |\epsilon|^2 = |\gamma|^2 + |\delta|^2 = 1$. The final state is given by the scattering matrix $S = I + iM$ and can be written in the flavor basis with generic coefficients c_{ij}

$$\begin{aligned} |\Phi_c\Phi_d\rangle &= (\delta_{ac}\delta_{bd} + iM_{ab,cd})|\Phi_a\rangle \otimes |\Phi_b\rangle = c_{ij}|i\rangle \otimes |j\rangle \\ c_{11} &= (1 + iM_{11,11})\kappa\gamma + iM_{12,11}\kappa\delta + iM_{21,11}\epsilon\gamma + iM_{22,11}\epsilon\delta, \\ c_{12} &= iM_{11,12}\kappa\gamma + (1 + iM_{12,12})\kappa\delta + iM_{21,12}\epsilon\gamma + iM_{22,12}\epsilon\delta, \\ c_{21} &= iM_{11,21}\kappa\gamma + iM_{12,21}\kappa\delta + (1 + iM_{21,21})\epsilon\gamma + iM_{22,21}\epsilon\delta, \\ c_{22} &= iM_{11,22}\kappa\gamma + iM_{12,22}\kappa\delta + iM_{21,22}\epsilon\gamma + (1 + iM_{22,22})\epsilon\delta, \end{aligned} \quad (2)$$

The concurrence $\Delta(|\Phi_c\Phi_d\rangle) = c_{11}c_{22} - c_{12}c_{21}$ reads

$$\begin{aligned} \Delta(|\Phi_c\Phi_d\rangle) &= i\kappa\epsilon\gamma\delta(M_{11,11} - M_{12,12} - M_{21,21} + M_{22,22}) \\ &\quad + i\kappa\epsilon(\gamma^2 - \delta^2)(M_{21,22} - M_{11,12}) + i(\kappa^2 - \epsilon^2)\gamma\delta(M_{12,22} - M_{11,21}) \\ &\quad - iM_{12,21}\kappa^2\delta^2 - iM_{21,12}\epsilon^2\gamma^2 + iM_{11,22}\kappa^2\gamma^2 + iM_{22,11}\epsilon^2\delta^2 + O((M_{ab,cd})^2). \end{aligned} \quad (3)$$

Since κ, ϵ, γ and δ are arbitrary, setting $\Delta(|\Phi_c\Phi_d\rangle) = 0$ leads to the conditions in Eqs. (13-15).

B. Derivation of the maximal symmetric potential of 2HDM:

In the Higgs basis $\{H_1, H_2\}$, where we defined

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \quad (4)$$

such that H_1 aligns with the VEV: $\langle H_1 \rangle = (0, \frac{v}{\sqrt{2}})^T$ and $\langle H_2 \rangle = (0, 0)^T$. The scalar potential has the form

$$\begin{aligned} \mathcal{V}(H_1, H_2) &= Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 - [Y_3 H_1^\dagger H_2 + \text{h.c.}] \\ &\quad + \frac{Z_1}{2} (H_1^\dagger H_1)^2 + \frac{Z_2}{2} (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &\quad + \left[\frac{Z_5}{2} (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + Z_7 (H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.} \right]. \end{aligned} \quad (5)$$

The minimization condition leads to the quadratic coefficients $Y_1 = -Z_1 v^2/2$ and $Y_3 = -Z_6 v^2/2$, while the mass matrices of the charged and CP even/odd neutral scalars are given by

$$m_+^2 = \begin{pmatrix} 0 & 0 \\ 0 & Y_2 + Z_3 v^2/2 \end{pmatrix}, \quad (6)$$

$$m_{\text{even}}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & Y_2 + (Z_3 + Z_4 + Z_5) v^2/2 \end{pmatrix}, \quad (7)$$

$$m_{\text{odd}}^2 = \begin{pmatrix} 0 & 0 \\ 0 & Y_2 + (Z_3 + Z_4 - Z_5) v^2/2 \end{pmatrix}. \quad (8)$$

The Feynman rules are given by (time goes from left to right)

$$H_1^0 \begin{array}{c} \nearrow H_a^+ \\ \searrow H_b^- \end{array} = \frac{iv}{\sqrt{2}} \begin{pmatrix} Z_1 & Z_6 \\ Z_6 & Z_3 \end{pmatrix}_{ab}, \quad (9)$$

$$\begin{array}{c}
H_a^+ \\
\swarrow \\
H_2^0 \\
\searrow \\
H_b^-
\end{array}
= \frac{iv}{\sqrt{2}} \begin{pmatrix} Z_6 & Z_5 \\ Z_4 & Z_7 \end{pmatrix}_{ab}, \quad (10)$$

$$\begin{array}{c}
H_a^0 \\
\swarrow \\
H_1^0 \\
\searrow \\
H_b^0
\end{array}
= \frac{iv}{\sqrt{2}} \begin{pmatrix} Z_1 & 2Z_6 \\ 2Z_6 & Z_5 \end{pmatrix}_{ab}, \quad (11)$$

$$\begin{array}{c}
H_a^0 \\
\swarrow \\
H_2^0 \\
\searrow \\
H_b^0
\end{array}
= \frac{iv}{\sqrt{2}} \begin{pmatrix} Z_6 & Z_3 + Z_4 \\ Z_3 + Z_4 & Z_7 \end{pmatrix}_{ab}, \quad (12)$$

$$\begin{array}{ccc}
H_a^+ & & H_c^+ \\
\searrow & \swarrow & \\
H_b^0 & & H_d^0
\end{array}
= i \begin{pmatrix} Z_1 & Z_6 & Z_6 & Z_5 \\ Z_6 & Z_3 & Z_4 & Z_7 \\ Z_6 & Z_4 & Z_3 & Z_7 \\ Z_5 & Z_7 & Z_7 & Z_2 \end{pmatrix}_{ab,cd}. \quad (13)$$

