BSM (CP) interpretations of LHC Higgs measurements

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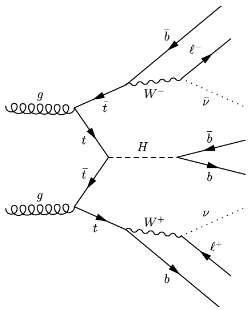
Scalar Extensions of the SM - why do they make us happy?

- They provide Dark Matter candidates compatible with all available experimental constraints;
- They provide new sources of CP-violation;
- They can change the di-Higgs cross section;
- They provide a means of having a strong first order phase transition;
- They provide a 125 GeV scalar in agreement with all data;
- You get a bunch of extra scalars, keeping everybody busy and happy.

The many faces of CP-violation

- Angular variables or CP-detecting variables;



$\gamma\gamma$

$$b_4 = \frac{p_t^z p_{\bar{t}}^z}{p_t p_{\bar{t}}}$$

Gunion, He, PRL77 (1996) 5172.

Many studies with angular variables in all kinds of final states.

- Combination of three decays;

$$h_{SM} \to ZZ \quad CP(h_{SM}) = 1$$
$$h_2 \to ZZ \quad CP(h_2) = 1$$
$$h_2 \to h_1 Z \quad CP(h_2) = -CP(h_1)$$

Fontes, Romão, RS, Silva, Phys.Rev.D 92 (2015) 5, 055014.

This scenario has the (dis)advantage that we need to find at leas one extra scalar (at tree-level). Or maybe we don't.

- Strange CP - Decays that are CP-even and CP-odd at the same time;

Fontes, Romão, RS, Silva, JHEP 06 (2015) 060.

$$h_{SM} \to \bar{t}t \qquad A_{SM} \to \tau^+\tau^-$$

In this case the particle has a different CP depending on the final state.

Our benchmark model - the C(2HDM)

Potentials are usually used in minimal versions using ad-hoc symmetries. We just want them to suit our benchmarking goals. The most general 2HDM is

$$V_{2HDM} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.)$$
$$\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$\left\{ \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right](\Phi_1^\dagger\Phi_2) + h.c. \right\}$$

With the fields defined as (VEVs may be complex)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

$v_2 = 0$, dark matter, IDM

Allows for a decoupling limit

The Z_2 symmetric version is

Complex parameters - explicit CP-violation

$$V_{2HDM} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.)$$
$$\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\left\{ \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c. \right\}$$

h_{125} couplings (gauge)

Lightest Higgs coupling modifiers

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha) g_{SM}^{hVV}$$

Although the models look very different, the couplings to gauge bosons have the same structure and are multiplied by a numerical factor (except for CP-violating Yukawa couplings).

$$g_{C2HDM}^{hVV} = \cos\alpha_2\, g_{2HDM}^{hVV}$$

CP-VIOLATING 2HDM

"PSEUDOSCALAR" COMPONENT (DOUBLET)

$|s_2| = 0 \;\Rightarrow\; h_1$ is a pure scalar,

$|s_2| = 1 \;\Rightarrow\; h_1$ is a pure pseudoscalar

Type I $\quad \kappa_U^I = \kappa_D^I = \kappa_L^I = \dfrac{\cos\alpha}{\sin\beta}$

Type II $\quad \kappa_U^{II} = \dfrac{\cos\alpha}{\sin\beta} \qquad \kappa_D^{II} = \kappa_L^{II} = -\dfrac{\sin\alpha}{\cos\beta}$

Type F(Y) $\quad \kappa_U^F = \kappa_L^F = \dfrac{\cos\alpha}{\sin\beta} \qquad \kappa_D^F = -\dfrac{\sin\alpha}{\cos\beta}$

Type LS(X) $\quad \kappa_U^{LS} = \kappa_D^{LS} = \dfrac{\cos\alpha}{\sin\beta} \qquad \kappa_L^{LS} = -\dfrac{\sin\alpha}{\cos\beta}$

These are coupling modifiers relative to the SM coupling for the CP-conserving version of the 2HDM. May increase Yukawa relative to the SM.

$$Y_{C2HDM} = \cos\alpha_2 Y_{2HDM} \pm i\gamma_5 \sin\alpha_2 \tan\beta (1/\tan\beta)$$

Higgs couplings in Scalar Extensions

Yukawa

$$Y_{NewModel} = f_Y(\alpha_i) Y_{SM} \pm i\gamma_5 \, g_Y(\alpha_i)$$

$f_Y(\alpha_i)$ and $g_Y(\alpha_i)$ are numbers - functions of mixing angles and (maybe) other parameters. $g_Y(\alpha_i) = 0$ in the CP-conserving limit.

Gauge

$$g_{NewModel} = f_g(\alpha_i) g_{SM}$$

$f_g(\alpha_i)$ is a number - function of mixing angles and (maybe) other parameters. $f_g(\alpha_i) = 0$ in the CP-conserving limit for a pseudoscalar state.

Scalar

$$\lambda_{NewModel} = f_\lambda(\alpha_i) \lambda_{SM}$$

Like for the couplings with gauge bosons it is the existence of combined terms that show that CP is broken.

CP-violation from C-violation

CP violation from C violation

Suppose we have a 2HDM extension of the SM but with no fermions. Also let us assume for the moment that the theory conserves C and P separately. The C and P quantum numbers of the Z boson are

$$C Z_\mu C^{-1} = -Z_\mu; \quad P Z_\mu P^{-1} = Z^\mu$$

Because we have vertices of the type hhh and HHH (h, H and A are C and P eigenstates),

$$P(h) = P(H) = 1; \; C(h) = C(H) = 1$$

Since the neutral Goldstone couples derivatively to the Z boson (and it mixes with the A)

$$P \partial^\mu G_0 Z_\mu P^{-1} = \partial_\mu G_0 Z^\mu \qquad C(Z_\mu \partial^\mu A h) = 1; P(Z_\mu \partial^\mu A h) = 1$$

Which means

$$P(G_0) = P(A) = 1; \; C(G_0) = C(A) = -1$$

In the absence of fermions, invariance under P is guaranteed. If the bosonic Lagrangian violates CP, CP-violation must be associated with a P-conserving C-violating observable.

How do we know if the model violates CP?

First you find the mass eigenstates to find that you have three mixing neutral states

$$h_1, h_2, h_3$$

and because they mix they have the same quantum numbers. Now you look for the interactions with gauge bosons and you find

$$h_1\, h_2\, \partial\, .\, Z; \quad h_2\, h_3\, \partial\, .\, Z; \quad h_1\, h_3\, \partial\, .\, Z$$

$\partial\, .\, Z$ is P-invariant

and to have a CP-conserving (C-conserving because we have P conservation) theory you would need

$$C[h_1\, h_2] = -1; C[h_1\, h_3] = -1; C[h_2\, h_3] = -1$$

which is impossible.

CP violation from C violation - three decays scenario

There are many other combinations if one moves away from the alignment limit

$$h_1 \to ZZ(+) \; h_2 \to ZZ(+) \; h_2 \to h_1 Z$$

Combinations of three decays

Forbidden in the exact alignment limit

$$h_1 \to ZZ \;\Leftarrow\; CP(h_1) = 1$$

$$h_3 \to h_2 h_1 \;\Rightarrow\; CP(h_3) = CP(h_2)$$

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

Fontes, Romão, RS, Silva, PRD92 (2015) 5, 055014

C2HDM Type I $H_{SM}=H_1$

Abouabid, Arhrib, Azevedo, El-Falaki, Ferreira, Mühlleitner, RS, JHEP 09 (2022) 011

Particle	H_1	H_2	H_3	H^+
Mass [GeV]	125.09	265	267	236
Width [GeV]	$4.106\ 10^{-3}$	$3.265\ 10^{-3}$	$4.880\ 10^{-3}$	0.37
σ_{prod} [pb]	49.75	0.76	0.84	

Values for a chosen benchmark point in a type I C2HDM with the lightest Higgs as the 125 GeV one.

Test of CP in decays:

- $\sigma_{prod}(H_3) \times BR(H_3\to H_1H_1) = 235$ fb CP+ AND $\sigma_{prod}(H_3) \times BR(H_3\to ZH_1) = 76$ fb CP-
- $\sigma_{prod}(H_3) \times BR(H_2\to H_1H_1) = 192$ fb CP+ AND $\sigma_{prod}(H_2) \times BR(H_2\to ZH_1) = 122$ fb CP-

CP violation from C violation

Let us now consider the CP-violating 2HDM, with scalar states h_1, h_2, h_3 . Let us make our life harder by considering we are in the alignment limit (meaning h_1 has exactly the SM couplings). In this limit the CP-violating vertices are

$$h_3h_3h_3; \quad h_3h_2h_2; \quad h_3H^+H^-; \quad h_3h_3h_3h_1; \quad h_3h_2h_2h_1; \quad h_3h_1H^+H^-;$$

A different choice of the parameters of the potential would interchange h_2 and h_3.

A combination of 3 decays signals CP-violation

$$h_2H^+H^-; \quad h_3H^+H^-; \quad Zh_2h_3$$

$$h_2h_kh_k; \quad h_3H^+H^-; \quad Zh_2h_3; \quad (k=2,3) \quad (2 \leftrightarrow 3)$$

$$h_2h_kh_k; \quad h_3h_lh_l;; \quad Zh_2h_3; \quad (k,l=2,3)$$

Haber, Keus, RS, PRD 106 (2022) 9, 095038

C2HDM at future colliders

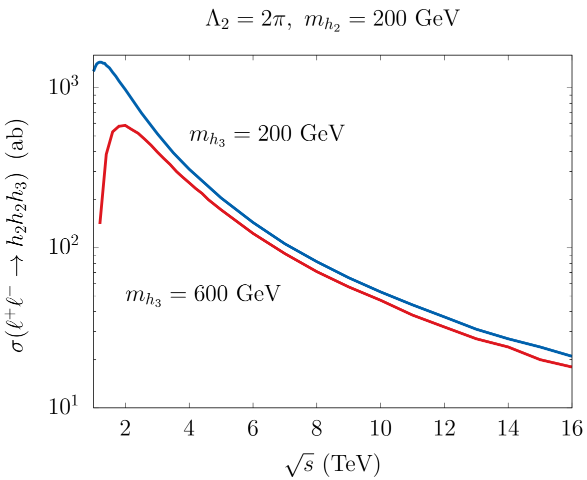
It could happen that at the end of the last LHC run we just move closer and closer to the alignment limit and to a very CP-even 125 GeV Higgs. Considering a few future lepton colliders

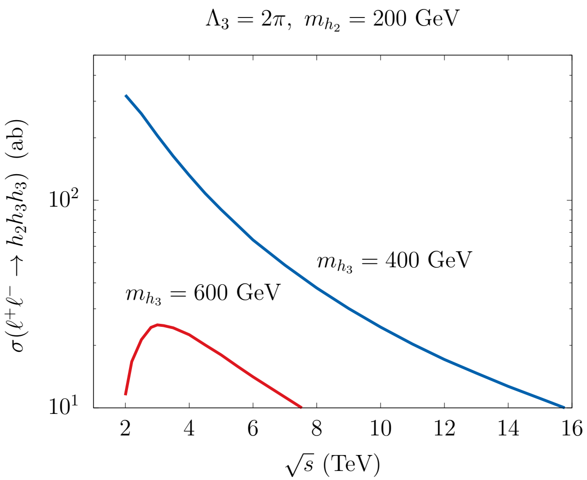
Accelerator	$\sqrt{s}$ (TeV)	Integrated luminosity (ab^{-1})
CLIC	1.5	2.5
CLIC	3	5
Muon Collider	3	1
Muon Collider	7	10
Muon Collider	14	20

