Physics beyond one Higgs boson

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Why study Higgs model extensions?

- T. D. Lee introduced extension of Higgs sector getting new source for CP violation.
- Supersymmetry requires at least two Higgs doublets.
- Dark matter models realized by Higgs extensions.
- Neutrino mixing models realized by Higgs extensions.
- Pragmatically, no reason for having only one doublet.

Higgs multiplets

isospin T	0	$1/2$	1	$3/2$	$\frac{m-1}{2}$
T_3	0	$-1/2, +1/2$	$-1, 0, +1$	$-3/2, \ldots, 3/2$	$-\frac{m-1}{2}, \ldots, +\frac{m-1}{2}$
multiplicity	1	2	3	4	m
multiplet	φ^1	$\begin{pmatrix} \varphi^1 \\ \varphi^2 \end{pmatrix}$	$\begin{pmatrix} \varphi^1 \\ \varphi^2 \\ \varphi^3 \end{pmatrix}$	$\begin{pmatrix} \varphi^1 \\ \vdots \\ \varphi^4 \end{pmatrix}$	$\begin{pmatrix} \varphi^1 \\ \vdots \\ \varphi^m \end{pmatrix}$

Restrictions from electroweak sector

- From the kinetic terms of electroweak gauge bosons, tree level,

$$\rho \equiv \frac{m_W^2}{\cos^2(\theta_W) m_Z^2} = \frac{\sum_i \left(T_i(T_i+1) - T_{3i}^2 \right) |v_i|^2}{2 \sum_i T_{3i}^2 |v_i|^2} \approx 1 \; .$$

T_i, T_{3i} :	isospin, z component of multiplet i
v_i :	VEV

- Multiplets corresponding to $\rho = 1$:

singlets:	$T = T_3 = 0,$
doublets:	$T = 1/2, T_3 = \pm 1/2,$
septuplets:	$T = 3, T_3 = \pm 2,$
$\vdots$	

- Restriction can be circumvented, for instance by combination of Higgs bosons, absence of VEV's.

- Example one doublet ($T = T_3 = 1/2$) and one quadruplet ($T = T_3 = 3/2$),

$$\rho = 1 - 6 \frac{v_{3/2}^2}{v_{1/2}^2 + 9 v_{3/2}^2}$$

Georgi, Machacek, NPB262 (1985)
Kannike JHEP01 (2024)

Gauge redundancies

- In conventional method Higgs multiplets plagued with gauge redundancies.
- Guiding principle: Physics independent of gauge.
- Caveat: Gauge symmetries versus physical symmetries.

Picture: chatGPT4.o

S Elitzur *Impossibility of spontaneously breaking local symmetries* **PRD12** (1975)

Fröhlich, Morchio, Strocchi *Higgs phenomenon without symmetry breaking order parameter* **NPB190** (1981)

- Simple example: Standard Model with one Higgs-boson doublet,

$$\varphi(x) = \begin{pmatrix} \varphi^1(x) \\ \varphi^2(x) \end{pmatrix}$$

Potential

$$V_{SM} = -\mu^2 \varphi^\dagger \varphi + \lambda (\varphi^\dagger \varphi)^2$$

- Conventional approach: gauge rotation and expansion around minimum

$$\varphi(x) = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \left(v + h(x) \right) \end{pmatrix}$$

- Potential

$$V_{SM} = \frac{\lambda}{4} v^2 - \frac{\mu^2}{2} v^2 + \left(\lambda v^3 - \mu^2 v \right) h + \left(\frac{3}{2} \lambda v^2 - \frac{\mu^2}{2} \right) h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

- Gauge symmetry hidden!

- Principal ideal: Construct gauge invariant model and keep gauge symmetry manifest.
- Define a real, gauge-invariant bilinear field

$$K(x) = \varphi^\dagger \varphi$$

- Domain: $K \geqslant 0$

$$V_{SM} = -\mu^2 K + \lambda K^2$$

- Minimum: $\langle K \rangle = \frac{\mu^2}{2\lambda}$ for $\lambda \neq 0$.
- Gauge symmetry manifest!

