CP-violation at the LHC

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LIP

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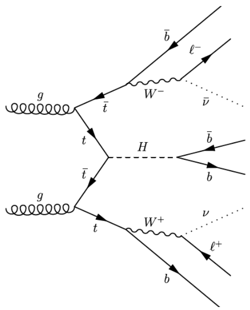
Scalar Extensions of the SM - why do they make us happy?

- 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 one needs to find at least 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's CP depend on the final state.

Our benchmark model - the C(2HDM)

In the SM the Higgs potential has only one quadratic and one quartic term

$$V_{SM} = \mu^2 |\Phi|^2 + \lambda(\Phi^\dagger\Phi)^2; \quad \mu^2 < 0; \quad \lambda > 0.$$

with the SU(2) Higgs field defined as

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \rho + i\eta) \end{pmatrix}$$

We end up with the SM Higgs boson and three Goldstone bosons. This potential does not allow for C or P violation, either explicit or spontaneously.

The potential has a minimum at

$$v = \sqrt{\frac{|\mu^2|}{\lambda}} = 246\,\text{GeV}$$

Which defines the electroweak scale

The Higgs mass is given by

$$m_h^2 = 2\lambda v^2 = \sqrt{2}\,|\mu|$$

and has to be determined experimentally.

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

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

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).

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

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

Lightest Higgs coupling modifiers

Type I $\quad \kappa^I_U = \kappa^I_D = \kappa^I_L = \frac{\cos\alpha}{\sin\beta}$

Type II $\quad \kappa^{II}_U = \frac{\cos\alpha}{\sin\beta} \qquad \kappa^{II}_D = \kappa^{II}_L = -\frac{\sin\alpha}{\cos\beta}$

Type F(Y) $\quad \kappa^F_U = \kappa^F_L = \frac{\cos\alpha}{\sin\beta} \qquad \kappa^F_D = -\frac{\sin\alpha}{\cos\beta}$

Type LS(X) $\quad \kappa^{LS}_U = \kappa^{LS}_D = \frac{\cos\alpha}{\sin\beta} \qquad \kappa^{LS}_L = -\frac{\sin\alpha}{\cos\beta}$

These are coupling modifiers relative to the SM coupling for the CP-conserving version of the 2HDM. Yukawa couplings can be larger than the SM ones.

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

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 if CP is broken.

<u>THE ALIGNMENT LIMIT</u> - IT IS A LIMIT WHERE ALL COUPLINGS TO A CHOSEN SCALAR ARE THE EXACTLY THE SM ONES.

CP violation from P violation -

assuming C and P are conserved separately

C and P numbers for the fields we know

The P and C transformations for a spin 1 field are (I will omit the fact that $\vec{r} \to -\vec{r}$ in the RHS)

$$CX_\mu C^{-1} = (-1)^C X_\mu; \quad PX_\mu P^{-1} = \pm X^\mu$$

For a real spin 0 field the P and C transformations are

$$C\phi C^{-1} = (-1)^C \phi; \quad P\phi P^{-1} = (-1)^P \phi$$

For spin 1/2 fields only the P and C of the pair can be measured

	P	C	CP
$\bar{\psi}\psi$	$\bar{\psi}\psi$	$\bar{\psi}\psi$	$\bar{\psi}\psi$
$\bar{\psi}\gamma_5\psi$	$-\bar{\psi}\gamma_5\psi$	$\bar{\psi}\gamma_5\psi$	$-\bar{\psi}\gamma_5\psi$
$\bar{\psi}\gamma_\mu\psi$	$\bar{\psi}\gamma^\mu\psi$	$-\bar{\psi}\gamma_\mu\psi$	$-\bar{\psi}\gamma^\mu\psi$
$\bar{\psi}\gamma_\mu\gamma_5\psi$	$-\bar{\psi}\gamma^\mu\gamma_5\psi$	$\bar{\psi}\gamma_\mu\gamma_5\psi$	$-\bar{\psi}\gamma^\mu\gamma_5\psi$

Dimension 4 InteractionTerms without fermions

Consider a gauge theory of spin-0 and spin-1 fields. The terms with neutral gauge bosons can be of the form

$$X_\mu X^\mu, \qquad X_\mu \partial^\mu$$

The more general couplings to scalars may have the form

$$X_\mu X^\mu AB, \qquad X_\mu \partial^\mu AB \qquad\qquad P(AB)P^{-1} = AB$$

In a P-conserving theory A and B have the same P-numbers. If there is at least one P-even scalar, the other scalar is also P-even. In the SM (due to spontaneous symmetry breaking)

$$hZZ \quad \Rightarrow \quad PhP^{-1} = h$$

Therefore all neutral Higgs that mix with the Higgs will be even under P. Clearly, in most scalar extensions of the SM where P is conserved, all scalars can be considered P-even.

Dimension 4 InteractionTerms without fermions

Let us now look at C-invariance. From the previous P-invariant terms

$$X_\mu X^\mu, \qquad X_\mu \partial^\mu$$

the first one is C-invariant while the second depends on the C-number of X_μ. The more general couplings are again

$$X_\mu X^\mu AB, \qquad C(AB)C^{-1} = AB$$

$$X_\mu \partial^\mu AB \qquad C(AB)C^{-1} = AB\ CX_\mu C^{-1}$$

If X_μ is C-even, A and B need to have the same C numbers. In the SM, the neutral gauge bosons are C-odd and this means that A and B need to have opposite C-numbers and the vertices of the type $X_\mu X^\mu AB$ is not allowed.

$$C(A) = -\,C(B)$$

Otherwise C is not conserved. Therefore, in the absence of fermions, invariance under P is guaranteed. <u>If the bosonic Lagrangian violates CP, CP-violation must be associated with a P-conserving C-violating observable.</u>

C and P in the SM without fermions

For the photon we have

$$CA_\mu C^{-1} = -A_\mu; \quad PA_\mu P^{-1} = A^\mu$$

By construction, the Z-boson has the same quantum numbers

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

The coupling with the Z fixes the Higgs C and P quantum numbers

$$hZZ \quad \Rightarrow \quad ChC^{-1} = h \quad PhP^{-1} = h$$

The neutral Nambu-Goldstone boson is the longitudinal component of the Z and so

$$P\partial^\mu G_0 Z_\mu P^{-1} = \partial_\mu G_0 Z^\mu \quad C\partial^\mu G_0 Z_\mu C^{-1} = \partial_\mu G_0 Z^\mu$$

And therefore

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

C and P in a 2HDM without fermions

Let us introduce one extra scalar - an SU(2) doublet. We have now eight degrees of freedom. Three are for the Goldstone bosons, two for the charged Higgs and three for the neutral states

$G^{\pm}, H^{\pm}$

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

The spectrum includes 3 neutral scalars. h_1, h_2 and h_3 are ordered by mass.

G_0, h, H, A or G_0, h_1, h_2, h_3

If the vertices of the type hhh and HHH are present (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)

$$P\partial^\mu G_0 Z_\mu P^{-1} = \partial_\mu G_0 Z^\mu$$

Which means

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

So how do we know if the model violates CP via C-violation?

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 - the triple gauge bosons loops

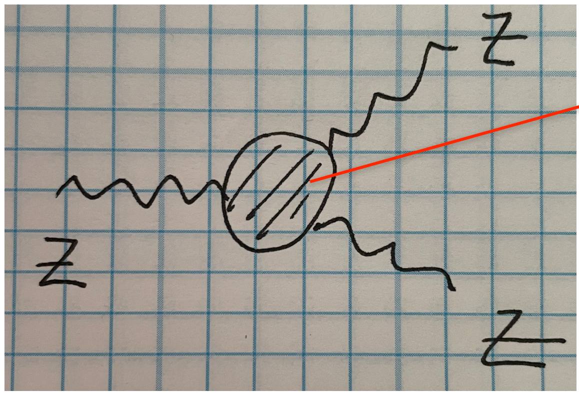
Assuming only Lorentz and $U(1)_{em}$ gauge invariance, the most general form of the ZZV (V = Z, γ), vertex can be written as

$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1, q_2, P) \;=\; \frac{i(P^2 - m_V^2)}{m_Z^2}\left[f_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) - f_5^V \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho\right]$$

where the two Z are on-shell, the V is off-shell but coupled to a conserved current. The corresponding operator is

$$\mathcal{L}_{NP} \;=\; \frac{e}{m_Z^2}\Big[-[f_4^\gamma(\partial_\mu F^{\mu\beta}) + f_4^Z(\partial_\mu Z^{\mu\beta})]Z_\alpha(\partial^\alpha Z_\beta) + [f_5^\gamma(\partial^\sigma F_{\sigma\mu}) + f_5^Z(\partial^\sigma Z_{\sigma\mu})]\widetilde{Z}^{\mu\beta} Z_\beta\Big]$$

P-CONSERVING CP-VIOLATING TERM



CP-VIOLATION IS INSIDE THE BLOB!

NOTE THAT THESE ARE DIMENSION SIX OPERATORS, THEY APPEAR AT ONE-LOOP IN RENORMALISABLE MODELS. THEY LEAD TO A FINITE RESULT WITH NO NEED FOR RENORMALISATION.

IN THE SM $f_4^V = 0$ AT ONE-LOOP.

