P-even, CP-violating Signals in Scalar Mediated Processes

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LHC Higgs WG2 and WG3 – CP violation and Higgs Sector

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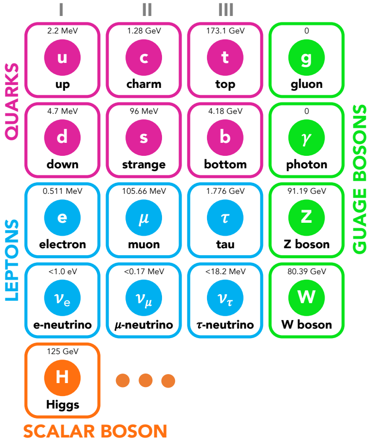
The Standard Model of Particle Physics

What is missing:

- a suitable Dark Matter candidate
- a successful baryogenesis mechanism
  - sufficient amount of CP violation
- a natural inflation framework
- an explanation for the fermion mass hierarchy
- a stable electroweak vacuum

⇒ beyond the Standard Model

⇒ **scalar extensions of the SM**



The 2-Higgs doublet model (2HDM)

The most general renormalizable 2HDM scalar potential:

$$
\begin{aligned}
\mathcal{V} \;=\;& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}] \\
&+\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&+\left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right\}
\end{aligned}
$$

With the fields and vevs:

$$
\Phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a^0 \end{pmatrix} \qquad \text{and} \qquad \langle\Phi_a\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_a \end{pmatrix}
$$

where

$$
v_1 = v\, c_\beta\,, \qquad v_2 = v\, s_\beta\, e^{i\xi}
$$

with $v = 246$ GeV.

The Higgs basis

Linear combinations of Φ_1 and Φ_2

$$\mathcal{H}_1 \equiv c_\beta \Phi_1 + s_\beta \Phi_2\,, \qquad \mathcal{H}_2 = e^{i\eta}\left[-s_\beta \Phi_1 + c_\beta \Phi_2\right]$$

such that

$$\langle \mathcal{H}_1^0 \rangle = v/\sqrt{2} \qquad \text{and} \qquad \langle \mathcal{H}_2^0 \rangle = 0$$

The scalar potential is now given by

$$\begin{aligned}
\mathcal{V} \;=\; & Y_1 \mathcal{H}_1^\dagger \mathcal{H}_1 + Y_2 \mathcal{H}_2^\dagger \mathcal{H}_2 + [Y_3 e^{-i\eta} \mathcal{H}_1^\dagger \mathcal{H}_2 + \mathrm{h.c.}] \\
& + \tfrac{1}{2} Z_1 (\mathcal{H}_1^\dagger \mathcal{H}_1)^2 + \tfrac{1}{2} Z_2 (\mathcal{H}_2^\dagger \mathcal{H}_2)^2 + Z_3 (\mathcal{H}_1^\dagger \mathcal{H}_1)(\mathcal{H}_2^\dagger \mathcal{H}_2) + Z_4 (\mathcal{H}_1^\dagger \mathcal{H}_2)(\mathcal{H}_2^\dagger \mathcal{H}_1) \\
& + \left\{ \tfrac{1}{2} Z_5 e^{-2i\eta} (\mathcal{H}_1^\dagger \mathcal{H}_2)^2 + \left[Z_6 e^{-i\eta} (\mathcal{H}_1^\dagger \mathcal{H}_1) + Z_7 e^{-i\eta} (\mathcal{H}_2^\dagger \mathcal{H}_2) \right] \mathcal{H}_1^\dagger \mathcal{H}_2 + \mathrm{h.c.} \right\}
\end{aligned}$$

The physical mass eigenstates

The charged scalar mass eigenstates: $G^{\pm} = \mathcal{H}_1^{\pm}\,, \quad H^{\pm} \equiv \mathcal{H}_2^{\pm}$