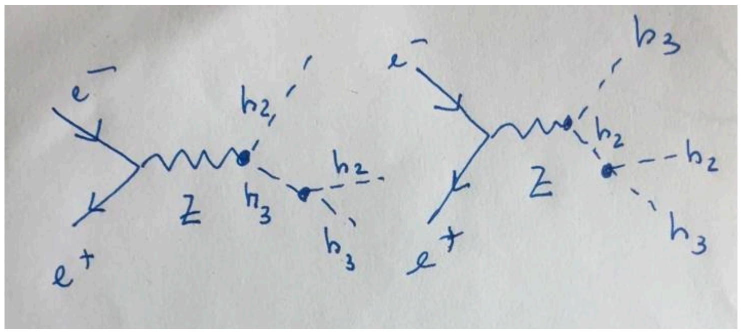
$$h_2H^+H^-; \quad h_3H^+H^-; \quad Zh_2h_3$$

$$h_2h_kh_k; \quad h_3H^+H^-; \quad Zh_2h_3; \quad (k=2,3) \quad (2 \leftrightarrow 3)$$

$$h_2h_kh_k; \quad h_3h_lh_l;; \quad Zh_2h_3; \quad (k,l=2,3)$$







$$h_2h_3h_3; \quad h_3h_2h_2; \quad Zh_2h_3$$

CP-violation from C-violation, but dark

CP violation from C-violation but inside loops (ZZZ)

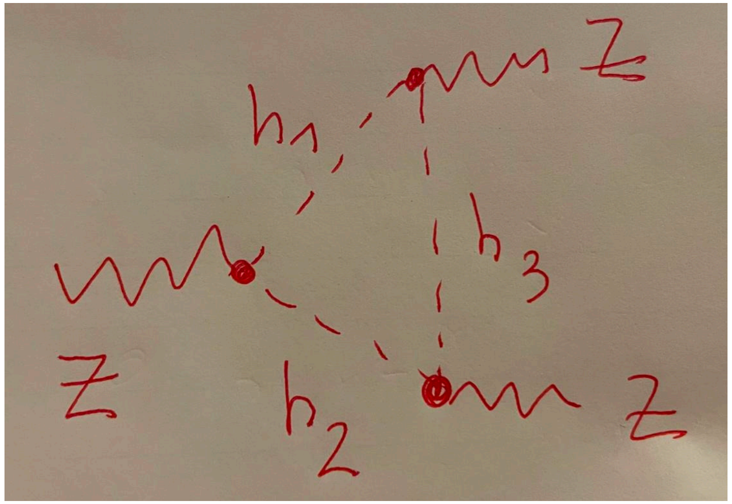
Another possibility of detecting P-even CP-violating signals is via loops. Remember CP-violation could be seen via the combination:

$$h_2 \to h_1 Z \quad CP(h_2) = -\, CP(h_1)$$

$$h_3 \to h_1 Z \quad CP(h_3) = -\, CP(h_1)$$

$$h_3 \to h_2 Z \quad CP(h_3) = -\, CP(h_2)$$

If we don't have access to the decays we can build a nice Feynman diagram with the same vertices.



And see if it is possible to extract information from the measurement of the triple ZZZ anomalous coupling.

Can we build such a model?

A sector with three invisible scalars

AZEVEDO, FERREIRA, MÜHLLEITNER, PATEL, RS, WITTBRODT, JHEP 1811 (2018) 091

Two doublets + one singlet and one exact Z_2 symmetry

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2, \qquad \Phi_S \to -\Phi_S$$

with the most general renormalizable potential

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + (A\Phi_1^\dagger \Phi_2 \Phi_S + h.c.)$$
$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \frac{\lambda_5}{2}\left[(\Phi_1^\dagger \Phi_2) + h.c.\right] + \frac{m_S^2}{2}\Phi_S^2 + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger \Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger \Phi_2)\Phi_S^2$$

and the vacuum preserves the symmetry

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG_0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\rho + i\eta) \end{pmatrix} \qquad \Phi_S = \rho_S$$

The potential is invariant under the CP-symmetry

$$\Phi_1^{CP}(t, \vec{r}) = \Phi_1^*(t, -\vec{r}), \qquad \Phi_2^{CP}(t, \vec{r}) = \Phi_2^*(t, -\vec{r}), \qquad \Phi_S^{CP}(t, \vec{r}) = \Phi_S(t, -\vec{r})$$

except for the term $(A\Phi_1^\dagger \Phi_2 \Phi_S + h.c.)$ **for complex A**. This is a type I model.

CP violation from C-violation but inside loops (ZZZ)

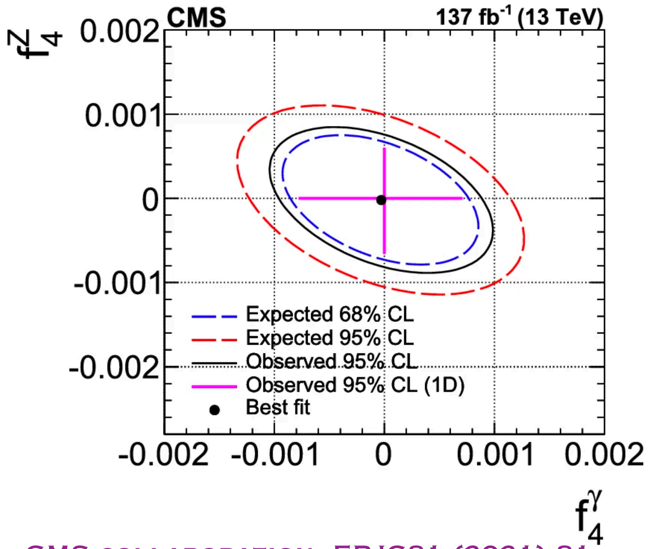
The most general form of the vertex includes a P-even CP-violating term of the form

$$i\Gamma_{\mu\alpha\beta} = -\,e\frac{p_1^2 - m_Z^2}{m_Z^2}\, f_4^Z\,(g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$

Gaemers, Gounaris, ZPC1 (1979) 259; Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB282 (1987) 253; Grzadkowski, Ogreid, Osland, JHEP 05 (2016) 025

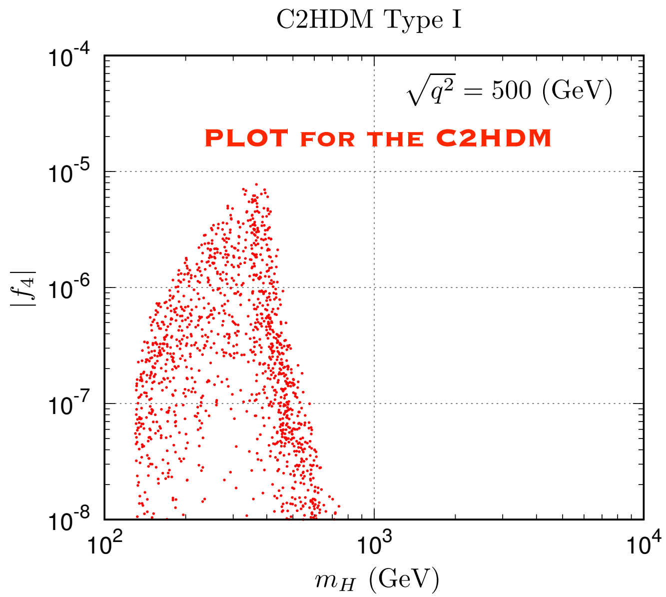
CMS collaboration, EPJC78 (2018) 165. $-1.2\times10^{-3} < f_4^Z < 1.0\times10^{-3}$

ATLAS collaboration, PRD97 (2018) 032005. $-1.5\times10^{-3} < f_4^Z < 1.5\times10^{-3}$

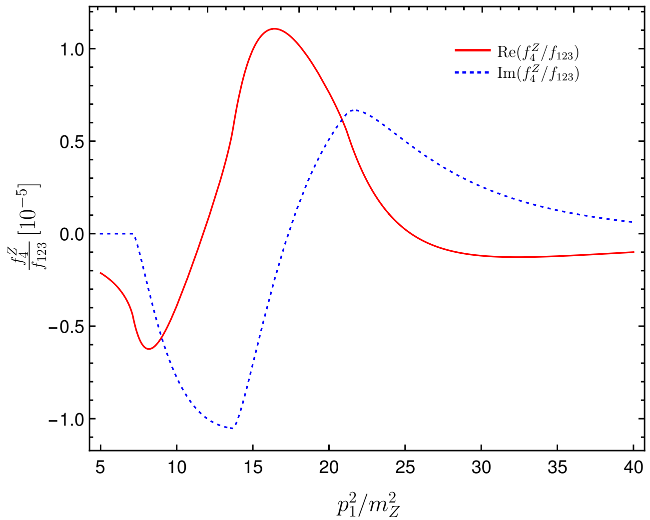


CMS collaboration, EPJC81 (2021) 81.

From: Bélusca-Maïto, Falkowski, Fontes, Romão, Silva, JHEP 04 (2018) 002



Plot for CP in the Dark



The typical maximal value for f_4 seems to be below 10^{-4}.

CP-violation from P-violation

Fermion currents with scalars can be CP (P) violating. Is there room for a CP-violating piece of the SM Higgs?

$\bar{\psi}\psi$ C even P even -> CP even

$\bar{\psi}\gamma_5\psi$ C even P odd -> CP odd

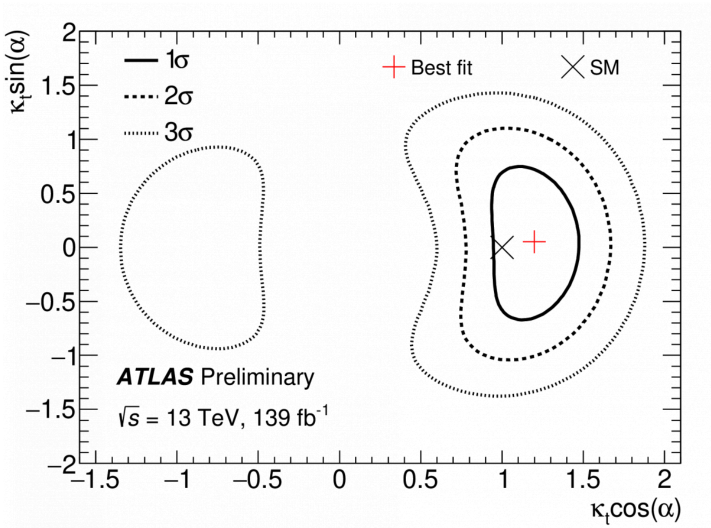
C conserving, CP violating interaction

$$\bar{\psi}(a + ib\gamma_5)\psi\,\phi$$

$$pp \to (h \to \gamma\gamma)\bar{t}t$$

To probe this type of CP-violation we need one Higgs only.

Consistent with the SM. Pure CP-odd coupling excluded at 3.9σ, and |α| > 43° excluded at 95% CL.



$$\mathcal{L}^{CPV}_{\bar{t}th} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h$$

$$\kappa_t = \kappa\,\cos\alpha$$

$$\tilde{\kappa}_t = \kappa\,\sin\alpha$$

Rates alone already constrained a lot the CP-odd component.

