A Two-Higgs-Doublet Model with maximal CP symmetry at LHC

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Abstract

We study CP transformations in Two-Higgs-Doublet Models (THDMs). In the formalism of bilinears generalised CP transformations have a simple geometric meaning: they correspond to improper rotations. We identify two different types, namely transformations which correspond to reflections on planes and a new type corresponding to a point reflection. We study in detail the general THDM Higgs potential, invariant under the point reflection. This model has four generalized CP symmetries. Carrying the CP transformations over to the Yukawa sector it turns out that one family can not be coupled to the Higgs sector. Thus we find a symmetry argument for family replication. With two families the Yukawa couplings are completely fixed if we require them not to vanish and not to give flavour-changing neutral currents. Treating a third family uncoupled, we present clear predictions for the production and subsequent decay of the Higgs bosons at the LHC. As salient feature we find rather large cross sections for Higgs-boson production via Drell–Yan type processes. With experiments at the LHC it should be possible to check these predictions.

CP transformations

- Standard CP transformation of the Higgs-doublet fields is defined by

$$\varphi_i(x) \to \quad \varphi_i^*(x')\,, \qquad i=1,2$$

- In terms of the bilinears, this $\mathrm{CP_s}$ transformation is simply [2]

$$K_0(x) \to K_0(x')\,,$$
$$\boldsymbol{K}(x) \to \underbrace{\mathrm{diag}(1,-1,1)}_{\bar{R}_2}\,\boldsymbol{K}(x')$$

Geometrically this is a reflection on the 1–3 plane.

Generalised CP transformations

- Generalised CP transformations (GCPs) are defined by

$$\varphi_i(x) \to U_{ij}\;\varphi_j^*(x'), \quad i,j=1,2\,.$$

- In terms of the bilinears this reads [2]

$$K_0 \to K_0,$$
$$\boldsymbol{K} \to \bar{R}\;\boldsymbol{K}$$

with an improper rotation matrix $\bar{R}$.

- Requiring $\bar{R}^2 = \mathbb{1}_3$ leads to two types of GCPs. In K space:

(i) $\bar{R} = -\mathbb{1}_3,$ point reflection

(ii) $\bar{R} = R^{\mathrm{T}}\;\bar{R}_2\;R,$ reflection on a plane

The Formalism

- Any THDM potential can be written in the simple form [1]

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

where the four bilinears $K_0, \boldsymbol{K}$ contain all gauge invariant scalar products of the two Higgs-doublet fields

$$\varphi_1 = \begin{pmatrix}\varphi_1^+\\ \varphi_1^0\end{pmatrix}, \qquad \varphi_2 = \begin{pmatrix}\varphi_2^+\\ \varphi_2^0\end{pmatrix},$$

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

References

[1] M. Maniatis, A. von Manteuffel, O. Nachtmann and F. Nagel, Eur. Phys. J. C **48**, 805 (2006) [arXiv:hep-ph/0605184].

[2] M. Maniatis, A. von Manteuffel and O. Nachtmann, Eur. Phys. J. C **57** (2008) 719 [arXiv:0707.3344 [hep-ph]].

[3] M. Maniatis, A. von Manteuffel and O. Nachtmann, Eur. Phys. J. C **57** (2008) 739 [arXiv:0711.3760 [hep-ph]].

[4] M. Maniatis and O. Nachtmann, JHEP **0905** (2009) 028 [arXiv:0901.4341 [hep-ph]].

[5] M. Maniatis and O. Nachtmann, JHEP **1004** (2010) 027 [arXiv:0912.2727 [hep-ph]].

For a complete list of references see the publications.

The model

- We study the most general model invariant under $\boldsymbol{K} \to -\boldsymbol{K}$ [3, 4, 5].
- The corresponding potential has to obey the conditions $\boldsymbol{\xi} = \boldsymbol{\eta} = 0$, i.e. $V_{\mathrm{MCPM}} = \xi_0\,K_0 + \eta_{00}\,K_0^2 + \boldsymbol{K}^{\mathrm{T}}\,E\,\boldsymbol{K}\,.$

This model is also invariant under three GCPs of type (ii).
We call this model therefore maximally CP symmetric model, MCPM.

- We find that at least two families are necessary in order to have non-vanishing Yukawa couplings. Absence of FCNC fixes then the Yukawa couplings completely.

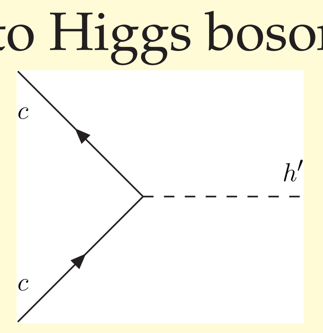
Example: lepton sector

$$\mathscr{L}_{\mathrm{Yuk}} = -\sqrt{2}\frac{m_\tau}{v}\left\{\bar{\tau}_R\,\varphi_1^\dagger\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L - \bar{\mu}_R\,\varphi_2^\dagger\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L\right\} + H.c.$$

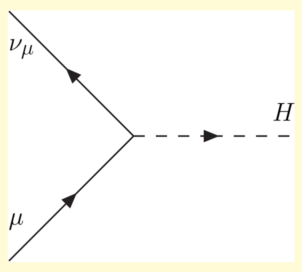
- EWSB: $\varphi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+\rho'\end{pmatrix}, \quad \varphi_2 = \begin{pmatrix}H^+\\ \frac{1}{\sqrt{2}}(h'+ih'')\end{pmatrix},$ with $v \approx 246$ GeV.

