ISEL INSTITUTO SUPERIOR DE ENGENHARIA DE LISBOA

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CP-violation measurements at the LHC

Where is the rest of it?

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BSM2021 - Special Edition

1 April 2021

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

Previously on "Searches for CPV at the LHC"

⊙ **A benchmark model was born for CPV searches - The Complex 2HDM or C2HDM**

⊙ **<u>Unexpected twist</u> - large CP-odd components of Yukawa couplings**

⊙ **<u>Season finale</u> - combination of 3 decays as a sign of CP-violation**

Season 2

⊙ **CP-violation in the Yukawas**

⊙ **CP-violation in the couplings to gauge bosons?**

⊙ **Conclusions**

The C2HDM

A benchmark model was born for CPV searches -

the Complex 2HDM

Softly broken Z_2 symmetric 2HDM Higgs potential

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

and CP is explicitly and not spontaneously broken

$$<\Phi_1> = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

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

➡ $\tan\beta = \frac{v_2}{v_1}$ ratio of vacuum expectation values

➡ 2 charged, $H^\pm$, and 3 neutral
CP-conserving - h, H and A
CP-violating - h_1, h_2 and h_3

➡ rotation angles in the neutral sector
CP-conserving – α
CP-violating - α_1, α_2 and α_3

➡ soft breaking parameter

CP-conserving – m^2_{12}

CP-violating – $\mathrm{Re}(m^2_{12})$

Lightest Higgs coupling modifiers (to gauge bosons)

h_{125} couplings measurements

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

CP-violating 2HDM

"Pseudoscalar" component (doublet)

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

$\sin\alpha_2 = 0 \implies$ h is a pure scalar

$\sin\alpha_2 = 1 \implies$ h is a pure pseudoscalar

The effective Lagrangian is written as

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

Only term in the C2HDM at tree-level

h_{125} couplings measurements

Lightest Higgs coupling modifiers (to fermions)

C2HDM parametrisation

$$\mathscr{L}^{huu}_{C2HDM} = g^{hff}_{SM}\,\bar{u}\left[\frac{R_{12}}{\sin\beta} - i\frac{R_{13}}{\tan\beta}\gamma_5\right] u\,h$$

ALL TYPES

$$\mathscr{L}^{hdd}_{C2HDM} = g^{hff}_{SM}\,\bar{d}\left[\frac{R_{12}}{\cos\beta} - iR_{13}\tan\beta\gamma_5\right] d\,h$$

TYPE II

$$[h_i]_{mass} = [R_{ij}][h_j]_{gauge} \qquad [R_{ij}] = \begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -(c_1s_2s_3 + s_1c_3) & c_1c_3 - s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3 + s_1s_3 & -(c_1s_3 + s_1s_2c_3) & c_2c_3 \end{pmatrix}$$

The effective Lagrangian is written as

$$\mathscr{L}_{hff} = \kappa_f y_f \bar{f}\,(\cos\alpha + i\,\gamma_5\, sin\alpha)\,f\,h$$

Yukawa types

For the real 2HDM (again for the lightest)

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

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

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

Type LS(X) $\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$ **Lepton-Specific**

For the C2HDM

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

What are the bounds on the Yukawa couplings from rates only?

With the most relevant experimental and theoretical constraints

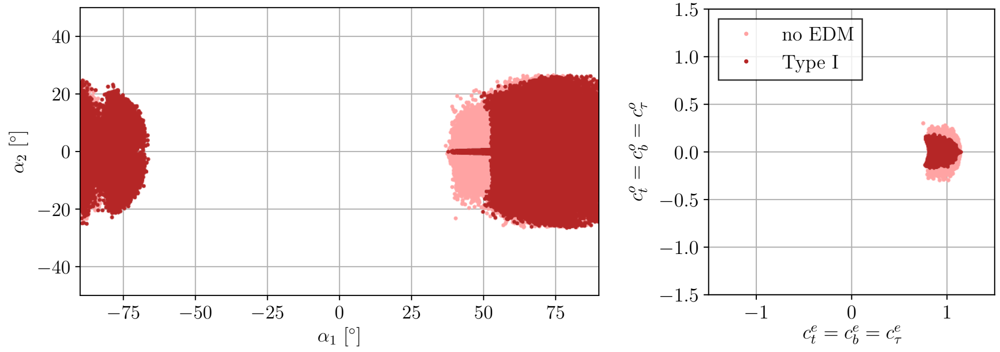


Figure 1. C2HDM Type I: for sample 1 (dark) and sample 2 (light) left: mixing angles α_1 and α_2 of the C2HDM mixing matrix R only including scenarios where $H_1 = h_{125}$; right: Yukawa couplings.

