Higgs and CP-violation (in BSM models)

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Outline

- Higgs CP-violation in the Standard Model;
- CP-violation from P-violation;
- CP-violation from C-violation;
- CP-violation from loops;
- Summary.

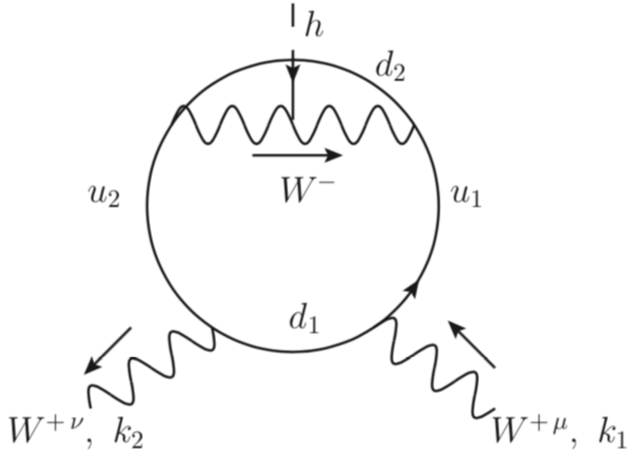
The most general WWh vertex can be written as

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

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

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



THE SM CONTRIBUTION SHOULD BE PROPORTIONAL TO THE JARLSKOG INVARIANT J = $\mathrm{Im}(V_{UD}V_{CD}^* V_{CS}V_{CD}^*) = 3.00\times10^{-5}$. THE CPV hW^+W^- VERTEX CAN ONLY BE GENERATED AT TWO-LOOP.

EXPERIMENTAL BOUND FROM ATLAS AND CMS

ATLAS COLLABORATION, EPJC 76 (2016) 658.

CMS COLLABORATION, PRD100 (2019) 112002.

	Observed/(10^{-3})		Expected/(10^{-3})	
Parameter	68% C.L.	95% C.L.	68% C.L.	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})		Expected/(10^{-3})	
	68% CL	95% CL	68% CL	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

Higgs couplings in Scalar Extensions

Yukawa

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

$f_Y(\alpha_i)$ 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

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

$f_g(\alpha_i)$ 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

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

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

A lot of 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' $N2HDM$: $\Phi_1 \to \Phi_1;\ \Phi_2 \to \Phi_2;\ \Phi_S \to -\Phi_S$

h_{125} couplings (gauge)

Lightest Higgs coupling modifiers (to gauge bosons)

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

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)

$$|s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar}$$

$$g^{hVV}_{N2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

Singlet component

SM + Complex singlet

$$g^{hVV}_{CxSM} = \cos\alpha_1 \cos\alpha_2 \, g^{hVV}_{SM}$$

SM + Real singlet

$$g^{hVV}_{RxSM} = \cos\alpha_1 \, g^{hVV}_{SM}$$

Real component

Imaginary component

h_{125} couplings (Yukawa)

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

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

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

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

These are coupling modifiers relative to the SM coupling. May increase Yukawa relative to the SM.

III = I' = Y = Flipped = 4…

IV = II' = X = Lepton Specific= 3…

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

$$Y_{N2HDM} = \cos\alpha_2 Y_{2HDM}$$

CP-violation from P-violation

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

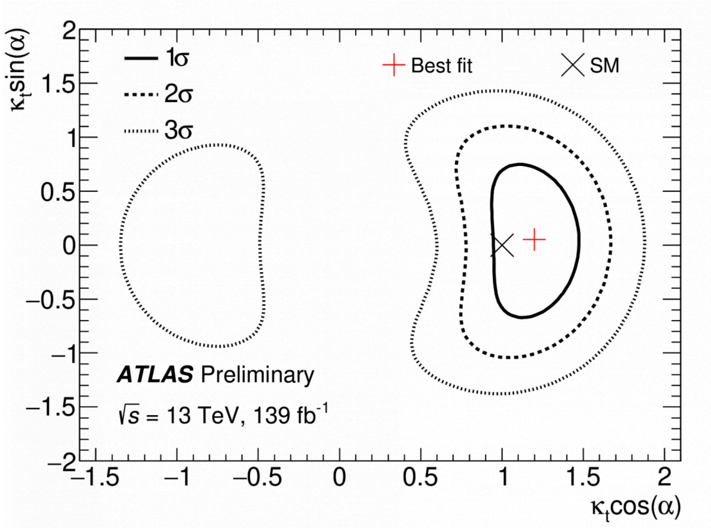
C conserving, CP violating interaction

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

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

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.



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

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

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

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

Now, also available in $pp \to (h \to \bar{b}b)\bar{t}t$.

Probing the nature of h in tth

The spin averaged cross section of tth productions has terms proportional to a^2+b^2 and to a^2-b^2. Terms a^2-b^2 are proportional to the top quark mass. We can define

$$\alpha[\mathcal{O}_{CP}] \equiv \frac{\int \mathcal{O}_{CP}\{d\sigma(pp \to tth)/dPS\}dPS}{\int \{d\sigma(pp \to tth)/dPS\}dPS}$$

$$\mathcal{L}_{H\bar{t}t} = -\frac{y_t}{\sqrt{2}}\bar{t}(a + ib\gamma_5)th$$

where the operator is chosen to maximise the sensitivity of α to the a^2-b^2 term. One of the best operators from the ones proposed is

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

Gunion, He, PRL77 (1996) 5172

Another option is to use angular distributions for which the CP-even and the CP-odd terms behave differently.

Can we use the idea for bbh?

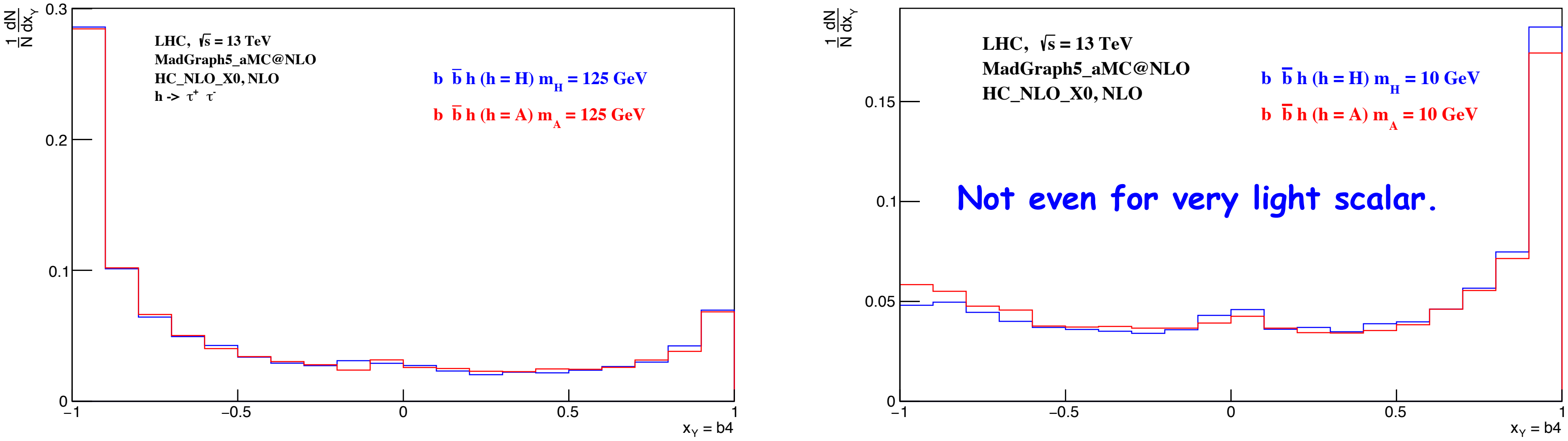


Figure 1: Parton level b_4 distributions at NLO, normalized to unity, for $m_\phi = 125$ GeV (left) and $m_\phi = 10$ GeV (right). Only events with $p_T(b) > 20$ GeV and $|\eta(b)| < 2.5$ were selected, with p_T and η being the transverse momentum and the pseudo-rapidity, respectively.

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.