CP violation from C violation - collider measurements

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

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

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

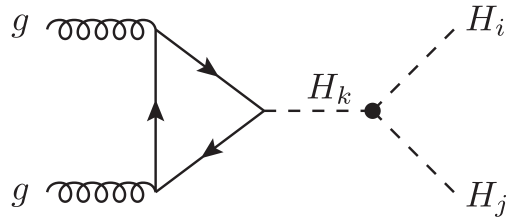
Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

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	



$$h_1 \to ZZ$$
$$h_3 \to h_1 h_1$$
$$h_3 \to h_1 Z$$

$$CP(h_3) = -CP(h_1)$$

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:

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

CP violation can appear only in the other scalars

In the alignment limit h_1 has exactly the SM couplings. In this case only if we find other particles a search for CP-violation makes sense.

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 signalling CP-violation is now

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

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

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

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

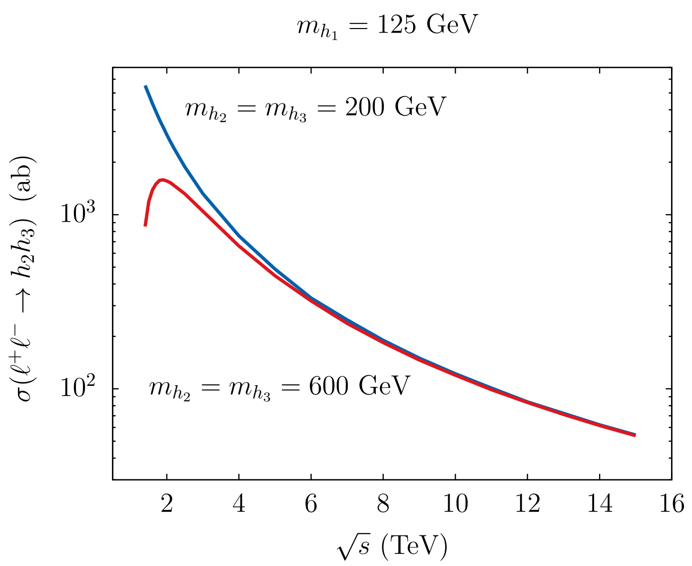
It could happen that at the end of the last LHC run we just move closer and closer to the alignment limit and to a very CP-even 125 GeV Higgs. Considering a few future lepton colliders

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

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

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

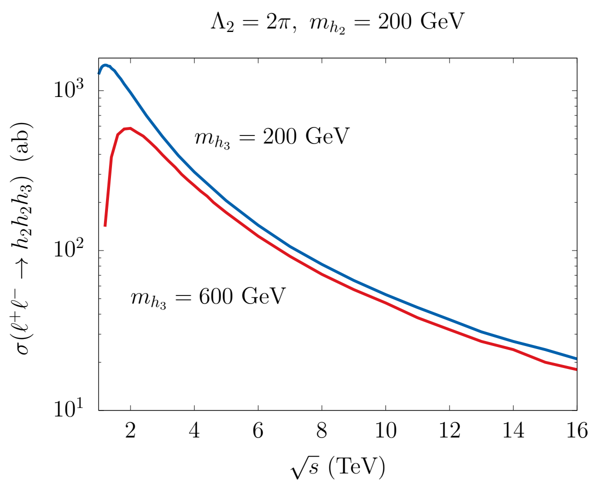
$$h_2h_kh_k; \quad h_3h_lh_l;\,; \quad Zh_2h_3; \quad (k,l=2,3)$$

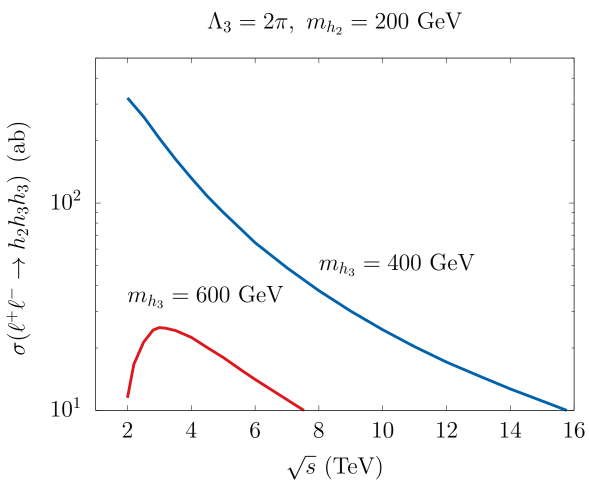


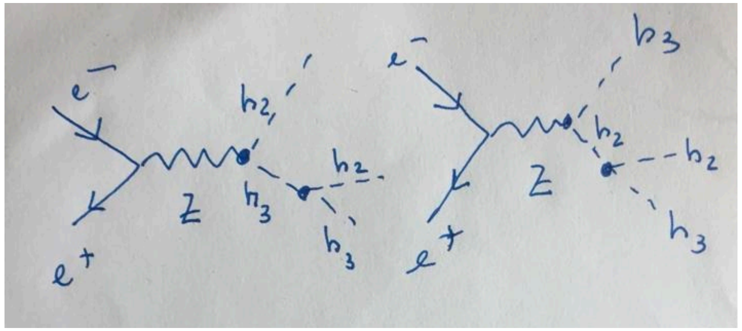
This is an s-channel process with a Z exchange and therefore a gauge coupling. We still need to detect the 2 scalars.

C2HDM at future colliders

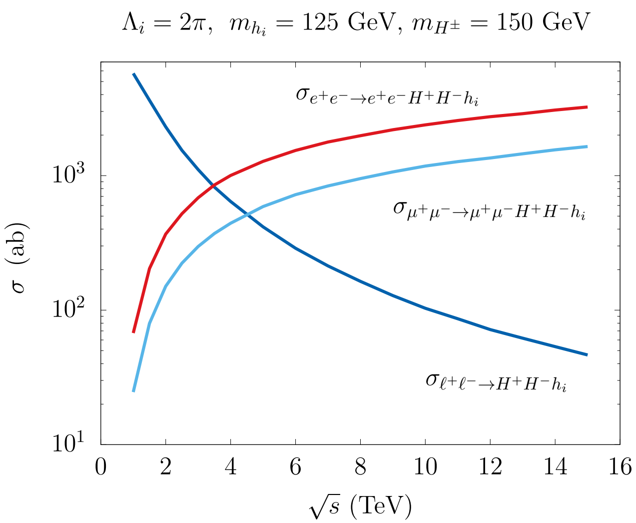
If the new particles are heavier we will need more energy. Still it will be a hard task.

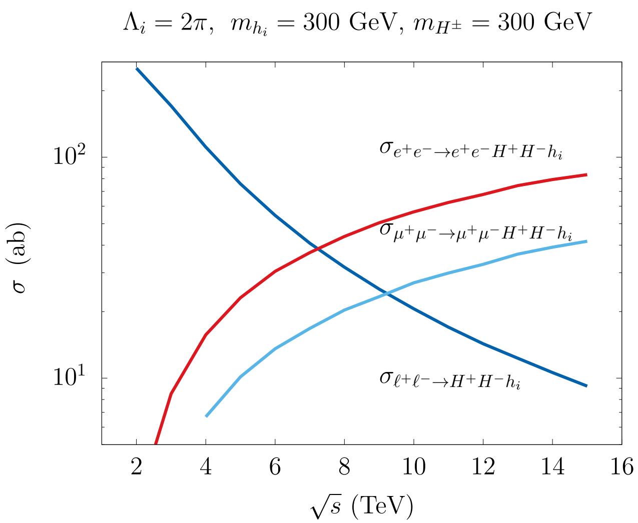


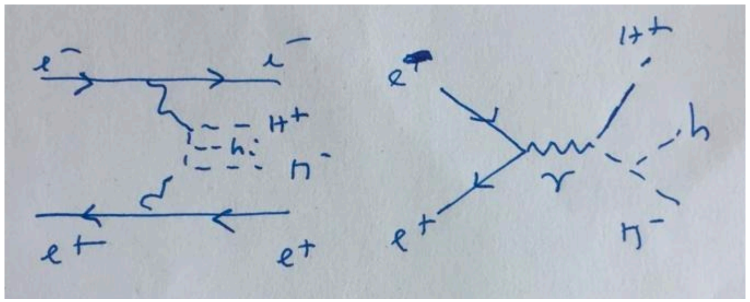




$$h_2 h_3 h_3; \quad h_3 h_2 h_2; \quad Z h_2 h_3$$

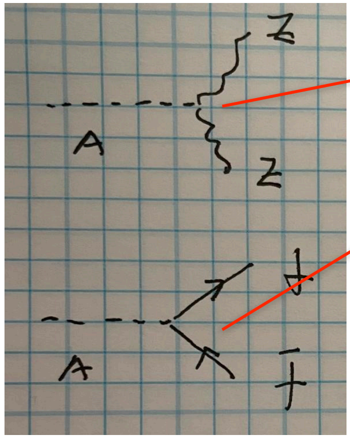






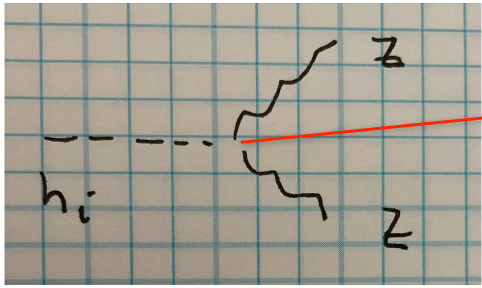
$$h_2 H^+ H^-; \quad h_3 H^+ H^-; \quad Z h_2 h_3$$

