Exploring the opportunities of the 3HDMs

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15th TeV Physics WG Symposium

July 20th, 2021

中山大學 物理与天文学院
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Non-minimal Higgs sectors

Non-minimal Higgs sectors: a conservative approach to New Physics.

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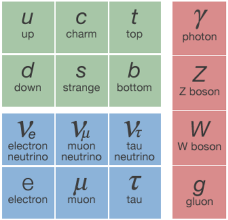

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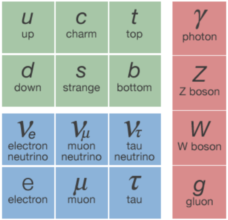
Multi-Higgs models



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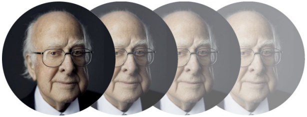

Several Higgs generations

Higgses can come in generations → N-Higgs-doublet models (NHDMs).

- T.D. Lee, 1973: 2HDM as a new source of CP-violation (CPV);
- Weinberg, 1976: 3HDM with natural flavour conservation (NFC) and CPV;
- Intense activity in 70–80's: trying to reconstruct hierarchical quark and lepton masses and mixing patterns from symmetries and their breaking;
- 1990–2000's: MSSM requires two Higgs doublets;
- Around 2000's: cosmological consequences of extra scalar fields: scalar dark matter candidates (protected by symmetries), strong first-order phase transitions leading to baryogenesis.
- In total, $\mathcal{O}(10^4)$ papers over 40 years; overview e.g. in [Ivanov, 1702.03776].

3HDM vs 2HDM

- more options for model-building (scalar and fermion) $\Rightarrow$ richer pheno;
  - many symmetry options [classic papers];
  - automatic scalar alignment from large symmetry groups;
  - new options for *CP* violation [Branco, Gerard, Grimus, 1984];
  - exotic *CP* symmetry of order 4 [Ivanov, Silva, 2015];
  - combining features of 2HDM: NFC + CPV [Weinberg, 1976; Branco, 1979], scalar DM + CPV [Grzadkowski et al, 2009].
- astroparticle consequnces:
  - more options for dark sectors [Cordero et al, 2017];
  - new options for baryon asymmetry [Davoudiasl, Lewis, Sullivan, 2019];
  - many minima $\rightarrow$ multi-step phase transitions $\rightarrow$ GW signals.

3HDMs

3HDMs bring numerous model-building opportunities which are barely explored.

But they also involve technical challenges which require new tools beyond straightfoward numerical scans.

3HDM in the vicinity of a large symmetry group

Curse of dimensionality

If you are given all numerical values of free parameters (single point in the parameter space), calculating phenomenology consequences is straightforward.

But how to explore the 54-dimensional parameter space (general 3HDM scalars sector)? Or 100+ dimensional parameter space if Yukawas are added?

No chance to cover the full 3HDM parameter space with a random scan!

If one wants to go beyond isolated examples, one must learn how to navigate in the entire parameter space. This task preceeds collider predictions!

The goal

learn where to look for benchmark models with desired phenomenological features — and then explore them in detail.

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Symmetries in 3HDM

The 3HDM potential with ϕ_a, $a = 1, 2, 3$,

$$V = Y_{ab}(\phi_a^\dagger \phi_b) + Z_{ab,cd}(\phi_a^\dagger \phi_b)(\phi_c^\dagger \phi_d)$$

can be invariant under global symmetries $\phi_a \to U_{ab}\phi_b$ forming a group G.

- General 3HDM $\to$ 54 free parameters in the scalar sector alone.
- Impose group G $\to$ reduce free parameters in scalar and Yukawa sectors.
- Pick up a minimum $\to$ deduce scalar and fermion properties, explore pheno consequences.

Symmetries in 3HDM

Which symmetry groups G are possible within 3HDM?

