Exploring Multi-Higgs Models With Softly Broken Large Discrete Symmetry Groups

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Overview

Motivation

BSM Physics:

- Needed
- Not found

Shape of BSM Physics?

$\Downarrow$

Explore Different Avenues

Motivation

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Common Paths

Extended Scalar Sectors

- Required by most BSM frameworks
- Proliferation of free parameters

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Explore Different Avenues

Common Paths

Extended Scalar Sectors

- Required by most BSM frameworks
- Proliferation of free parameters

Flavour Symmetries

- Atenuates parameter proliferation
- Increases predictivity

Motivation

Extended Scalar Sectors

- 2HDMs: Already Deeply Studied
- 3HDMs: Next Step in the nHDMs extensions
    - Same number of flavours in Fermionic and Scalar Sectors
    - Opens up $3D$ irrep flavour Groups (G)

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Symmetry Constrained 3HDMs

Small Groups $\rightarrow$ Still Flexible

Large Groups $\rightarrow$ Highly Constraining

$\Rightarrow$ Softly-Broken Large Groups

Softly-Broken Large Discrete Symmetries in 3HDMs

Large Discrete Symmetries $\equiv \phi \sim \mathbf{3}$

$$V_0 = -m^2 \left(\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2 + \phi_3^\dagger \phi_3 \right) + V_4,$$

where V_4 depends on G.

$$\begin{aligned} V_{\text{soft}} &= m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 + m_{33}^2 \phi_3^\dagger \phi_3 + \\ &+ \left(m_{12}^2 \phi_1^\dagger \phi_2 + m_{13}^2 \phi_1^\dagger \phi_3 + m_{23}^2 \phi_2^\dagger \phi_3 + h.c. \right) \end{aligned}$$

9 Soft-Breaking Parameters

Explicit Computations: Straightforward, Not Enlightening

Structural Changes *vs.* Numerical Shifts

Softly-Broken Large Discrete Symmetries in 3HDMs

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Main Goal

Tame the Large Number of Parameters

Study Their Consequences

$\Sigma(36)$-Symmetric 3HDM

Scalar Potential

$$
\begin{aligned}
V_0 \;=\; & -m^2\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]+\lambda_1\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]^2 \\
& -\lambda_2\Big[|\phi_1^\dagger\phi_2|^2+|\phi_2^\dagger\phi_3|^2+|\phi_3^\dagger\phi_1|^2- \\
& \qquad -(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)-(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3)-(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1)\Big] \\
& +\lambda_3\left[|\phi_1^\dagger\phi_2-\phi_2^\dagger\phi_3|^2+|\phi_2^\dagger\phi_3-\phi_3^\dagger\phi_1|^2+|\phi_3^\dagger\phi_1-\phi_1^\dagger\phi_2|^2\right]
\end{aligned}
$$

Automatic CP Invariance

$\Sigma(36)$-Symmetric 3HDM

Scalar Potential

$$
\begin{aligned}
V_0 \quad = \quad & -m^2 \left[\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3\right] + \lambda_1 \left[\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3\right]^2 \\
& -\lambda_2 \Big[|\phi_1^\dagger\phi_2|^2 + |\phi_2^\dagger\phi_3|^2 + |\phi_3^\dagger\phi_1|^2 - \\
& \qquad -(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) - (\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) - (\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1)\Big] \\
& +\lambda_3 \left[|\phi_1^\dagger\phi_2 - \phi_2^\dagger\phi_3|^2 + |\phi_2^\dagger\phi_3 - \phi_3^\dagger\phi_1|^2 + |\phi_3^\dagger\phi_1 - \phi_1^\dagger\phi_2|^2\right]
\end{aligned}
$$

4 Real Parameters

$\Sigma(36)$-Symmetric 3HDM

Scalar Potential

$$
\begin{aligned}
V_0 \;=\; & -m^2\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]+\lambda_1\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]^2\\
& -\lambda_2\Big[|\phi_1^\dagger\phi_2|^2+|\phi_2^\dagger\phi_3|^2+|\phi_3^\dagger\phi_1|^2-\\
& \qquad -(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)-(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3)-(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1)\Big]\\
& +\lambda_3\left[|\phi_1^\dagger\phi_2-\phi_2^\dagger\phi_3|^2+|\phi_2^\dagger\phi_3-\phi_3^\dagger\phi_1|^2+|\phi_3^\dagger\phi_1-\phi_1^\dagger\phi_2|^2\right]
\end{aligned}
$$