Predictions for LHC

- 5 physical Higgs particles: $\rho', h', h'', H^\pm$
- ρ' couples exclusively to (τ, t, b) family, ρ' behaves like SM Higgs.
- $h', h'', H^\pm$ couple exclusively to (μ, c, s) family with strengths given by third generation fermion masses.
- The (e, u, d) family is uncoupled to Higgs bosons.
- Examples of Yukawa couplings:



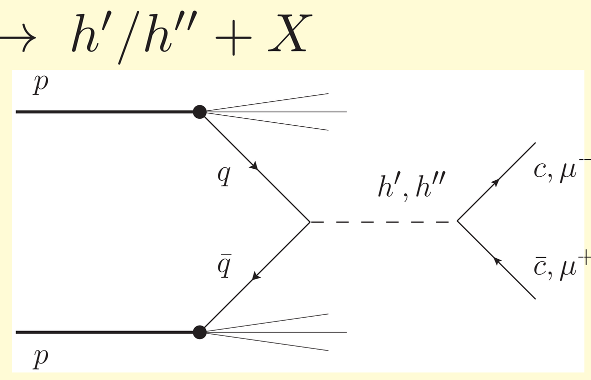
$i\frac{m_t}{v}$



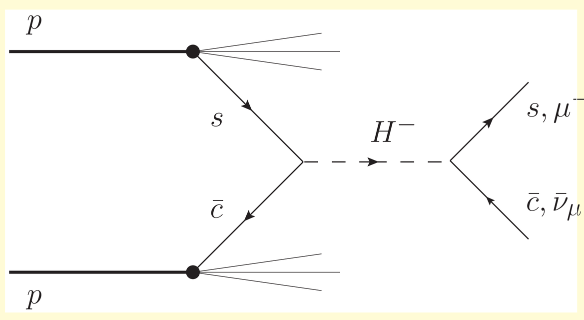
$i\frac{m_\tau}{\sqrt{2}v}(1+\gamma_5)$

- Large cross sections for Drell–Yan Higgs boson production. Main decays give c quarks.

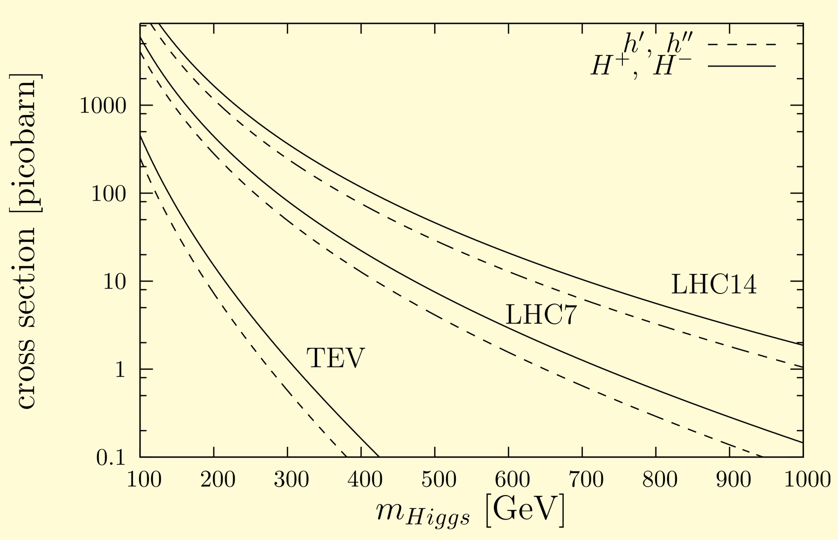
- $p + p \longrightarrow h'/h'' + X$



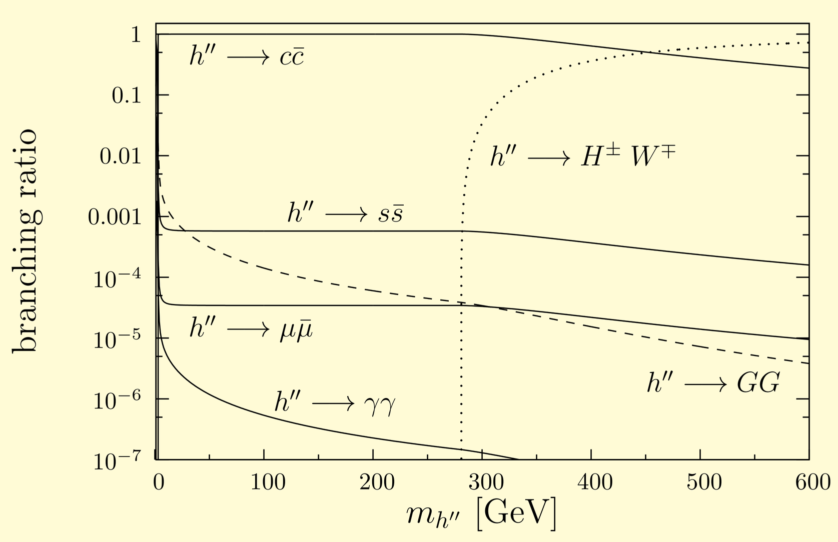
- $p + p \longrightarrow H^- + X$



- Total cross sections



- Branching ratios of the h″



- For Higgs-boson masses $h', h'', H^\pm$ of 200 GeV we get a total cross section of 850 pb for LHC7!
- With the branching ratio of $3\cdot10^{-5}$ into μ-pairs, this gives about 25 μ events from h' (h'') at LHC7 at 1 fb^{-1}.