

系列学术报告

Higgs Alignment and CP Violation in 2HDM

Xiao-Ping Wang $(\pm I)\Psi$ Beihang University Aug,26,2023 Based on *Phys.Rev.D* 105 (2022) 3, 035009 Collaborated with Ian Low, Nausheen R. Shah

A LONG WAY FROM SM HIGGS I

$\left\langle \mathbf{S}^{\mathcal{A}}_{\mathcal{A}}\right\rangle$ status of SM Higgs search boson pairs (*HH*) and measuring the Higgs boson self-coupling HHH is a crucial validation of the BEH mechanism. Any deviation from the Standard Model (SM) predictions would open a window to new physics. We are the Standard Model (SM) predictions would open a window to new physics. We are the standard model (SM) predictio

• SM Higgs self-interaction: \sim two amplitudes: the first (A1) represented by the diagrams (a) and (b), and the second (A2) represented by the second (A2)

full top-quark mass dependence $[13]$ (confirmed later in Ref. [14] and analytically computed with some α

EXTRA NEUTRAL HIGGS SEARCH

ATLAS, JHEP 1904 (2019) 092

EXTRA CHARGED HIGGS SEARCH

CMS, JHEP07 (2019) 142

ATLAS-CONF-2020-039 $b_{\rm T}$ is band surrounding the expected limit show the $\frac{1}{2}$

In the SM, generically, **decoupling** effect goes like:

$$
\mathcal{O}\left(\frac{v^2}{M_{\text{new}}^2}\right) \sim 5\% \times \left(\frac{1\,\text{TeV}}{\Lambda}\right)^2
$$

For O(15%) accuracy in HVV couplings, $M_{\text{new}} > \sim 600 \text{GeV}$!

Question:

If we continue to pursue the precision in the Higgs coupling measurements, is there any value in direct searches for additional, heavy Higgs bosons?

Yes! It goes by the name of "Alignment without decoupling."

-
-

TWO HIGGS DOUBLET MODEL

• To see how "alignment without decoupling" arises by CP even Higgs couplings:

$$
g_{h_iVV} = \frac{1}{2} g^2 v_i , i = 1,2
$$

• It is possible to rotate to Higgs basis

$$
\mathcal{V} = Y_1 H_1^{\dagger} H_1 + Y_2 H_2^{\dagger} H_2 + \left[Y_3 e^{-i\eta} H_1^{\dagger} H_2 + h.c. \right] \n+ \frac{Z_1}{2} (H_1^{\dagger} H_1)^2 + \frac{Z_2}{2} (H_2^{\dagger} H_2)^2 + Z_3 (H_1^{\dagger} H_1) (H_2^{\dagger} H_2) + Z_4 (H_1^{\dagger} H_2) (H_2^{\dagger} H_1) \n+ \left[\frac{Z_5}{2} e^{-2i\eta} (H_1^{\dagger} H_2)^2 + Z_6 e^{-i\eta} (H_1^{\dagger} H_1) (H_1^{\dagger} H_2) + Z_7 e^{-i\eta} (H_2^{\dagger} H_2) (H_1^{\dagger} H_2) + h.c. \right] \n+ \frac{Z_1}{2} H_1 = \begin{pmatrix} H_1^{\dagger} \\ H_1^0 \end{pmatrix} \equiv \frac{v_1 \Phi_1 + v_2 \Phi_2}{v} \qquad H_2 = \begin{pmatrix} H_2^{\dagger} \\ H_2^0 \end{pmatrix} \equiv \frac{v_1 \Phi_2 - v_2 \Phi_1}{v} \qquad \langle H_1^0 \rangle = \frac{v}{\sqrt{2}} , \qquad \langle H_2^0 \rangle = 0 .
$$

TWO HIGGS DOUBLET MODEL ² (*^v* ⁺ ⁰ ² (⁰ **G**₁ and **a** galaxy bosons. The neutral fields are neglected as a set of the neutral fields are $\frac{1}{2}$ *Z* \overline{V} \overline{V} \overline{V} \overline{C} \overline{C} ² Im (*Z*5) ¹ ² [*Z*³⁴ Re (*Z*5)] + *^Y*² \overline{OUBLE}