The neutral scalar mass eigenstates: $G^0 = \sqrt{2}\ \mathrm{Im}\ \mathcal{H}_1^0$

and three states $h_1,\ h_2,\ h_3$ with the neutral squared-mass matrix

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & \mathrm{Re}(\bar{Z}_6) & -\mathrm{Im}(\bar{Z}_6) \\ \mathrm{Re}(\bar{Z}_6) & \frac{1}{2}\left[Z_{34} + \mathrm{Re}(\bar{Z}_5)\right] + Y_2/v^2 & -\frac{1}{2}\mathrm{Im}(\bar{Z}_5) \\ -\mathrm{Im}(\bar{Z}_6) & -\frac{1}{2}\mathrm{Im}(\bar{Z}_5) & \frac{1}{2}\left[Z_{34} - \mathrm{Re}(\bar{Z}_5)\right] + Y_2/v^2 \end{pmatrix}$$

in the basis $\{\sqrt{2}\,\mathrm{Re}\,\mathcal{H}_1^0 - v,\ \sqrt{2}\,\mathrm{Re}\,\mathcal{H}_2^0,\ \sqrt{2}\,\mathrm{Im}\,\mathcal{H}_2^0\}$ diagonalized by

$$R\mathcal{M}^2R^{\mathsf{T}} = \mathrm{diag}\,(m_1^2\,,\ m_2^2\,,\ m_3^2)$$

where $R \equiv R_{12}R_{13}R_{23}$ is the product of three rotation matrices parametrized by θ_{12}, θ_{13} and θ_{23}, respectively, and

$$Z_{34} \equiv Z_3 + Z_4, \qquad \bar{Z}_5 \equiv Z_5 e^{-2i\eta}, \qquad \bar{Z}_6 \equiv Z_6 e^{-i\eta}, \qquad \bar{Z}_7 \equiv Z_7 e^{-i\eta}$$

The Higgs alignment limit

Providing $Z_6 = 0$, the mass-squared matrix becomes diagonal

$$\mathcal{M}_0^2 = \begin{pmatrix} Z_1 v^2 & 0 & 0 \\ 0 & Y_2 + \frac{1}{2}v^2\left[Z_{34} + \mathrm{Re}\,\bar{Z}_5\right] & -\frac{1}{2}v^2\,\mathrm{Im}\,\bar{Z}_5 \\ 0 & -\frac{1}{2}v^2\,\mathrm{Im}\,\bar{Z}_5 & Y_2 + \frac{1}{2}v^2\left[Z_{34} - \mathrm{Re}\,\bar{Z}_5\right] \end{pmatrix}$$

With the rephasing freedom we can assume Z_5 is real without loss of generality. Thus, the only complex parameter in the scalar potential is Z_7.

$$m_h^2 = Z_1 v^2\,, \qquad m_{H,A}^2 = Y_2 + \tfrac{1}{2}(Z_3 + Z_4 \pm Z_5)$$

The neutral scalar mass eigenstates are states of definite CP with h_1 identified as the SM Higgs boson.

When $\mathrm{Re}(\bar{Z}_7)\,\mathrm{Im}(\bar{Z}_7) \neq 0$ the only potential source of CP violation resides in the scalar self-interactions.

The condition $\mathrm{Re}(\bar{Z}_7)\,\mathrm{Im}(\bar{Z}_7) \neq 0$

neutral scalar	$\mathrm{Re}(\bar{Z}_7) \neq 0$ and $\mathrm{Im}(\bar{Z}_7) = 0$	$\mathrm{Re}(\bar{Z}_7) = 0$ and $\mathrm{Im}(\bar{Z}_7) \neq 0$
h_1	CP-even	CP-even
h_2	CP-even	CP-odd
h_3	CP-odd	CP-even
G	CP-odd	CP-odd

The interactions of h_1 remain CP-conserving while cubic and quartic scalar interactions involving h_2 and h_3 violate CP:

$$h_3 h_3 h_3 \quad h_3 h_2 h_2 \quad h_3 H^+ H^-, \quad h_3 h_3 h_3 h_1, \quad h_3 h_1 h_2 h_2, \quad h_3 h_1 H^+ H^-$$

since each interaction vertex involves an odd number of would-be CP-odd scalar fields.