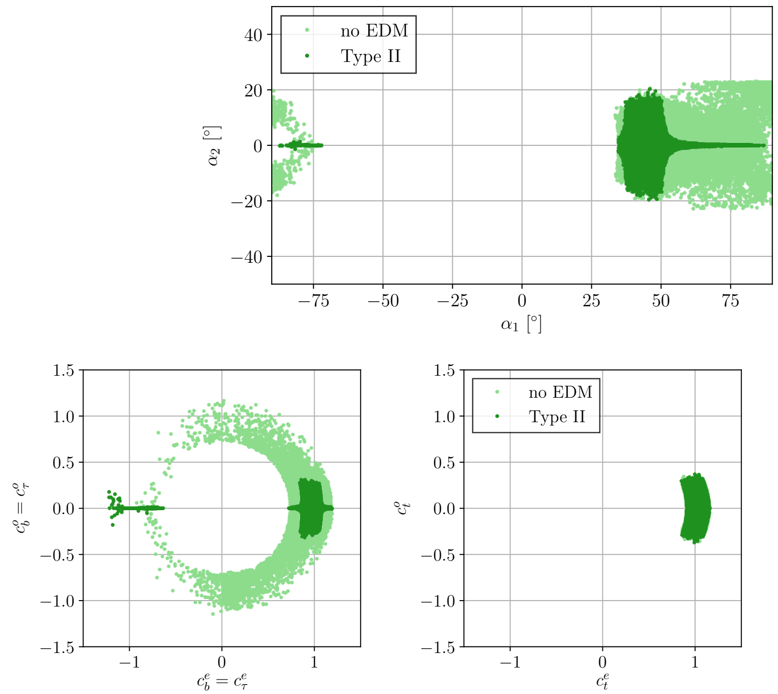
$$g^{hVV}_{C2HDM} = \cos\alpha_2 \, \cos(\beta - \alpha_1) g^{hVV}_{SM}$$

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

$$\mu_{VV} > 0.79 \Rightarrow \cos\alpha_2 > 0.89 \Rightarrow \alpha_2 < 27^o$$

$$\cos 20^o = 0.94 \qquad \sin 20^o = 0.34$$

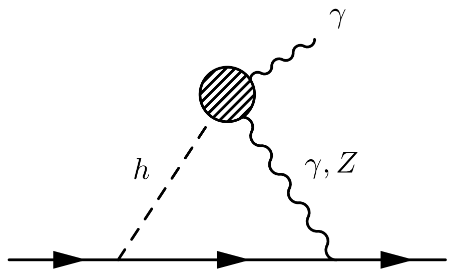
$$\tan\beta > 1$$



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

Figure 3. C2HDM Type II, $h_{125} = H_1$: Yukawa couplings to bottom quarks and tau leptons (left) and top quarks (right) for sample 1 (dark) and sample 2 (light).