 $\overline{}$

Potential in Eq. (12), Mass matrix: charged field is *H*⁺. The mass-squared matrix in ⁰

Im (*Z*6) ¹

$$
\mathcal{M}^{2} = v^{2} \begin{pmatrix} Z_{1} & \text{Re}\left(Z_{6}e^{-i\eta}\right) & -\text{Im}\left(Z_{6}e^{-i\eta}\right) \\ \text{Re}\left(Z_{6}e^{-i\eta}\right) & \frac{1}{2}\left[Z_{34} + \text{Re}\left(Z_{5}e^{-2i\eta}\right)\right] + \frac{Y_{2}}{v^{2}} & -\frac{1}{2}\text{Im}\left(Z_{5}e^{-2i\eta}\right) \\ -\text{Im}\left(Z_{6}e^{-i\eta}\right) & -\frac{1}{2}\text{Im}\left(Z_{5}e^{-2i\eta}\right) & \frac{1}{2}\left[Z_{34} - \text{Re}\left(Z_{5}e^{-2i\eta}\right)\right] + \frac{Y_{2}}{v^{2}} \end{pmatrix}
$$

$$
\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = R \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ a^0 \end{pmatrix} \qquad R = \begin{pmatrix} c_{12}c_{13} & \cdots & \cdots \\ c_{13}s_{12} & \cdots & \cdots \\ s_{13} & \cdots & \cdots \end{pmatrix}
$$

 σ mass matrix can be diagonalized by a special real order or σ • Higgs -V-V couplings:

$$
g_{h_iVV} = \frac{1}{2}g^2v * R_{i1}, i = 1,2
$$

- **E** "Alignment without decoupling" occurs when Higgs basis = Mass eigen basis
- -

CP VIOLATION THDM

5Z² 67)

• Counting the number of d.o.f. in CPX 2HDM T_{S} and T_{S} and mass of exemption T_{S} and T_{S}

(Z1 − Z2) Imperial

±2iD '

$$
\mathcal{V} = Y_1 H_1^{\dagger} H_1 + Y_2 H_2^{\dagger} H_2 + \left[Y_3 e^{-i\eta} H_1^{\dagger} H_2 + h.c. \right] \n+ \frac{Z_1}{2} (H_1^{\dagger} H_1)^2 + \frac{Z_2}{2} (H_2^{\dagger} H_2)^2 + Z_3 (H_1^{\dagger} H_1) (H_2^{\dagger} H_2) + Z_4 (H_1^{\dagger} H_2) (H_2^{\dagger} H_1) \n+ \left[\frac{Z_5}{2} e^{-2i\eta} (H_1^{\dagger} H_2)^2 + Z_6 e^{-i\eta} (H_1^{\dagger} H_1) (H_1^{\dagger} H_2) + Z_7 e^{-i\eta} (H_2^{\dagger} H_2) (H_1^{\dagger} H_2) + h.c. \right]
$$

6Z7) + Im(Z[∗]

In Eq. (12) every parameter is the Higgs basis: • Minimization condition in the Higgs basis:

$$
Y_1 = -\frac{1}{2}Z_1v^2 \qquad \qquad Y_3 = -\frac{1}{2}Z_6v^2
$$

• Z_2 Symmetry: \overline{z}

 $\frac{1}{\sqrt{2}}$ Haber+collaborators: 2001.01430

$$
(Z_1 - Z_2) [Z_{34}Z_{67}^* - Z_1 Z_7^* - Z_2 Z_6^* + Z_5^* Z_{67})] - 2Z_{67}^* (|Z_6|^2 - |Z_7|^2) = 0.
$$

• Free parameters:

- $\begin{pmatrix} Y & 7 & 7 & 7 \end{pmatrix} \rightarrow \begin{pmatrix} Y & 7 & 7 & 7 \end{pmatrix}$ z_1 , z_2 , z_3 , z_4 , z_5 , z_6 z_7 , z_8 ${Y_2, Z_1, Z_2, Z_3, Z_4} \Rightarrow {Y_2, Z_1, Z_3, Z_4}$
	- the three phases are physical as one phase can be removed by choosing a particular value of $\{Z_5, Z_6, Z_7\} \Rightarrow \{Z_5, Z_6, \text{Re}[Z_7]\}$ and the \blacksquare
- **•** 9 real free parameters!