However…



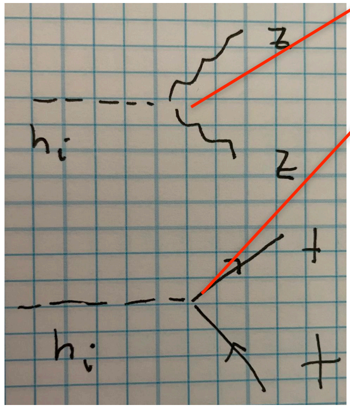
Disallowed in a CP conserving model. A is a pseudoscalar

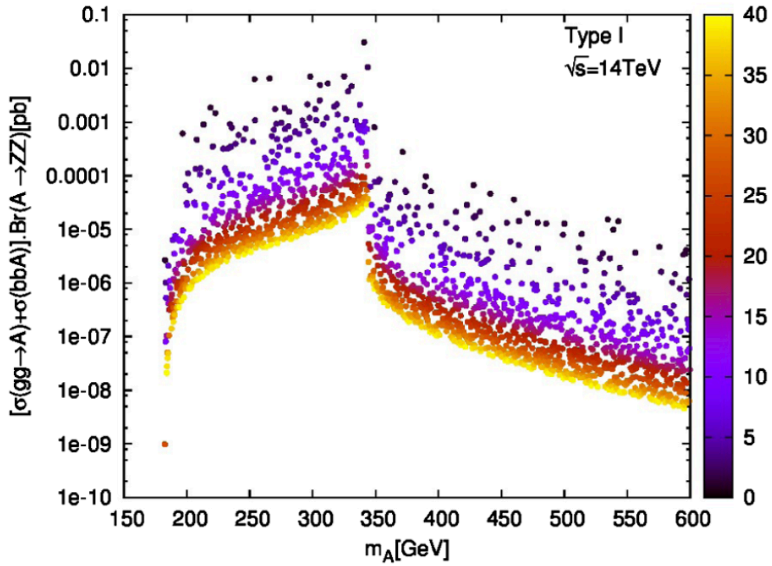
Allowed in a CP-conserving model.

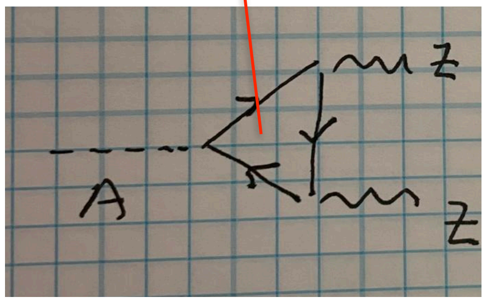


If this tree-level coupling is very small (of the order of the loop process below) it is not possible to distinguish the models.

Both allowed in a CP-violating model.







CP-violation from C-violation in loops

- also available in the dark version

CP violation from C violation but inside loops (ZZZ)

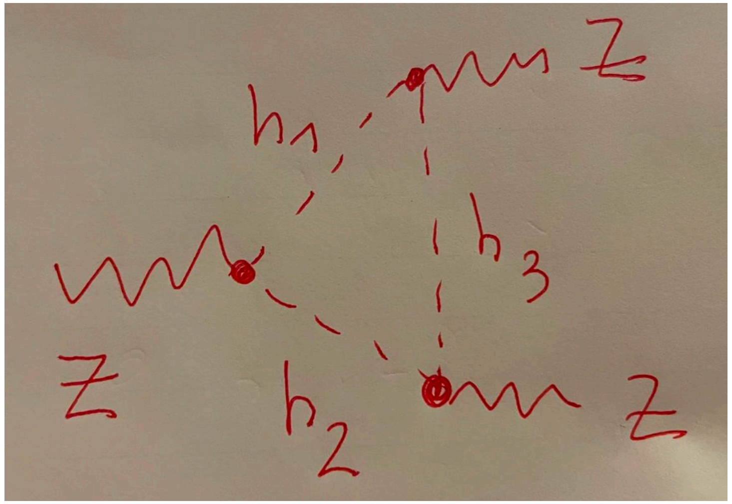
Another possibility of detecting P-even CP-violating signals is via loops. Remember CP violation could be seen via the combination

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

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

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

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 renormalisable potential

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

CP violating portal term ($A\Phi_1^\dagger\Phi_2\Phi_S + h.c.$)

CP conserving portal terms (λ_3, λ_4, λ_7 terms)

and the vacuum preserves the symmetry

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

No VEVs - Z_2 is preserved - there are three DM candidates

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)

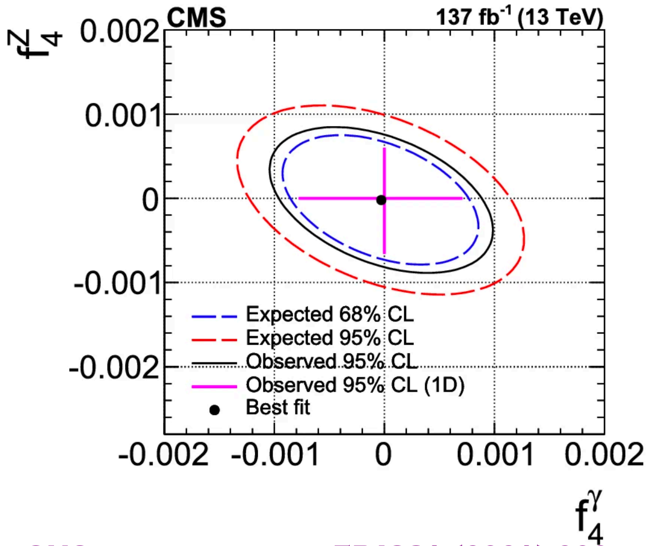
The most general form of the vertex includes a P-even CP-violating term of the form

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

GAEMERS, GOUNARIS, ZPC1 (1979) 259; HAGIWARA, PECCEI, ZEPPENFELD, HIKASA, NPB282 (1987) 253; GRZADKOWSKI, OGREID, OSLAND, JHEP 05 (2016) 025

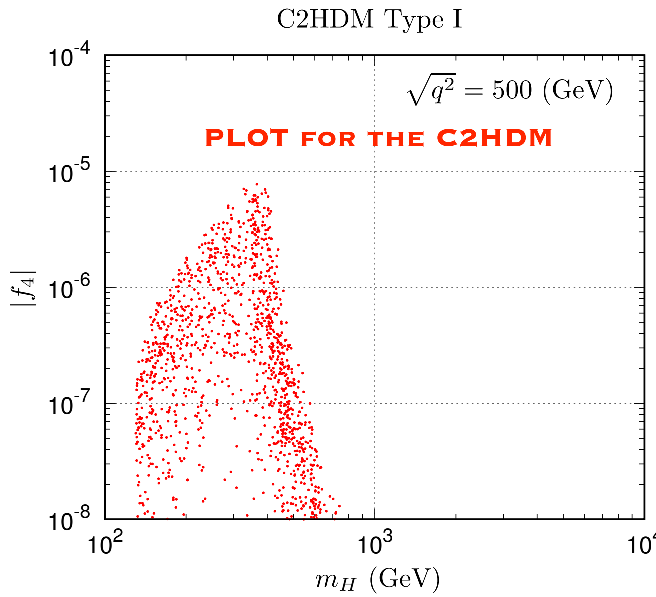
CMS COLLABORATION, EPJC78 (2018) 165. $-1.2\times10^{-3} < f_4^Z < 1.0\times10^{-3}$

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

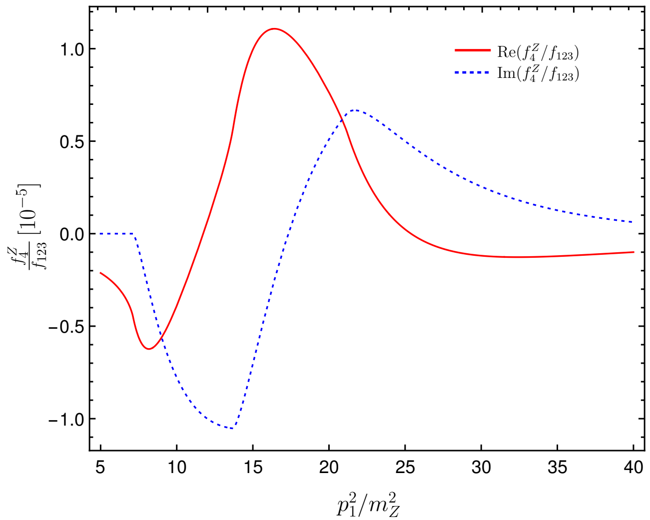


CMS COLLABORATION, EPJC81 (2021) 200.

FROM: BÉLUSCA-MAÏTO, FALKOWSKI, FONTES, ROMÃO, SILVA, JHEP 04 (2018) 002



PLOT FOR CP IN THE DARK



The invariant mass distribution of the four-lepton system is used to set limits on anomalous ZZZ and ZZγ couplings in $pp \to ZZ$.

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

CP violation from P violation

CP violation from P violation

As discussed, for a real spin 0 field the P and C transformations are

$$C\phi C^{-1} = (-1)^C \phi; \quad P\phi P^{-1} = (-1)^P \phi$$

and for spin 1/2 fields only the parity of the pair can be measured?