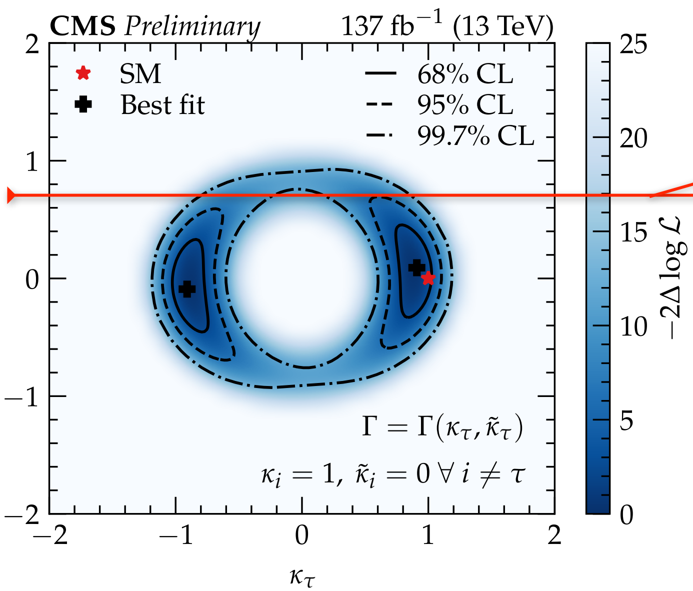
Measurement of CPV angle in ττh

$$\boxed{pp \to h \to \tau^+\tau^-}$$

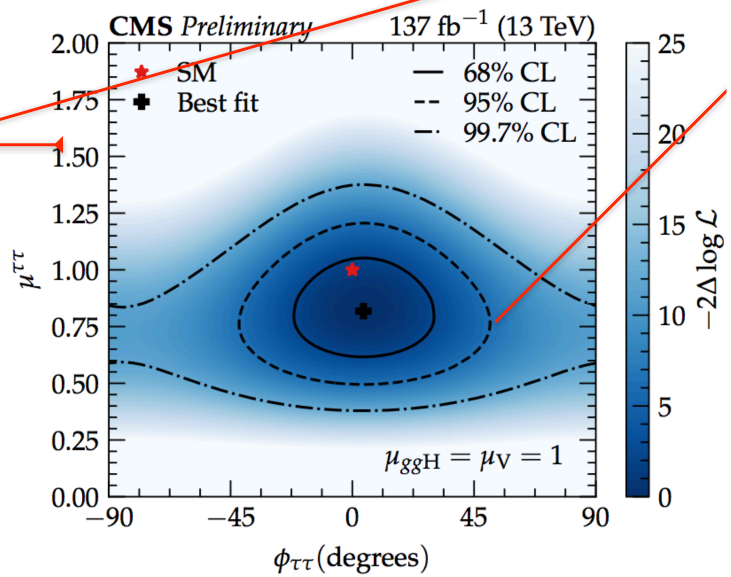
$$\mathscr{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\, h$$

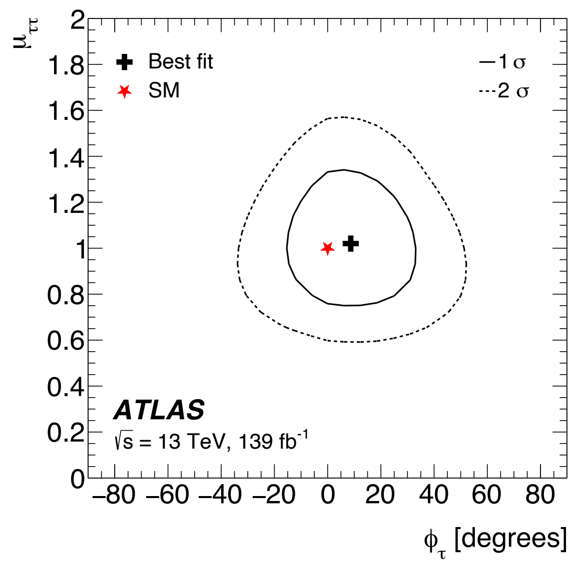
Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°. Compatible with SM predictions.

Scenario excluded at 95% CL



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

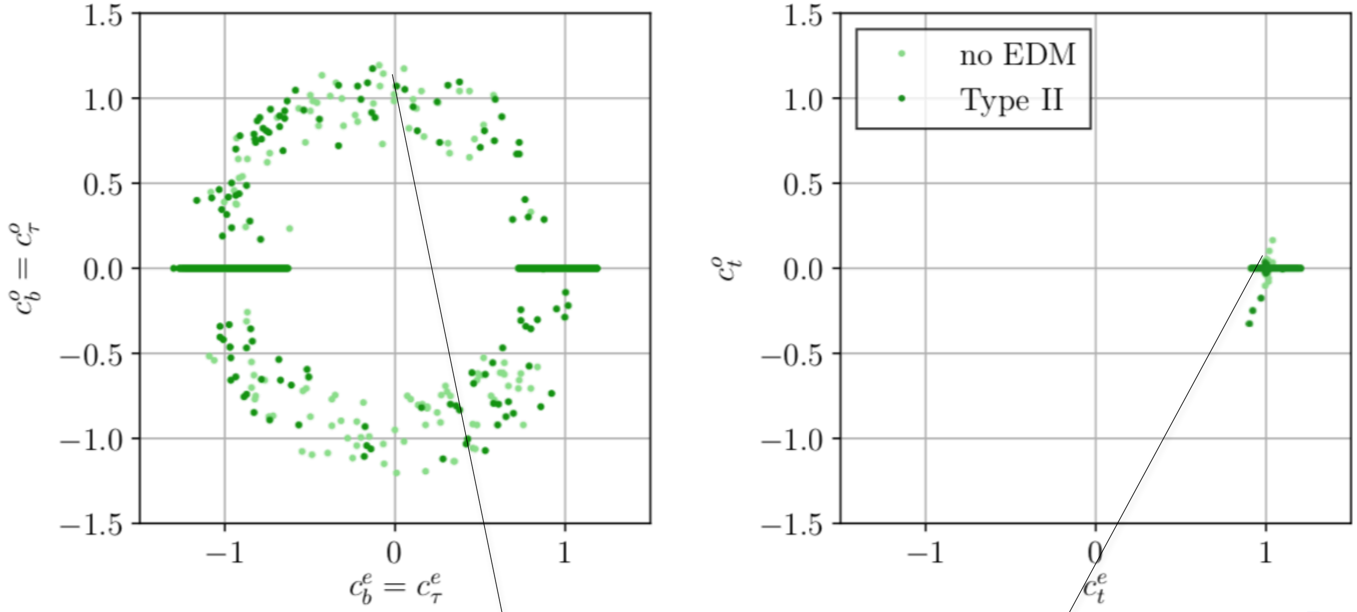




$$\phi_{\tau\tau} = \alpha$$

ATLAS collaboration, ArXiv:2212.05833v1.

CP violation from P violation (only strange!)



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

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

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

With the latest EDM result

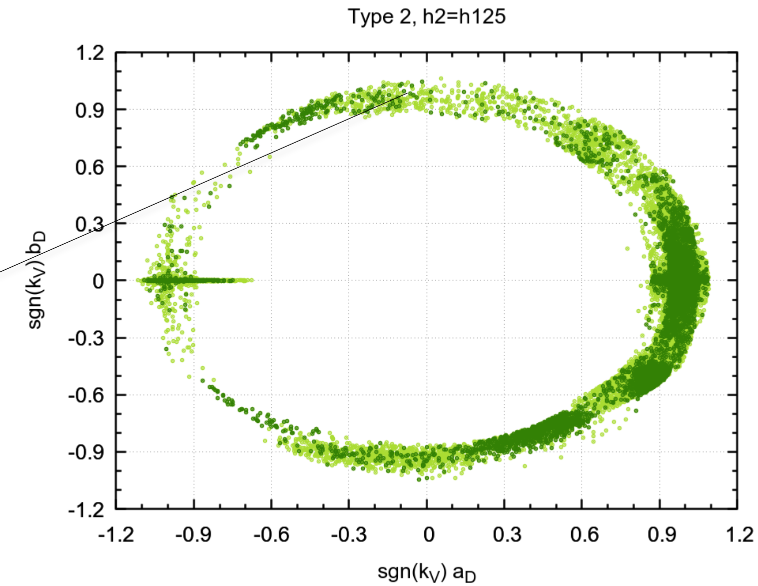
Roussy et al., Science 381 (2023) 6653. adg4084, Science 381 (2023) 46.

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

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

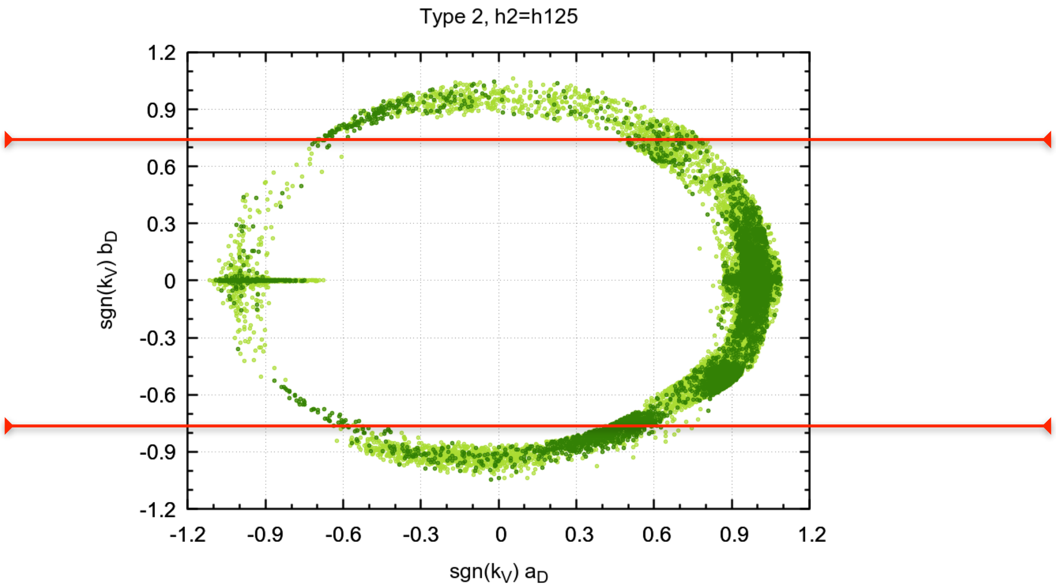
and the other decaying to taus as CP-odd

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



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

CP violation from P violation (only strange!)