$SU(3)$-Symmetric

$\Sigma(36)$-Symmetric 3HDM

Scalar Potential

$$
\begin{aligned}
V_0 \quad = \quad & -m^2\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]+\lambda_1\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]^2 \\
& -\lambda_2\left[|\phi_1^\dagger\phi_2|^2+|\phi_2^\dagger\phi_3|^2+|\phi_3^\dagger\phi_1|^2-\right. \\
& \qquad \left.-(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)-(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3)-(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1)\right] \\
& +\lambda_3\left[|\phi_1^\dagger\phi_2-\phi_2^\dagger\phi_3|^2+|\phi_2^\dagger\phi_3-\phi_3^\dagger\phi_1|^2+|\phi_3^\dagger\phi_1-\phi_1^\dagger\phi_2|^2\right]
\end{aligned}
$$

Selects $\Sigma(36)$ Subgroup

$\Sigma(36)$-Symmetric 3HDM

Scalar Potential

$$\begin{aligned} V_0 \;=\; & -m^2\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]+\lambda_1\left[\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3\right]^2 \\ & -\lambda_2\Big[|\phi_1^\dagger\phi_2|^2+|\phi_2^\dagger\phi_3|^2+|\phi_3^\dagger\phi_1|^2- \\ & \qquad -(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)-(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3)-(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1)\Big] \\ & +\lambda_3\left[|\phi_1^\dagger\phi_2-\phi_2^\dagger\phi_3|^2+|\phi_2^\dagger\phi_3-\phi_3^\dagger\phi_1|^2+|\phi_3^\dagger\phi_1-\phi_1^\dagger\phi_2|^2\right] \end{aligned}$$

$\lambda_2 > 0$ Selects Neutral Minima

$\Sigma(36)$-Symmetric 3HDM

Rigid Minima Structure

vev Alignments:

$\lambda_3 < 0$:

$$A : (\omega, 1, 1), \qquad A' : \left(\omega^2, 1, 1\right),$$

$\Sigma(36)$-Symmetric 3HDM

Rigid Minima Structure

vev Alignments:

$\lambda_3 > 0$:

$$B : (1,\, 0,\, 0)\,, \qquad C : (1,\, 1,\, 1)\,, \qquad \left(1,\, \omega,\, \omega^2\right), \qquad \left(1,\, \omega^2,\, \omega\right).$$

$\Sigma(36)$-Symmetric 3HDM

Rigid Minima Structure

vev Alignments:

$\lambda_3 < 0$:

$$A : (\omega, 1, 1), \qquad A' : \left(\omega^2, 1, 1\right),$$

$\lambda_3 > 0$:

$$B : (1, 0, 0), \qquad C : (1, 1, 1), \qquad \left(1, \omega, \omega^2\right), \qquad \left(1, \omega^2, \omega\right).$$

2 Distinct Phenomenological Situations

Physical Higgs Bosons

Points A, A'

$$\begin{aligned} m^2_{h_{SM}} &= 2\lambda_1 v^2, \\ m^2_{H^\pm} &= \frac{1}{2}\lambda_2 v^2, \\ m^2_h &= \frac{1}{2}\lambda_3 v^2, \\ m^2_H &= \frac{3}{2}\lambda_3 v^2, \end{aligned}$$

Points B, C

$$\begin{aligned} m^2_{h_{SM}} &= 2(\lambda_1 + \lambda_3) v^2, \\ m^2_{H^\pm} &= \frac{1}{2}(\lambda_2 - 3\lambda_3) v^2, \\ m^2_h &= -\frac{1}{2}\lambda_3 v^2, \\ m^2_H &= -\frac{3}{2}\lambda_3 v^2, \end{aligned}$$

- Automatic Scalar Alignment
- Pair-wise Degeneracy $\begin{pmatrix} m^2_{H_1^\pm} = m^2_{H_2^\pm} = m^2_{H^\pm} \\ m^2_{h_1} = m^2_{h_2} = m^2_h \\ m^2_{H_1} = m^2_{H_2} = m^2_H \end{pmatrix}$

$\Sigma(36)$ 3HDM: Summary

Features of the $\Sigma(36)$ 3HDM

- vev Alignment restricted to points A, A', B, or C
- Spontaneous CP violation impossible
- Automatic Scalar Alignment (h_{SM} is SM-like)
- Pair-wise degeneracy of the scalars
- Constrained Neutral Higgses Masses: $m_h^2 = 3m_H^2$
- Lightest Nonstandard Higgs Stable Against Decays to SM Fields (No vev Alignment Fully Breaks G)

How to Preserve vev Alignment?