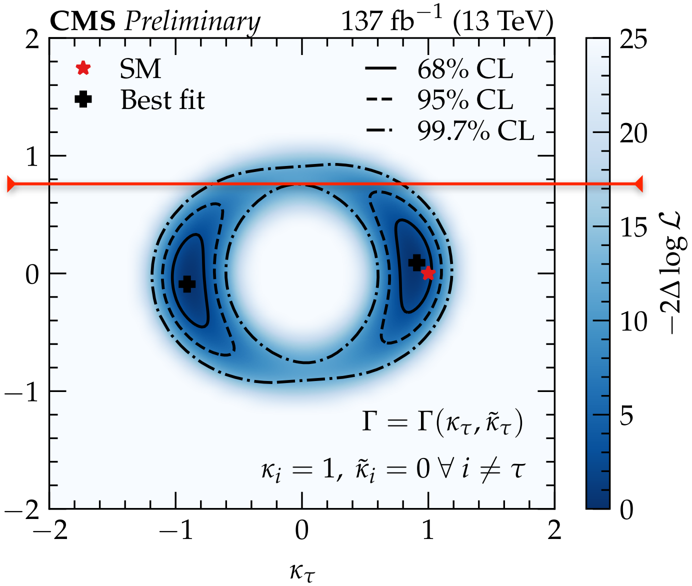
Measurement of CPV angle in ττh

$$pp \to h \to \tau^+\tau^-$$

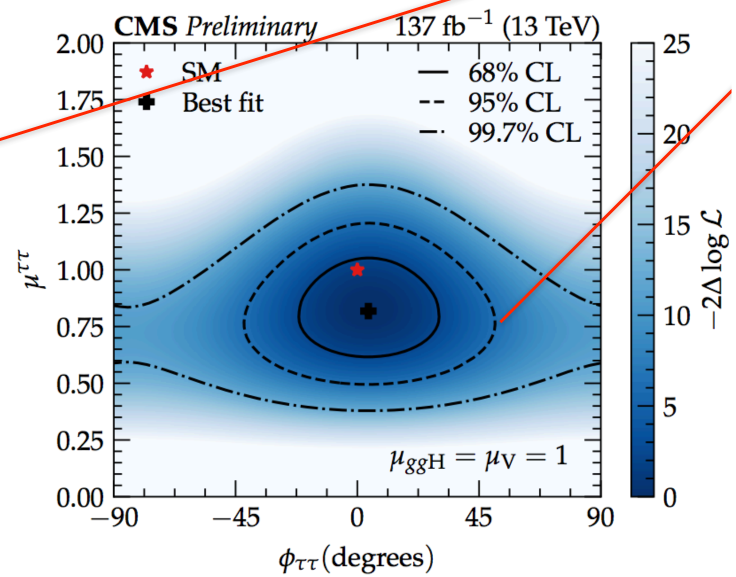
$$\mathscr{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\,h$$

Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°. Compatible with SM predictions.

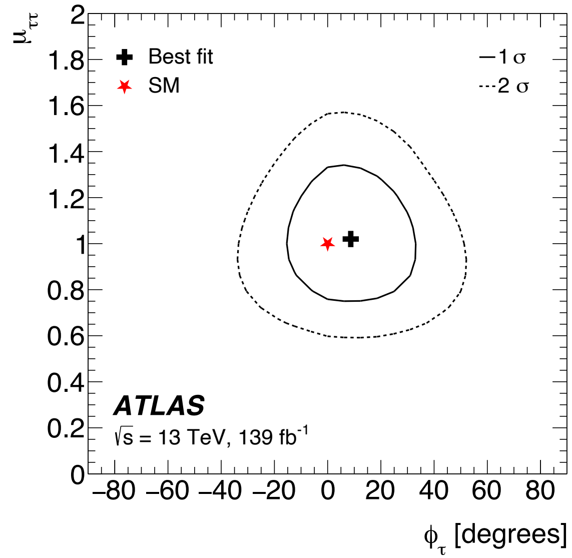
Scenario excluded at 95% CL



CMS collaboration, CMS-PAS-HIG-20-006



$$\phi_{\tau\tau} = \alpha$$



ATLAS collaboration, arXiv:2212.05833v1.

What if?

$$pp \to (h \to \gamma\gamma)\bar{t}t$$

$$\mathscr{L}_{\bar{t}th}^{CPV} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h$$

$$\kappa_t \approx 1, \quad \tilde{\kappa}_t \approx 0 \qquad \mathscr{L}_{\bar{t}th}^{CPV} = -\frac{y_f}{\sqrt{2}}\,\kappa_t\bar{t}\,t\,h$$

Scalar

$$pp \to h \to \tau^+\tau^-$$

$$\mathscr{L}_{\bar{\tau}\tau h}^{CPV} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\,h$$

$$\kappa_\tau \approx 0; \quad \tilde{\kappa}_\tau \approx 1 \qquad \mathscr{L}_{\bar{\tau}\tau h}^{CPV} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(i\tilde{\kappa}_\tau\gamma_5)\,\tau\,h$$

Pseudoscalar

CP violation from P violation - a strange CP scenario

There is a different way to look at the same problem

$\alpha_1 = \pi/2$

$\bar{t}(a_t + i b_t \gamma_5) t\, \phi$	$b_t \approx 0$	$a_t \bar{t} t \phi$	**Scalar**
$\bar{\tau}(a_\tau + i b_\tau \gamma_5) \tau\, \phi$	$a_\tau \approx 0$	$b_\tau \bar{\tau} \tau\, \phi$	**Pseudoscalar**

Taking the C2HDM couplings and setting $\alpha_1 = \pi/2$,

$$g^{hVV}_{C2HDM} = \cos\alpha_2 \, \cos(\beta - \alpha_1) g^{hVV}_{SM}$$

$$g^{huu}_{C2HDM} = \left(\cos\alpha_2 \frac{\sin\alpha_1}{\sin\beta} - i \frac{\sin\alpha_2}{\tan\beta} \gamma_5 \right) g^{hff}_{SM}$$

$$g^{hbb}_{C2HDM} = \left(\cos\alpha_2 \frac{\cos\alpha_1}{\cos\beta} - i \sin\alpha_2 \, \tan\beta \, \gamma_5 \right) g^{hff}_{SM}$$

$$g^{hVV}_{C2HDM} = \cos\alpha_2 \, \sin\beta \, g^{hVV}_{SM}$$

Close to 1

$$g^{huu}_{C2HDM} = \left(\frac{\cos\alpha_2}{\sin\beta} - i \frac{\sin\alpha_2}{\tan\beta} \gamma_5 \right) g^{hff}_{SM}$$

Small

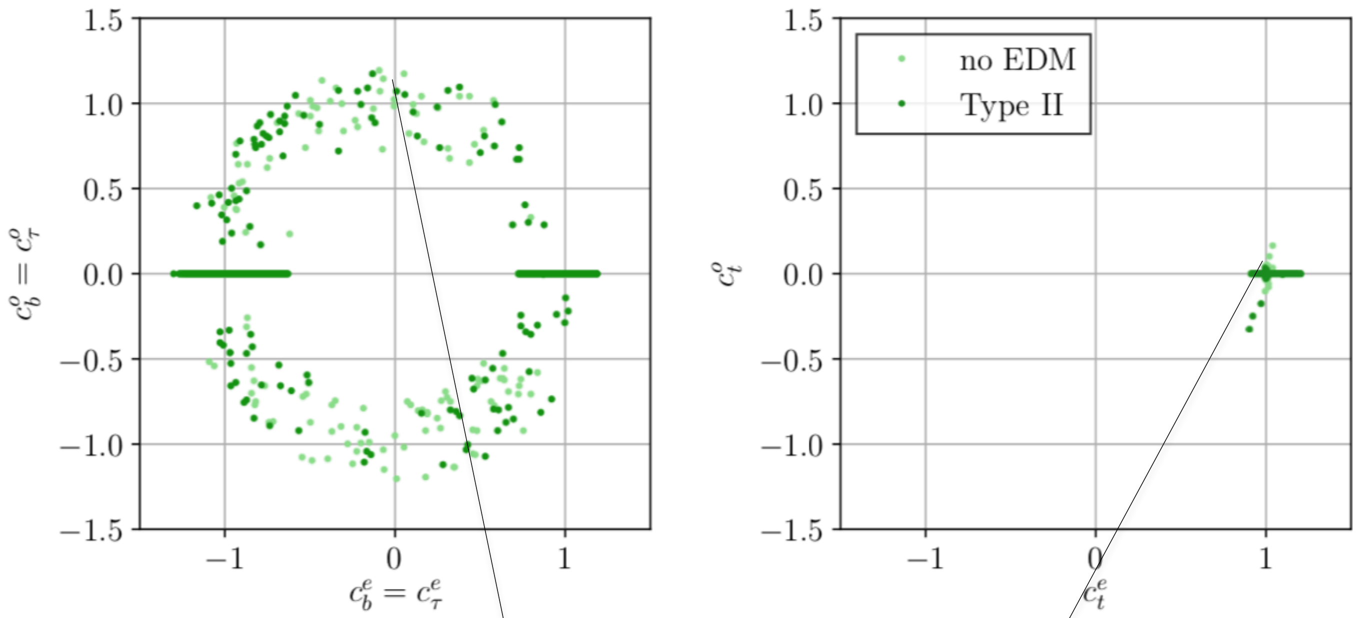
$$g^{hbb}_{C2HDM} = \left(-i \sin\alpha_2 \, \tan\beta \, \gamma_5 \right) g^{hff}_{SM}$$

Can be large

Experiment tells us

$$\frac{\sin\alpha_2}{\tan\beta} \ll 1 \qquad \textbf{But} \qquad \sin\alpha_2 \, \tan\beta = \mathcal{O}(1)$$

CP violation from P violation - a strange CP scenario



$$Y_{C2HDM} = a_F + i\gamma_5 b_F$$

$$b_U \approx 0; \ a_D \approx 0$$

A Type II model where H_2 is the SM-like Higgs.

With the EDM result

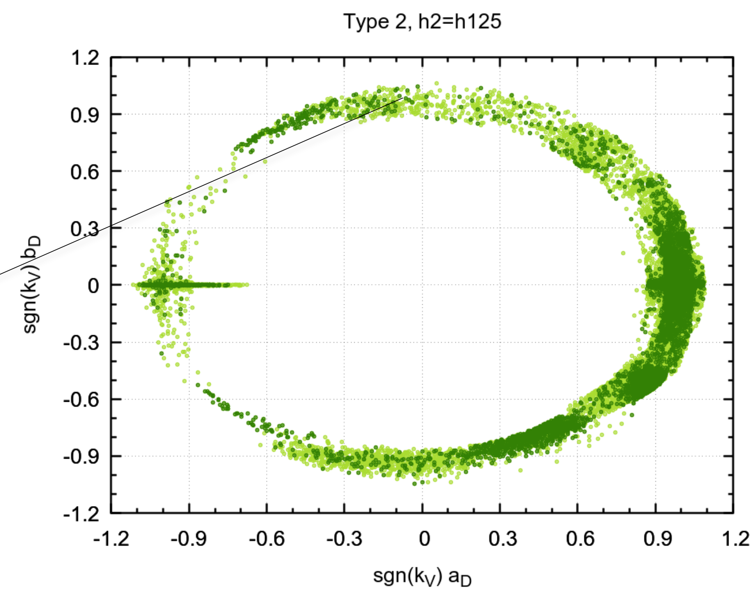
[ACME 18]

Find two particles of the same mass one produced in Association with tops as CP-even

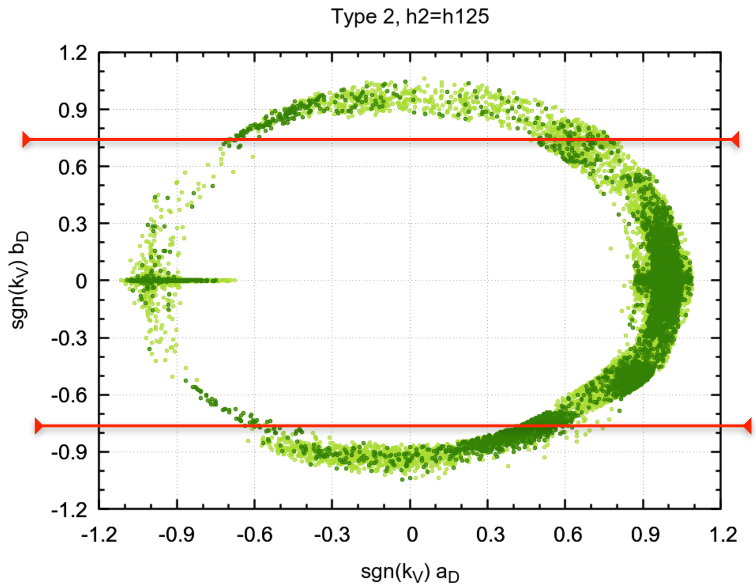
$$h_2 = H; pp \to Ht\bar{t}$$

and the other decaying to taus as CP-odd

$$h_2 = A \to \tau^+\tau^-$$



CP violation from P violation - a strange CP scenario



LHC (direct) experiments give us information <u>beyond</u> <u>EDMs</u>.