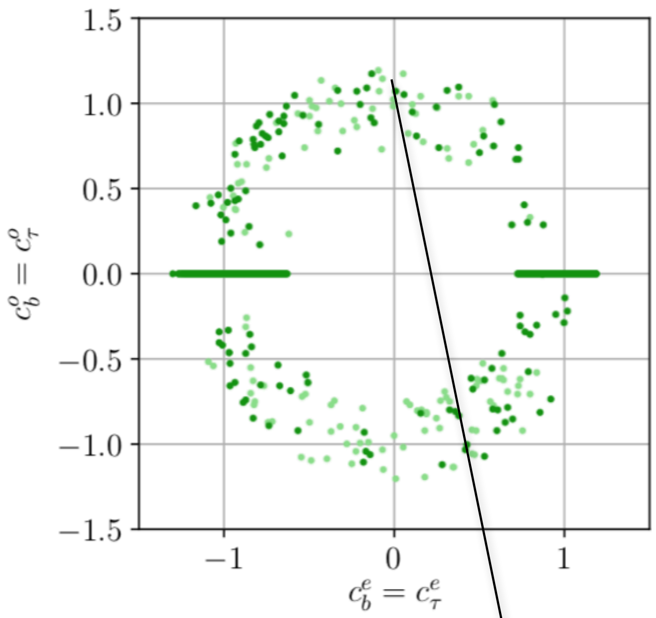
EDMs

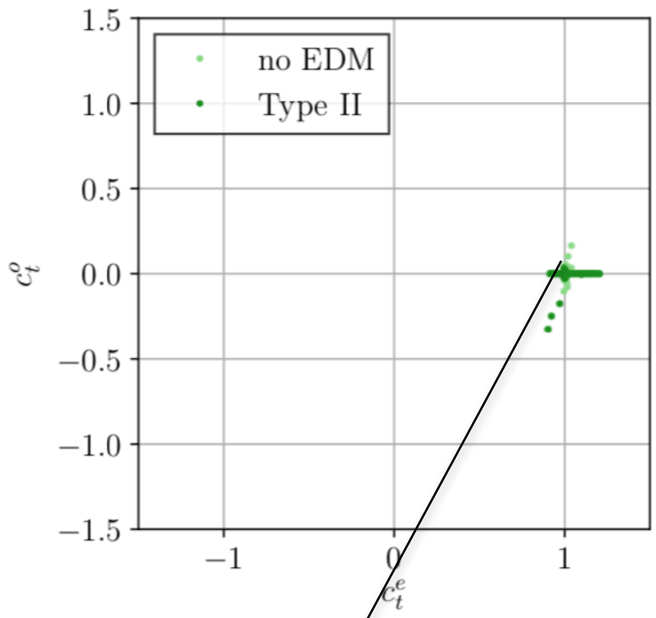


Fontes, Mühlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

Unexpected twist! - large CP-odd components of Yukawa couplings

EDMs kill large pseudoscalar components in Type II. Not in Flipped and Lepton Specific.





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

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

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

Find two particles of the same mass one decaying to tops as CP-even

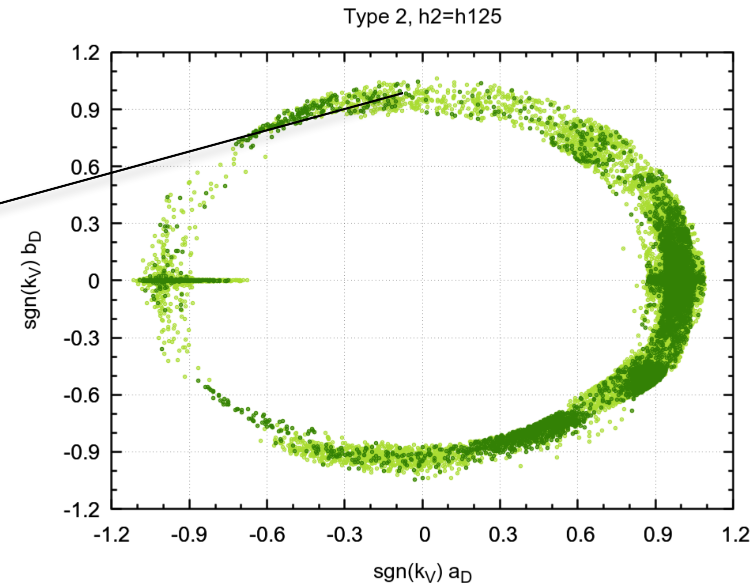
$$h_2 = H; pp \to Ht\bar{t}$$

and the other decaying to taus as CP-odd

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

Probing one Yukawa coupling is not enough!

With the new EDM result



Fontes, Mühlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

Season finale - combination of 3 decays as a sign of CP-violation

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

Combinations of three decays

Many other combinations

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

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

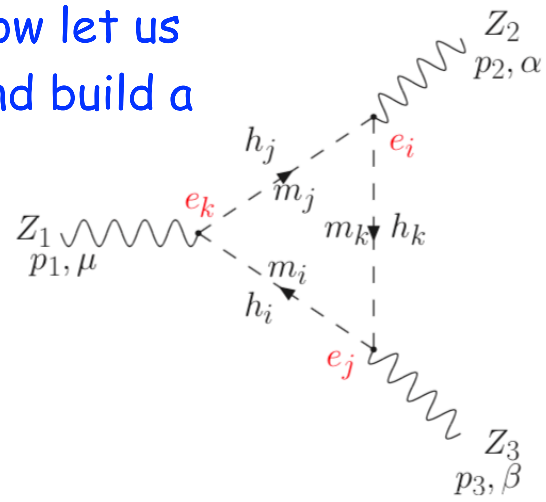
Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