	P	C	CP
$\bar{\psi}\psi$	$\bar{\psi}\psi$	$\bar{\psi}\psi$	$\bar{\psi}\psi$
$\bar{\psi}\gamma_5\psi$	$-\bar{\psi}\gamma_5\psi$	$\bar{\psi}\gamma_5\psi$	$-\bar{\psi}\gamma_5\psi$

This means that a coupling of the type is P-violating and conserves C - it is CP-violating

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

Again higher order operators may violate CP via P violation as shown below

P-VIOLATING, CP VIOLATION

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

CP violation from P violation - the top Yukawa

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

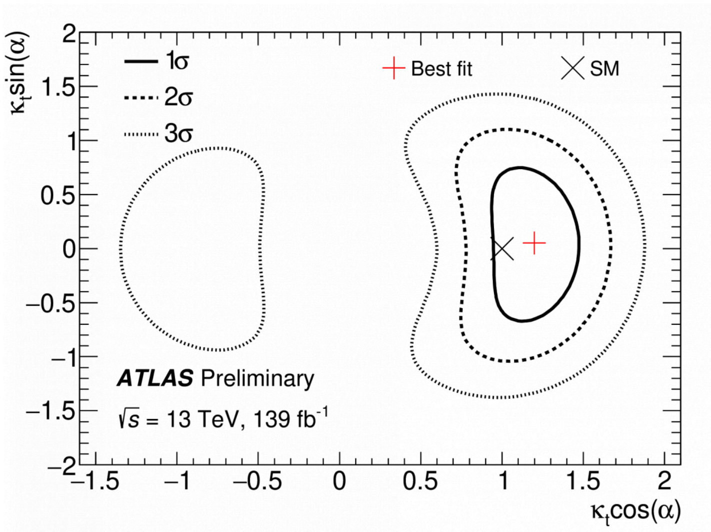
C conserving, CP violating interaction

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

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

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.



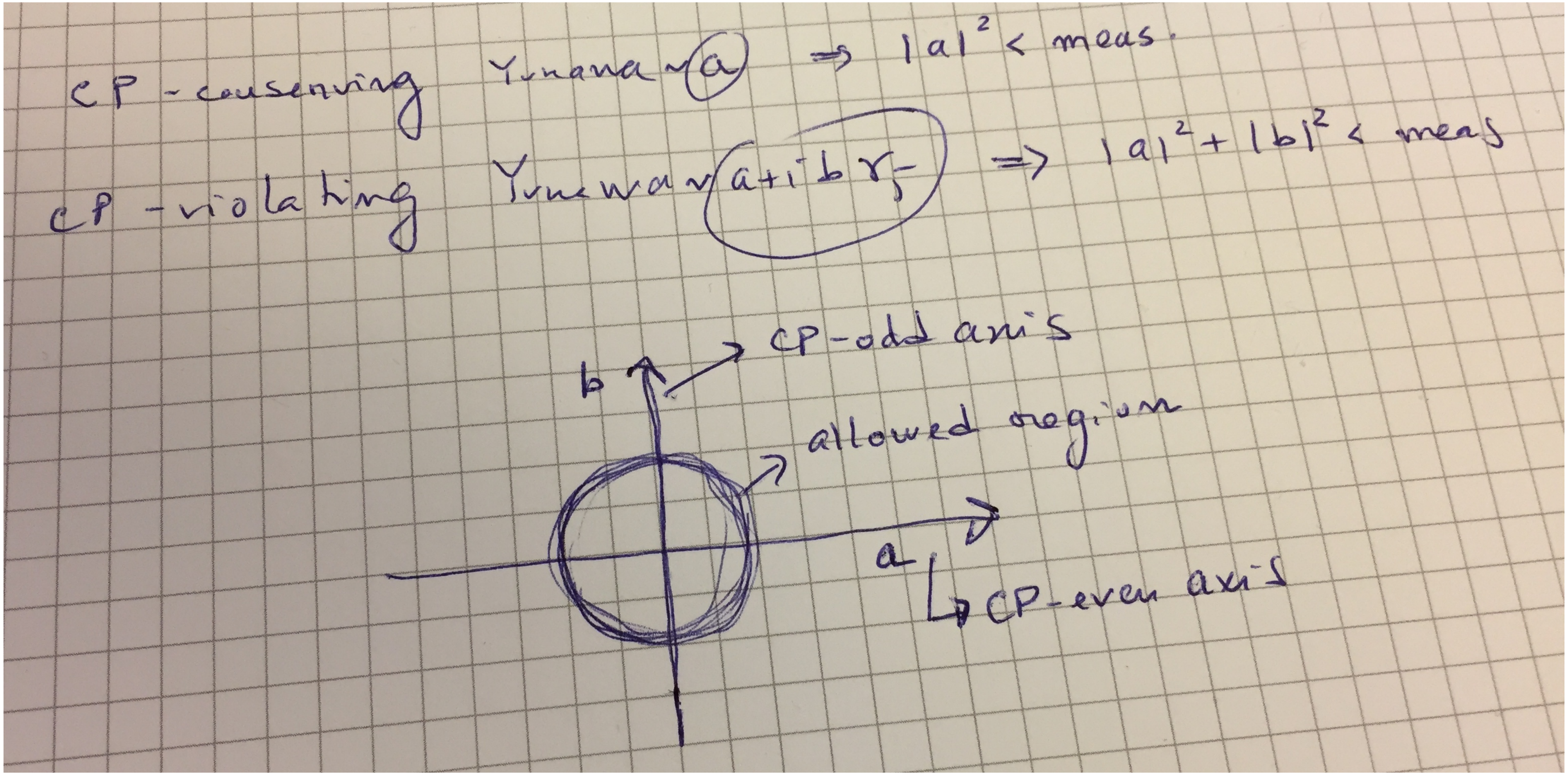
$$\mathcal{L}_{\bar{t}th}^{CPV} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h$$

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

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

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

Allowed region in the Yukawa plane



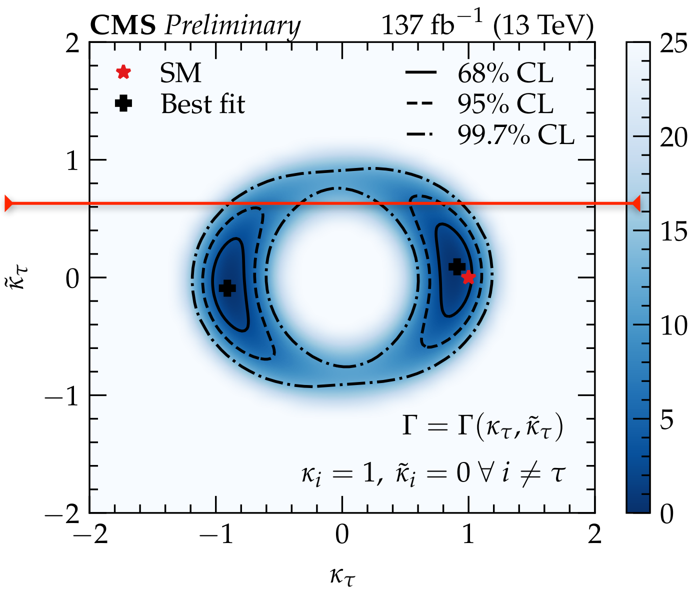
Measurement of CPV angle in ττh

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

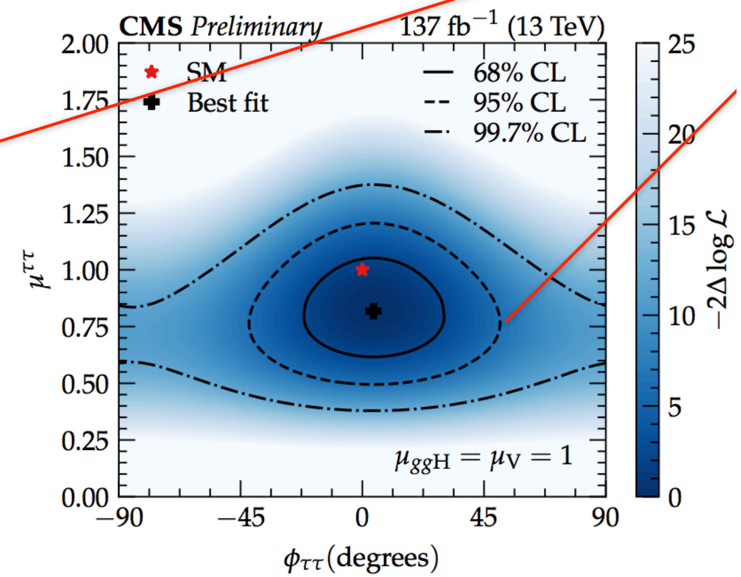
$$\mathcal{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\,h$$

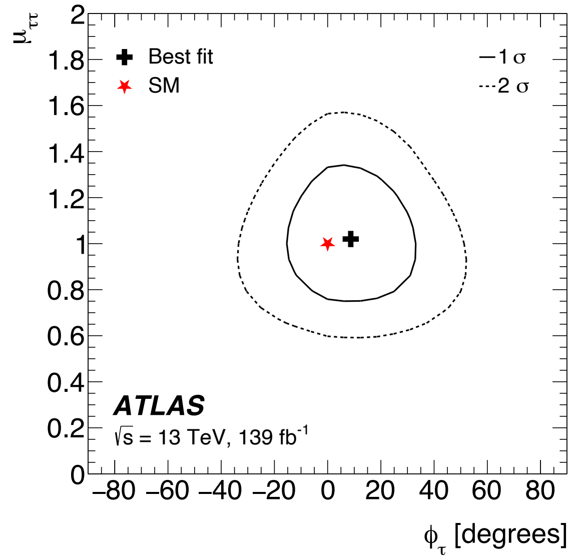
Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°. Compatible with SM predictions.

Scenario excluded at 95% CL



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





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

ATLAS collaboration, ArXiv:2212.05833v1.

What if?