 $\ddot{}$

 \blacksquare \bullet ¹ ! ¹ and ² ! 2, which can be broken softly

In the Higgs basis, the existence of a softly broken Z² symmetry is guaranteed through the condition [36, 41],

 \mathcal{F}

 $1.1 < x < 2.2$

 \bullet , in severe conflict with data. One simple possesses

 \ldots

thogonal matrix *R* relating ~ = (⁰

²)=0 *.* (6)

FREE PARAMETERS IN CTHDM cos de la 23 and ã∑23 and observa- $\left\{ \begin{array}{ll} \mathcal{R}_{\text{max}}^{\text{max}} & \text{if } \mathbf{R}^{\text{max}} \text{ and } \mathbf{R}^{\text{max}} \text{ and$ eigenstates ~ *^h* ⁼ *^R ·* ~ [36], **c**) and $\mathbf{r} = \mathbf{r}$ ² and *a*⁰, which cor-Re[*Z*˜6] Re[*Z*˜5] + *^A*²*/v*² ¹ ² Im[*Z*˜5] ² Im[*Z*˜5] *^A*²*/v*² **DA DA AAFTEDS INI CTHINA**

2

¹ *,* (54) where *|*✏*|* ⌧ 1 and ✏ *<* 0. The mixing matrix in Eq. (75) now exhibits the following pattern,

1
• Diagonalize the mass matrix responds to the phase rotation *^H*² ! *^eⁱ*✓ = @ *s*¹² *c*¹² 0 ıgonalız $\overline{}$ *s*¹³ 0 *c*¹³ A @ 0 ¯*c*²³ *s*¯²³ 0 ¯*s*²³ *c*¯²³ eigenstates ~ *h* = (*h*3*, h*2*, h*1)*^T* , ~ \mathbb{Z} motivation \mathbb{Z} *R* $\frac{1}{2}$ *R₁ <i>R*₂33 *R*₁ *R*₂ *R*₂ • Diagonalize the mass matrix \sum_{α} \sum_{α} rotation is the measure is the shift of t \mathbb{Z} Diagonalize the mass matrix $t \mapsto$ the bosonic sector of the \mathbf{H} and *^A* ⁼ *^Y*2+*v*2(*Z*3+*Z*4Re[*Z*˜5]). Alignment is achieved 3 ponalize the mass mat

*c*¹³ 0 *s*¹³

where *Z*˜⁵ = *Z*5*e*2*i*✓²³ , *Z*˜6*/*⁷ = *Z*6*/*7*ei*✓²³ , ✓²³ = ⌘ + ¯✓²³

$$
R = R_{12}R_{13}\overline{R}_{23} = \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & -s_{13} \\ 0 & 1 & 0 \\ s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \overline{c}_{23} & -\overline{s}_{23} \\ 0 & \overline{s}_{23} & \overline{c}_{23} \end{pmatrix}
$$

10 0

¯23*H*2. Therefore

h = (*h*3*, h*2*, h*1)*^T*

 \bullet Redefine the mass matrix ${\bf Redefine the mass matrix}$ e me n ass matrix • Redefine the mass matrix e define the mass matrix tions result in tree-level flavor-changing neutral currents (FCNCs), in severe conflict with data. One simple pos-

$$
\widetilde{\mathcal{M}}^2 \equiv \overline{R}_{23} \, \mathcal{M}^2 \, \overline{R}_{23}^T \quad = v^2 \left(\begin{array}{ccc} Z_1 & \text{Re}[\tilde{Z}_6] & -\text{Im}[\tilde{Z}_6] \\ \text{Re}[\tilde{Z}_6] & \text{Re}[\tilde{Z}_5] + A^2/v^2 & -\frac{1}{2}\text{Im}[\tilde{Z}_5] \\ -\text{Im}[\tilde{Z}_6] & -\frac{1}{2}\text{Im}[\tilde{Z}_5] & A^2/v^2 \end{array} \right)
$$

second relation in the are only the independent of the independent of the independent of the independent of the
International conduction of the independent of the independent of the independent of the independent of the in complex parameters, usually taken to be *{Z*5*, Z*6*, Z*7*}*. If where *Z*˜⁵ = *Z*5*e*2*i*✓²³ *.* (4) • Alignment Limit: \sim *^M*f² can be diagonalized by just two angles. Hence **e** Alignment Limit: Eq. (6) assumes *Z*6+*Z*⁷ 6= 0 and *Z*¹ 6= *Z*2, and eliminates ment Limit: when the full same \mathbf{r}