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

But what if the three scalars are invisible?
CPV in the triple gauge bosons couplings

$$h_2 \to h_1 Z \quad CP(h_2) = -\,CP(h_1)$$
$$h_3 \to h_1 Z \quad CP(h_3) = -\,CP(h_1)$$
$$h_3 \to h_2 Z \quad CP(h_3) = -\,CP(h_2)$$

Is there CP-violation here? Now let us take these three processes and build a nice Feynman diagram



With one Z off-shell ZZZ vertex has a CP-odd term

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

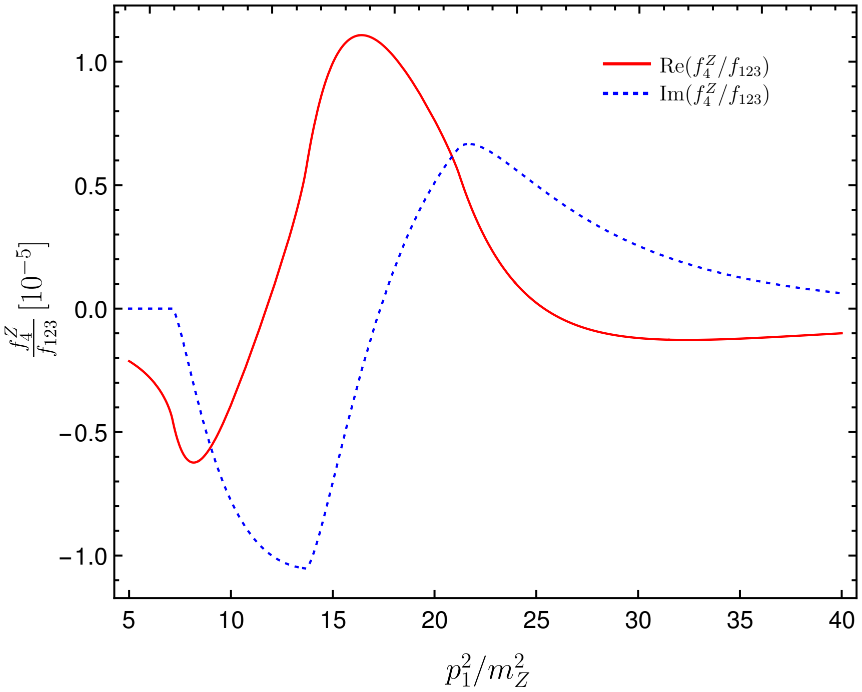
Gaemers, Gounaris, ZPC1 (1979) 259, Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB282 (1987) 253, Grzadkowski, Ogreid, Osland, JHEP 05 (2016) 025

in our model it has the simple expression

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

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

Dark CP-violating model



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.

Azevedo, Ferreira, Mühlleitner, Patel, RS, Wittbrodt, JHEP 1811 (2018) 091

Cordero-Cid, Hernández-Sánchez, Keus, King, S. Moretti, Rojas, Sokolowska, JHEP 12 (2016) 014

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.

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

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

Season 2

The Yukawa Couplings

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

Done!