- abelian groups: [Ferreira, Silva, 1012.2874; Ivanov, Keus, Vdovin, 1112.1660]

$$\mathbb{Z}_2, \quad \mathbb{Z}_3, \quad \mathbb{Z}_4, \quad \mathbb{Z}_2 \times \mathbb{Z}_2, \quad U(1), \quad U(1) \times \mathbb{Z}_2, \quad U(1) \times U(1)\,.$$

- discrete non-abelian groups: [Ivanov, Vdovin, 1210.6553]:

$$S_3, \quad D_4, \quad A_4, \quad S_4, \quad \Delta(54), \quad \Sigma(36)\,.$$

- The classification is exhaustive: imposing any other discrete group in the 3HDM scalar sector will produce an accidental continuous symmetry.
- symmetry breaking patterns $G \to G_v$: [Ivanov, Nishi, 1410.6139]
- interplay between G and CP [many classical works].
- accidental symmetries of the potential: [Darvishi, Pilaftsis, 1912.00887].

The symmetry dilemma of the 3HDM

Some history:

- The original idea from 1970's: pick up a large G, extend it to the fermion sector, observe $G \to G_v$ at the minimum $\to$ derive masses/mixing/CPV.
- Many combinations of G + irreps + vevs were tested $\to$ severe problems in the quark sector; A_4, S_4 illustrations in [Gonzales Felipe et al, 2013].
- The fundamental obstacle [Leurer, Nir, Seiberg, 1993]:

  If the (active) Higgs sector is equipped with G, vevs must break G completely in order to produce physical m_q's and CKM.
- For large G, this is algebraically impossible [Gonzales Felipe et al, 2014]
- For small G, too many free parameters $\to$ poor predictive power.

3HDMs with approximate symmetries seem to be perfecty viable candidates.

But we need to learn how to work efficiently in the entire parameter space.

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An illustration: 3HDM with softly broken $\Sigma(36)$

$\Sigma(36)$ is the largest discrete group for the 3HDM scalar sector:

$$V = -m^2(\phi_a^\dagger \phi_a) + V_4\,,$$

where V_4 contains just λ_1, λ_2, λ_3 [Ivanov, Vdovin, 2013]. The model leads to

- rigid vev alignments: $(1, 0, 0)$, $(1, 1, 1)$, etc.;
- pairwise mass degenerate Higgses with the extra relation $m_H^2 = 3m_h^2$;
- exact scalar alignment;
- no *CP* violation in the scalar sector;
- scalar DM candidates.

What if we add soft breaking terms to explore the vicinity of the exact symmetry?

An illustration: 3HDM with softly broken $\Sigma(36)$

Soft breaking terms $m^2_{ab}(\phi^\dagger_a \phi_b)$ can violate all these features.

But are these 9 free parameters m^2_{ab} on equal footing?

5 free parameters preserve the vev alignment:

- can be found explicitly for any choice of the minimum;
- induce mass splitting of degenerate Higgses;
- control the choice of local vs. global minimum;
- lead to loop-induced decays of previously stable scalars;
- do not spoil the scalar alignment.

More details in [Varzielas, Ivanov, Levy, 2107.08227].

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CP4 3HDM

The freedom of defining CP

General CP transformation:

$$J: \quad \phi_i \xrightarrow{CP} X_{ij}\phi_j^*\,, \quad X \in U(N)\,,$$

[Grimus, Rebelo, 1997; Branco, Lavoura, Silva, 1999].

Applying J twice leads to family transformation $J^2 = XX^*$ which may be non-trivial. It may happen than only $J^k = \mathbb{I}$ ($k =$ power of 2).

CP-symmetry does not have to be of order 2

The usual CP = CP2, the first non-trivial is CP4, then CP8, CP16, etc.

CP4 3HDM

CP4 3HDM [Ivanov, Silva, 2015], which is physically distinct from the usual CP [Haber, Ogreid, Osland, Rebelo, 2018].