*c*¹² *s*¹² 0

$$
\widetilde{R} = R_{12}R_{13} = \begin{pmatrix} c_{12}c_{13} & -s_{12} & -c_{12}s_{13} \\ s_{12}c_{13} & c_{12} & -s_{12}s_{13} \\ s_{13} & 0 & c_{13} \end{pmatrix}
$$
\n
$$
= \begin{pmatrix} -\epsilon c_{12} & -s_{12} & -c_{12}s_{13} \\ -\epsilon s_{12} & c_{12} & -s_{12}(1 - \epsilon^2/2) \\ 1 - \epsilon^2/2 & 0 & -\epsilon \end{pmatrix}
$$
\n
$$
= \begin{pmatrix} -\epsilon c_{12} & -s_{12} & -c_{12}(1 - \epsilon^2/2) \\ -\epsilon s_{12} & c_{12} & -s_{12}(1 - \epsilon^2/2) \\ 1 - \epsilon^2/2 & 0 & -\epsilon \end{pmatrix}
$$
\n
$$
I_m[\widetilde{Z}_6] = \frac{\epsilon}{2v^2} s_{2\theta_{12}} \begin{pmatrix} 1 \\ m_{12} & m_{12} \end{pmatrix}
$$
\n
$$
I_m[\widetilde{Z}_6] = \frac{\epsilon}{2v^2} (m_{h_2}^2 - n_{h_2}^2 - n_{h_2}^2) \begin{pmatrix} 1 \\ m_{22} & m_{22} \end{pmatrix}
$$
\n
$$
I_m[\widetilde{Z}_6] = \frac{\epsilon}{2v^2} (m_{h_2}^2 - n_{h_2}^2 - n_{h_2}^2) \begin{pmatrix} 1 \\ m_{22} & m_{22} \end{pmatrix}
$$
\n
$$
I_m[\widetilde{Z}_6] = \frac{\epsilon}{2v^2} (m_{h_2}^2 - n_{h_2}^2 - n_{h_2}^2) \begin{pmatrix} 1 \\ m_{22} & m_{22} \end{pmatrix}
$$
\n
$$
I_m[\widetilde{Z}_6] = \frac{\epsilon}{2v^2} (m_{h_2}^2 - n_{h_2}^2 - n_{h_2}^2) \begin{pmatrix} 1 \\ m_{22} & m_{22} \end{pmatrix}
$$
\n
$$
I_m[\widetilde{Z}_6] = \frac{\epsilon}{2v^2} s_{2\theta_{12}} \begin{pmatrix} 1 \\ m_{22} &
$$

 \bullet \bullet will be important when discussing C -conservation.

1:
\n
$$
Z_{1} = \frac{1}{v^{2}} [m_{h_{1}}^{2} + \epsilon^{2} (m_{h_{3}}^{2} c_{12}^{2} + m_{h_{2}}^{2} s_{12}^{2} - m_{h_{1}}^{2})]
$$
\n
$$
Re[\tilde{Z}_{5}] = \frac{1}{v^{2}} [c_{2\theta_{12}} (m_{h_{2}}^{2} - m_{h_{3}}^{2}) + \epsilon^{2} (m_{h_{3}}^{2} c_{12}^{2} + m_{h_{2}}^{2} s_{12}^{2} - m_{h_{2}}^{2})]
$$
\n
$$
Im[\tilde{Z}_{5}] = \frac{1}{v^{2}} s_{2\theta_{12}} \left(1 - \frac{\epsilon^{2}}{2}\right) (m_{h_{2}}^{2} - m_{h_{3}}^{2}),
$$
\n
$$
Re[\tilde{Z}_{6}] = \frac{\epsilon}{2v^{2}} s_{2\theta_{12}} (m_{h_{3}}^{2} - m_{h_{2}}^{2}),
$$
\n
$$
Im[\tilde{Z}_{6}] = \frac{\epsilon}{2v^{2}} s_{2\theta_{12}} (m_{h_{3}}^{2} - m_{h_{2}}^{2}),
$$
\n
$$
Im[\tilde{Z}_{6}] = \frac{\epsilon}{v^{2}} (m_{h_{2}}^{2} - m_{h_{3}}^{2} c_{12}^{2} - m_{h_{1}}^{2} s_{12}^{2}),
$$
\n**25.**