Proposed Method

Potential

$$V_0 = -m^2 \phi_i^\dagger \phi_i + V_4$$

Extremum Conditions

$$\frac{\partial V_0}{\partial \phi_i^*} = -m^2 \phi_i + \frac{\partial V_4}{\partial \phi_i^*} = 0 \Leftrightarrow \left.\frac{\partial V_4}{\partial \phi_i^*}\right|_{V_0 \text{ extremum}} = \left. m^2 \phi_i \right|_{V_0 \text{ extremum}}$$

Soft-Breaking Terms

$$V_{\text{soft}} = \phi_i^\dagger M_{ij} \phi_j, \qquad M_{ij} = \begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ (m_{12}^2)^* & m_{22}^2 & m_{23}^2 \\ (m_{13}^2)^* & (m_{23}^2)^* & m_{33}^2 \end{pmatrix}$$

How to Preserve vev Alignment?

Proposed Method

Potential (with SBPs)

$$V = -m^2 \phi_i^\dagger \phi_i + V_{\text{soft}} + V_4$$

Extremum Conditions

$$\frac{\partial V}{\partial \phi_i^*} = M_{ij}\phi_j - m^2\phi_i + \frac{\partial V_4}{\partial \phi_i^*} = 0$$

Require

$$v\Big|_{V \text{ extremum}} = \zeta \cdot v\Big|_{V_0 \text{ extremum}} \Rightarrow \frac{\partial V_4}{\partial \phi_i^*}\Big|_{V \text{ extremum}} = \zeta^2 \cdot m^2 \phi_i\Big|_{V \text{ extremum}}$$

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Proposed Method

Potential (with SBPs)

$$V = -m^2 \phi_i^\dagger \phi_i + V_{\text{soft}} + V_4$$

Extremum Conditions

$$\frac{\partial V}{\partial \phi_i^*} = M_{ij}\phi_j - m^2 \phi_i + \zeta^2 m^2 \phi_i = 0$$

Require

$$v\Big|_{V \text{ extremum}} = \zeta \cdot v\Big|_{V_0 \text{ extremum}} \Rightarrow \frac{\partial V_4}{\partial \phi_i^*}\Big|_{V \text{ extremum}} = \zeta^2 \cdot m^2 \phi_i\Big|_{V \text{ extremum}}$$

How to Preserve vev Alignment?

Proposed Method

Potential (with SBPs)

$$V = -m^2 \phi_i^\dagger \phi_i + V_{\text{soft}} + V_4$$

Extremum Conditions

$$M_{ij}\phi_j = (1-\zeta^2) m^2 \phi_i$$

SBPs Preserve vev iff it is an Eigenvector of M

Example: $C = (\,1,\,1,\,1)$

General Hermitian Matrix M:

$$M_{ij} = \mu_1 n_{1i} n^*_{1j} + \mu_2 n_{2i} n^*_{2j} + \mu_3 n_{3i} n^*_{3j}$$

where μ_i are eigenvalues, and n_i are eigenvectors.
Preserve vev Alignment $\rightarrow n_1 =$ vev alignment.

$$n_1 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$e_2 \perp e_3 \perp n_1$:

$$e_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}, \qquad e_3 = \frac{1}{\sqrt{6}} \begin{pmatrix} -2 \\ 1 \\ 1 \end{pmatrix}$$

Example: $C = (1,\ 1,\ 1)$

$$e_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}, \qquad e_3 = \frac{1}{\sqrt{6}}\begin{pmatrix} -2 \\ 1 \\ 1 \end{pmatrix}$$

General Basis:

$$n_i = \mathcal{U} e_i, \qquad \mathcal{U} = \begin{pmatrix} \cos\theta & e^{i\xi}\sin\theta \\ -e^{-i\xi}\sin\theta & \cos\theta \end{pmatrix}$$