What about other combinations of Yukawa?

$$h_2 = H; pp \to Ht\bar{t}$$

In many extensions of the SM, probing one Yukawa coupling is not enough!

and the other decaying to b-quarks as CP-odd?

$$h_2 = A \to \bar{b}b$$

One attempt I know of

Alonso, Fraser-Taliente, Hays, Spannowsky, JHEP 08 (2021) 167

$$h \to b\bar{b} \to \Lambda_b \bar{\Lambda}_b$$
$$h \to c\bar{c} \to \Lambda_c \bar{\Lambda}_c$$

The Higgs boson yields therefore need to be very high to approach sensitivity, O(10^9) events, beyond the reach of all proposed colliders except a high-luminosity 100 TeV muon collider. With such a collider it may be possible to test maximal CP violation at the 2σ level

Can we use the tth idea for bbh?

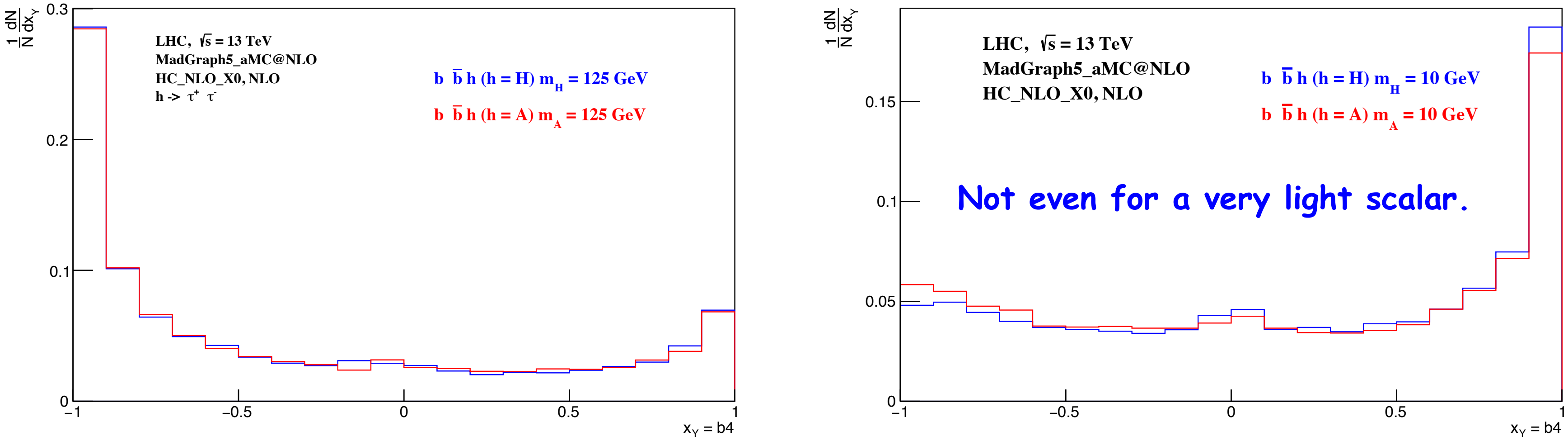


Figure 1: Parton level b_4 distributions at NLO, normalized to unity, for $m_\phi = 125$ GeV (left) and $m_\phi = 10$ GeV (right). Only events with $p_T(b) > 20$ GeV and $|\eta(b)| < 2.5$ were selected, with p_T and η being the transverse momentum and the pseudo-rapidity, respectively.

The answer is no - the reason is that the interference term is proportional to the quark mass. We have tried with bb and single b production.

Azevedo, Capucha, Onofre, RS, JHEP06 (2020) 155.

CP violation from P violation - a strange CP scenario

Biekötter, Fontes, Mühlleitner, Romão, RS, Silva, e-Print: 2403.02425 [hep-ph]

2017

- Signal strength constraints on h_{125} from the combination of ATLAS and CMS data collected at 7 TeV and 8 TeV [43];
- HiggsBounds 4.3.1 [44], for data from searches for additional scalars;
- The electron electric dipole moment (eEDM) limit of 8.7×10^{-29} e.cm [45];
- The lower bound of 580 GeV on the charged Higgs boson mass, $m_{H^\pm}$, from radiative B-meson decays in the Type-II and Flipped models (introduced below) [46].

Recently we came back to analyse this scenario with all new data.

2024

- The latest LHC data on the h_{125} signal strengths, including the full Run 2 data collected at 13 TeV, for the different production and decay modes that have so far been detected. We specifically use the ATLAS results summarized in figure 3 of ref. [53], demanding that the predicted signal rates agree within 2σ with each individual signal-rate measurement. The ATLAS measurements are well in agreement with the corresponding CMS results, such that all our conclusions would remain unchanged if instead the CMS results or a combination of ATLAS+CMS results were used;
- The impact of the latest data of direct searches for CP-violation by CMS using angular correlations in decay planes of τ leptons produced in Higgs boson decays $h_{125} \to \tau\bar{\tau}$ [54], setting an upper limit of $\alpha_{h\tau\tau} < 41^\circ$ on the effective mixing angle between the CP-even and CP-odd τ-Yukawa coupling at the 2σ confidence level (which, as we will show, has a very strong impact on our analysis);[3]
- The impact of new searches for additional scalars, as compiled in `HiggsBounds` 5.7.1 and 5.9.1 [44, 56–58] and in the newest `HiggsTools` 1.1.3 [59], incorporating the newest version 6 of `HiggsBounds`, extending the previous versions by a large set of searches that were performed including the full Run 2 data collected at 13 TeV;
- The recent 90% confidence-level limit on the eEDM of 1.1×10^{-29} e.cm reported by the ACME collaboration [60] and the most recent limit of 4.1×10^{-30} e.cm measured at JILA [61];
- Updated bounds on the mass of the charged Higgs bosons from measurements of radiative B-meson decays (see the discussion in section 3.1).

The strange CP scenario - type II - bbh coupling

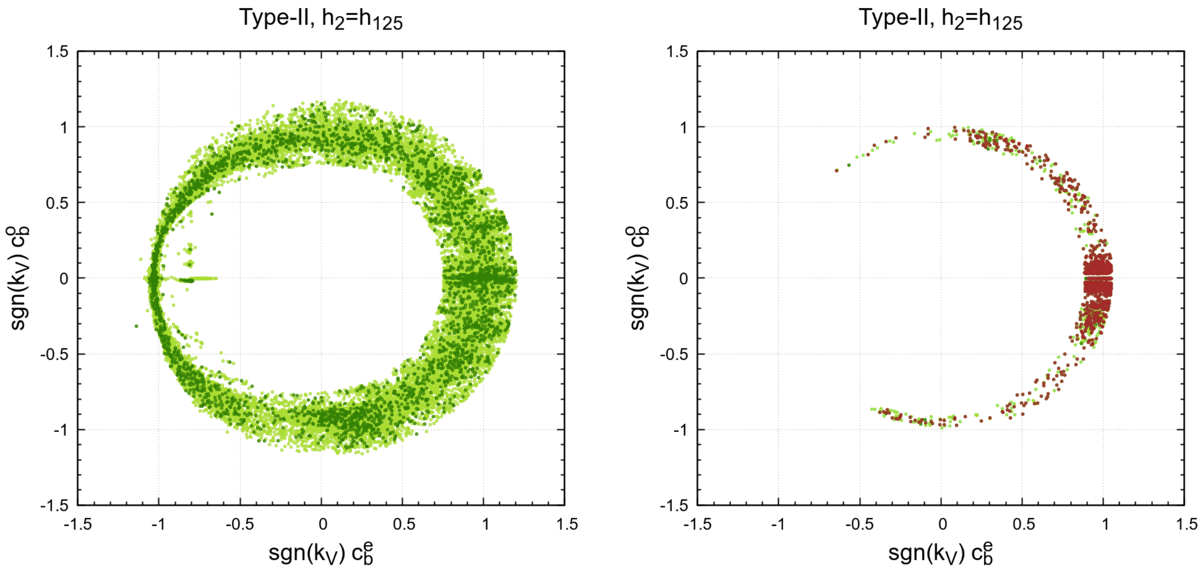


Figure 1. CP-odd vs. CP-even component in the $h_{125}b\bar{b}$ coupling of allowed parameter points in Type-II, assuming $h_2 = h_{125}$. Left panel: LHC 2017 data on h_{125} and constraints from beyond-SM (BSM) scalar searches at 7 and 8 TeV using HB-4.3.1. Right panel: LHC 2022 data on h_{125} and constraints from BSM scalars including 13 TeV data using HT-1.1.3. The light green points are consistent with the old eEDM of 8.7×10^{-29} e.cm [45, 76], the dark green points with the more recent ACME result 1.1×10^{-29} e.cm [60]. The dark red points obey the currently strongest limit on the eEDM 4.1×10^{-30} e.cm reported by JILA [61]. The fermion masses in the loops of diagrams contributing to the eEDM were taken as pole masses. The limit $\alpha_{h\tau\tau} < 41°$ [54] from searches for CP-violation in angular correlations of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays has not been applied in either of the plots in this figure.

Difference between old and new LHC data (left and right) and old and new eEDM (light and dark points). Limit from tau angle not included.

Note that most scenarios were already excluded in the 2017 study. That is why we start with the second Higgs being the 125 GeV one. In this case h1 is lighter than h2.

The strange CP scenario - type II - bbh coupling

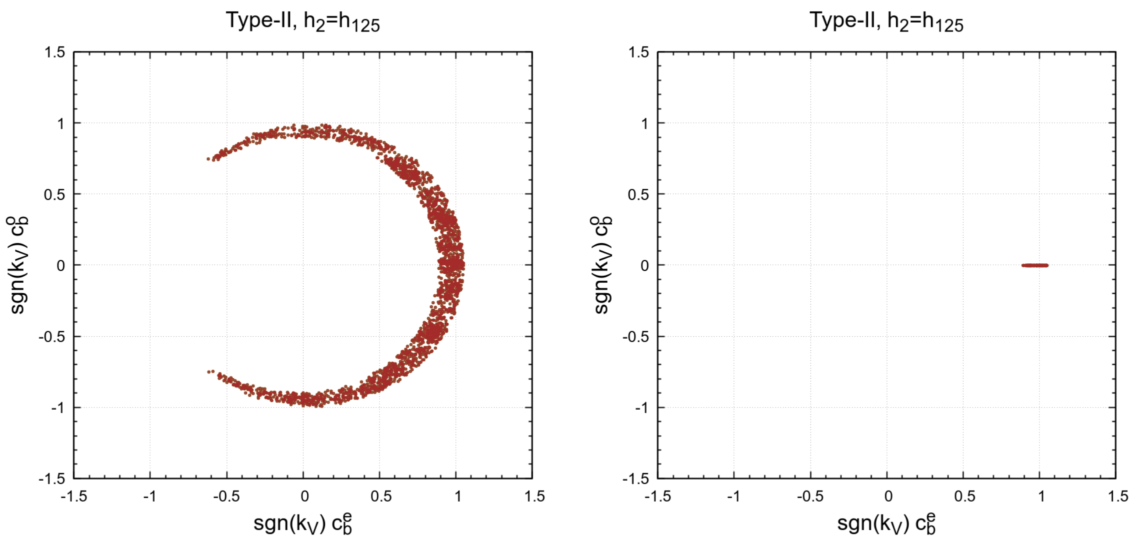


Figure 2. CP-odd vs. CP-even component in the $h_{125}b\bar{b}$ coupling of allowed parameter points in Type-II, assuming $h_2 = h_{125}$. All points obey the current experimental limit on the eEDM [61], where here the masses of the fermions in the loops of diagrams contributing to the eEDM were taken to be the running masses at the M_Z scale (see text for details). Also applied are the constraints from the h_{125} cross section measurements using LHC 2022 data collected at 13 TeV. The left panel does not include the LHC constraints on the extra scalars while in the right panel these constraints are applied including the most recent searches at 13 TeV using HT-1.1.3.