LHC (direct) experiments give us information beyond EDMs.

Any scenario in any extension of the SM involving couplings to top-quarks and to tau-leptons, where the 125 GeV has an anomalous coupling (close to pure pseudoscalar) is now excluded. Still

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

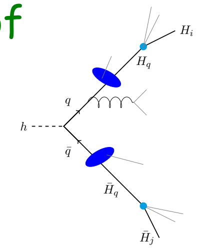
and the other decaying to b-quarks as CP-odd?

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

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

One attempt I know of

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



"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."

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

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 is

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

Because we have vertices of the type hhh and HHH,

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

Since the neutral Goldstone couples derivatively to the Z boson (and 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

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

CP violation from C violation

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

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 vertices that are CP-violating

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

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

CP violation from C violation

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

$$\boxed{h_1 \to ZZ(+) h_2 \to ZZ(+) h_2 \to h_1 Z}$$

Combinations of three decays

Forbidden in the exact alignment limit

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

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

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 T1 $H_{SM}=H_1$

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	

Resonant production : $\sigma_{prod}(H_2) \times BR(H_2\to H_1H_1) = 760$ fb $\times\ 0.252 = 192$ fb

$+\ \sigma_{prod}(H_3) \times BR(H_3\to H_1H_1) = 840$ fb $\times\ 0.280 = 235$ fb

Interesting feature: Test of CP in decays:

- $\sigma_{prod}(H_3) \times BR(H_3\to WW) = 316$ fb and $\sigma_{prod}(H_3) \times BR(H_3\to H_1H_1) = 235$ fb CP+ AND
- $\sigma_{prod}(H_3) \times BR(H_3\to ZH_1) = 76$ fb CP-

- $\sigma_{prod}(H_2) \times BR(H_2\to WW) = 255$ fb and $\sigma_{prod}(H_3) \times BR(H_2\to H_1H_1) = 192$ fb CP+ AND
- $\sigma_{prod}(H_2) \times BR(H_2\to ZH_1) = 122$ fb CP-

C2HDM at future colliders

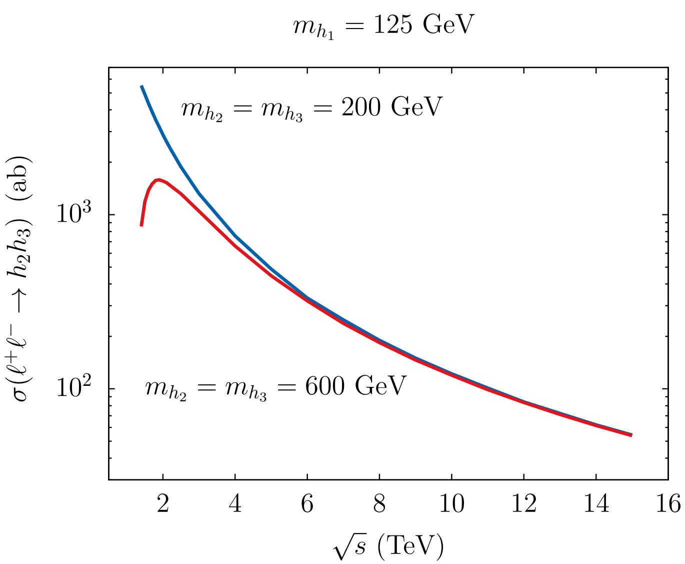
It could happen that at the end of the last LHC run we just move closer and closer to the alignment limit and to a very CP-even 125 GeV Higgs. Considering a few future lepton colliders

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

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

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

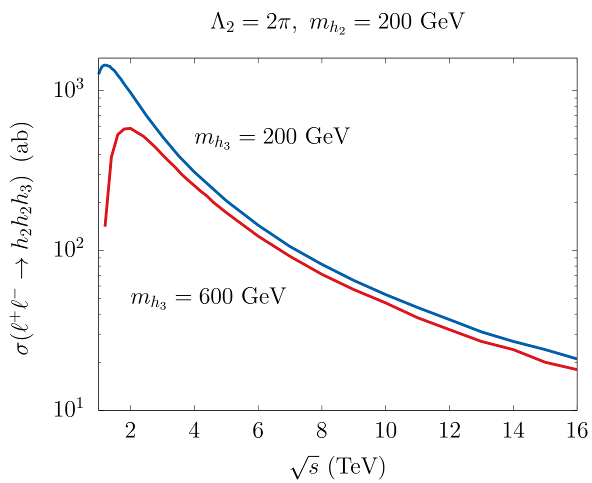
$$h_2h_kh_k; \quad h_3h_lh_l;\,; \quad Zh_2h_3; \quad (k,l=2,3)$$

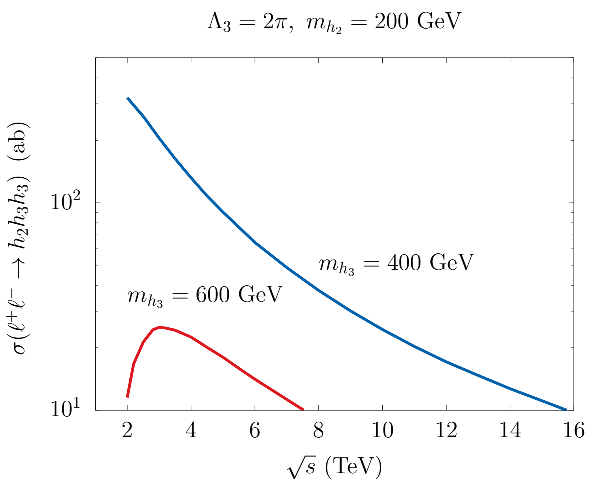


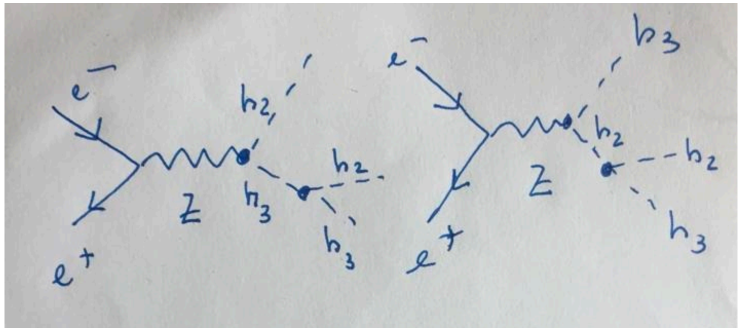
This is an s-channel process with a Z exchange and therefore a gauge coupling. We still need to detect the 2 scalars.

C2HDM at future colliders

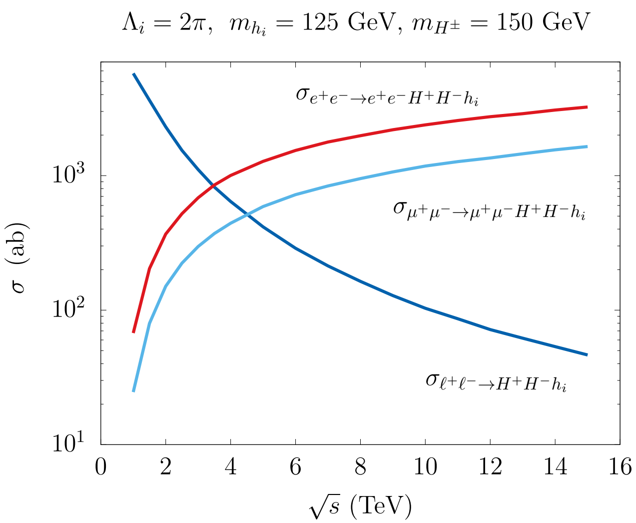
If the new particles are heavier we will need more energy. Still it will be a hard task.