$$
\left\{\n \begin{array}{ll}\n m_{h_1}, m_{h_2}, m_{h_3}, \theta_{12}, \epsilon, Z_3, m_{H^{\pm}}, \text{Re}[\tilde{Z}_7], v\n \end{array}\n\right\}
$$

² + *ia*⁰)*/*

 $\ddot{}$

CP CONSERVATIVE LIMIT *R*e = *R*12*R*¹³ = @ *s*12*c*¹³ *c*¹² *s*12*s*¹³ **S2E LIAALT** *s*12*c*¹³ *c*¹² *s*12*s*¹³ CP C A *.* (9) CP CONSERVATIVE HALL **SP SORGERVAILLE EIN**

¹*,* ˜⁰

² *c*12*c*²³

²*,* ˜⁰

<u>If we define the definition</u>

Small departures from alignment can be parameterized

³)*^T* = (*R*²³ *·* ~)*^T* , the mass eigen-

² *^c*12*s*²³ *c*12+23 ⁺ ✏²

eigenstate in which case the observed by Higgs mixing: $\mathcal{L} = \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L$ \mathbf{B} liggs m \times *i*ng:

*h*3

If we define (⁰

¹*,* ˜⁰

²*,* ˜⁰

✏*c*¹² *s*12+23 ⁺ ✏²

• Higgs mixing:
\n
$$
\begin{pmatrix} h_3 \ h_2 \ h_1 \end{pmatrix} = \widetilde{R} \begin{pmatrix} \phi_1^0 \\ \tilde{\phi}_2^0 \\ \tilde{\phi}_3^0 \end{pmatrix} = \begin{pmatrix} -\epsilon c_{12} & -s_{12} & -c_{12}(1-\epsilon^2/2) \\ -\epsilon s_{12} & c_{12} & -s_{12}(1-\epsilon^2/2) \\ 1-\epsilon^2/2 & 0 & -\epsilon \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ c_{23} & \phi_2^0 - s_{23} & a^0 \\ s_{23} & \phi_2^0 + c_{23} & a^0 \end{pmatrix} \qquad \theta_{13} = \frac{\pi}{2} + \epsilon
$$

■ *Z***6** + *Z*₇ *Z*₇ *Z*₇ will be interesting C₂^{*m*} and \overline{X} ³ will be interesting C₂^{*m*} and \overline{X} ²)=0 *.* (6) ² and *a*⁰, and • HHH couplings: • The constraints are The constraints are The charged Higgs related **A** eigenstates follow from their CP-property and the EDM

$$
g_{h_1H^+H^-} = v \left[\left(1 - \frac{\epsilon^2}{2} \right) Z_3 + \epsilon \text{Im}[\tilde{Z}_7] \right]
$$

\n
$$
g_{h_2H^+H^-} = v \left[-\epsilon s_{12} Z_3 + c_{12} \text{Re}[\tilde{Z}_7] + s_{12} \left(1 - \frac{\epsilon^2}{2} \right) \text{Im}[\tilde{Z}_7] \right]
$$

\n
$$
g_{h_3H^+H^-} = v \left[-\epsilon c_{12} Z_3 - s_{12} \text{Re}[\tilde{Z}_7] + c_{12} \left(1 - \frac{\epsilon^2}{2} \right) \text{Im}[\tilde{Z}_7] \right]
$$

\n
$$
\cdots \cdots \qquad \text{Case I:} \qquad \theta_{13} = \frac{\pi}{2}, \theta_{23} = 0, \theta_{12} = \left\{ 0, \frac{\pi}{2} \right\}, \text{Im} [Z_7] = 0
$$