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

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

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

Scalar

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

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

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

Pseudoscalar

This scenario is possible in the C2HDM

There is a different way to look at the same problem

$\alpha_1 = \pi/2$

$$\bar{t}(a_t + i b_t \gamma_5) t\, \phi \qquad b_t \approx 0 \qquad a_t \bar{t} t \phi$$ **Scalar**

$$\bar{\tau}(a_\tau + i b_\tau \gamma_5) \tau\, \phi \qquad a_\tau \approx 0 \qquad b_\tau \bar{\tau} \tau\, \phi$$ **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

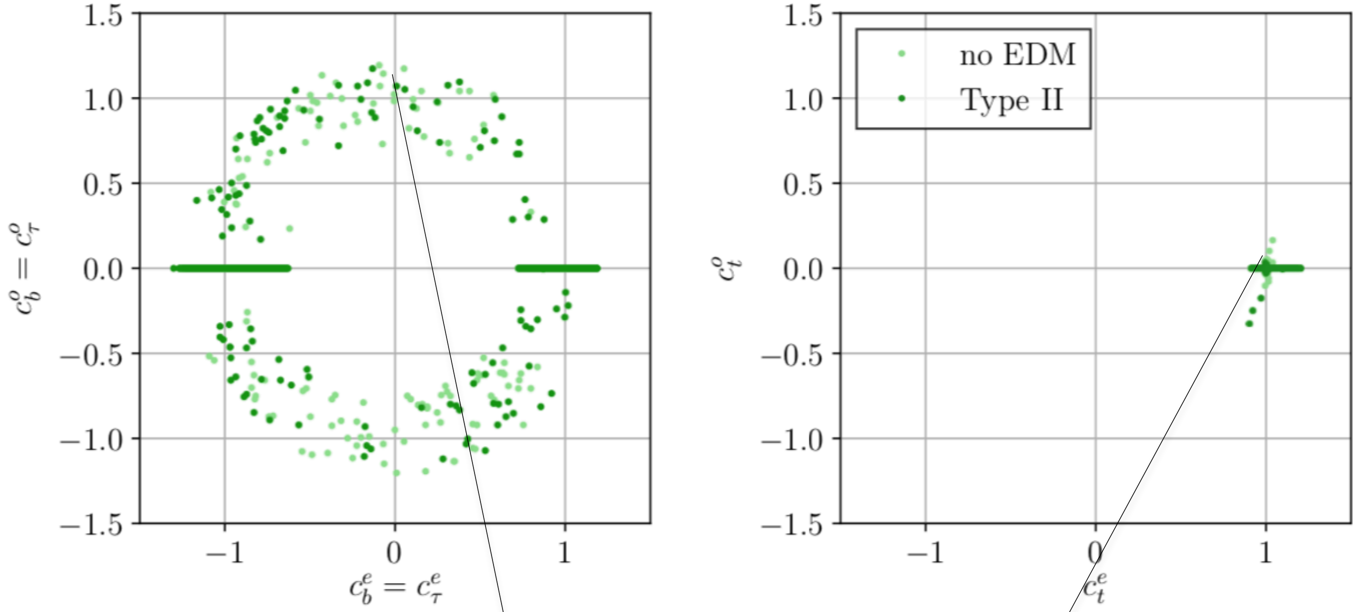
$$g^{hbb}_{C2HDM} = \left(-i \sin\alpha_2 \, \tan\beta\, \gamma_5 \right) g^{hff}_{SM}$$

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

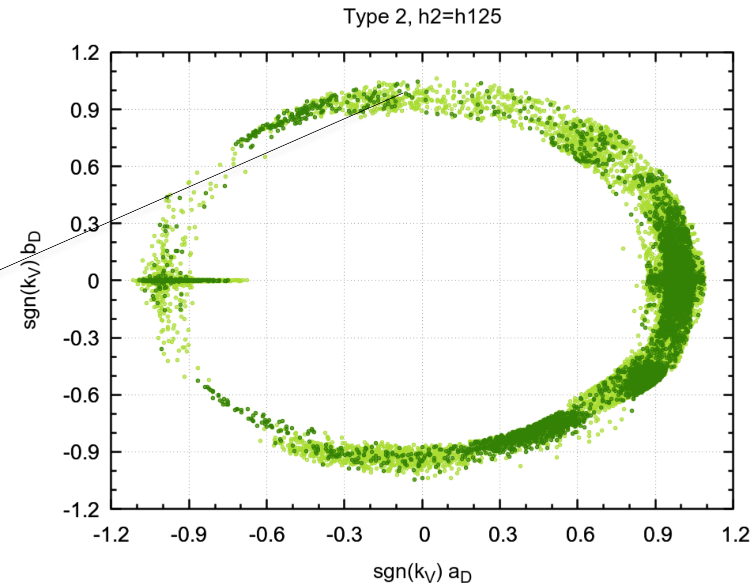
[ACME 18]

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

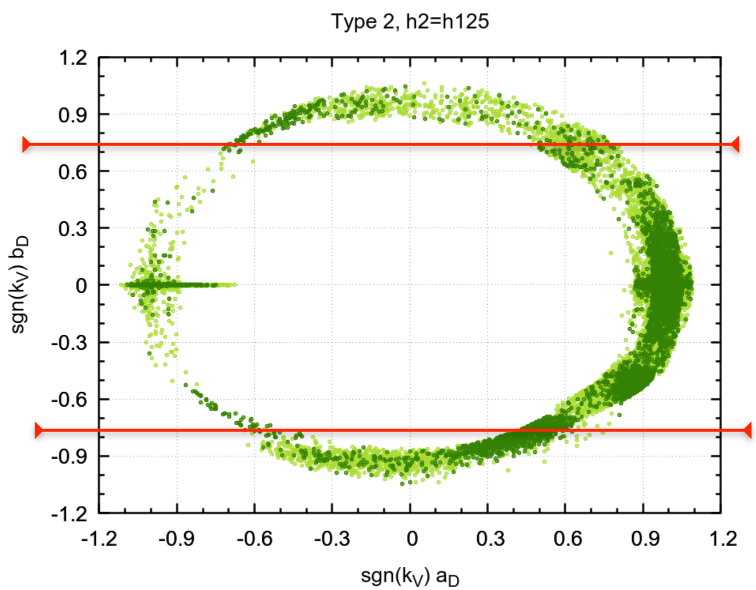
$$h_2 = H; pp \to Ht\bar{t}$$

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 beyond EDMs.

What about other combinations of Yukawa?

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

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

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

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

CP violation from P violation - a strange CP scenario

BIEKÖTTER, FONTES, MÜHLLEITNER, ROMÃO, RS, SILVA, JHEP 05 (2024) 127.

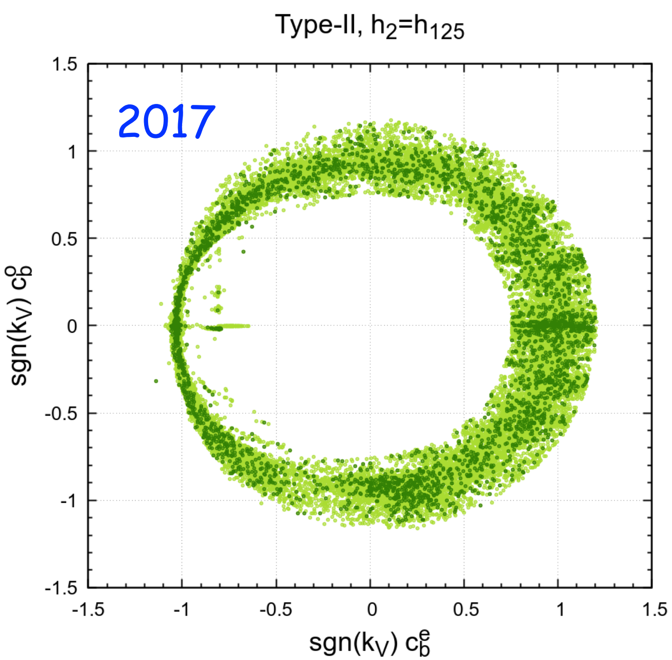
2017

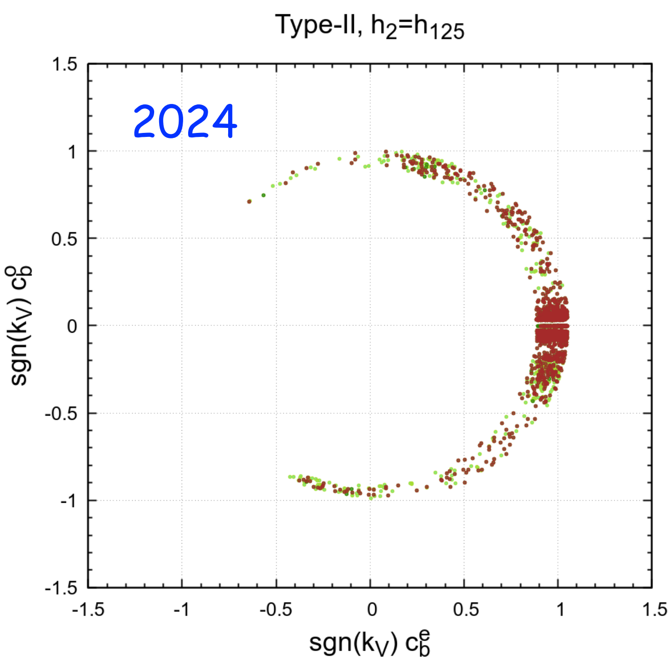
- 125 Higgs signal strengths from the combination of ATLAS and CMS collected at 7 TeV and 8 TeV;
- HiggsBounds 4.3.1 for data from searches for additional scalars;
- The electron dipole moment (eEDM) limit of 8.7×10^{-29} e.cm;
- The lower bound of 580 GeV on the charged Higgs mass from B-meson decays in the Type II and Flipped models.