P-conserving, CP-violating processes in the 2HDM

We impose these requirements:

- all processes survive the Higgs alignment limit
- no quartic scalar couplings are involved (due to coupling and phase space suppressions)
- the dominant contribution to the CP-violating signal is P-even (C-even, CP-violating contributions due to scalar-fermion couplings are absent or suppressed)

Simultaneous observation of processes involving:

1. $h_2 H^+ H^-$, $h_3 H^+ H^-$, $Z h_2 h_3$,
2. $h_2 h_k h_k$, $h_3 H^+ H^-$, $Z h_2 h_3$, (for $k = 2$ or 3),
3. $h_3 h_k h_k$, , $h_2 H^+ H^-$, $Z h_2 h_3$, (for $k = 2$ or 3),
4. $h_2 h_k h_k$, $h_3 h_\ell h_\ell$, $Z h_2 h_3$, (for $k, \ell = 2$ or 3).

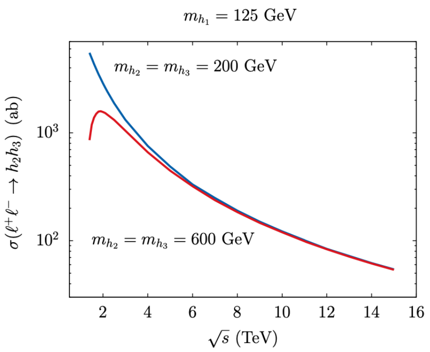
would signal CP violation.

Practical considerations and discovery potential

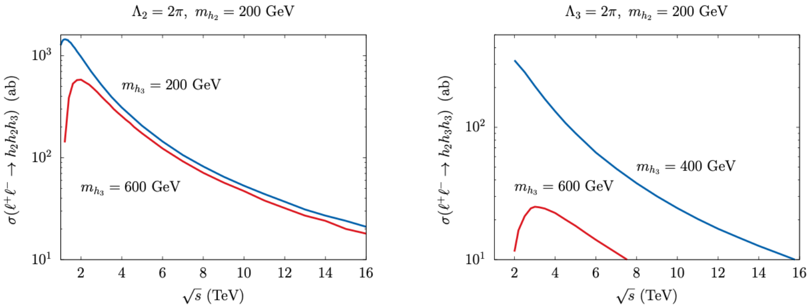
- Some scenarios involve only the discovery of just two neutral states while some also require the observation of a charged Higgs boson
- We omit cases that involve the cubic self interaction of a given scalar
- We focus on processes where h_2, h_3 can be observed via an s-channel Z exchange
- We also study processes in which h_2, h_3 and $H^{\pm}$ can be observed
- Once h_2 and h_3 are established, one can search for $h_2 h_2 h_3$ and $h_2 h_3 h_3$ production (which are also mediated via an s-channel Z exchange)
- Simultaneous observation of both production channels would signal the presence of P-even CP violation

Discovery potential at future colliders

Accelerator	$\sqrt{s}$ (TeV)	Integrated luminosity (ab^{-1})
CLIC	1.5	2.5
CLIC	3	5
Muon Collider	3	1
Muon Collider	7	10
Muon Collider	14	20



Discovery potential at future colliders



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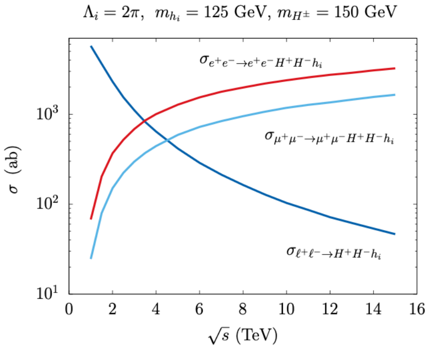