\n
$$
\cdots \cdots \qquad \text{Case 2:} \quad \theta_{23} = \pi/2 \ , \ \theta_{12} = \left\{ 0, \pi/2 \right\} \ , \ \ \text{Im}[Z_7] = 0
$$

the CP CONSERVATIVE LIMIT and type II μ and type II μ and type II μ and type II μ relations are the approximate alignment limit, and in the approximate alignment limit, and

• Relationships between Z_i and mixing angles: ⇤ *,* (12)

⁵] = ¹

$$
\text{Im}[\tilde{Z}_5] = \frac{1}{v^2} s_{2\theta_{12}} \left(1 - \frac{\epsilon^2}{2} \right) \left(m_{h_2}^2 - m_{h_3}^2 \right)
$$

\n
$$
\text{Re}[\tilde{Z}_6] = \frac{\epsilon}{2v^2} s_{2\theta_{12}} \left(m_{h_3}^2 - m_{h_2}^2 \right) ,
$$

\n
$$
\text{Im}[\tilde{Z}_6] = \frac{\epsilon}{v^2} \left(m_{h_2}^2 - m_{h_3}^2 c_{12}^2 - m_{h_1}^2 s_{12}^2 \right) ,
$$

$$
\begin{aligned}\n\text{CPC1}: \ \operatorname{Im}[\tilde{Z}_5] &= \operatorname{Im}[\tilde{Z}_6] = \operatorname{Im}[\tilde{Z}_7] = 0 \\
\therefore \ \text{CPC2}: \ \operatorname{Im}[\tilde{Z}_5] &= \operatorname{Re}[\tilde{Z}_6] = \operatorname{Re}[\tilde{Z}_7] = 0 \\
\therefore \ \end{aligned}
$$

$$
\begin{array}{c}\n\bullet & \bullet & \bullet & \bullet \\
\bullet & \bullet & \bullet & \bullet \\
\bullet & \bullet & \bullet & \bullet\n\end{array}
$$

- CP CONSERVATIVE AND ALIGNMENT LIMIT CTHDM
- We are interested in the interplay between the Higgs alignment and CPX in C2HDM. There are two important experimental observations:
	- The 125 GeV Higgs is SM-like. $(m_{h_1} = 125 \text{GeV})$
	- EDM places stringent constraints on CPX.
- These motivates considering the small departures from
	- The exact alignment limit. (Mixing among 3 Higgs)
	- The exact CP-conserving limit. $(\text{Im}[Z_7]\sim 0, \text{Re}[Z_7]\sim 0, \theta_{23} \neq 0, \frac{\pi}{2})$ 2)

CHARGED HIGGS SEARCH

CMS, JHEP 2001 (2020) 096

- We choose $\tan \beta > 1$
-
-

$\begin{minipage}{0.4\linewidth} \textbf{ELECTRON EDM CoNSTRAN} \hspace{0.2cm} \textbf{1:} \hspace{0.2cm} \textbf{2:} \hspace{0.2cm} \textbf{2:} \hspace{0.2cm} \textbf{2:} \hspace{0.2cm} \textbf{2:} \hspace{0.2cm} \textbf{3:} \hspace{0.2cm} \textbf{4:} \hspace{0.2cm} \textbf{5:} \hspace{0.2cm} \textbf{6:} \hspace{0.2cm} \textbf{5:} \hspace{0.2cm} \textbf{6:} \hspace{0.2cm} \textbf{7:} \hspace{$ $F = F - T P - N F P M - N S T P M N T P N T T$ $\frac{\log 2}{\log 1 + \log 1}$ a *O*(2) order smaller neutron edm comparing to the constraints. So we only consider the