The conclusions from the previous slide, in the Type-II, crucially depend on a significant fine-tuning of the model parameters in order to be compatible with the stringent experimental upper bounds on the eEDM.

These limits can be evaded only as a result of a cancellation between different contributions to the eEDM at two-loop level in the perturbative expansion.

This cancellation gives rise to a strong dependence of the predicted eEDM on the model parameters, including the values for the masses of the fermions that appear as virtual particles in the loops of Barr-Zee type diagrams.

The strange CP scenario - type LS - tautauh coupling

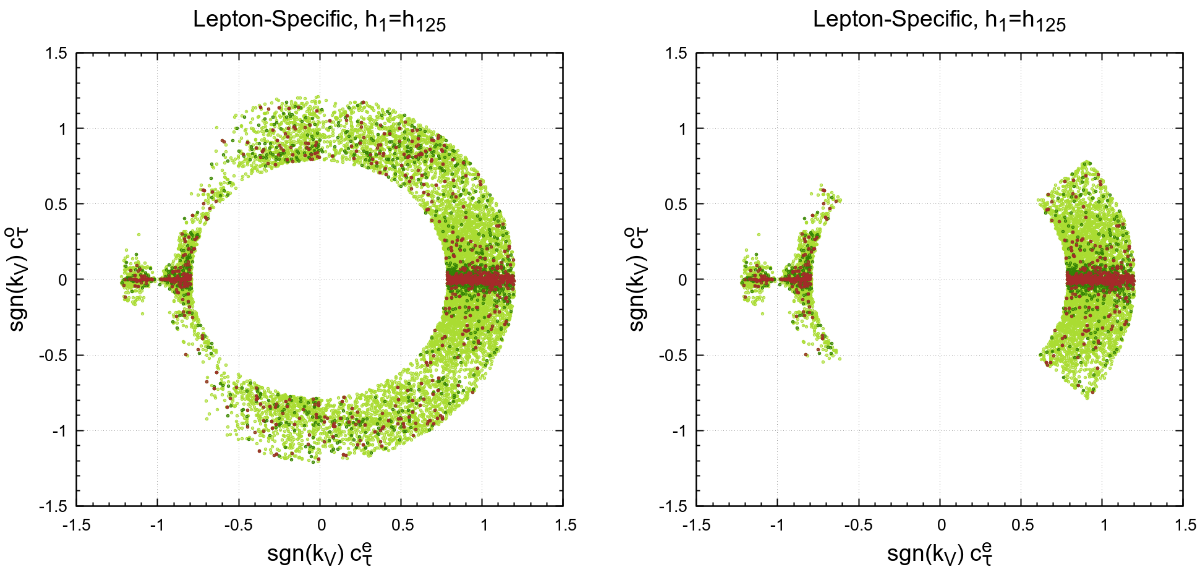


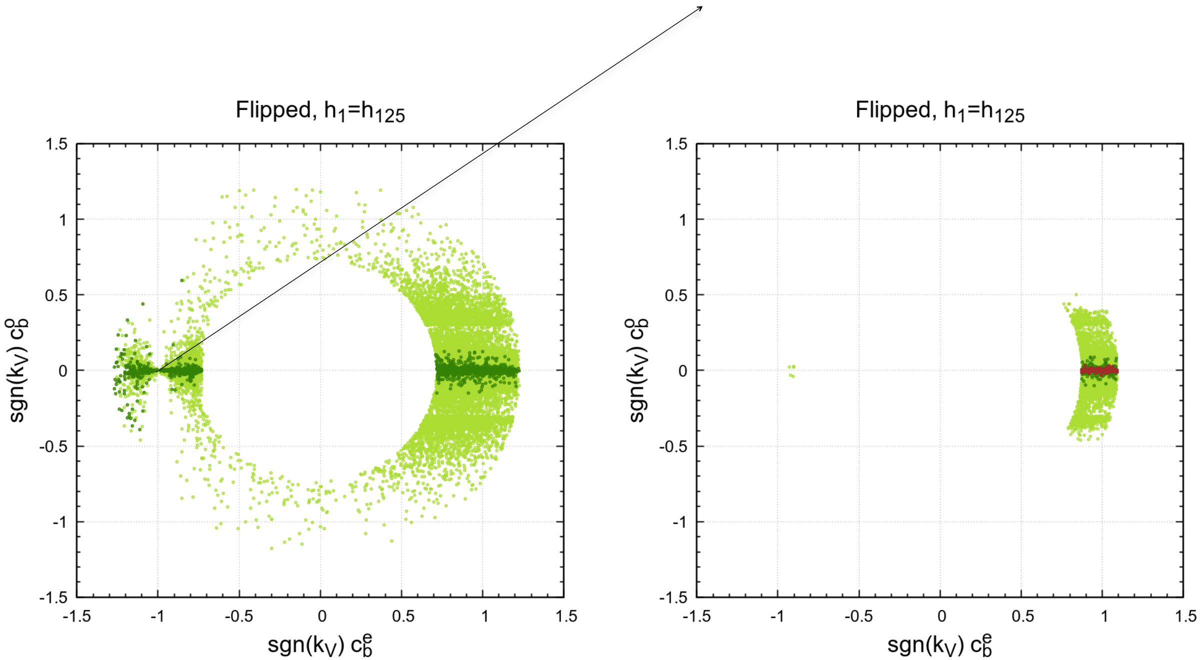
Figure 4. CP-odd vs. CP-even component in the $h_{125}\tau\bar{\tau}$ coupling for the allowed parameter points in the LS model, assuming $h_1 = h_{125}$, using 13 TeV LHC Higgs data on h_{125} collected until 2022 and constraints from BSM scalar searches included in HT-1.1.3. In the left panel, the limit $\alpha_{h\tau\tau} < 41°$ from angular correlations of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays is not applied, whereas the right panel includes this limit. Colour code as in figure 1.

All data included in type LS except limit from tau angle included only in the right plot.

LHC (direct) experiments give us information beyond EDMs.

The strange CP scenario - type Flipped - bbh coupling

Wrong sign scenario.



Difference between old and new LHC data (left and right) and old and new eEDM (light and dark points).

Figure 7. CP-odd vs. CP-even component in the $h_{125}b\bar{b}$ coupling for allowed parameter points in the Flipped model, assuming $h_1 = h_{125}$. Left panel: LHC 2017 data on h_{125} and constraints from BSM scalar searches at 7 and 8 TeV included in HB-4.3.1. Right panel: LHC 2022 data on h_{125}, constraints from BSM scalar searches including searches at 13 TeV using HT-1.1.3 and the latest eEDM limit. Colour code as in figure 1.

Conclusions for the strange CP scenario

Can we still find large Yukawa couplings?

Type	I	II	LS	Flipped
$h_1 = h_{125}$	$\times$	$\times$	τ	$\underline{\times}$
$h_2 = h_{125}$	$\times$	$\underline{\times}$	τ	$\times$
$h_3 = h_{125}$	$\times$	$\times$	τ	$\times$

Table 3. Current results for the large Yukawa couplings. A cross means that it is not possible to have large CP-odd couplings, i.e. $|c^0| \gtrsim |c^e|$. The notation τ means that c^o/c^e is limited by the direct searches for CP-violating angular correlations of τ leptons in $h_{125} \to \tau\bar{\tau}$ decays [54]. Underlined crosses indicate a change from allowed ($\checkmark$) to excluded ($\times$) compared to the previous analysis carried out in 2017 [26].

More CP-violation from loops

CP violation from loops (hWW)

The most general Lorentz invariant Lagrangian is

$$\mathscr{L}_{hZZ} = \kappa \frac{m_Z^2}{v} h Z_\mu Z^\mu + \frac{\alpha}{v} h Z_\mu \partial_\alpha \partial^\alpha Z^\mu + \frac{\beta}{v} h Z_{\mu\nu} Z^{\mu\nu} + \frac{\gamma}{v} h Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

ONLY TERM IN THE C2HDM (AND SM) AT TREE-LEVEL

$$i\Gamma^{\mu\nu}_{hWW} = i(g_2 m_w) \left[g^{\mu\nu} \left(1 + a_W - \frac{b_{W1}}{m_W^2} (k_1 \,.\, k_2) \right) + \frac{b_{W2}}{m_W^2} k_1^\nu k_2^\mu + \frac{c_W}{m_W^2} \epsilon^{\mu\nu\rho\sigma} k_{1\rho} \,.\, k_{2\sigma}) \right]$$

P-VIOLATING, CP VIOLATION

$$\mathscr{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+} \epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu} \tilde{f}^{*-\,\mu\nu}$$

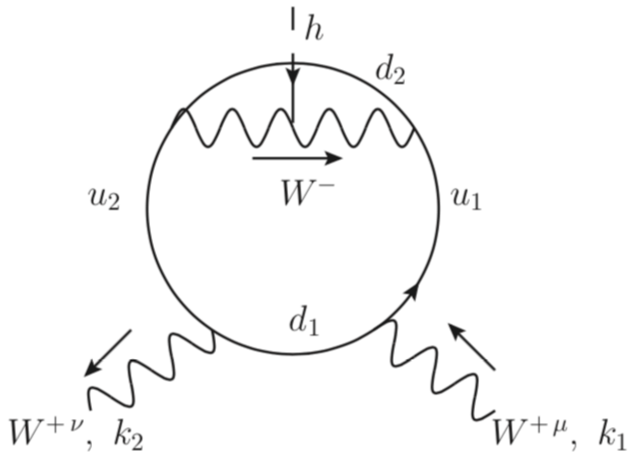
CP violation from loops (hWW)

In this case we start with the most general WWh vertex

$$\mathscr{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+} \epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu} \tilde{f}^{*-\,\mu\nu}$$

TERM COMING FROM A CPV OPERATOR.
CONTRIBUTION FROM THE SM AT 2-LOOP

TERM IN THE SM AT TREE-LEVEL
BUT ALSO IN MODELS WITH CP-VIOLATION



$$\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}} \in [-0.81, 0.31]$$

EXPERIMENTAL BOUND FROM ATLAS AND CMS

THE SM CONTRIBUTION SHOULD BE PROPORTIONAL TO THE JARLSKOG INVARIANT $J = \mathrm{Im}(V_{ud} V_{cd}^* V_{cs} V_{cd}^*) = 3.00 \times 10^{-5}$. THE CPV hW^+W^- VERTEX CAN ONLY BE GENERATED AT TWO-LOOP.

ATLAS COLLABORATION, EPJC 76 (2016) 658.

CMS COLLABORATION, PRD100 (2019) 112002.