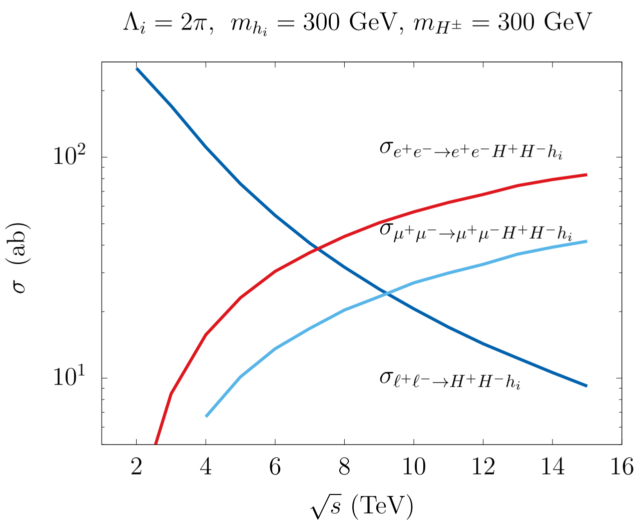


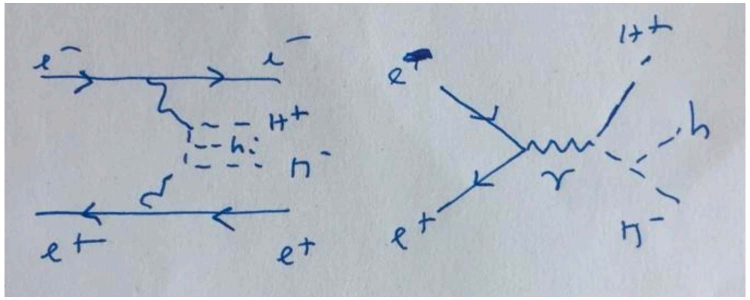




$$\boxed{h_2 h_3 h_3; \quad h_3 h_2 h_2; \quad Z h_2 h_3}$$







$$\boxed{h_2 H^+ H^-; \quad h_3 H^+ H^-; \quad Z h_2 h_3}$$

CP-violation from loops

CP violation from loops (ZZZ)

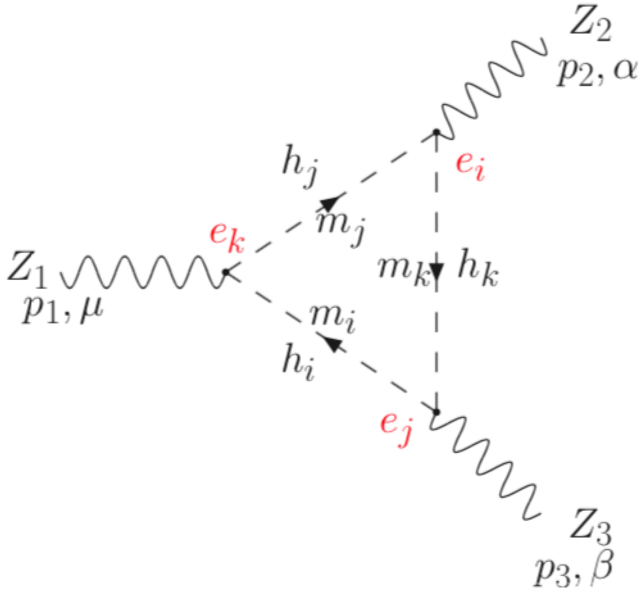
Another possibility of detecting P-even CP-violating signals is via loops. Remember CP-violation could be seen via the combination:

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

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

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

So we can take these three processes and build a nice Feynman diagram.



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

D. Azevedo, P.M. Ferreira, M. Mühlleitner S. Patel, RS, J. Wittbrodt, JHEP 11 (2018) 091.

CP violation from loops (ZZZ)

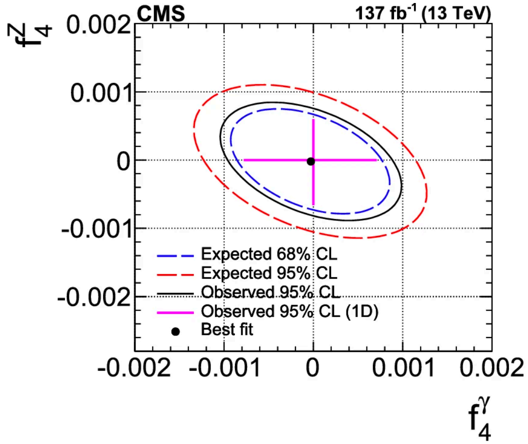
The most general form of the vertex includes a P-even CP-violating term of the form

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

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

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

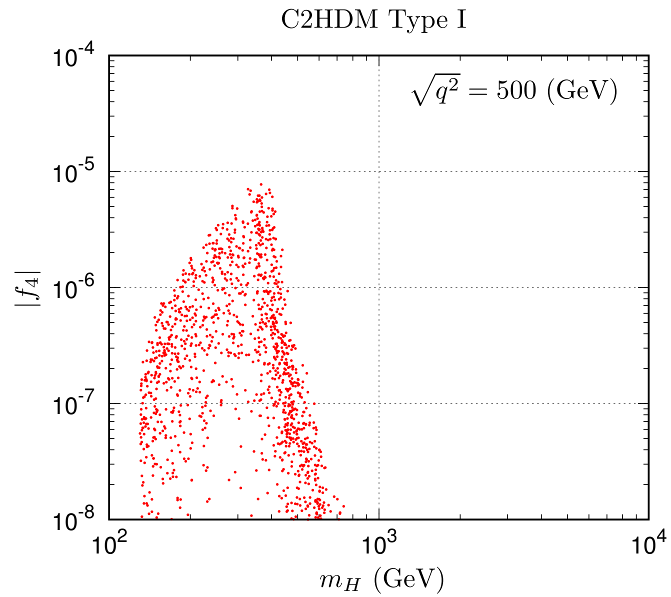
ATLAS COLLABORATION, PRD97 (2018) 032005. $-1.5\times10^{-3} < f_4^Z < 1.5\times10^{-3}$



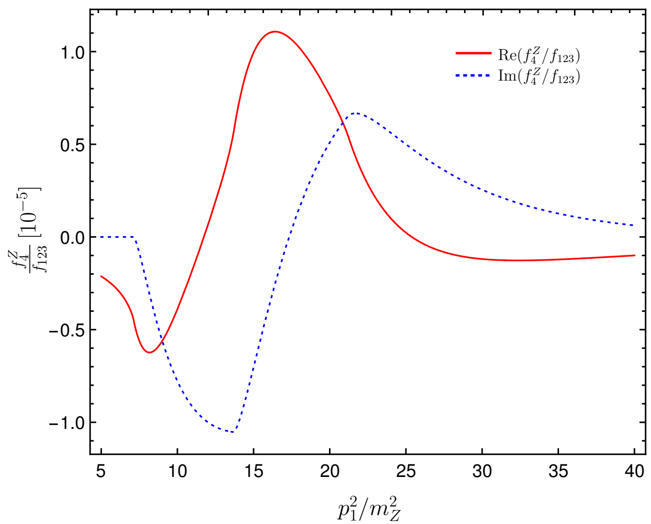
CMS COLLABORATION, EPJC81 (2021) 81.

PLOT FOR THE C2HDM

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

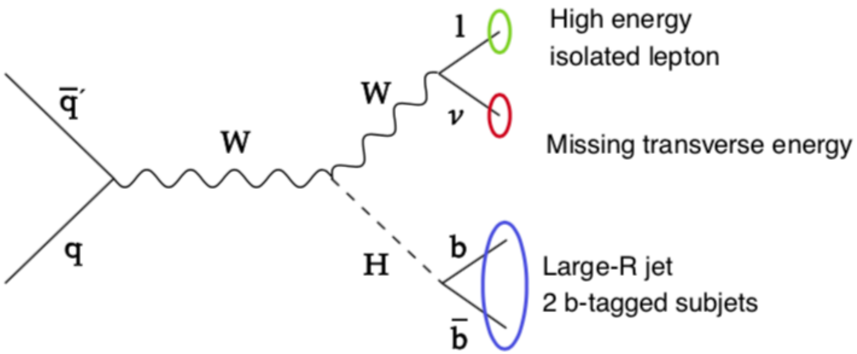


PLOT FOR CP IN THE DARK



The form factor f_4 normalised to f_{123} for m_1=80.5 GeV, m_2=162.9 GeV and m_3=256.9 GeV as a function of the squared off-shell Z-boson 4-momentum, normalised to m_Z^2.