2024 Recently we analysed this scenario with all new data.

- 125 Higgs signal strengths ATLAS and CMS with all Run 2 data collected at 13 TeV;
- HiggsBounds 5.7.1 for data from searches for additional scalars with all available LHC data;
- The electron dipole moment (eEDM) limit of 1.1×10^{-29} e.cm (ACME) and 4.1×10^{-30} e.cm (JILA);
- Updates bounds on the mass of the charged Higgs bosons from B-meson decays (discussion later);
- The impact of direct searches and in particular the one using angular correlations in decay planes of the tau-lepton in $h_{125} \to \tau^+\tau^-$ setting an upper limit on the pseudoscalar component of the tau Yukawa coupling with a very strong impact in our analysis.

We have 3 neutral scalars h_1, h_2 and h_3. h_1 is always the lightest and h_3 is always the heaviest. In this scenario h_2 is the SM-like Higgs.

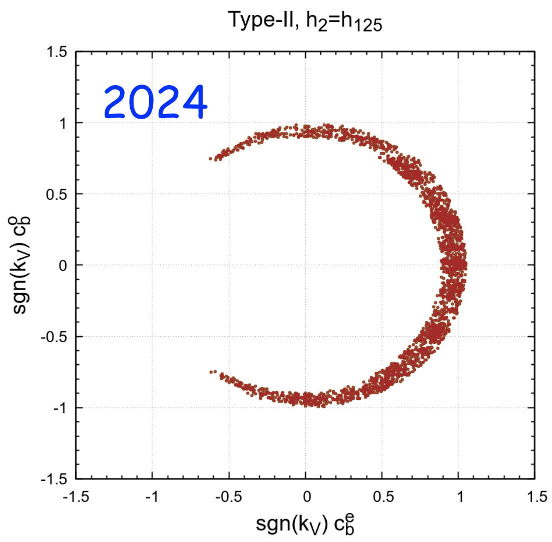


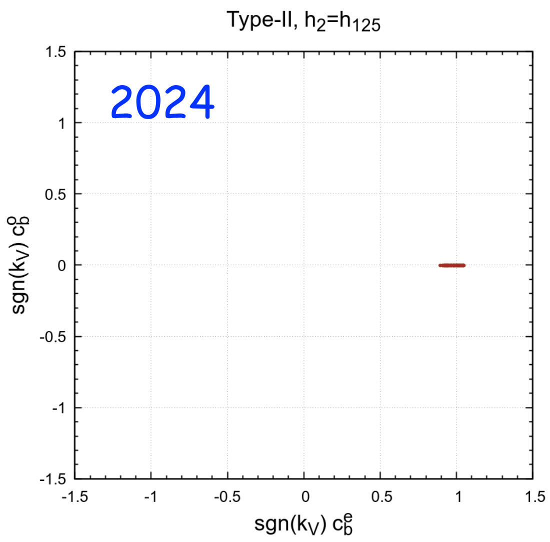


Note that most scenarios were already excluded in the 2017 study.

That is why we start with the second Higgs being the 125 GeV one. In this case h_1 has a mass below 125 GeV

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





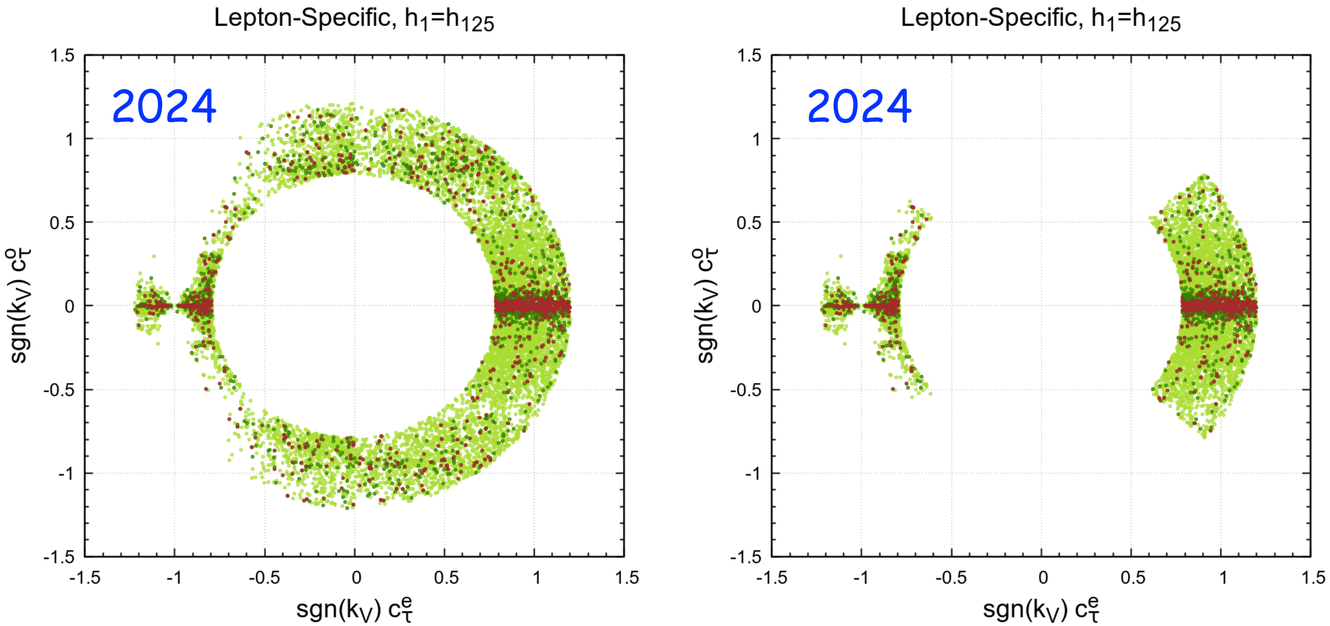
Left - no constraints from searches from extra scalars Right - constraints taken into account (all running masses in the loop taken at the Z scale).

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 - $\bar{\tau}\tau h$ coupling



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

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

Left - no constraints from direct $h\tau^+\tau^-$, Right - constraints taken into account. Colour code as before - green 2017, red 2014, light and dark refer to eEDMs.

Conclusions for the strange CP scenario in 2024

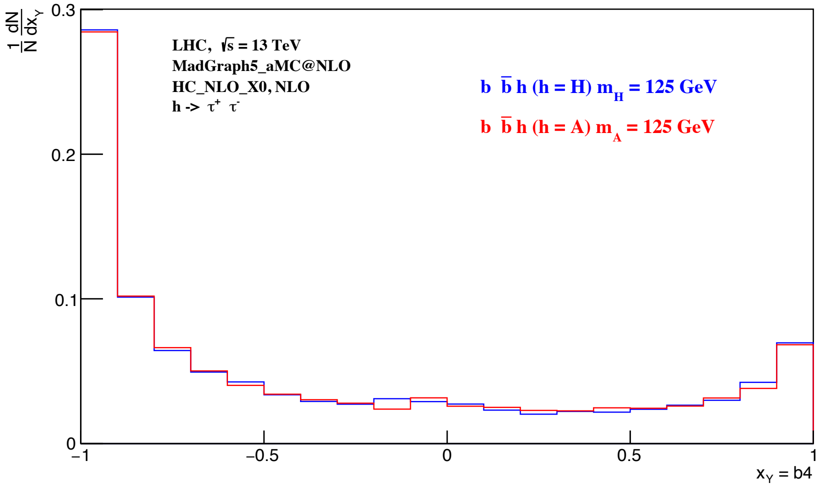
Can we still find large Yukawa couplings?

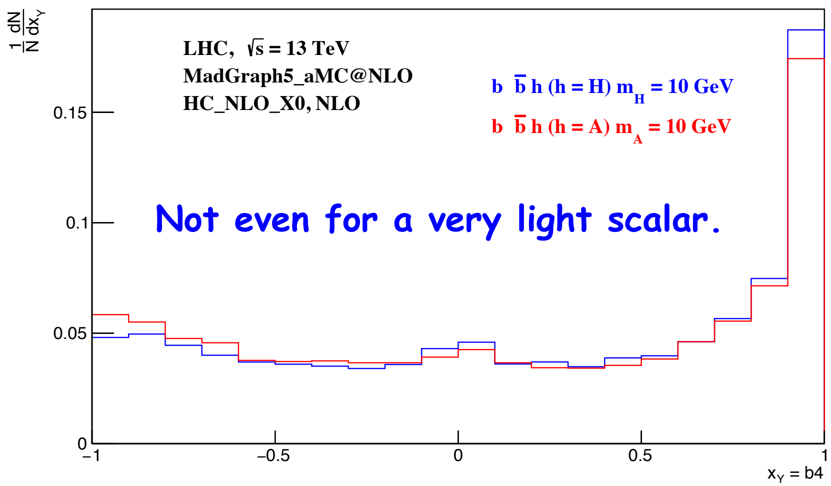
Type	I	II	LS	Flipped
$h_1 = h_{125}$	$\times$	$\times$	τ	$\underline{\times}$
$h_2 = h_{125}$	$\times$	$\underline{\times}$	τ	$\times$
$h_3 = h_{125}$	$\times$	$\times$	τ	$\times$

Current results for the large Yukawa couplings:

- A cross (x) means that is not possible to have a large CP-odd component;
- The notation τ means that the exclusion comes from the direct searches for CP-violation in $h \to \tau^+\tau^-$;
- Underlined crosses refer to scenarios that were previously allowed.

