# $H^{\pm}W^{\mp}Z$ vertices as a probe of symmetry structures of the Higgs sector and their test at future colliders


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## Introduction

Problem: baryon asymmetry of the universe

- Baryogenesis – requires new source of CP violation – can come from extended Higgs model

Problem: true Higgs potential is unknown

- Knowledge of underlying symmetry → Understanding of true Higgs sector
- Custodial symmetry
  - Global symmetry remaining in SM Higgs potential after EW symmetry breaking
  - Responsible for ρ = 1. Experimentally, ρ ≈1
- CP symmetry and custodial symmetry can be related. Example of two Higgs doublet model (2HDM). [A. Pomarol and R. Vega (1993); H. E. Haber and D. O'Neil (2010)]

$H^{\pm}W^{\mp}Z$ vertices connection to custodial symmetry and CPV in the 2HDM [S. Kanemura and Y. Mura (2024)]

Can we detect/constrain CPV in extended Higgs models using this vertex?

## CP violation and custodial symmetry in the general 2HDM

Most general Higgs potential that can be constructed from two doublets:

$$
\begin{aligned}
V = &- Y_1^2\Phi_1^\dagger\Phi_1 - Y_2^2\Phi_2^\dagger\Phi_2 - \left(Y_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{1}{2}Z_1\left(\Phi_1^\dagger\Phi_1\right)^2 \\
&+ \frac{1}{2}Z_2\left(\Phi_2^\dagger\Phi_2\right)^2 + Z_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + Z_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\
&+ \left\{\left(\frac{1}{2}Z_5\Phi_1^\dagger\Phi_2 + Z_6\Phi_1^\dagger\Phi_1 + Z_7\Phi_2^\dagger\Phi_2\right)\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\},
\end{aligned}
$$

Generally, potential violates CP symmetry and custodial symmetry.

Conditions for symmetry (real $Z_5$ basis):

- CP symmetry $\quad Z_5\,\mathrm{Im}\,(Z_6^2) = Z_5\,\mathrm{Im}\,(Z_7^2) = \mathrm{Im}\,(Z_6^* Z_7) = 0$
- Custodial symmetry $\quad Z_4 = Z_5, \quad \mathrm{Im}\,Z_6 = \mathrm{Im}\,Z_7 = 0, \quad$ (usual)
  $\quad Z_4 = -Z_5, \quad \mathrm{Re}\,Z_6 = \mathrm{Re}\,Z_7 = 0, \quad$ (twisted)

Presence of CPV in potential → loss of custodial symmetry

## Significance of $H^{\pm}W^{\mp}Z$ vertices

Important vertices connected to custodial symmetry and CP violation

- General relation to ρ parameter [J.A. Grifols and A. Mendez (1980)]

$$\mathcal{L} = -gM_Z\xi(Z^\mu W_\mu^+ H^- + \text{h.c.}) \quad \xi^2 = \frac{g^2}{4M_W^2}\left\{\sum_k Y_k^2\left[4T_k(T_k+1) - Y_k^2\right]|v_k|^2\right\} - \frac{1}{\rho^2}$$

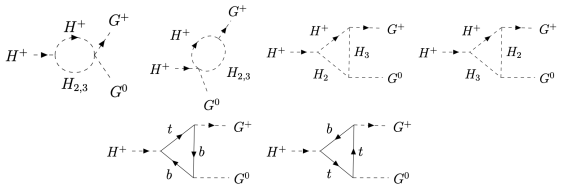
- In NHDM, ξ = 0 and ρ = 1 at tree level, but loop induced $H^{\pm}W^{\mp}Z$ vertices due to cust. sym viol.
- In Georgi-Machacek model, ξ ≠ 0 and ρ = 1 [H. Georgi and M. Machacek (1985)]
- Constrained by LHC search [ATLAS (2023); CMS (2021)]

## $H^{\pm}W^{\mp}Z$ vertices with CP violating phases

In 2HDM, custodial sym. viol. → loop induced $H^{\pm}W^{\mp}Z$ vertices.

Contribution from CP violating parameters.