Consider 3HDM with the following potential $V = V_0 + V_1$ (notation: $i \equiv \phi_i$):

$$V_0 = -m_{11}^2(1^\dagger 1) - m_{22}^2(2^\dagger 2 + 3^\dagger 3) + \lambda_1(1^\dagger 1)^2 + \lambda_2\left[(2^\dagger 2)^2 + (3^\dagger 3)^2\right]$$
$$+\lambda_3(1^\dagger 1)(2^\dagger 2 + 3^\dagger 3) + \lambda_3'(2^\dagger 2)(3^\dagger 3) + \lambda_4\left[(1^\dagger 2)(2^\dagger 1) + (1^\dagger 3)(3^\dagger 1)\right] + \lambda_4'(2^\dagger 3)(3^\dagger 2)\,,$$

with all parameters real, and

$$V_1 = \frac{\lambda_6}{2}\left[(2^\dagger 1)^2 - (3^\dagger 1)^2\right] + \lambda_8(2^\dagger 3)^2 + \lambda_9(2^\dagger 3)\left[(2^\dagger 2) - (3^\dagger 3)\right] + h.c.$$

with real λ_6 and complex $\lambda_{8,9}$. It is invariant under CP4 $\phi_i \xrightarrow{CP} X_{ij}\phi_j^*$ with

$$X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix}\,, \quad \mathrm{CP4}^2 = \mathrm{diag}(1,\,-1,\,-1)\,, \quad \mathrm{CP4}^4 = \mathbb{I}\,.$$

Phenomenology of CP4 3HDM

If vevs conserve CP4 $\to$ scalar DM candidates stabilized by exotic CP [Koepke, 2018; Ivanov, Laletin, 2018].

flavored CP4 3HDM:

- CP4 can be extended to the Yukawa sector, four realizations found [Aranda, Ivanov, Jimenez, 2017; Ferreira et al, 2017];
- CP4 must be spontaneously broken $\to$ peculiar patterns in the flavor sector;
- Parameter space scan of [Ferreira et al, 2017] identified many points compatible with theory constraints, EWPT, fermion masses and mixing, meson oscillation parameters.
- However, the scan of [Ferreira et al, 2017] produced many points with $H_i^\pm$ lighter than top, leading to

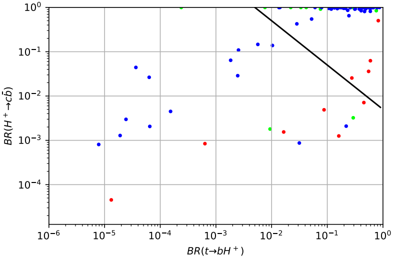
$$t \to H^+ d_i \,, \quad H^+ \to \bar{d}_i u_j \,,$$

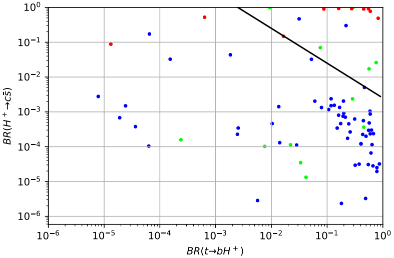
with a variety of $H^+ d_i u_j$ coupling patterns.

Phenomenology of CP4 3HDM

In [Ivanov, Obodenko, 2021] we took all these points and checked for

- the total $\Gamma_t = 1.42^{+0.19}_{-0.15}$ GeV [PDG];
- $Br(t \to H^+ b) \times Br(H^+ \to c\bar{b}) < 0.5\%$ based on [CMS, 2018];
- $Br(t \to H^+ b) \times Br(H^+ \to c\bar{s}) < 0.25\%$ based on [CMS, 2020].





Almost all points were excluded. Exotic cases survived: $H^+ \to u\bar{b}$ as the dominant decay mode or $t \to H^+ s$ as the main production mode.

Single assumption $\to$ numerous consequences $\to$ requires further study.

Conclusions

- In terms of phenomenological signals, 3HDMs can offer much more than 2HDMs. But they were mostly explored for isolated 3HDM examples.
- Navigating the huge parameter space of the general 3HDM is challenging and requires methods beyond straightforward numerical scans.
- The complete classification of 3HDM symmetries and efficient basis-invariant tools open up a way to systematic exploration of phenomenologically distinct situations of the general 3HDM, leading to collider and astroparticle predictions.
- A team in SYSU, Zhuhai, is being set up to investigate these issues in detal.

We are open to all sorts of collaboration.

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