What about the other Yukawas?





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

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.

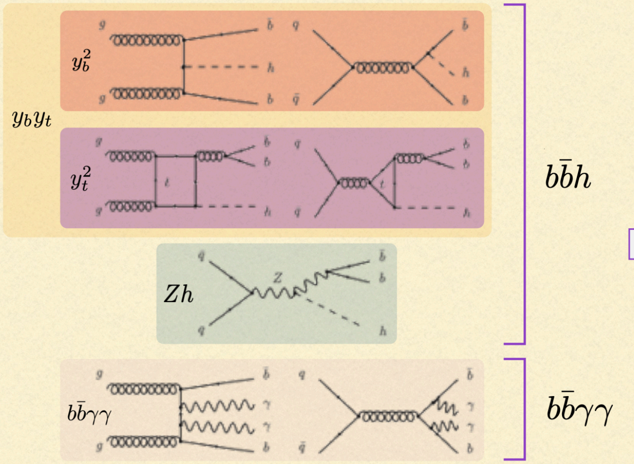
Alonso, Fraser-Taliente, Hays, Spannowsky, JHEP 08 (2021) 167

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

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

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

GROJEAN, PAUL, QIAN, JHEP 04 (2021) 139.



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

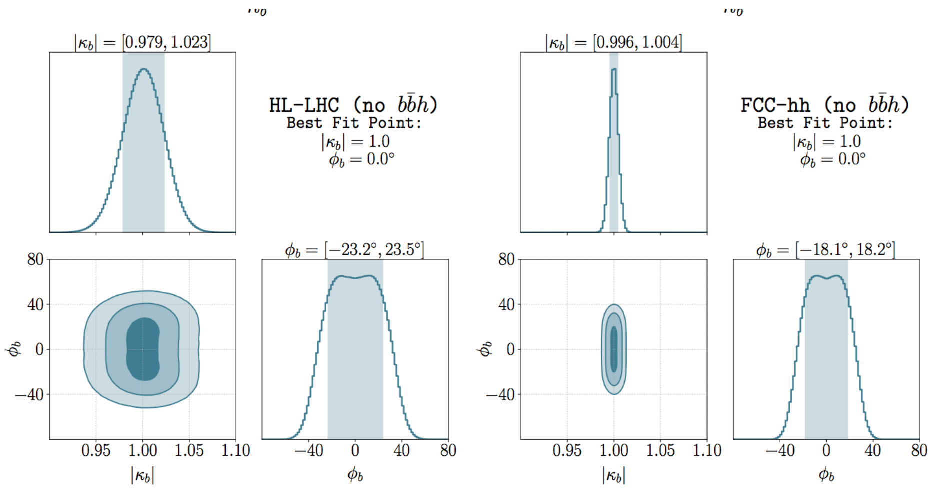
Channel	LO σ (fb)	NLO-k-fact	6 ab^{-1} [#evt]	2b-jets[%]
y_b^2	0.0648	1.5	583	7.7%
$y_b y_t$	-0.00829	1.9	-95	4.0%
y_t^2	0.123	2.5	1,840	12%
Zh	0.0827	1.3	645	21%
$\sum b\bar{b}h$	0.262	-	2,970	-
$b\bar{b}\gamma\gamma$	12.9	1.5	116,000	14%

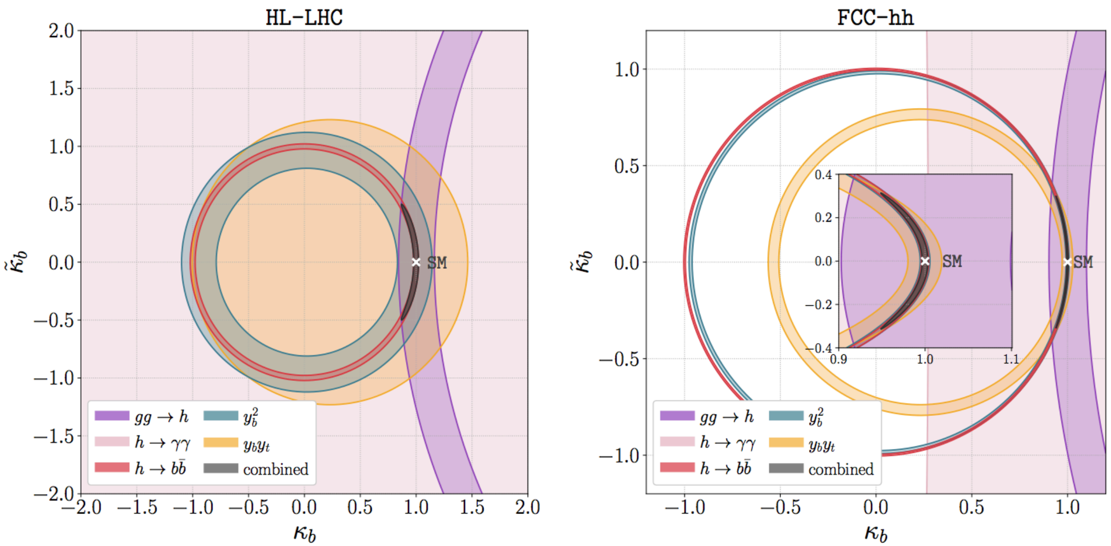
$b\bar{b}h$ background QCD-QED background

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

SLIDE FROM
Zhuoni Qian, HPNP2021
March 25th 2021

GROJEAN, PAUL, QIAN, ARXIV 2011.13945





More CP-violation from loops

CP violation from loops (hWW)

Back to the hZZ dimension six Lagrangian

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

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

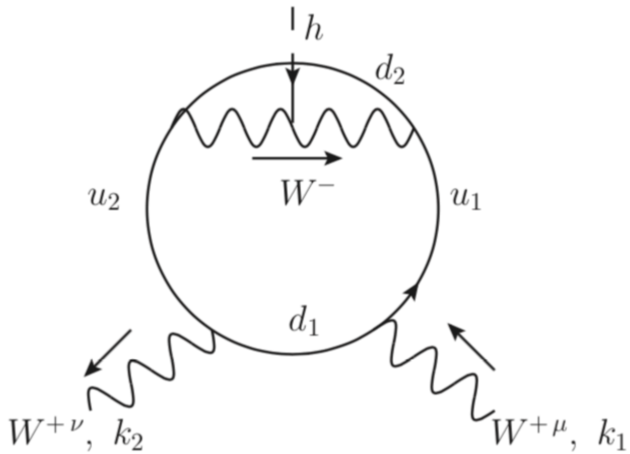
$$\mathscr{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+} \epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu} \tilde{f}^{*-\mu\nu}$$

CP violation from loops (hWW)

In this case we start with the most general WWh vertex

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

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 = Im($V_{ud}V_{cd}^*$ $V_{cs}V_{cd}^*$) = 3.00x10^{-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

What are the experiments doing?

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

EFFECTIVE LAGRANGIAN (CMS NOTATION)

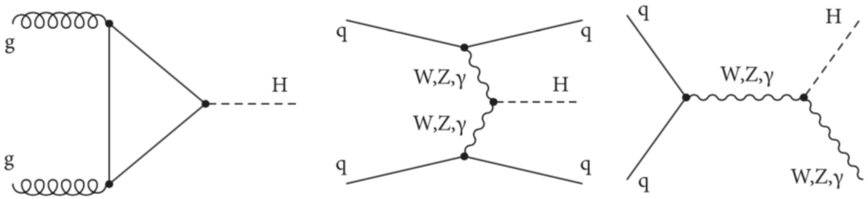


FIG. 1. Examples of leading-order Feynman diagrams for H boson production via the gluon fusion (left), vector boson fusion (middle), and associated production with a vector boson (right). The HWW and HZZ couplings may appear at tree level, as the SM predicts. Additionally, HWW, HZZ, $HZ\gamma$, $H\gamma\gamma$, 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.

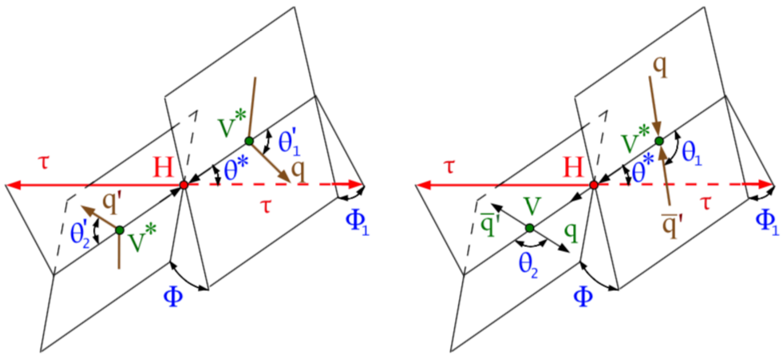


FIG. 2. Illustrations of H boson production in $qq' \to gg(qq') \to H(qq') \to \tau\tau(qq')$ or VBF $qq' \to V^*V^*(qq') \to H(qq') \to \tau\tau(qq')$ (left) and in associated production $q\bar{q}' \to V^* \to VH \to q\bar{q}'\tau\tau$ (right). The $H \to \tau\tau$ decay is shown without further illustrating 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].