Applying the entanglement suppression conditions Eqs. (13-15) in the main text to the four-point coupling in Eq. (13) we arrive at

$$\begin{aligned}
Z_1 + Z_2 &= 2Z_3, \\
Z_4 &= Z_5 = 0, \\
Z_6 &= Z_7.
\end{aligned} \quad (14)$$

Using the relations in Eq. (14), the s/u -channel amplitudes are,

$$M_1^s = \begin{pmatrix} Z_1^2 & Z_1 Z_6 & Z_1 Z_6 & 0 \\ Z_1 Z_6 & Z_6^2 & Z_6^2 & 0 \\ Z_1 Z_6 & Z_6^2 & Z_6^2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \quad (15)$$

$$M_2^s = \begin{pmatrix} Z_6^2 & 0 & Z_3 Z_6 & Z_6^2 \\ 0 & 0 & 0 & 0 \\ Z_3 Z_6 & 0 & Z_3^2 & Z_3 Z_6 \\ Z_6^2 & 0 & Z_3 Z_6 & Z_6^2 \end{pmatrix}, \quad (16)$$

$$M_1^u = \begin{pmatrix} Z_1^2 & Z_1 Z_6 & Z_1 Z_6 & Z_6^2 \\ Z_1 Z_6 & Z_6^2 & 0 & 0 \\ Z_1 Z_6 & 0 & Z_6^2 & 0 \\ Z_6^2 & 0 & 0 & 0 \end{pmatrix}, \quad (17)$$

$$M_2^u = \begin{pmatrix} Z_6^2 & 0 & Z_3 Z_6 & 0 \\ 0 & 0 & Z_6^2 & 0 \\ Z_3 Z_6 & Z_6^2 & Z_3^2 & Z_3 Z_6 \\ 0 & 0 & Z_3 Z_6 & Z_6^2 \end{pmatrix}, \quad (18)$$

The condition $M_{11,22} = M_{12,21} = 0$ then requires

$$Z_6 = 0 . \quad (19)$$

The resulting amplitude in the t -channel is:

$$M_1^t = \begin{pmatrix} 8Z_1^2 s_{\bar{\alpha}}^2 & -2Z_1 Z_3 c_{\bar{\alpha}} s_{\bar{\alpha}} & 0 & 0 \\ -2Z_1 Z_3 c_{\bar{\alpha}} s_{\bar{\alpha}} & 4Z_1 Z_3 s_{\bar{\alpha}}^2 & 0 & 0 \\ 0 & 0 & 8Z_1 Z_3 s_{\bar{\alpha}}^2 & -2Z_3^2 c_{\bar{\alpha}} s_{\bar{\alpha}} \\ 0 & 0 & -2Z_3^2 c_{\bar{\alpha}} s_{\bar{\alpha}} & 4Z_3^2 s_{\bar{\alpha}}^2 \end{pmatrix} , \quad (20)$$

$$M_2^t = \begin{pmatrix} 8Z_1^2 c_{\bar{\alpha}}^2 & 2Z_1 Z_3 c_{\bar{\alpha}} s_{\bar{\alpha}} & 0 & 0 \\ 2Z_1 Z_3 c_{\bar{\alpha}} s_{\bar{\alpha}} & 4Z_1 Z_3 c_{\bar{\alpha}}^2 & 0 & 0 \\ 0 & 0 & 8Z_1 Z_3 c_{\bar{\alpha}}^2 & 2Z_3^2 c_{\bar{\alpha}} s_{\bar{\alpha}} \\ 0 & 0 & 2Z_3^2 c_{\bar{\alpha}} s_{\bar{\alpha}} & 4Z_3^2 c_{\bar{\alpha}}^2 \end{pmatrix} , \quad (21)$$

$$M_3^t = M_4^t = 0 . \quad (22)$$

Solving for $M_{11,12} = M_{21,22}$ we get $Z_1 = Z_3$ and, together with Eqs. (14) and (19), this leads to the first half of Eq. (22) in the main text,

$$Z_1 = Z_2 = Z_3 = Z , \quad Z_i = 0 \text{ for } i \neq 1, 2, 3 . \quad (23)$$

Then both M_i^t , $i = 1, 2$, satisfy the entanglement suppression conditions, including the diagonal condition: $M_{11,11} - M_{12,12} - M_{21,21} + M_{22,22} = 0$. However, for $M^{s,u}$ we now have

$$M_1^s = M_1^u = \begin{pmatrix} Z^2 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{pmatrix} , \quad M_2^s = M_2^u = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & Z^2 & \\ & & & 0 \end{pmatrix} , \quad (24)$$

which do not individually satisfy the diagonal condition. The only solution is thus to require $P_{s,1} = P_{s,2}$ and $P_{u,1} = P_{u,2}$ so that the sum of the two matrices above satisfies the diagonal condition. This requires the two charged scalars to be degenerate in mass, $m_{H^\pm} = m_{G^\pm} = 0$. Given the mass matrix of the charged scalars in eq. (6), it implies that $Y_2 = -Zv^2/2 = Y_1$ and all scalars other than h are massless Goldstone bosons, which lead to the $SO(8)$ symmetric potential.