Parameter	Observed/(10^{-3}) 68% C.L.	Observed/(10^{-3}) 95% C.L.	Expected/(10^{-3}) 68% C.L.	Expected/(10^{-3}) 95% C.L.
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$

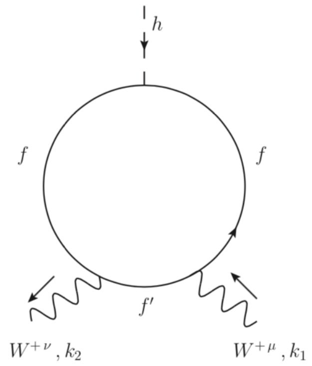
Parameter	Observed/(10^{-3}) 68% CL	Observed/(10^{-3}) 95% CL	Expected/(10^{-3}) 68% CL	Expected/(10^{-3}) 95% CL
f_{a3}	$0.20^{+0.26}_{-0.16}$	$[-0.01, 0.88]$	0.00 ± 0.05	$[-0.21, 0.21]$

CMS COLLABORATION, ARXIV:2205.05120V1.

THE BOUND HAS IMPROVED AT LEAST TWO ORDERS OF MAGNITUDE

CP violation from loops (hWW)

THE C2HDM



Starting with f=t and f'=b

Is it worth it?

$$i\mathcal{M}_{tb}^{\text{C2HDM}} \sim \frac{ig^2 N_c c_t^o}{16\pi^2 v} \frac{m_t^2}{m_W^2} |V_{tb}|^2 \epsilon_{\mu\nu\rho\sigma} k_1^\rho k_2^\sigma \mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right)$$

$$\mathcal{I}_1(x,y) \equiv \int_0^1 d\alpha \frac{\alpha^2}{\alpha x + (1-\alpha)y - \alpha(1-\alpha)}$$

And because f=b and f'=t can also contribute, the final result is

$$c_{\text{CPV}}^{\text{C2HDM}} = \frac{N_c g^2}{32\pi^2} |V_{tb}|^2 \left[\frac{c_t^o m_t^2}{m_W^2} \mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) + \frac{c_b^o m_b^2}{m_W^2} \mathcal{I}_1\left(\frac{m_b^2}{m_W^2}, \frac{m_t^2}{m_W^2}\right)\right]$$

$$c_{\text{CPV}} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

$$c_{\text{CPV}}^{\text{C2HDM}} \simeq 6.6 \times 10^{-4} \sim \mathcal{O}(10^{-3})$$

Using all experimental (and theoretical) bounds

Huang, Morais, RS, JHEP 01 (2021) 168

Summary

- Direct searches for a CP-odd component in the Higgs Yukawa couplings gives information that cannot be obtained from the eEDMs.
- So far only tau and top couplings were probed directly for CP-odd components.
- Combination of data (with eEDMs) has shown to be crucial to probe the entire parameter space of the models, including the searches for new scalars.
- Anomalous couplings experimental information is moving closer to the largest theoretical estimates in simple models with CP-violation in the scalar sector.
- SM measurements are the starting point to probe BSM models.

The End

Dark matter from tt

Dark Matter from tt - what if there is a very light scalar hidden in tt?

Azevedo, Capucha, Chaves, Martins, Onofre, RS, JHEP 11 (2023) 125

We used the simplified DM model DMsimp where, besides the scalar Y0 boson, we also have a dark sector that couples only to Y0. We focus only on the couplings to the top. We do not see (or look for) Y0 that is supposed to be very light

$$\mathcal{L}_{\rm SM}^{Y_0} = \frac{y_{33}^t}{\sqrt{2}}\bar{t}(g_{u_{33}}^S + i g_{u_{33}}^P \gamma^5) t Y_0$$

The b_4 and $\Delta\phi_{l^+l^-}$ distributions were then used to set confidence level limits (CLs) on the exclusion of the SM with a new CP-mixed massless DM mediator particle, Y_0, assuming the SM hypothesis as the null hypothesis (Scenario 1).

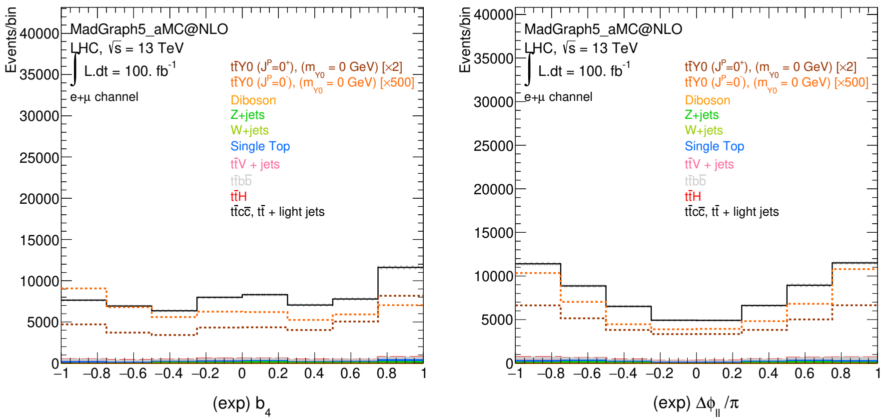


Figure 5. The b_4 (left) and $\Delta\phi_{\ell^+\ell^-}$ (right) distributions for scalar and pseudo-scalar signals (dashed curves) together with the SM processes (full lines) with dileptonic final states, are represented after event selection and kinematic reconstruction (exp), for a reference luminosity of $100\,\text{fb}^{-1}$. Scaling factors are applied to the scalar and pseudo-scalar signals for convenience.

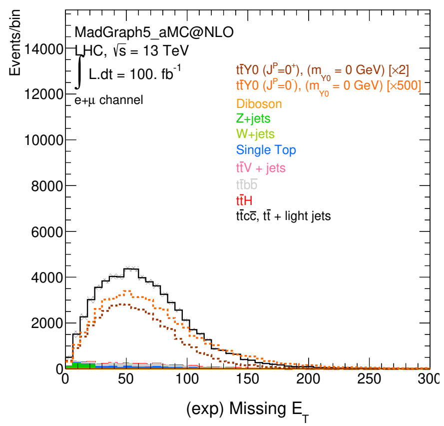


Figure 6. Missing transverse energy (E_T) distributions for scalar and pseudo-scalar signals (dashed curves) together with the SM processes (full lines) with dileptonic final states, are represented after event selection and kinematic reconstruction (exp), for a reference luminosity of $100\,\text{fb}^{-1}$. Scaling factors are applied to the scalar and pseudo-scalar signals for convenience.

For this scenario, the exclusion plots are

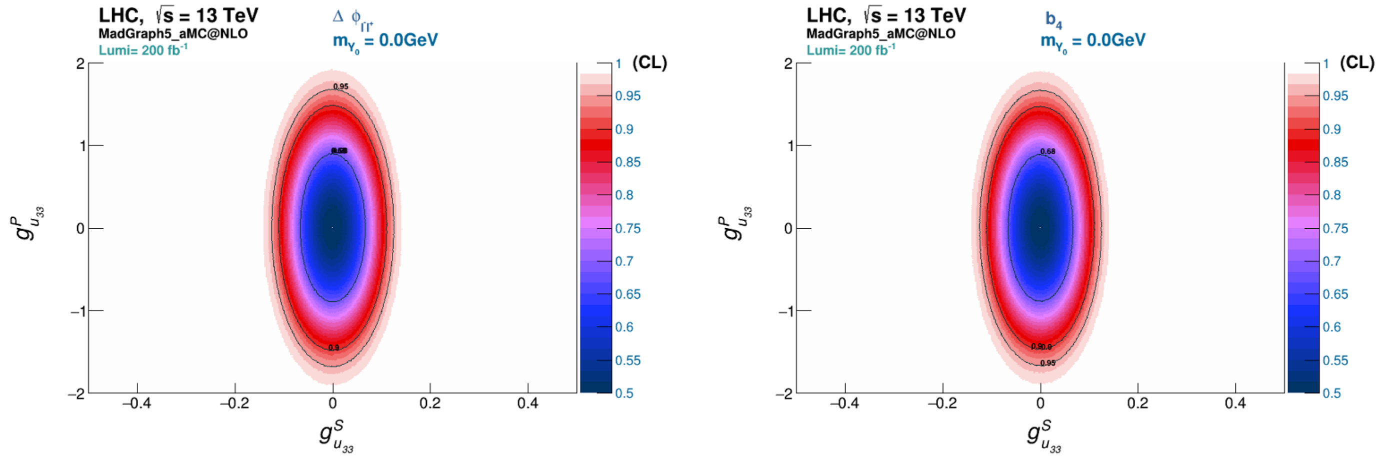


Figure 7. CLs for the exclusion of the SM with a massless DM mediator, Y_0, with mixed scalar and pseudo-scalar couplings with the top quarks, against the SM as null hypothesis, for the $\Delta\phi$ between the charged leptons, $\Delta\phi_{\ell^+\ell^-}$ (left), and b_4 (right) observables. Limits are shown for a luminosity of $L = 200\,\text{fb}^{-1}$.

Exclusion Limits from $\Delta\phi_{l^+l^-}$		$L = 200\,\text{fb}^{-1}$ (68% CL)	$L = 200\,\text{fb}^{-1}$ (95% CL)	$L = 3000\,\text{fb}^{-1}$ (68% CL)	$L = 3000\,\text{fb}^{-1}$ (95% CL)
$m_{Y_0} = 0\,\text{GeV}$	$g^S_{u33} \in$	[-0.067, +0.067]	[-0.125, +0.125]	[-0.022, +0.022]	[-0.052, +0.052]
	$g^P_{u33} \in$	[-0.91, +0.91]	[-1.71, +1.71]	[-0.44, +0.44]	[-0.85, +0.85]

Table 1. Exclusion limits for the $t\bar{t}Y_0$ CP-couplings for fixed luminosities of $200\,\text{fb}^{-1}$ and $3000\,\text{fb}^{-1}$ of the SM plus Y_0, assuming the SM as the null hypothesis. The limits are shown at confidence levels of 68% and 95%, for the $\Delta\phi_{l^+l^-}$ variable.

All potentials in one slide

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{m_S^2}{2}\Phi_S^2$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

Allows for a decoupling limit

Particle (type) spectrum depends on the symmetries imposed on the model, and whether they are spontaneously broken or not.

with fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \qquad \Phi_S = v_S + \rho_S$$

$v_2 = 0$, dark matter, IDM

$v_S = 0$, singlet dark matter

The one with the larger spectrum is the N2HDM with two charged and four neutral particles.

magenta $\Longrightarrow$ SM

magenta + blue $\Longrightarrow$ RxSM (also CxSM) Complex version - CP-violation

magenta + black $\Longrightarrow$ 2HDM (also C2HDM)

magenta + black + blue + red $\Longrightarrow$ N2HDM

- m^2_{12} and λ_5 real 2HDM
- m^2_{12} and λ_5 complex C2HDM

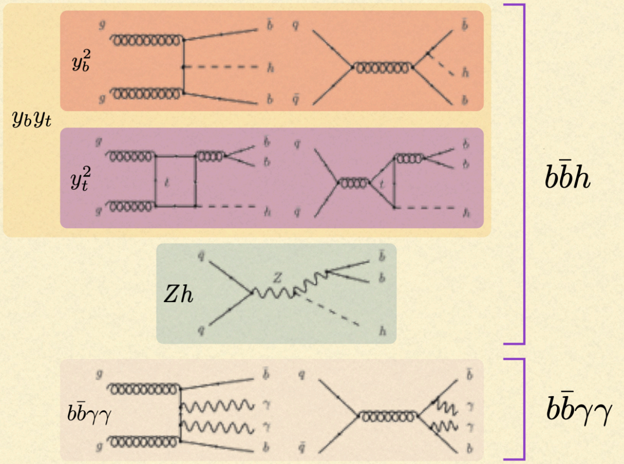
softly broken Z_2 $2HDM$: $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2$

softly broken Z_2 $N2HDM$: $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2;\ \Phi_S \to \Phi_S$

exact Z_2' $N2HDM$: $\Phi_1 \to \Phi_1;\ \Phi_2 \to \Phi_2;\ \Phi_S \to -\Phi_S$

Resurrecting $b\bar{b}h$ with kinematic shapes

Grojean, Paul, Qian, arXiv 2011.13945



Traditional cut-based analysis cannot separate the different $b\bar{b}h$ contributions – no y_b sensitivity at HL-LHC