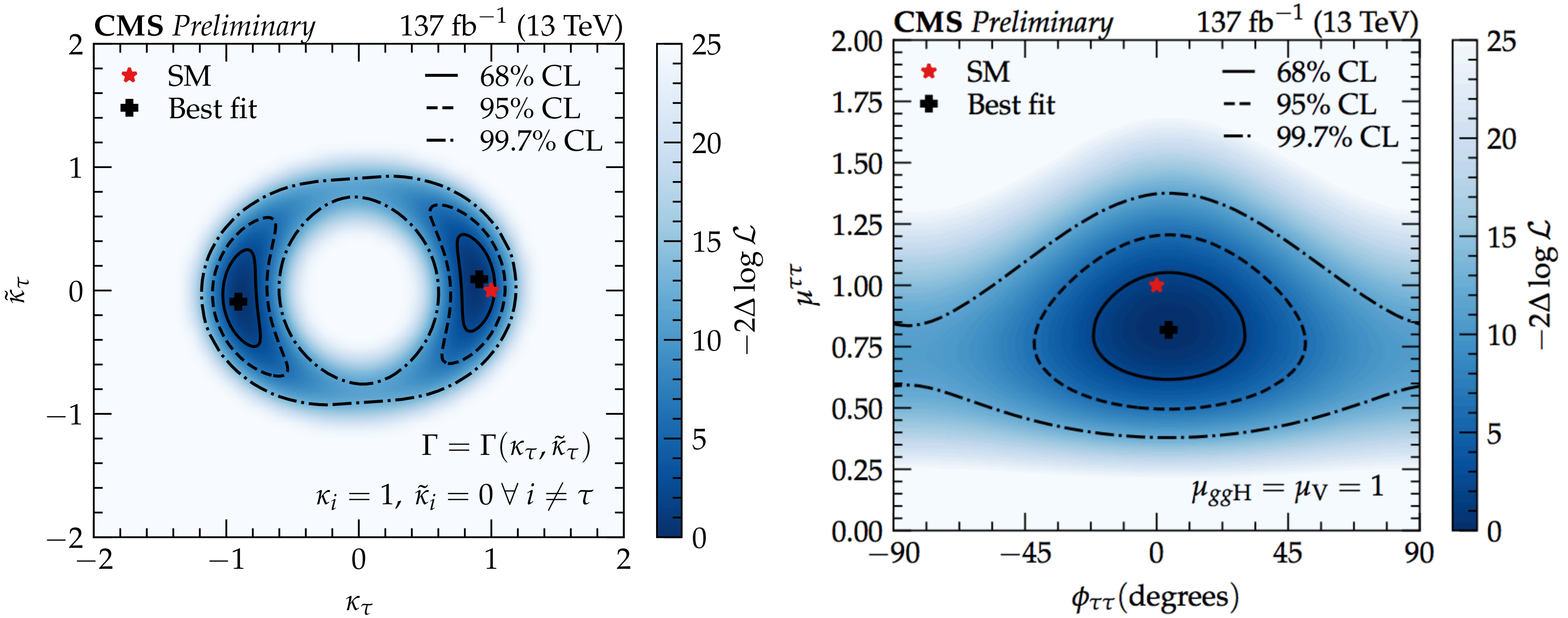
$$pp \to h \to \tau^+\tau^-$$

Great first episode - first appearance of a measurement of the tau CPV angle!

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

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

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)°.
Results compatible with SM predictions.



$$\kappa_\tau = \kappa\,\cos\phi_{\tau\tau}$$

$$\tilde{\kappa}_\tau = \kappa\,\sin\phi_{\tau\tau}$$

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

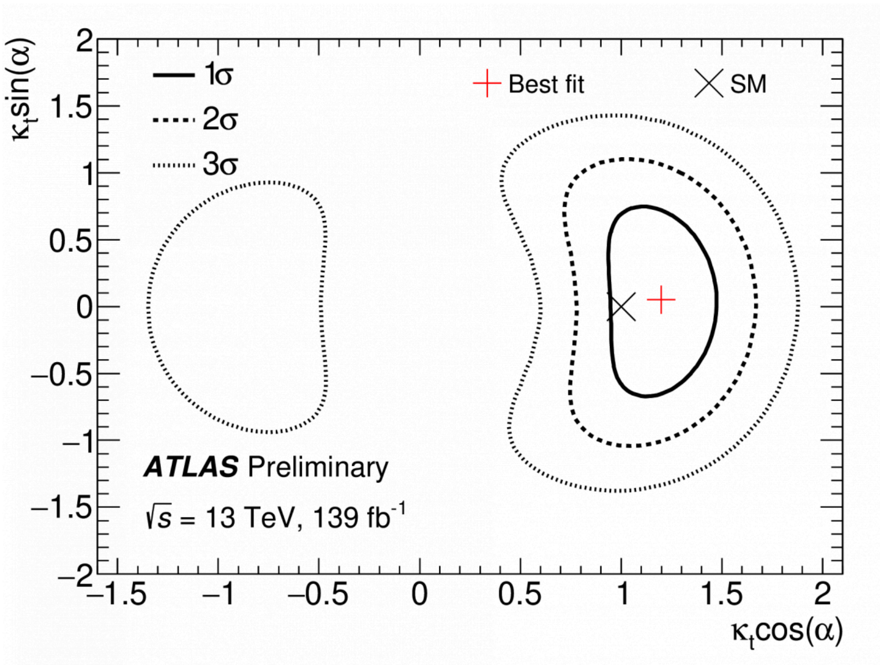
CMS collaboration, CMS-PAS-HIG-20-006

And also the first appearance of the top CPV angle!