• Fermion contributions: *dV ^f* (*f*⁰) = *em^f* **CONTEN** $Fermion$ *contributions: ^f* (*f*⁰ $(11011C)$ σ *p n f i b u* figures *n* σ *f* (*formion contribution*)
*f vf*0*f*0*Q^f*0*N^C*

$$
d_f^V(f') \propto \sum_j^3 \int_0^1 dz \left\{ \text{Im}[\kappa_f^j] \text{Re}[\kappa_{f'}^j] \left(\frac{1}{z} - 2(1-z) \right) + \text{Re}[\kappa_f^j] \text{Im}[\kappa_{f'}^j] \frac{1}{z} \right\} C_{f'f'}^{VH_j^0}(z)
$$

son-lor Higgs boson-loop contributions: • Higgs boson-loop contributions:

$$
d_f^V(H^{\pm}) = -\frac{em_f}{(16\pi^2)^2} 4g_{Vff}^v g_{H^+H^-V} \sum_j^3 \text{Im}[\kappa_f^j] \frac{g_{H^+H^-H_j^0}}{v} \int_0^1 dz \,(1-z) \, C_{H^{\pm}H^{\pm}}^{VH_0^0}(z)
$$

$$
d_f^V(H^{\pm}H^0) = -\frac{eg^2 m_f}{2\,(16\pi^2)^2} \sum_j^3 \text{Im}[\kappa_f^j] \frac{g_{H^+H^-H_j^0}}{v} \int_0^1 dz \,(1-z) \, C_{H^{\pm}H_j^0}^{WH^{\pm}}(z).
$$

f gauge-loop contributions \mathbf{r} $\mathop{{\rm \text{}}\nolimits}$ $\mathop{{\rm \text{}}\nolimits}$ $\mathop{{\rm \text{}}\nolimits}$ $\mathop{{\rm \text{}}\nolimits}$ $\mathop{{\rm \text{}}\nolimits}$ $rac{1}{2}$ \overline{v}

gauge-loop contributions
\n
$$
d_f^V(W) = \frac{em_f}{(16\pi^2)^2} 8g_{Vff}^v g_{WWV} \frac{m_W^2}{v^2} \sum_j^3 \widetilde{R}_{j1} \text{Im}[\kappa_f^j] \times \int_0^i dz \left[\left\{ \left(6 - \frac{m_V^2}{m_W^2} \right) + \left(1 - \frac{m_V^2}{2m_W^2} \right) \frac{m_{H_j^0}^2}{m_W^2} \right\} \frac{1 - z}{2} - \left(4 - \frac{m_V^2}{m_W^2} \right) \frac{1}{z} \right] C_{WW}^{VH_j^0}(z)
$$
\n**3.11**
\n**4.**
\n**5.**
\n**6.**
\n**6.**
\n**7.**
\n**8.**
\n**8.**
\n**9.**
\n**9.**
\n**10.**
\n**11.**
\n**11.**
\n**12.**
\n**13.**
\n**14.**
\n**1**
\n**1**

ELECTRON EDM CONSTRAINT

$$
\{m_{h_3}, \theta_{12} = \frac{\pi}{2}, \epsilon, Z_3, \text{Re}[\tilde{Z}_7], m_{h_2} = m_{H^{\pm}}\} + \theta_{23}
$$

COLLIDER PHENOMENOLOGY Re[*Z*˜ ⁶] = ✏ ²*v*² *^s*2✓¹² *m*² *^h*³ *^m*² $\frac{1}{\sqrt{2}}$

• Branching ratios for benchmark points: $g_{h_1h_2h_3} = \epsilon\, v\, \operatorname{Re}[\tilde{Z}_7 e^{-2i\theta_{12}}]$

 $5.8nh \qquad \sigma (aa \rightarrow h) \approx 2.7nh$ σ ₍₉₉, σ ₁₇) σ $\sigma(gg \to h_2) \simeq 5.8 \text{pb}, \qquad \sigma(gg \to h_3) \simeq 2.7 \text{pb}$

- THERE IS AN INTERESTING INTERPLAY BETWEEN ALIGNMENT LIMIT AND CP CONSERVING LIMIT IN C2HDM. IN ONE CASE, THE ALIGNMENT LIMIT IS IDENTICAL WITH THE CP-LIMIT, WHILE IN THE OTHER CASE THEY ARE INDEPENDENT.
- **•** THERE IS A SMOKING-GUN SIGNAL FOR CP VIOLATION AT THE LHC IN C2HDM, WITHOUT THERE 18 A SMORING CON SIGNAL FOR CENTROLATION THE LITE IN CZHBM, of *^L* = 3000 fb¹, we will have approximately 10⁴ CPV

$$
h_3 \to h_2 h_1 \to h_1 h_1 h_1
$$