Basic selection (14 TeV HL-LHC):

signals

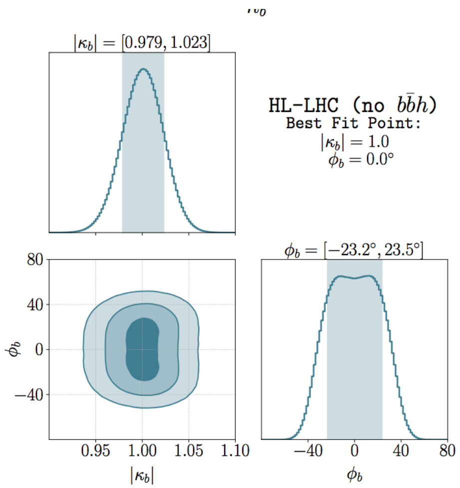
Channel	LO σ (fb)	NLO-k-fact	6 ab^{-1} [#evt]	$2b$-jets[%]
y_b^2	0.0648	1.5	583	7.7%
$y_b y_t$	-0.00829	1.9	-95	4.0%
y_t^2	0.123	2.5	1,840	12%
Zh	0.0827	1.3	645	21%
$\sum b\bar{b}h$	0.262	-	2,970	-
$b\bar{b}\gamma\gamma$	12.9	1.5	116,000	14%

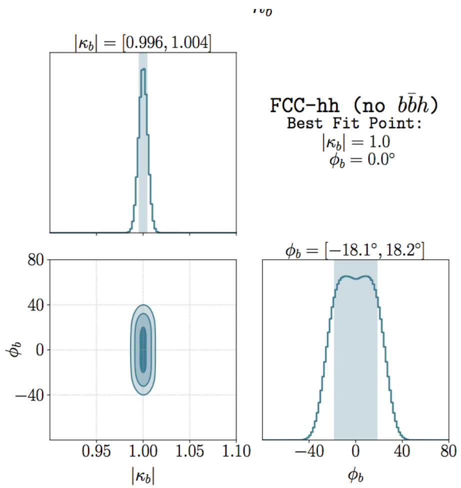
$b\bar{b}h$ background

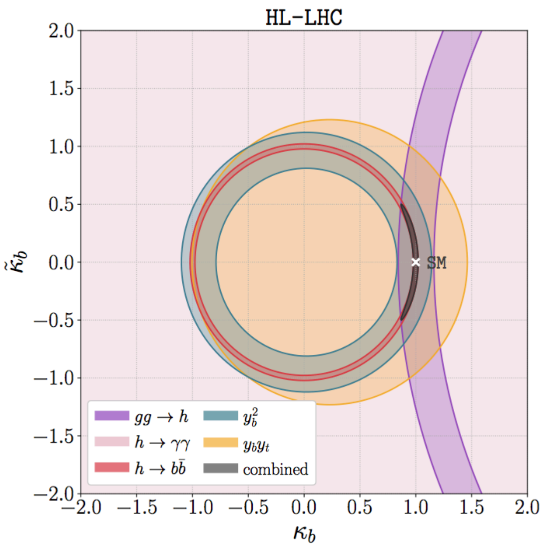
QCD-QED background

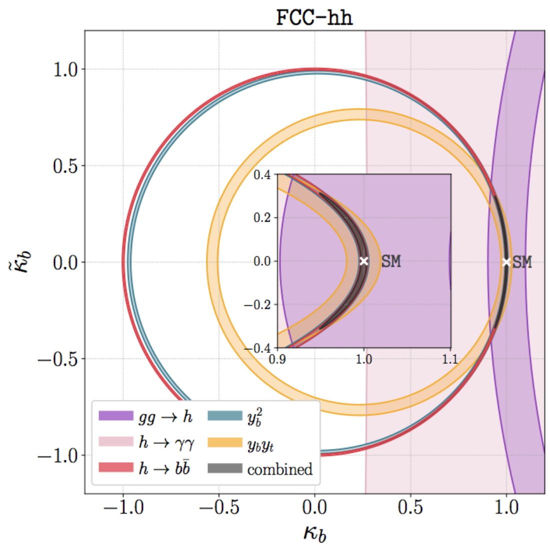
$$p_T^{bjet} > 30\,\text{GeV},\ p_T^{\gamma jet} > 20\,\text{GeV},$$
$$\eta_{bjet,\gamma jet} < 2.5,\ 110 < m_{\gamma\gamma}\,(\text{GeV}) < 140.$$

SLIDE FROM
Zhuoni Qian, HPNP2021
March 25th 2021









What are the experiments doing?

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

EFFECTIVE LAGRANGIAN (CMS NOTATION)

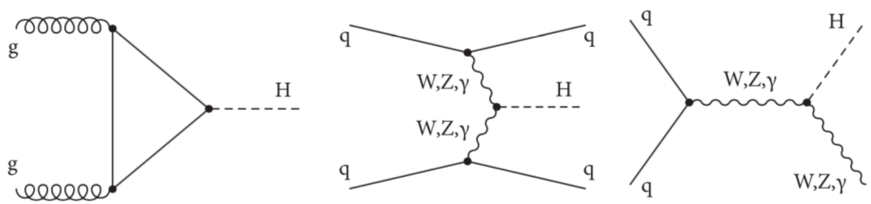


FIG. 1. Examples of leading-order Feynman diagrams for H boson production via the gluon fusion (left), vector boson fusion (middle), and associated production with a vector boson (right). The HWW and HZZ couplings may appear at tree level, as the SM predicts. Additionally, HWW, HZZ, $HZ\gamma$, $H\gamma\gamma$, and Hgg couplings may be generated by loops of SM or unknown particles, as indicated in the left diagram but not shown explicitly in the middle and right diagrams.

CMS collaboration, PRD100 (2019) 112002.

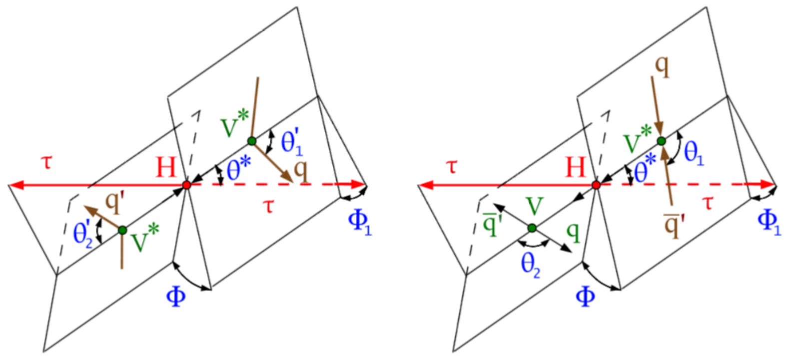


FIG. 2. Illustrations of H boson production in $qq' \to gg(qq') \to H(qq') \to \tau\tau(qq')$ or VBF $qq' \to V^*V^*(qq') \to H(qq') \to \tau\tau(qq')$ (left) and in associated production $q\bar{q}' \to V^* \to VH \to q\bar{q}'\tau\tau$ (right). The $H \to \tau\tau$ decay is shown without further illustrating the τ decay chain. Angles and invariant masses fully characterize the orientation of the production and two-body decay chain and are defined in suitable rest frames of the V and H bosons, except in the VBF case, where only the H boson rest frame is used [26,28].

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{\Lambda 1},$$

$$f_{\Lambda 1}^{Z\gamma} = \frac{\tilde{\sigma}_{\Lambda 1}^{Z\gamma}/(\Lambda_1^{Z\gamma})^4}{|a_1|^2\sigma_1 + \tilde{\sigma}_{\Lambda 1}^{Z\gamma}/(\Lambda_1^{Z\gamma})^4 + \cdots}, \qquad \phi_{\Lambda 1}^{Z\gamma},$$

$$\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}} = c_W \in [-0.81, 0.31]$$

Is it worth it?

The SM contribution arise from the CKM phase δ, and should therefore be proportional to the Jarlskog invariant $J = \mathrm{Im}(V_{ud}V_{cd}^{*}\,V_{cs}V_{cd}^{*}) = 3.00\times10^{-5}$. So, the CPV $hW^{+}W^{-}$ vertex can only be generated at two-loop so that we have enough CKM matrix element insertions in the corresponding Feynman diagrams.

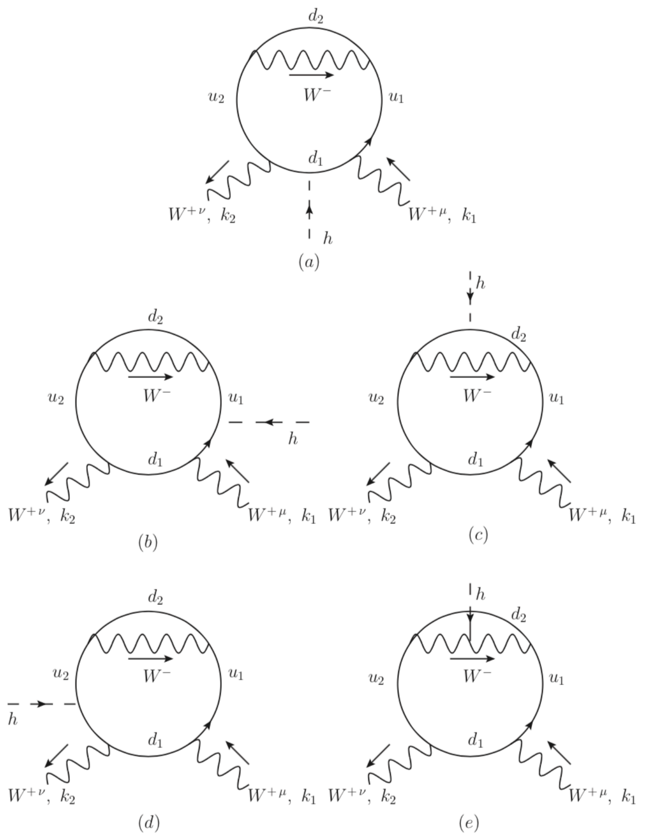


Figure 1. Feynman diagrams leading to the CPV $hW^{+}W^{-}$ coupling in the SM.

$$i\mathcal{M}_{(b)} \sim -\frac{N_c J}{v}\left(\frac{g}{\sqrt{2}}\right)^4 \int_{l_1}\int_{l_2}\left(\frac{g_{\rho\sigma} - l_{2\,\rho} l_{2\,\sigma}/m_W^2}{l_2^2 - m_W^2}\right)$$
$$\times \mathrm{Tr}[\gamma^\mu \not{l}_1 \gamma^\nu (\not{l}_1 + \not{k}_2)\gamma^\sigma(\not{l}_1 + \not{l}_2 + \not{k}_2)\gamma^\rho(2\not{l}_1 + \not{k}_1 + \not{k}_2)P_R]$$
$$\times \frac{\prod_{i>j}(m_{u_i}^2 - m_{u_j}^2)(m_{d_i}^2 - m_{d_j}^2)(l_1+k_1)^2[(l_1+l_2+k_2)^2 - l_1^2]}{\prod_i[(l_1+k_1)^2 - m_{u_i}][(l_1+k_2)^2 - m_{u_i}^2](l_1^2 - m_{d_i}^2)[(l_1+l_2+k_2)^2 - m_{d_i}^2]} \quad (2.6)$$