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

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

All measurements are consistent with the SM expectations, and the possibility of a pure CP-odd coupling between the Higgs boson and top quark is severely constrained. A pure CP-odd coupling is excluded at 3.9σ, and |α| > 43° is excluded at 95% CL.



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

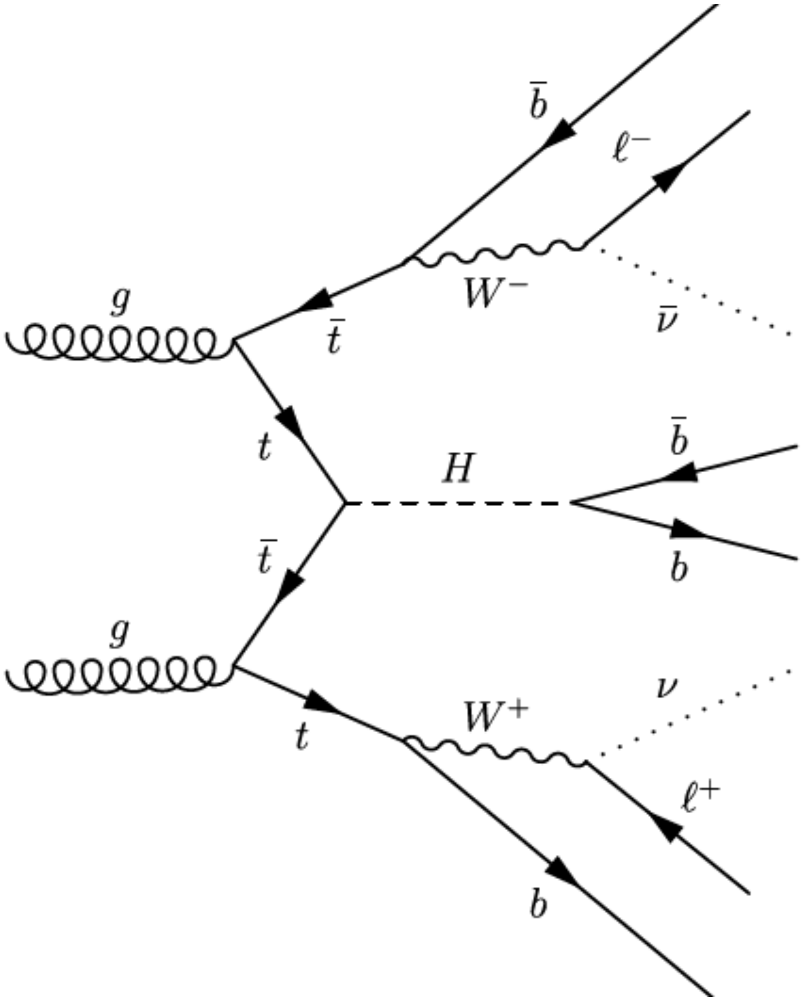
$$\tilde{\kappa}_t = \kappa\ \sin\alpha$$