How to get rid of gauge degrees for n doublets?

- n Higgs doublets $\varphi_1 = \begin{pmatrix} \varphi_1^+ \\ \varphi_1^0 \end{pmatrix}, \ldots, \quad \varphi_n = \begin{pmatrix} \varphi_n^+ \\ \varphi_n^0 \end{pmatrix}$
- Observation: all physical d.o.f. in one matrix

$$\underline{K} \equiv \begin{pmatrix} \varphi_1^\dagger \varphi_1 & \cdots & \varphi_n^\dagger \varphi_1 \\ \vdots & \ddots & \vdots \\ \varphi_1^\dagger \varphi_n & \cdots & \varphi_n^\dagger \varphi_n \end{pmatrix}$$

  $\underline{K}$ manifestly gauge invariant.
- Decompose in basis of (scaled) unit matrix and generalized Pauli matrices.

$$\underline{K} = \frac{1}{2} K_\mu \lambda_\mu, \qquad \mu \in \{0, \ldots, n^2 - 1\}, \qquad \lambda_0 \equiv \sqrt{2/n} \cdot \mathbb{1}_n.$$

- Coefficients $K_0, \ldots, K_{n^2-1}$ called bilinears.
- One-to-one correspondence between Higgs doublets and Hermitean matrix $\underline{K}$ with rank $\leqslant 2$.

Example: two doublets

- Matrix

$$\underline{K} = \begin{pmatrix} \varphi_1^\dagger \varphi_1 & \varphi_2^\dagger \varphi_1 \\ \varphi_1^\dagger \varphi_2 & \varphi_2^\dagger \varphi_2 \end{pmatrix}$$

- Basis: Pauli matrices and unit matrix $\sigma_0 = \mathbb{1}_2$

$$\underline{K} = \frac{1}{2} K_\alpha \sigma_\alpha, \qquad \alpha = 0, 1, \ldots, 3$$

- Gauge-invariant bilinears

$$\begin{aligned} K_0 &= \varphi_1^\dagger \varphi_1 + \varphi_2^\dagger \varphi_2, \\ K_1 &= \varphi_1^\dagger \varphi_2 + \varphi_2^\dagger \varphi_1, \\ K_2 &= i\varphi_2^\dagger \varphi_1 - i\varphi_1^\dagger \varphi_2, \\ K_3 &= \varphi_1^\dagger \varphi_1 - \varphi_2^\dagger \varphi_2. \end{aligned}$$

Symmetries

- Symmetry studies conventionally plagued by gauge symmetries.
- Symmetries of bilinears: subgroups of proper rotations R
  – keeping kinetic terms invariant.
- Context with unitary mixing of doublets with matrix U: $U^\dagger \lambda_a U = \bar{R}_{ab}(U)\lambda_b$.

I. F. Ginzburg, M. Krawczyk, PRD 72 (2005)
I. P. Ivanov and C. C. Nishi, PRD 82 (2010)
MM, O. Nachtmann, JHEP 11 151 (2011)
V. Keus, S.F. King, S. Moretti, JHEP 1401 (2014)
B. Grzadkowski, MM, J. Wudka, JHEP 1111 (2011)
P. M. Ferreira, H. E. Haber, MM, O. Nachtmann, J. P. Silva, Int.J.Mod.Phys. A26 (2011)

Standard CP transformations

- CP transformation of the doublet fields

$$\varphi_i(x) \longrightarrow \varphi_i^*(x'), \qquad i = 1, \ldots n, \quad x = (t, \boldsymbol{x})^{\mathrm{T}}, \quad x' = (t, -\boldsymbol{x})^{\mathrm{T}}$$