Very complicated, so you estimate

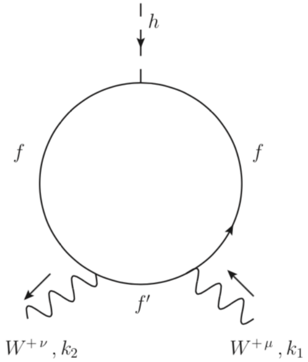
SM estimate

$$|c_{\mathrm{CPV}}^{\mathrm{SM}}| \sim \frac{N_c J}{(16\pi^2)^2}\left(\frac{g}{\sqrt{2}}\right)^4 \frac{\prod_{i>j}(m_{u_i}^2 - m_{u_j}^2)(m_{d_i}^2 - m_{d_j}^2)}{m_W^{12}} \simeq 9.1\times10^{-24} \sim \mathcal{O}(10^{-23})$$

Is it worth it?

$$c_{\text{CPV}} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

THE C2HDM



Starting with f=t and f'=b

HUANG, MORAIS, RS, JHEP 01 (2021) 168

$$\begin{aligned} i\mathcal{M}_{tb}^{\text{C2HDM}} &= (-1)N_c \int_l \text{Tr}\Bigg[\left(-\frac{ig}{\sqrt{2}}V_{tb}\gamma_\mu P_L\right)\frac{i}{\not{l}-m_b}\left(-\frac{ig}{\sqrt{2}}V_{tb}^*\gamma_\nu P_L\right)\frac{i}{\not{l}+\not{k}_2-m_t} \\ &\quad\times\left(-i\frac{m_t}{v}\right)(c_t^e+ic_t^o\gamma_5)\frac{i}{\not{l}+\not{k}_1-m_t}\Bigg] \\ &= -\frac{N_c g^2 m_t |V_{tb}|^2}{2v}\frac{\text{Tr}[\gamma_\mu\not{l}\gamma_\nu P_L(\not{l}+\not{k}_2+m_t)(c_t^e+ic_t^o\gamma_5)(\not{l}+\not{k}_1+m_t)]}{(l^2-m_b^2)[(l+k_2)^2-m_t^2][(l+k_1)^2-m_t^2]} \cdot (\end{aligned}$$

We can now extract the operator for this case

$$i\mathcal{M}_{tb}^{\text{C2HDM}} \sim \frac{ig^2N_c c_t^o}{16\pi^2 v}\frac{m_t^2}{m_W^2}|V_{tb}|^2\epsilon_{\mu\nu\rho\sigma}k_1^\rho k_2^\sigma \mathcal{I}_1\left(\frac{m_t^2}{m_W^2},\frac{m_b^2}{m_W^2}\right) \qquad \mathcal{I}_1(x,y) \equiv \int_0^1 d\alpha \frac{\alpha^2}{\alpha x+(1-\alpha)y-\alpha(1-\alpha)}$$

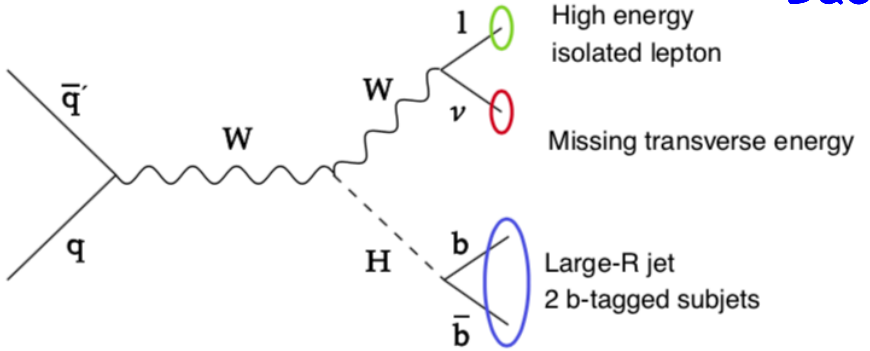
And because f=b and f'=t can also contribute, the final result is

$$c_{\text{CPV}}^{\text{C2HDM}} = \frac{N_c g^2}{32\pi^2}|V_{tb}|^2\left[\frac{c_t^o m_t^2}{m_W^2}\mathcal{I}_1\left(\frac{m_t^2}{m_W^2},\frac{m_b^2}{m_W^2}\right)+\frac{c_b^o m_b^2}{m_W^2}\mathcal{I}_1\left(\frac{m_b^2}{m_W^2},\frac{m_t^2}{m_W^2}\right)\right]$$

$$c_{\text{CPV}}^{\text{C2HDM}} \simeq 6.6\times10^{-4} \sim \mathcal{O}(10^{-3})$$

USING THE BOUNDS CALCULATED BEFORE.

Back to experiment



If indeed it is worth it, let us look at other processes to look for CP-violation in VVh

Godbole, Miller, Mohan, White, JHEP 15 (2015) 4.
Barrué, MSc thesis, 2020
Barrué, Conde-Muiño, Dao, RS, work in progress

$$i\Gamma^{\mu\nu}_{hWW} = i(g_2 m_w)\left[g^{\mu\nu}\left(1 + a_W - \frac{b_{W1}}{m_W^2}(k_1 \, . \, k_2)\right) + \frac{b_{W2}}{m_W^2}\, k_1^\nu k_2^\mu + \frac{c_W}{m_W^2}\epsilon^{\mu\nu\rho\sigma} k_{1\rho} \, . \, k_{2\sigma})\right]$$

- 4 benchmark couplings, $\sqrt{s} = 14$ TeV
  - $a_W = c_W = 0, b_{W1} = 0.05$; $a_W = c_W = 0, b_{W1} = 0.1$
  - $a_W = b_{W1} = 0, c_W = 0.05$; $a_W = b_{W1} = 0, c_W = 0.1$
  - generated SM-like sample ($a_W = b_{W1} = c_W = 0$) for comparison purposes

$$\cos\theta^* = \frac{\mathrm{p}_\ell^{(W)} \cdot \mathrm{p}_W}{|\mathrm{p}_\ell^{(W)}||\mathrm{p}_W|} \qquad \cos\delta^+ = \frac{\mathrm{p}_\ell^{(W)} \cdot (\mathrm{p}_H \times \mathrm{p}_W)}{|\mathrm{p}_\ell^{(W)}||\mathrm{p}_H \times \mathrm{p}_W|}$$

- $\mathrm{p}_\ell^{(W)}$: 3-momentum of electron or muon in the W boson rest frame
  - all other 3-momenta are defined in the lab frame.

Pre-Preliminary!

Slide from Ricardo Barrué MSc thesis.

$\cos\delta^+$ asymmetry

High purity signal region, $p_{T_W} > 250$ GeV

$$A(\cos\delta^+) = \frac{N(\cos\delta^+ > 0) - N(\cos\delta^+ < 0)}{N(\cos\delta^+ > 0) + N(\cos\delta^+ < 0)} \quad (2)$$

Samples	$A(\cos\delta^+)$ (stat. unc.)
Backgrounds	0.003 ± 0.028
SM	-0.002 ± 0.133
SM + $b_{w1} = 0.05$	0.142 ± 0.087
SM + $b_{w1} = 0.1$	-0.081 ± 0.055
SM + $c_w = 0.05$	-0.319 ± 0.112
SM + $c_w = 0.1$	-0.123 ± 0.082

- for CP-even signals, asymmetry is non-zero, different signs
- for CP-odd signals, asymmetry decreases with value of coupling
- generated luminosities are higher than current luminosity
  - differences start to be visible, higher luminosities are necessary

CMS PAS FTR-18-011

Table 10: Summary of the 95% CL intervals for $f_{a3}\cos(\phi_{a3})$, under the assumption $\Gamma_H = \Gamma_H^{SM}$, and for Γ_H under the assumption $f_{ai} = 0$ for projections at $3000\,\text{fb}^{-1}$. Constraints on $f_{a3}\cos(\phi_{a3})$ are multiplied by 10^4. Values are given for scenarios S1 (with Run 2 systematic uncertainties [47]) and the approximate S2 scenario, as described in the text.

Parameter	Scenario	Projected 95% CL interval
$f_{a3}\cos(\phi_{a3}) \times 10^4$	S1, only on-shell	$[-1.8, 1.8]$
$f_{a3}\cos(\phi_{a3}) \times 10^4$	S1, on-shell and off-shell	$[-1.6, 1.6]$
Γ_H (MeV)	S1	$[2.0, 6.1]$
Γ_H (MeV)	S2	$[2.0, 6.0]$

$$\gamma/\kappa = c_z = \mathcal{O}(10^{-2})$$

The fraction as defined below is related to the effective coupling

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

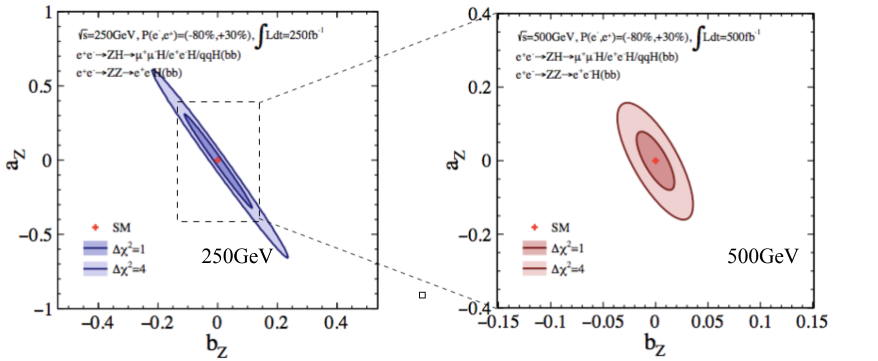
σ_i = (cross section for a_i-term with $a_i = 1$)

$\tilde{\sigma}_{\Lambda 1}$ = (cross section for the Λ_1-term with $\Lambda_1 = 1$ TeV) $\times$ [TeV]^4

Anomalous ZZH/γZH couplings

3-parameter fit

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H \quad (\Lambda=1\text{TeV})$$



5-parameter fit

$ZH + ZZ$ at $250 + 500$ GeV with $H20$

https://arxiv.org/abs/1506.07830

1σ bounds including 500 GeV operation

$$\begin{cases} a_Z = \pm 0.0223 \quad (\eta_Z = \pm 0.5\%) \\ \zeta_{ZZ} = \pm 0.0067 \\ \zeta_{AZ} = \pm 0.0024 \\ \tilde{\zeta}_{ZZ} = \pm 0.0109 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -.837 & -.134 & -.009 & -.010 \\ - & 1 & .040 & .008 & .013 \\ - & - & 1 & .006 & -.0012 \\ - & - & - & 1 & .600 \\ - & - & - & - & 1 \end{pmatrix}$$

ZZH / γZH structures can be measured to ~0.5%

Slide from Keisuke Fujii's presentation at Higgs Couplings 2018, Tokyo

The most comprehensive study for futures colliders so far was performed for the ILC. The work presents results are for polarised beams $P(e^-, e^+) = (-80\%, 30\%)$ and two COM energies 250 GeV (and an integrated luminosity of 250 fb^{-1}) and 500 GeV (and an integrated luminosity 500fb^{-1}). Limits obtained for an energy of 250 GeV were $c^W_{CPV} \in [-0.321, 0.323]$ and $c^Z_{CPV} \in [-0.016, 0.016]$. For 500 GeV we get $c^W_{CPV} \in [-0.063, 0.062]$ and $c^Z_{CPV} \in [-0.0057, 0.0057]$.

Ogawa, PhD Thesis (2018)

Therefore models such as the C2HDM may be within the reach of these machines. can be used to constraint the C2HDM at loop-level