CP violation from loops (WWW)

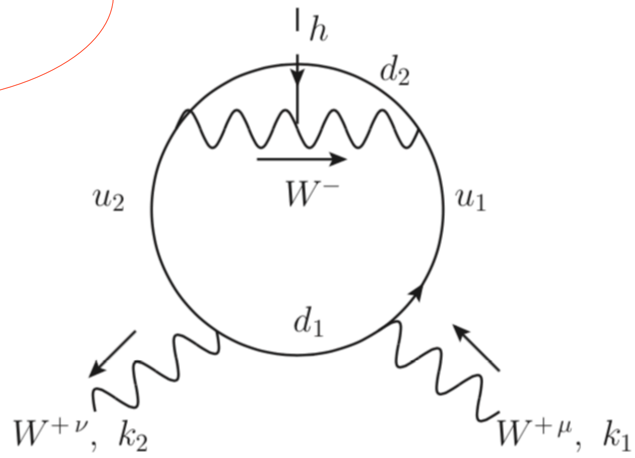


In this case we start with the most general WWh vertex

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

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

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



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

PRESENT EXPERIMENTAL BOUND
FROM ATLAS AND CMS

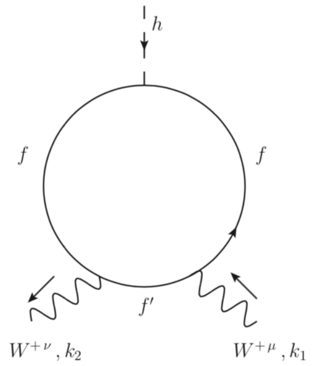
THE SM CONTRIBUTION SHOULD BE PROPORTIONAL TO THE JARLSKOG INVARIANT J = IM($V_{UD}V_{CD}^*$ $V_{CS}V_{CD}^*$) = 3.00x10^{-5} . THE CPV HW$^+$W$^-$ VERTEX CAN ONLY BE GENERATED AT TWO-LOOP.

CMS COLLABORATION, PRD100 (2019) 112002.

ATLAS COLLABORATION, EPJC 76 (2016) 658.

CP violation from loops (WWW)

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

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

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

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

USING ALL EXPERIMENTAL (AND THEORETICAL) BOUNDS

D. HUANG, A.P. MORAIS, RS, JHEP 01 (2021) 168.

Sensitivity projections for future colliders (hWW)

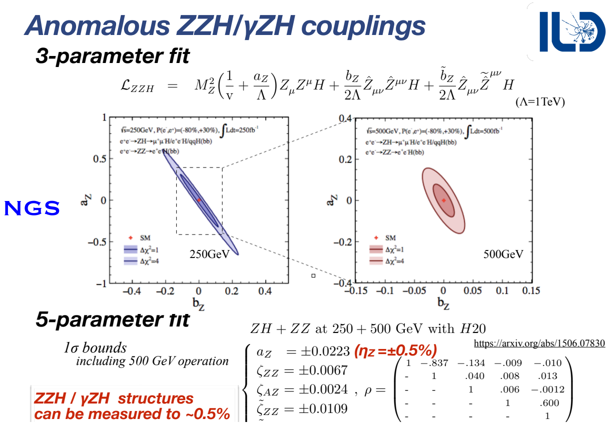
Table 10: Summary of the 95% CL intervals for $f_{a3}\cos(\phi_{a3})$, under the assumption $\Gamma_H = \Gamma_H^{SM}$, and for Γ_H under the assumption $f_{ai} = 0$ for projections at $3000\,\text{fb}^{-1}$. Constraints on $f_{a3}\cos(\phi_{a3})$ are multiplied by 10^4. Values are given for scenarios 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	$[2.0, 6.0]$

CMS PAS FTR-18-011

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

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



Most comprehensive study performed for the ILC. The work presents results are for polarised beams P $(e^-, e^+) = (-80\%, 30\%)$ and two CM 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 (barely) within the reach of these machines. Can be used to constraint the C2HDM at loop-level

Light Higgs

$L = 3000\,\mathrm{fb}^{-1}$		Exclusion Limits from $b_2^{t\bar{t}\phi}$ (68% CL)	Exclusion Limits from $b_2^{t\bar{t}\phi}$ (95% CL)	Exclusion Limits from $b_4^{t\bar{t}\phi}$ (68% CL)	Exclusion Limits from $b_4^{t\bar{t}\phi}$ (95% CL)
$m_\phi = 12\,\mathrm{GeV}$	$\kappa \in$	[-0.05, +0.05]	[-0.11, +0.11]	[-0.05, +0.05]	[-0.11, +0.11]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 20\,\mathrm{GeV}$	$\kappa \in$	[-0.07, +0.07]	[-0.13, +0.13]	[-0.07, +0.07]	[-0.13, +0.13]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.49, +0.49]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 30\,\mathrm{GeV}$	$\kappa \in$	[-0.07, +0.07]	[-0.14, +0.14]	[-0.07, +0.07]	[-0.14, +0.14]
	$\tilde{\kappa} \in$	[-0.26, +0.20]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 40\,\mathrm{GeV}$	$\kappa \in$	[-0.17, +0.17]	[-0.32, +0.32]	[-0.17, +0.17]	[-0.32, +0.32]
	$\tilde{\kappa} \in$	[-0.53, +0.53]	[-1.00, +1.00]	[-0.53, +0.53]	[-1.01, +1.01]

Table 2. Exclusion limits for the $t\bar{t}\phi$ CP-couplings as a function of the ϕ boson mass, and a fixed luminosity of $3000\,\mathrm{fb}^{-1}$. The limits are shown at confidence levels of 68% and 95%, for the variables $b_2^{t\bar{t}\phi}$ and $b_4^{t\bar{t}\phi}$.

Invisible Higgs

Exclusion Limits from $\Delta\phi_{l^+l^-}$		$L = 200\ \mathrm{fb}^{-1}$ (68% CL)	$L = 200\ \mathrm{fb}^{-1}$ (95% CL)	$L = 3000\ \mathrm{fb}^{-1}$ (68% CL)	$L = 3000\ \mathrm{fb}^{-1}$ (95% CL)
$m_{Y_0} = 1$ GeV	$g^S_{u33} \in$	[-0.073, +0.073]	[-0.142, +0.142]	[-0.038, +0.038]	[-0.068, +0.068]
	$g^P_{u33} \in$	[-0.89, +0.89]	[-1.65, +1.65]	[-0.43, +0.43]	[-0.83, +0.83]
$m_{Y_0} = 10$ GeV	$g^S_{u33} \in$	[-0.198, +0.198]	[-0.368, +0.372]	[-0.098, +0.098]	[-0.188, +0.188]
	$g^P_{u33} \in$	[-0.87, +0.87]	[-1.65, +1.65]	[-0.44, +0.44]	[-0.83, +0.83]
$m_{Y_0} = 125$ GeV	$g^S_{u33} \in$	[-0.328,+0.322]	[-0.608, +0.612]	[-0.162, +0.162]	[-0.308, +0.308]
	$g^P_{u33} \in$	[-1.48, +1.49]	[-2.77, +2.78]	[-0.75, +0.75]	[-1.41, +1.41]

Table 2: Exclusion limits for the $t\bar{t}Y_0$ CP-couplings for fixed luminosities of 200 fb^{-1} and 3000 fb^{-1} of the SM plus Y_0, assuming the SM as null hypothesis, for Y_0 masses of 1 GeV (top), 10 GeV (middle) and 125 GeV (bottom). The limits are shown at confidence levels of 68% and 95%, for the $\Delta\phi_{l^+l^-}$ variable.

Summary

- Direct searches for a CP-odd component in the Higgs Yukawa couplings gives information that cannot be obtained from the EDMs.
- However the combination of EDMs and direct searches will most probably exclude a lot of scenarios in specific models.
- While CP-violation coming from P-violation needs only one Higgs, the one coming from C-violation needs at least two.
- As expected, clean signatures of these C-originated CP-violation signals would be more easily studied at lepton colliders.
- Still, discovering extra scalars and test their CP-numbers at the LHC is within the reach of many models.
- Loop induced processes can also provide information on the models.

Thank you!

LHC Higgs Working Group

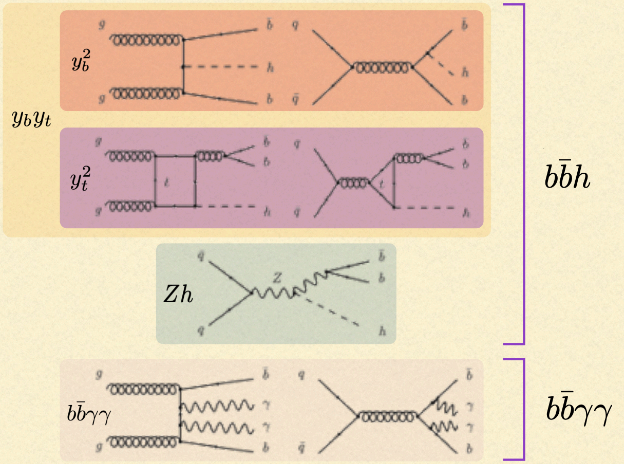
Announcement!