Equivalence theorem → high energy contribution to $H^{\pm}W^{\mp}Z$ vertices




Asymmetry in decay – observable for CPV.

- Imaginary part of fermion loops → strong phase

$$\mathcal{M}(H^+ \to W^+Z) = \zeta + \eta e^{i\delta}$$
$$\mathcal{M}(H^- \to W^-Z) = \zeta^* + \eta^* e^{i\delta}$$
$$\Delta \equiv \Gamma(H^+ \to W^+Z) - \Gamma(H^- \to W^-Z) = 4\,\mathrm{Im}\,(\zeta\eta^*)\sin\delta$$

Feasibility of observing this asymmetry at colliders?

## Effective CP violating HWZ vertex

Formulate effective field theory with HWZ vertices as:

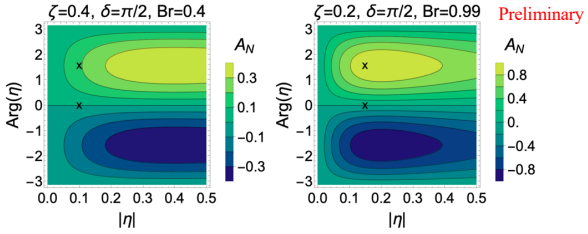
$$\mathcal{L} = -gM_Z\xi g^{\mu\nu}H^+W_\mu^- Z_\nu - gM_Z\xi' g^{\mu\nu}H^-W_\mu^+ Z_\nu \qquad \begin{aligned}\xi &= \zeta + \eta e^{i\delta} \\ \xi' &= \zeta^* + \eta^* e^{i\delta}\end{aligned}$$

ζ : tree level or loop induced, η : loop induced, δ : strong phase

Consider vector boson fusion (VBF) process, decay to $W^{\pm}Z$

Asymmetry in the expected number of events:

$$A_N = \frac{N_{WZ}^+ - \epsilon_p^{-1}N_{WZ}^-}{N_{WZ}^+ + \epsilon_p^{-1}N_{WZ}^-} = -\overline{\mathrm{Br}}_{WZ}\frac{2|\zeta||\eta|\sin(\theta_\zeta - \theta_\eta)\sin\delta}{|\zeta|^2 + |\eta|^2 + 2|\zeta||\eta|\cos(\theta_\zeta - \theta_\eta)\cos\delta}$$




## High energy hadron collider simulation of effective vertex

Consider a future high energy extension to the LHC, $\sqrt{s}$ = 27 TeV.

Simulation using MG5aMC@NLO at leading order, NN23LO1 parton distribution function.

Parton level analysis - hadronization and detector simulation left for future

Two benchmark parameter points are:

**BP1:**

CPC: $m_{H^\pm} = 300$ GeV, $\zeta = 0.4$, $|\eta| = 0.1$, $\theta_\eta = 0$, $\delta = \pi/2$, $\overline{\mathrm{BR}} = 0.4$

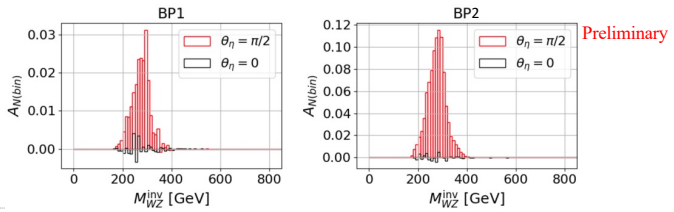
CPV: $m_{H^\pm} = 300$ GeV, $\zeta = 0.4$, $|\eta| = 0.1$, $\theta_\eta = \frac{\pi}{2}$, $\delta = \frac{\pi}{2}$, $\overline{\mathrm{BR}} = 0.4$

**BP2:**

CPC: $m_{H^\pm} = 300$ GeV, $\zeta = 0.2$, $|\eta| = 0.15$, $\theta_\eta = 0$, $\delta = \pi/2$, $\overline{\mathrm{BR}} = 0.99$