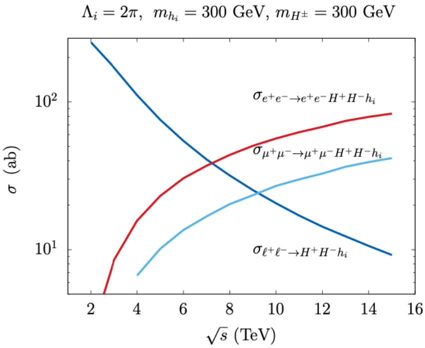

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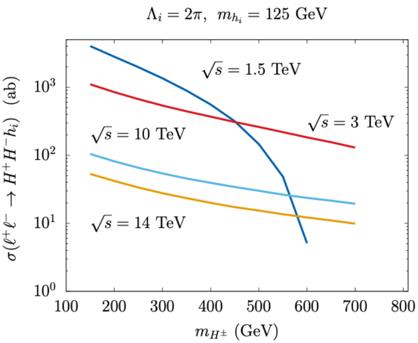
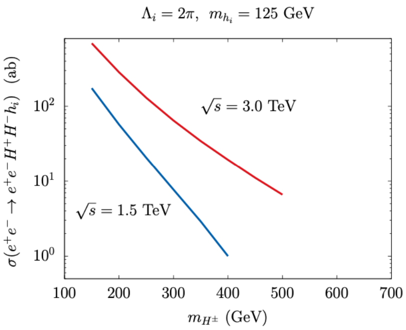
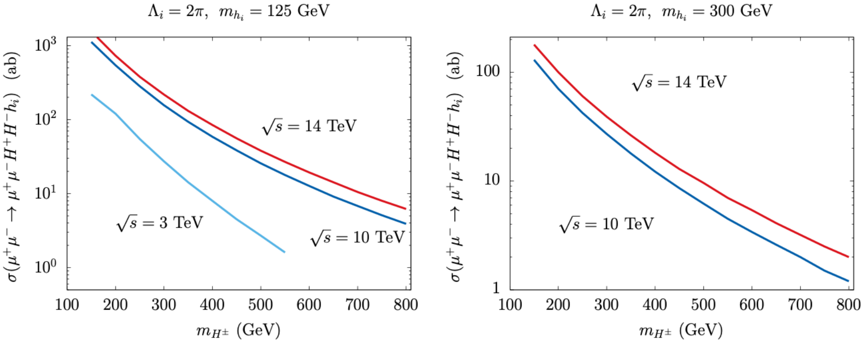


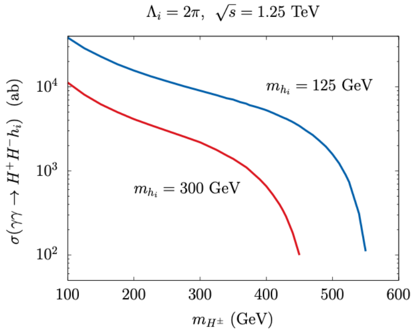
Discovery potential at future colliders

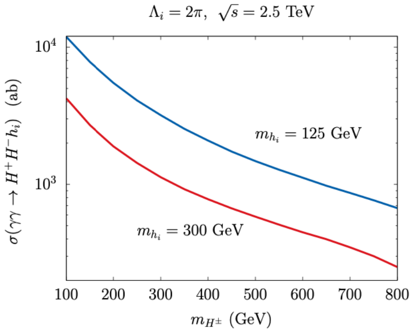


Discovery potential at future colliders



Discovery potential at future colliders





Summary

- Most studies of Higgs sector CP violation focus on the detection of CP-violating neutral Higgs-fermion Yukawa couplings, which yield P-odd, CP-violating phenomena.
- There is some literature on purely bosonic signatures of Higgs sector CP violation, where the simultaneous observation of three processes (suitably chosen) constitutes a signal of P-even CP violation.
- However, in the examples previously analyzed, some of the processes are strongly suppressed in the approximate Higgs alignment limit (corresponding to the existence of a Standard Model like Higgs boson as suggested by LHC data), in which case the proposed CP-violating signals are difficult to observe in practice.
- We examine processes that do not vanish in the Higgs alignment limit and whose simultaneous observation would provide unambiguous evidence for scalar mediated P-even CP violation.
- We assess the discovery potential of such signals at various future multi-TeV lepton (and $\gamma\gamma$) colliders.
- For loop-induced P-even, CP-violating phenomena, I refer you to our paper ;)