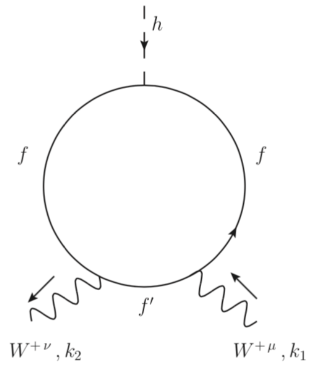
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

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

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

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

THE C2HDM



Starting with f=t and f'=b

Is it worth it?

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

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

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

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

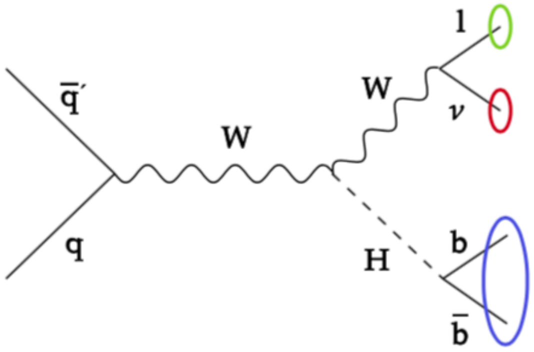
$$c_{\mathrm{CPV}} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

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

USING ALL EXPERIMENTAL (AND THEORETICAL) BOUNDS

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

And now with a different final state



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

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

- 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.

R. Barrué, P. Conde-Muíño, V. Dao, RS, "Simulation based inference in the search for CP-violation in leptonic WH production", JHEP 04 (2024) 014.

$\cos\delta^+$ 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

Summary

- Direct searches for a CP-odd component in the Higgs Yukawa couplings provide 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

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 $2HDM: \quad \Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2$

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

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

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)

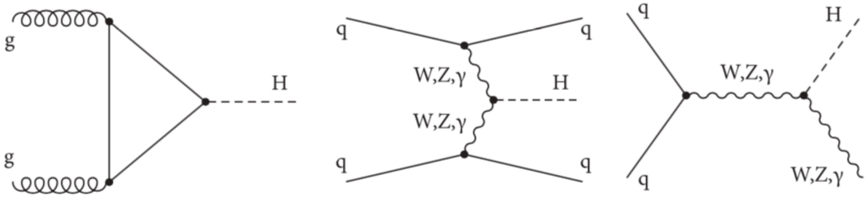


FIG. 1. Examples of leading-order Feynman diagrams for H boson production via the gluon fusion (left), vector boson fusion (middle), and associated production with a vector boson (right). The HWW and HZZ couplings may appear at tree level, as the SM predicts. Additionally, HWW, HZZ, $HZ\gamma$, $H\gamma\gamma$, 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.

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

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

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

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

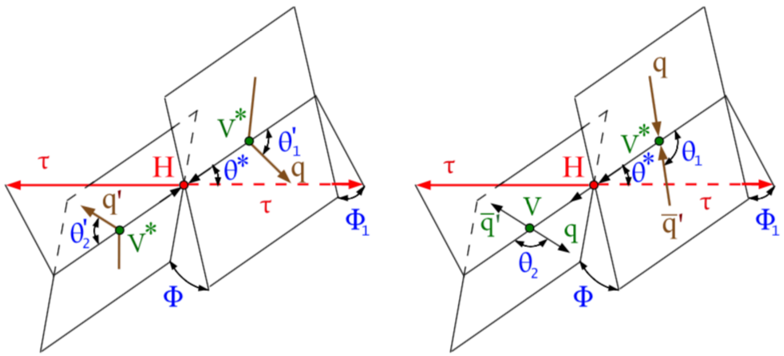


FIG. 2. Illustrations of H boson production in $qq' \to gg(qq') \to H(qq') \to \tau\tau(qq')$ or VBF $qq' \to V^*V^*(qq') \to H(qq') \to \tau\tau(qq')$ (left) and in associated production $q\bar{q}' \to V^* \to VH \to q\bar{q}'\tau\tau$ (right). The $H \to \tau\tau$ decay is shown without further illustrating 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].

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

Is it worth it?

THE SM CONTRIBUTION ARISE FROM THE CKM PHASE Δ, AND SHOULD THEREFORE BE PROPORTIONAL TO THE JARLSKOG INVARIANT J = IM($V_{UD}V_{CD}^{*}$ $V_{CS}V_{CD}^{*}$) = 3.00×10^{-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.

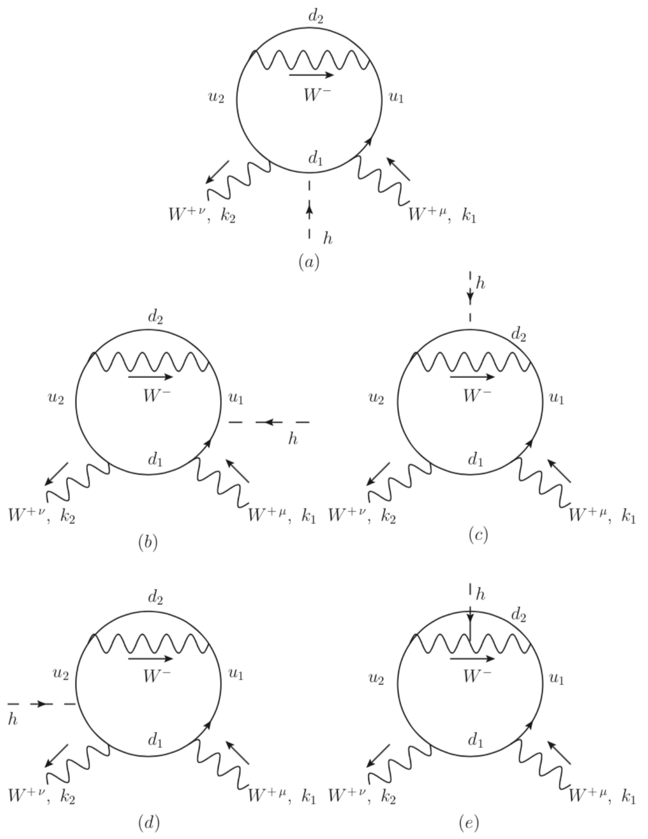


Figure 1. Feynman diagrams leading to the CPV $hW^{+}W^{-}$ coupling in the SM.

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

VERY COMPLICATED, SO YOU ESTIMATE

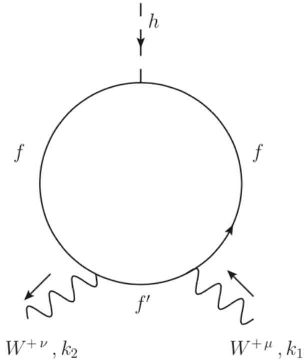
SM ESTIMATE

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

Is it worth it?

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

THE C2HDM



Starting with f=t and f'=b

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

$$iM_{tb}^{\rm C2HDM} = (-1)N_c \int_l {\rm Tr}\Bigg[\left(-\frac{ig}{\sqrt{2}}V_{tb}\gamma_\mu P_L\right)\frac{i}{\not{l}-m_b}\left(-\frac{ig}{\sqrt{2}}V_{tb}^*\gamma_\nu P_L\right)\frac{i}{\not{l}+\not{k}_2-m_t}$$
$$\times\left(-i\frac{m_t}{v}\right)(c_t^e+ic_t^o\gamma_5)\frac{i}{\not{l}+\not{k}_1-m_t}\Bigg]$$
$$= -\frac{N_c g^2 m_t|V_{tb}|^2}{2v}\frac{{\rm Tr}[\gamma_\mu\not{l}\gamma_\nu P_L(\not{l}+\not{k}_2+m_t)(c_t^e+ic_t^o\gamma_5)(\not{l}+\not{k}_1+m_t)]}{(l^2-m_b^2)[(l+k_2)^2-m_t^2][(l+k_1)^2-m_t^2]}\,. \,($$

We can now extract the operator for this case

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

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

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

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

USING THE BOUNDS CALCULATED BEFORE.

CMS PAS FTR-18-011

Table 10: Summary of the 95% CL intervals for $f_{a3}\cos(\phi_{a3})$, under the assumption $\Gamma_{\mathrm{H}} = \Gamma_{\mathrm{H}}^{\mathrm{SM}}$, and for Γ_{H} under the assumption $f_{ai} = 0$ for projections at 3000 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

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

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

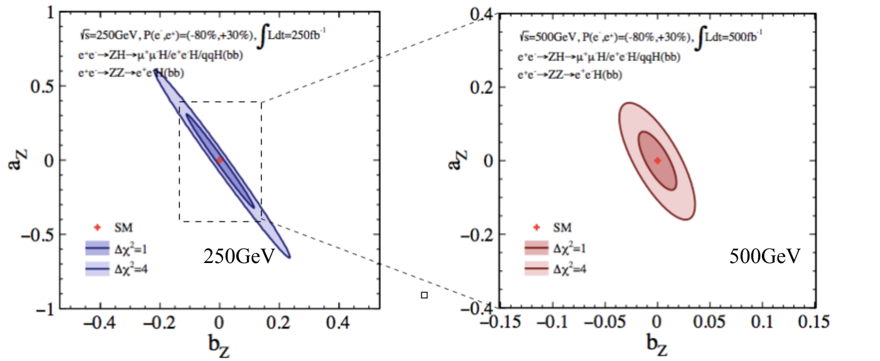
$\tilde{\sigma}_{\Lambda 1}$ = (cross section for the Λ_1-term with $\Lambda_1 = 1$ TeV) $\times$ [TeV]^4

Anomalous ZZH/γZH couplings

3-parameter fit

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

(Λ=1TeV)



5-parameter fit

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

https://arxiv.org/abs/1506.07830

1σ bounds including 500 GeV operation

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

(η_Z =±0.5%)

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