CPV: $m_{H^\pm} = 300$ GeV, $\zeta = 0.2$, $|\eta| = 0.15$, $\theta_\eta = \frac{\pi}{2}$, $\delta = \frac{\pi}{2}$, $\overline{\mathrm{BR}} = 0.99$

For VBF production, WZ decay process, asymmetry in the number of events in a bin, for reconstructed WZ mass



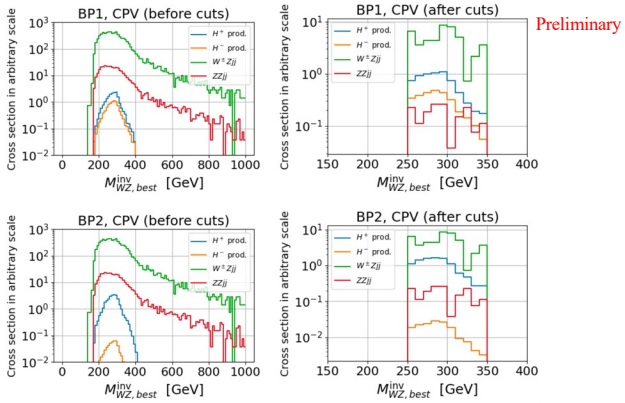

Signal competes with backgrounds $W^{\pm}Zjj$ and $ZZjj$ - cuts applied to improve significance ($A_1$-$A_3$)

Effect of cuts shown on event distribution (reconstructed $W^{\pm}Z$ mass) for the CPV signal and background

$A_1$: $\eta_{j_1}\eta_{j_2} < 0$, $M_{j_1j_2} > 500$ GeV

$A_2$: $|\Delta\eta_{j_1j_2}| > 5.5$

$A_3$: $|M_{inv}^{WZ} - m_{h^\pm}| < 50$ GeV




Consider two signals of new physics.

- Existence of the HWZ vertex: $N_S = N^+ + N^-$
- Existence of CP violation: $N_S^{CPV} = N^+ - N^-/\epsilon_p$

Event number for signal and background and significance, with $\mathcal{L} = 15\ \mathrm{ab}^{-1}$

Preliminary

| Cut applied | BG events at $\mathcal{L} = 15$ ab$^{-1}$ $W^{\pm}Zjj$ | $ZZjj$ | BP1 (CPC) $N_S$ | Z | BP2 (CPC) $N_S$ | Z |
|---|---|---|---|---|---|---|
| Before cuts | $1.08 \cdot 10^7$ | $5.67 \cdot 10^5$ | 51,135 | 15.1 | 46,620 | 13.8 |
| A1 | $1.15 \cdot 10^6$ | 40,541 | 38,646 | 35.3 | 35,207 | 32.1 |
| A2 | $1.49 \cdot 10^5$ | 6,407 | 23,050 | 57.2 | 20,959 | 52.1 |
| A3 | 70,493 | 2,495 | 17,019 | 60.8 | 15,393 | 55.1 |

| | BP1 (CPV) | | | | BP2 (CPV) | | | |
|---|---|---|---|---|---|---|---|---|
| Cut applied | CPC signal $N_S$ | Z | CPV signal $N_S^{CPV}$ | Z | CPC signal $N_S$ | Z | CPV signal $N_S^{CPV}$ | Z |
| Before cuts | 42,795 | 12.7 | 9,105 | 2.7 | 44,310 | 13.1 | 42,436 | 12.6 |
| A1 | 32,400 | 29.6 | 7,669 | 7.0 | 34,039 | 31.1 | 32,642 | 29.8 |
| A2 | 19,300 | 48.1 | 5,032 | 12.7 | 20,867 | 51.9 | 20,046 | 49.9 |
| A3 | 14,264 | 51.2 | 3,638 | 13.4 | 15,275 | 54.7 | 14,679 | 52.7 |

$$Z = \sqrt{2[(N_S + N_B)\ln(1 + N_S/N_B) - N_S]}$$

**Observation of $H^{\pm}W^{\mp}Z$ vertices may be tested and excluded at a future collider.**

**Also possible to use these vertices to detect/constrain CPV in Higgs potential.**

Further collider analysis is needed.