Alignment Preserving Soft-Breaking Parameters

$$\mu_1 = (1-\zeta^2)m^2, \quad \mu_2, \quad \mu_3, \quad \theta, \quad \xi$$

Example: $C = (\,1,\,1,\,1)$

$$e_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\-1\end{pmatrix}, \qquad e_3 = \frac{1}{\sqrt{6}}\begin{pmatrix}-2\\1\\1\end{pmatrix}$$

General Basis:

$$n_i = \mathcal{U} e_i, \qquad \mathcal{U} = \begin{pmatrix}\cos\theta & e^{i\xi}\sin\theta\\ -e^{-i\xi}\sin\theta & \cos\theta\end{pmatrix}$$

Alignment and Magnitude Preserving Soft-Breaking Parameters

$$\mu_1 = (1-\zeta^2)m^2, \quad \Sigma = \mu_2 + \mu_3, \quad \delta = \mu_2 - \mu_3, \quad \theta, \quad \xi$$

Basis vectors for other points

	A	A'	B	C
e_1	$\frac{1}{\sqrt{3}}\begin{pmatrix}\omega\\1\\1\end{pmatrix}$	$\frac{1}{\sqrt{3}}\begin{pmatrix}\omega^2\\1\\1\end{pmatrix}$	$\begin{pmatrix}1\\0\\0\end{pmatrix}$	$\frac{1}{\sqrt{3}}\begin{pmatrix}1\\1\\1\end{pmatrix}$
e_2	$\frac{1}{\sqrt{3}}\begin{pmatrix}0\\1\\-1\end{pmatrix}$	$\frac{1}{\sqrt{3}}\begin{pmatrix}0\\1\\-1\end{pmatrix}$	$\frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\i\end{pmatrix}$	$\frac{1}{\sqrt{3}}\begin{pmatrix}0\\1\\-1\end{pmatrix}$
e_3	$\frac{1}{\sqrt{6}}\begin{pmatrix}-2\omega\\1\\1\end{pmatrix}$	$\frac{1}{\sqrt{6}}\begin{pmatrix}-2\omega^2\\1\\1\end{pmatrix}$	$\frac{1}{\sqrt{2}}\begin{pmatrix}0\\i\\1\end{pmatrix}$	$\frac{1}{\sqrt{6}}\begin{pmatrix}-2\\1\\1\end{pmatrix}$

Physical Scalars in the Softly-Broken Case

Features of the Physical Scalars in this Scenario

- Retains the Scalar Alignment $\rightarrow$ SM-like Higgs
- $\mu_1 = 0$ Preserves the Magnitude of $v \rightarrow m^2_{h_{SM}}$ Unchanged
- Masses are functions of *only* $\Sigma, \delta, x = \sqrt{1 - (\sin 2\theta \sin \xi)^2}$

$$\Delta m^2_{H_1^\pm} = \mu_2 = \frac{\Sigma + \delta}{2}, \qquad \Delta m^2_{H_2^\pm} = \mu_3 = \frac{\Sigma - \delta}{2}$$

$$m^2_{h_1} = \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma - \sqrt{(\lambda_3 v^2)^2 + \delta^2 + 2x|\lambda_3||\delta|v^2}\right),$$

$$m^2_{h_2} = \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma - \sqrt{(\lambda_3 v^2)^2 + \delta^2 - 2x|\lambda_3||\delta|v^2}\right),$$

$$m^2_{H_1} = \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma + \sqrt{(\lambda_3 v^2)^2 + \delta^2 - 2x|\lambda_3||\delta|v^2}\right),$$

$$m^2_{H_2} = \frac{1}{2}\left(2|\lambda_3|v^2 + \Sigma + \sqrt{(\lambda_3 v^2)^2 + \delta^2 + 2x|\lambda_3||\delta|v^2}\right).$$

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  $\rightarrow x^{\perp}$ Should Adjust *Additional* Features

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- (Constrained) Degeneracy Lifting of the Nonstandard Scalars

$$m^2_{h_2} - m^2_{h_1} = m^2_{H_2} - m^2_{H_1}$$

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Universal Formulas (valid for points A+A' as well as B+C)

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- Decoupling Limit (Large μ_2, μ_3) and 2HDM limit (Large μ_3):

$$m^2_{h_1,h_2} \approx \mu_2 + |\lambda_3| v^2 \mp \frac{x}{2} |\lambda_3| v^2, \qquad m^2_{H_1,H_2} \approx \mu_3 + |\lambda_3| v^2 \mp \frac{x}{2} |\lambda_3| v^2$$