- In terms of bilinears

$$K_\mu(x) \longrightarrow \bar{R}_{\mu\nu}\, K_\nu(x'), \qquad \mu, \nu \in \{0, \ldots, n^2 - 1\}$$

- $\bar{R}$ is defined by the generalized Pauli matrices

$$\lambda_\mu^{\mathrm{T}} = \bar{R}_{\mu\nu} \lambda_\nu .$$

2HDM: $\bar{R} = \mathrm{diag}(1, 1, -1, 1)$

3HDM: $\bar{R} = \mathrm{diag}(1, 1, -1, 1, 1, -1, 1, -1, 1)$

4HDM: $\bar{R} = \mathrm{diag}(1, 1, -1, 1, 1, -1, 1, -1, 1, 1, -1, 1, -1, 1, -1, 1)$

MM, O. Nachtmann, PRD 100 (2019)

- CP transformation are geometric reflections!

- 2HDM:

$$K_0(x) \rightarrow K_0(x'), \quad \begin{pmatrix} K_1(x) \\ K_2(x) \\ K_3(x) \end{pmatrix} \rightarrow \begin{pmatrix} K_1(x') \\ -K_2(x') \\ K_3(x') \end{pmatrix}$$

- CP symmetry easily detectable in any NHDM.

- Note, CP transformation is in the 4HDM not a reflection!

C. Nishi **PRD 74** (2006),
MM, A. Manteuffel, O. Nachtmann, EPJC57 (2008)
P. M. Ferreira, H. E. Haber, MM, O. Nachtmann, J. P. Silva, Int.J.Mod.Phys. A26 (2011)

Generalized CP symmetry in the 2HDM

- Definition,

$$\varphi_i(x) \xrightarrow{\mathrm{CP_g}} U_{ij}\, \varphi_j^*(x'), \quad i,j = 1,2$$

G.Ecker, W.Grimus, W.Konetschny, **NPB 191** (1981)

- We expect two CP transformations give the same physical state.
- Identification of type not similar to standard CP transformation:

$$K_0 \to K_0, \quad \begin{pmatrix} K_1 \\ K_2 \\ K_3 \end{pmatrix} \to \begin{pmatrix} -K_1 \\ -K_2 \\ -K_3 \end{pmatrix}$$

Point reflection

- Transformation of original Higgs doublets

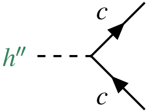
$$\begin{pmatrix} \varphi_1(x) \\ \varphi_2(x) \end{pmatrix} \to \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \varphi_1^*(x') \\ \varphi_2^*(x') \end{pmatrix}$$

O. Nachtmann, A. Manteuffel, MM **EPJC 57** (2007), O. Nachtmann, MM **JHEP 0905** (2009),
P. Ferreira, J. Silva, **PR D83** (2011)

Application: Maximally CP invariant model

- Model: 2HDM, invariant under point reflections.
- Potential automatically invariant under standard CP transformation.
- Highly restricted model.
- Every 2HDM has 5 Higgs bosons: ρ', h', h'', $H^{\pm}$.
- Additional parameters: Masses of Higgs bosons.

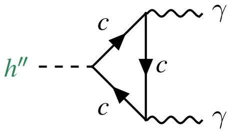
- Point reflection fix Yukawa sector.
- Not possible with one fermion family.
- Yukawa couplings: One family gives vanishing couplings.
- Absence of large FCNC fixes all couplings, two light families, one heavy family!
- Yukawa coupling of 2nd family fermions proportional to 3rd family mass!
- In particular h'' to $c\bar{c}$ coupling