The WG2- CP-violation and WG3 - Extended scalars - one day meeting to discuss CP-violation in the Higgs couplings in your favourite BSM/scalar extension model. The meeting is scheduled for 26 September 2023.

https://indico.cern.ch/event/1327545/

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

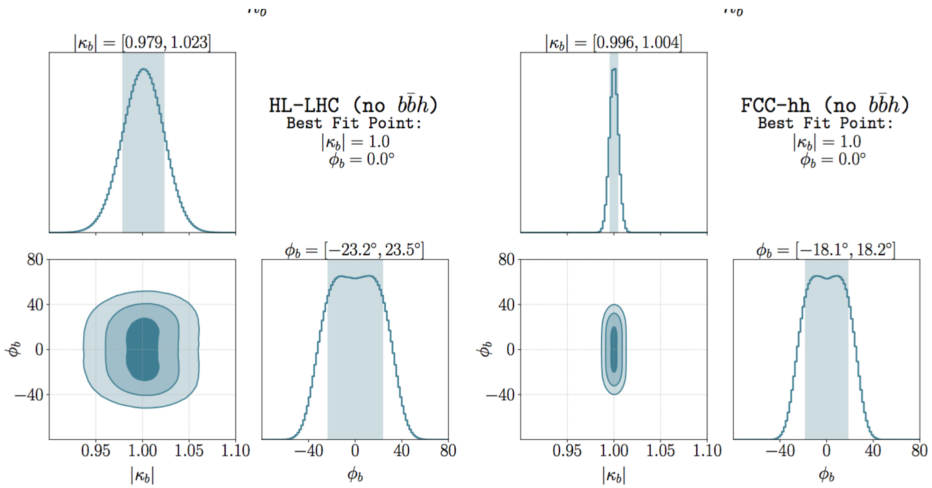
Basic selection (14 TeV HL-LHC): **signals**

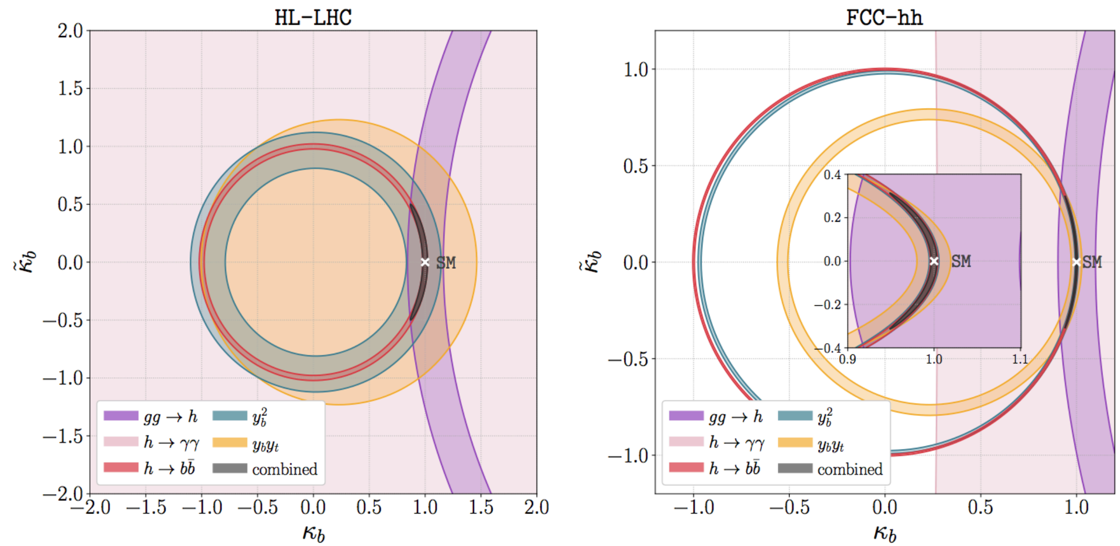
Channel	LO σ (fb)	NLO-k-fact	6 ab^{-1} [#evt]	$2b$-jets[%]
y_b^2	0.0648	1.5	583	7.7%
$y_b y_t$	-0.00829	1.9	-95	4.0%
y_t^2	0.123	2.5	1,840	12%
Zh	0.0827	1.3	645	21%
$\sum b\bar{b}h$	0.262	-	2,970	-
$b\bar{b}\gamma\gamma$	12.9	1.5	116,000	14%

$b\bar{b}h$ 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

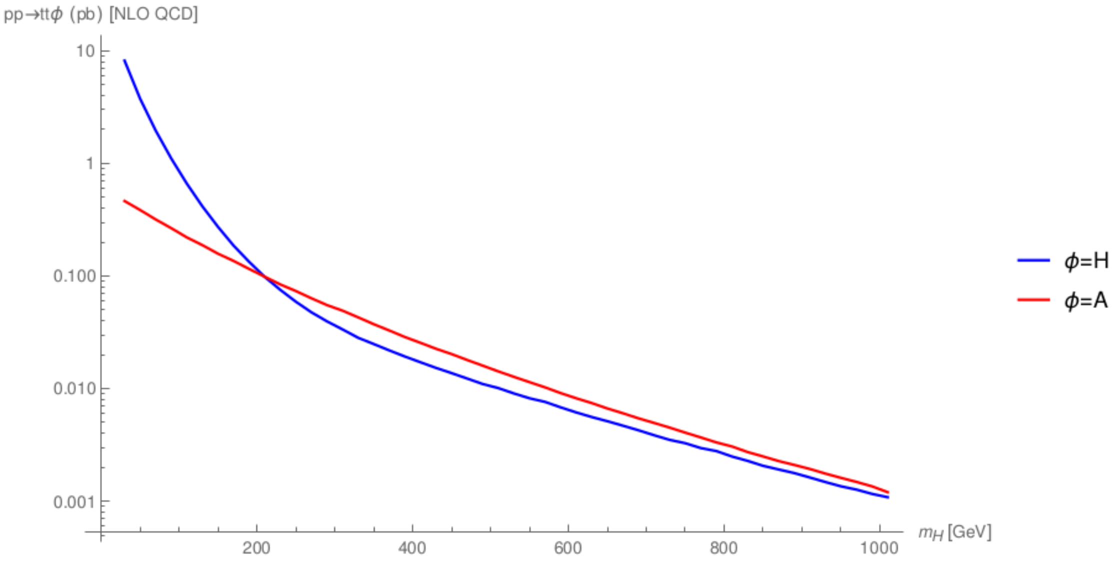


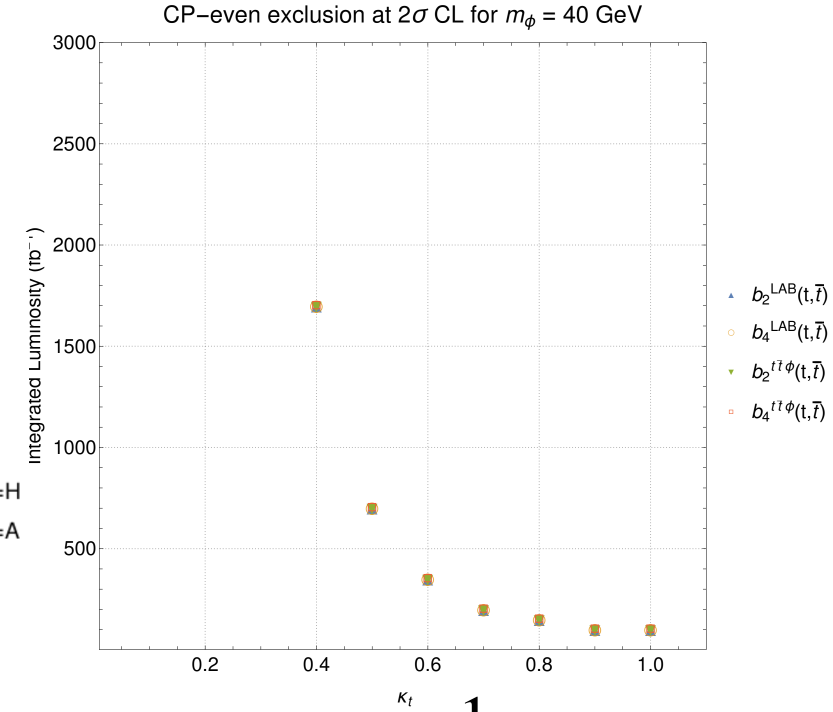


Finally the search for low/high mass scalars

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

$$\mathcal{L} = \kappa_t y_t \bar{t}(\cos\alpha - i\gamma_5 \sin\alpha) t\phi$$





$$L \propto \frac{1}{\kappa_t^4}$$

These are the best possible results - we assume a CP-even scalar with SM-like coupling modified by the factor κ_t only. Now what can we say for a simple model like the C2HDM with these results?