Physical Scalars in the Softly-Broken Case

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Universal Formulas (valid for points A+A' as well as B+C)

- Decoupling Limit (Large μ_2, μ_3) and 2HDM limit (Large μ_3)
- Constrained Splittings

$$m^2_{H_1^\pm} - m^2_{h_1} = \frac{1}{2} v^2 \left(\lambda_2 + \lambda_3 f(x)\right), \quad m^2_{h_2} - m^2_{h_1} = x|\lambda_3|v^2$$

where $f(x) = x + 1$ for $\lambda_3 > 0$ and $f(x) = 2 - x$ for $\lambda_3 < 0$.
Identical Expressions for $H_2^\pm$, H_1, H_2.

Physical Scalars in the Softly-Broken Case

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- Retains the Scalar Alignment → SM-like Higgs
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Universal Formulas (valid for points A+A' as well as B+C)

- Decoupling Limit (Large μ_2, μ_3) and 2HDM limit (Large μ_3)
- Constrained Splittings
- 2 Mass Scales: $\left(H_1^\pm,\, h_1,\, h_2\right) \sim \mu_2$ and $\left(H_2^\pm,\, H_1,\, H_2\right) \sim \mu_3$

Global vs Local Minima

Assumption: Symmetric vev Remains Global

Symmetric Case: Points A+A' and B+C Linked, Degenerate, Global

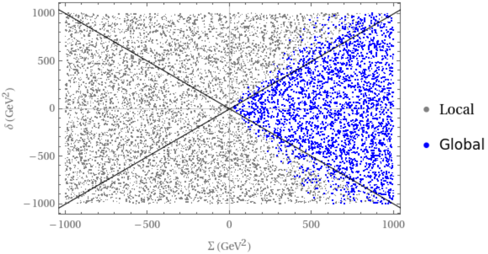
SBPs Destroy Symmetry: Minima No Longer Equivalent

$\downarrow$

Preserved Minimum Not Necessarily Global

Global vs Local Minima

Numerical Study



$\mu_2, \mu_3 > 0$ Sufficient For Global Condition

Summary

- Large Groups Are Very Restrictive $\rightarrow$ Introduce Soft-Breaking
- Rigid (Symmetric) Minima Structure $\rightarrow$ Preserve vev Alignment
- No Residual Symmetry, But Inherited Properties
- Degeneracy Liftings: Universal Formulas + Constrained Splittings
- First Step. More To Come

Thank You

Back Up

Example: $C = (1,\ 1,\ 1)$

Example Soft-Breaking Matrix for Point C

$$
\begin{aligned}
M_{11} &= m_{11}^2 = \frac{1}{3}\left(\Sigma - \delta\cos 2\theta\right) \\
M_{22} &= m_{22}^2 = \frac{1}{3}\left[\Sigma + \delta\left(\frac{\sqrt{3}}{2}\sin 2\theta\cos\xi + \frac{1}{2}\cos 2\theta\right)\right] \\
M_{33} &= m_{33}^2 = \frac{1}{3}\left[\Sigma + \delta\left(-\frac{\sqrt{3}}{2}\sin 2\theta\cos\xi + \frac{1}{2}\cos 2\theta\right)\right] \\
M_{12} &= m_{12}^2 = \frac{1}{6}\left[-\Sigma + \delta(-\sqrt{3}\sin 2\theta e^{i\xi} + \cos 2\theta)\right] \\
M_{31} &= m_{31}^2 = \frac{1}{6}\left[-\Sigma + \delta(\sqrt{3}\sin 2\theta e^{-i\xi} + \cos 2\theta)\right] \\
M_{23} &= m_{23}^2 = \frac{1}{6}\left[-\Sigma - \delta(i\sqrt{3}\sin 2\theta\sin\xi + 2\cos 2\theta)\right]
\end{aligned}
$$

Decays Of The Nonstandard Higgs

Symmetric Situation

No vev Breaks G Completely

$\downarrow$

Lightest Nonstandard Higgs Stable Against Decay

Softly Broken Situation

No Residual Symmetries

No Tree-Level Decay Mediating Couplings

Decays Of The Nonstandard Higgs

Softly Broken Situation

No Residual Symmetries

No Tree-Level Decay Mediating Couplings

Loop-Processes Open