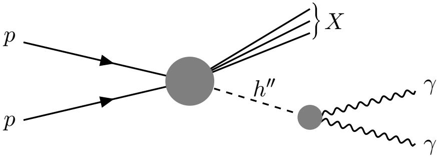


$$= \frac{m_t}{v_0}\gamma_5$$

Drell–Yan Higgs production at LHC

- Prediction in the MCPM



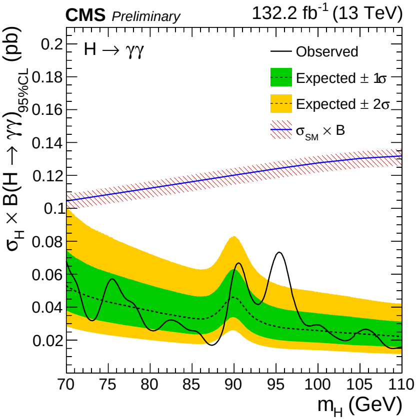


$$p + p \to h'' + X\ .$$
$$\hookrightarrow \gamma + \gamma$$

- For $m_{h''} = 95.4$ GeV, cross section about 0.01 pb.

O. Nachtmann, MM, arXiv:2309.04869

- Possible resonance measured



CMS collaboration, CMS-PAS-HIG-20-002 (2023)

Conclusion

- Main idea: Keep gauge invariance manifest, bilinears are the clue.
- Concise study of models beyond one Higgs boson:
  Stability, electroweak symmetry breaking, mass matrices,
  symmetries, radiative corrections.
- Surprising results, for instance: different type of CP symmetry.

Thank you for your attention!

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Change of basis

- Consider the following unitary mixing of the doublets

$$\begin{pmatrix} \varphi_1(x)^{\mathrm{T}} \\ \vdots \\ \varphi_n(x)^{\mathrm{T}} \end{pmatrix} \rightarrow U \begin{pmatrix} \varphi_1(x)^{\mathrm{T}} \\ \vdots \\ \varphi_n(x)^{\mathrm{T}} \end{pmatrix}$$

- Bilinears transform as

$$\psi \rightarrow U\psi, \qquad \underline{K} = \psi\psi^\dagger \rightarrow U\underline{K}U^\dagger$$

hence,

$$\begin{aligned} K_0 &= \mathrm{tr}\left(\underline{K}\lambda_0\right) \rightarrow \mathrm{tr}\left(U\underline{K}U^\dagger\lambda_0\right) = \mathrm{tr}\left(U\underline{K}\lambda_0 U^\dagger\right) = \mathrm{tr}\left(\underline{K}\lambda_0\right) = K_0, \\ K_a &= \mathrm{tr}\left(\underline{K}\lambda_a\right) \rightarrow \mathrm{tr}\left(U\underline{K}U^\dagger\lambda_a\right) = \mathrm{tr}\left(\underbrace{U^\dagger\lambda_a U}_{\equiv R_{ab}\lambda_b}\underline{K}\right) = R_{ab}K_b \end{aligned}$$

- Change of basis correspond to proper rotations $R = (R_{ab}) \in SO(n^2-1)$.

- Under a change of basis

$$K_0 \to K_0, \quad \boldsymbol{K} \to R\boldsymbol{K}$$

The potential

$$V = \xi_0 K_0 + \boldsymbol{\xi}^{\mathrm{T}}\boldsymbol{K} + \eta_{00}{K_0}^2 + 2K_0\,\boldsymbol{\eta}^{\mathrm{T}}\boldsymbol{K} + \boldsymbol{K}^{\mathrm{T}}E\boldsymbol{K}$$

changes to

$$V' = \xi_0 K_0 + \boldsymbol{\xi}^{\mathrm{T}}R\boldsymbol{K} + \eta_{00}{K_0}^2 + 2K_0\,\boldsymbol{\eta}^{\mathrm{T}}R\boldsymbol{K} + \boldsymbol{K}^{\mathrm{T}}R^{\mathrm{T}}ER\boldsymbol{K}$$

- Potential invariant, $V = V'$, iff

$$\boldsymbol{\xi} = R\,\boldsymbol{\xi}, \quad \boldsymbol{\eta} = R\,\boldsymbol{\eta}, \quad E = R\,E\,R^{\mathrm{T}}.$$