Light Higgs

$L = 3000\,\text{fb}^{-1}$		Exclusion Limits from $b_2^{t\bar{t}\phi}$ (68% CL)	Exclusion Limits from $b_2^{t\bar{t}\phi}$ (95% CL)	Exclusion Limits from $b_4^{t\bar{t}\phi}$ (68% CL)	Exclusion Limits from $b_4^{t\bar{t}\phi}$ (95% CL)
$m_\phi = 12\,\text{GeV}$	$\kappa \in$	[-0.05, +0.05]	[-0.11, +0.11]	[-0.05, +0.05]	[-0.11, +0.11]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 20\,\text{GeV}$	$\kappa \in$	[-0.07, +0.07]	[-0.13, +0.13]	[-0.07, +0.07]	[-0.13, +0.13]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.49, +0.49]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 30\,\text{GeV}$	$\kappa \in$	[-0.07, +0.07]	[-0.14, +0.14]	[-0.07, +0.07]	[-0.14, +0.14]
	$\tilde{\kappa} \in$	[-0.26, +0.20]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 40\,\text{GeV}$	$\kappa \in$	[-0.17, +0.17]	[-0.32, +0.32]	[-0.17, +0.17]	[-0.32, +0.32]
	$\tilde{\kappa} \in$	[-0.53, +0.53]	[-1.00, +1.00]	[-0.53, +0.53]	[-1.01, +1.01]

Table 2. Exclusion limits for the $t\bar{t}\phi$ CP-couplings as a function of the ϕ boson mass, and a fixed luminosity of $3000\,\text{fb}^{-1}$. The limits are shown at confidence levels of 68% and 95%, for the variables $b_2^{t\bar{t}\phi}$ and $b_4^{t\bar{t}\phi}$.

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$m_{Y_0} = 1$ GeV	$g_{u33}^S \in$	[-0.073, +0.073]	[-0.142, +0.142]	[-0.038, +0.038]	[-0.068, +0.068]
	$g_{u33}^P \in$	[-0.89, +0.89]	[-1.65, +1.65]	[-0.43, +0.43]	[-0.83, +0.83]
$m_{Y_0} = 10$ GeV	$g_{u33}^S \in$	[-0.198, +0.198]	[-0.368, +0.372]	[-0.098, +0.098]	[-0.188, +0.188]
	$g_{u33}^P \in$	[-0.87, +0.87]	[-1.65, +1.65]	[-0.44, +0.44]	[-0.83, +0.83]
$m_{Y_0} = 125$ GeV	$g_{u33}^S \in$	[-0.328,+0.322]	[-0.608, +0.612]	[-0.162, +0.162]	[-0.308, +0.308]
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Table 2: Exclusion limits for the $t\bar{t}Y_0$ CP-couplings for fixed luminosities of 200 fb^{-1} and 3000 fb^{-1} of the SM plus Y_0, assuming the SM as null hypothesis, for Y_0 masses of 1 GeV (top), 10 GeV (middle) and 125 GeV (bottom). The limits are shown at confidence levels of 68% and 95%, for the $\Delta\phi_{l^+l^-}$ variable.

CP violation from P violation (but strange!)

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**

If an experiment can tell us that ϕ couples approximately as scalar do top quarks and as a pseudoscalar to tau leptons, it is a sign of CP-violation.

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

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

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

Close to 1

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

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

Small

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

Can be large

Experiment tells us

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

Also available for invisible scalars

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

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

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

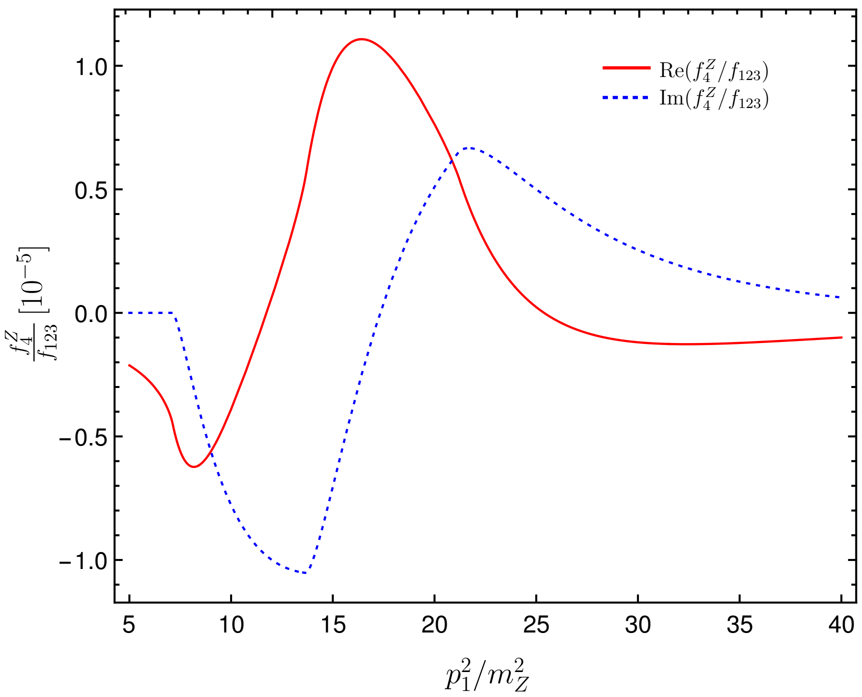
$$\Phi_1^{CP}(t,\vec{r}) = \Phi_1^*(t,-\vec{r}), \qquad \Phi_2^{CP}(t,\vec{r}) = \Phi_2^*(t,-\vec{r}), \qquad \Phi_S^{CP}(t,\vec{r}) = \Phi_S(t,-\vec{r})$$

except for the term $(A\Phi_1^\dagger \Phi_2 \Phi_S + h.c.)$ for complex A

Also available for invisible scalars

In our model it has the simple expression

$$f_4^Z(p_1^2) = -\frac{2\alpha}{\pi s^3_{2\theta_W}} \frac{m_Z^2}{p_1^2 - m_Z^2} f_{123} \sum_{i,j,k} \epsilon_{ijk}\, C_{001}(p_1^2, m_Z^2, m_Z^2, m_i^2, m_j^2, m_k^2) \qquad f_{123} = R_{13}R_{23}R_{33}$$



The form factor f_4 normalised to f_{123} for m_1=80.5 GeV, m_2=162.9 GeV and m_3=256.9 GeV as a function of the squared off-shell Z-boson 4-momentum, normalised to m_Z^2.

But the bounds we have from present measurements by ATLAS and CMS, show that we are still two orders of magnitude away from what is needed to probe these models. 3HDMs may get us closer.

CP numbers of the discovered Higgs (WWh and ZZh)

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

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

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

TERM COMING FROM A CPV OPERATOR.

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

PRESENT RESULTS

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

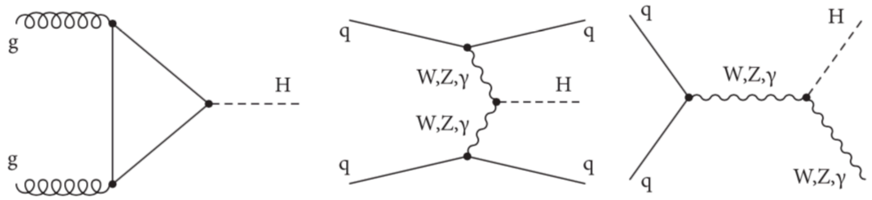
CMS COLLABORATION, PRD100 (2019) 112002.

ATLAS COLLABORATION, EPJC 76 (2016) 658.

What are the experiments doing?

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

EFFECTIVE LAGRANGIAN (CMS NOTATION)



CMS COLLABORATION, PRD100 (2019) 112002.

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.

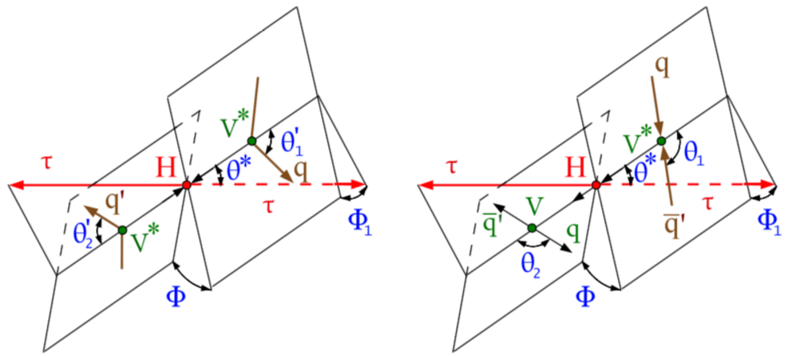


FIG. 2. Illustrations of H boson production in $qq' \to gg(qq') \to H(qq') \to \tau\tau(qq')$ or VBF $qq' \to V^*V^*(qq') \to H(qq') \to \tau\tau(qq')$ (left) and in associated production $q\bar{q}' \to V^* \to VH \to q\bar{q}'\tau\tau$ (right). The $H \to \tau\tau$ decay is shown without further illustrating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

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda1} = \frac{\tilde{\sigma}_{\Lambda1}/(\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{\Lambda1},$$

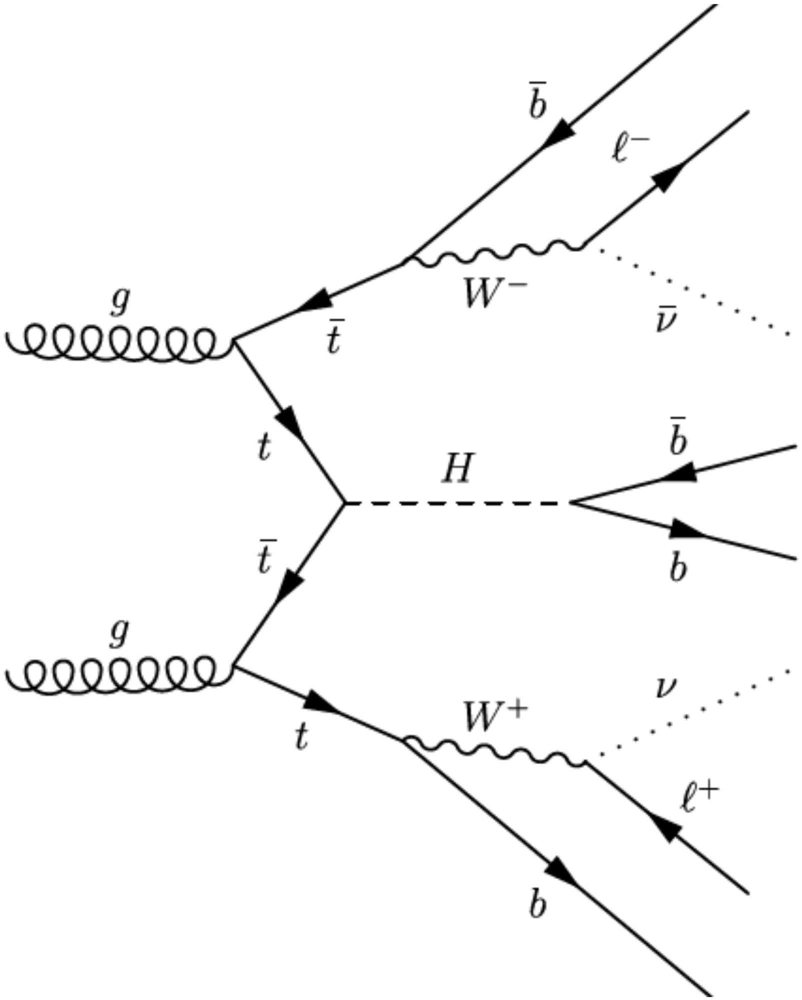
$$f_{\Lambda1}^{Z\gamma} = \frac{\tilde{\sigma}_{\Lambda1}^{Z\gamma}/(\Lambda_1^{Z\gamma})^4}{|a_1|^2\sigma_1 + \tilde{\sigma}_{\Lambda1}^{Z\gamma}/(\Lambda_1^{Z\gamma})^4 + \cdots}, \qquad \phi_{\Lambda1}^{Z\gamma},$$

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

Can we get something of the same order with H->bb?

$$pp \to H\bar{t}t$$

Gunion, He, PRL77 (1996) 5172
Boudjema, Godbole, Guadagnoli, Mohan, PRD92 (2015) 015019
Amor dos Santos eal PRD96 (2017) 013004

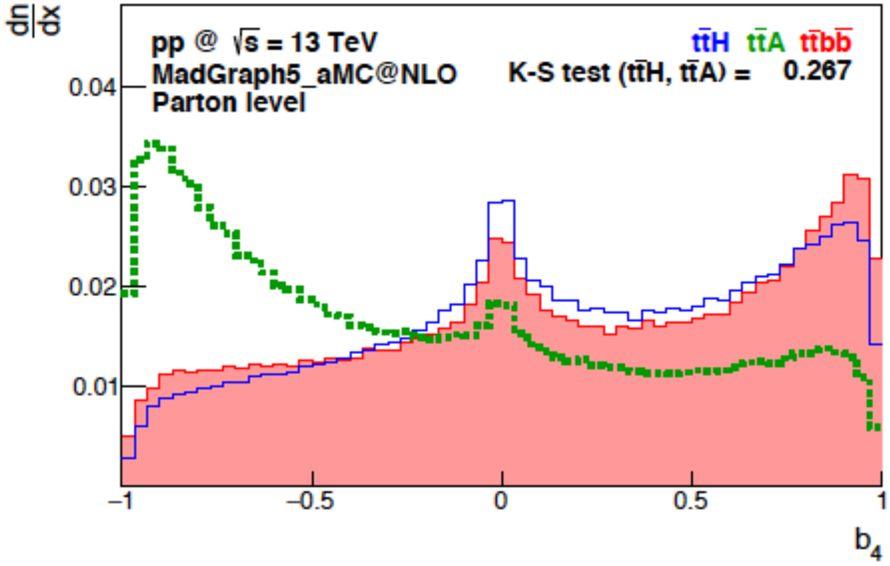


$$\mathscr{L}_{H\bar{t}t} = -\frac{y_t}{\sqrt{2}}\bar{t}(a + ib\gamma_5)th$$

Signal: we consider the tt fully leptonic (but could add the or semi-leptonic case) and H -> bb

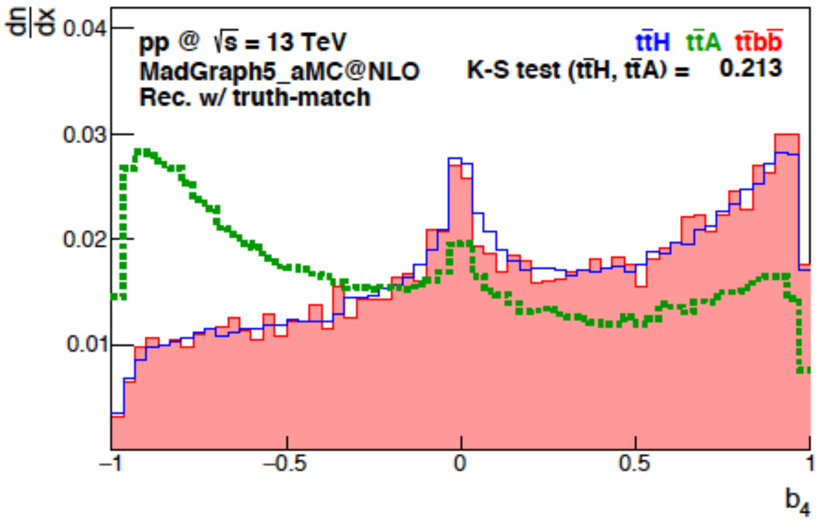
Background: most relevant is the irreducible tt background

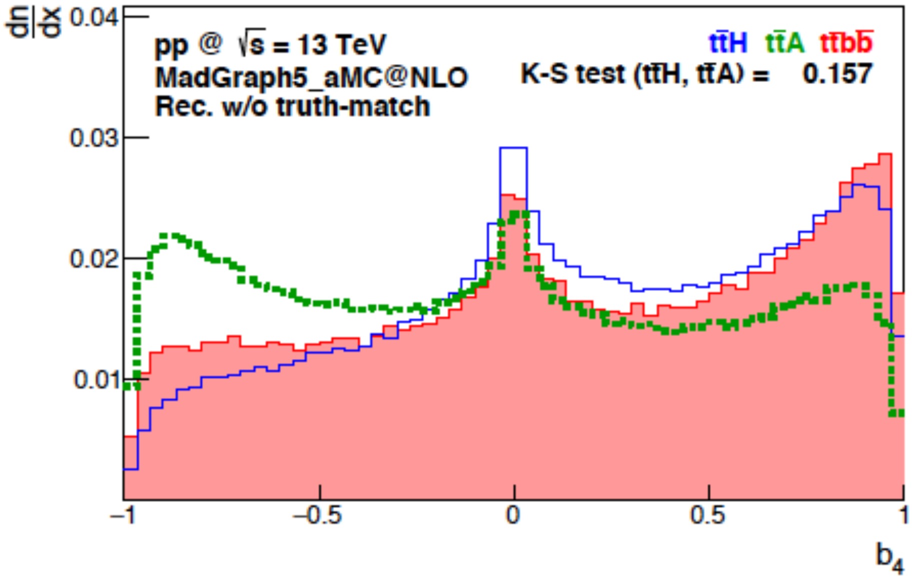
The spin averaged cross section of tth productions has terms proportional to a^2+b^2 and to a^2-b^2. Terms a^2-b^2 are proportional to the top quark mass. There are many operators that can distinguish CP-even and CP-odd parts (maximize the a^2-b^2 term).



Gunion, He, PRL77 (1996) 5172

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





The 2-Higgs doublet model (IDM)

So to get dark matter we just need to set to zero the VEV of one of the doublets

$$V_{IDM} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2$$

$m_{12}^2 = 0$, minimum condition

$$\frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger \Phi_2)^2 + h.c.\right]$$

With

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG_0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_0 + iA_0) \end{pmatrix}$$

CP violation not possible. To have CP-violation and dark matter one needs to further extend the model. Add a singlet.

$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_0 + iA_0) \end{pmatrix}$$

Inert doublet

Inert scalars

There is an exact discrete symmetry that forces the second doublet to have only stable particles.

$$\Phi_2 \to -\Phi_2$$