ATLAS COLLABORATION, PRL 125 (2020) 6, 061802

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

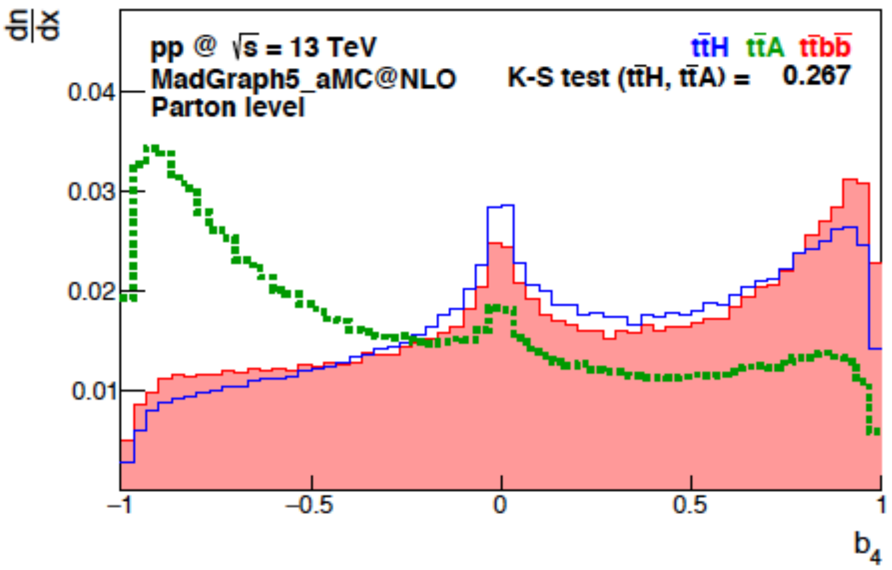


$$\mathscr{L}_{H\bar{t}t} = -\frac{y_t}{\sqrt{2}}\bar{t}(a + ib\gamma_5)th$$

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

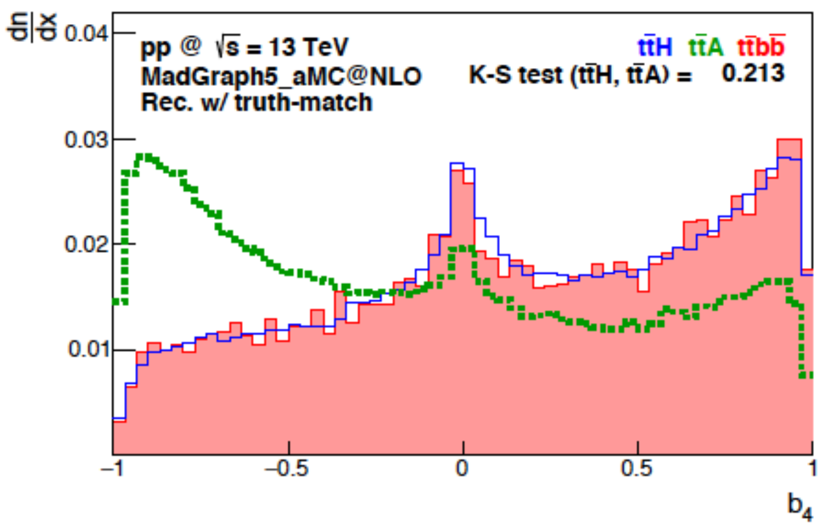
Background: most relevant is the irreducible tt background

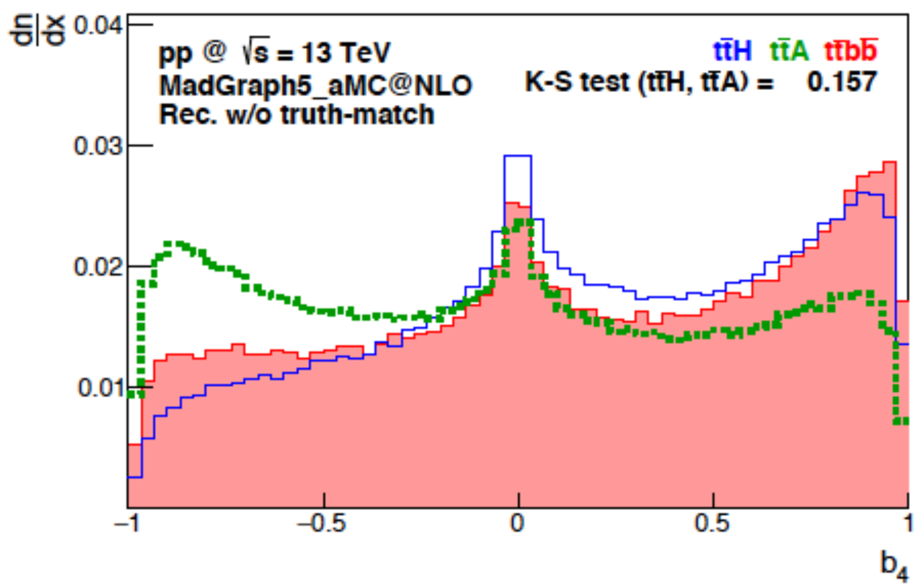
The spin averaged cross section of tth productions has terms proportional to a^2+b^2 and to a^2-b^2. Terms a^2-b^2 are proportional to the top quark mass. There are many operators that can distinguish CP-even and CP-odd parts (maximize the a^2-b^2 term).



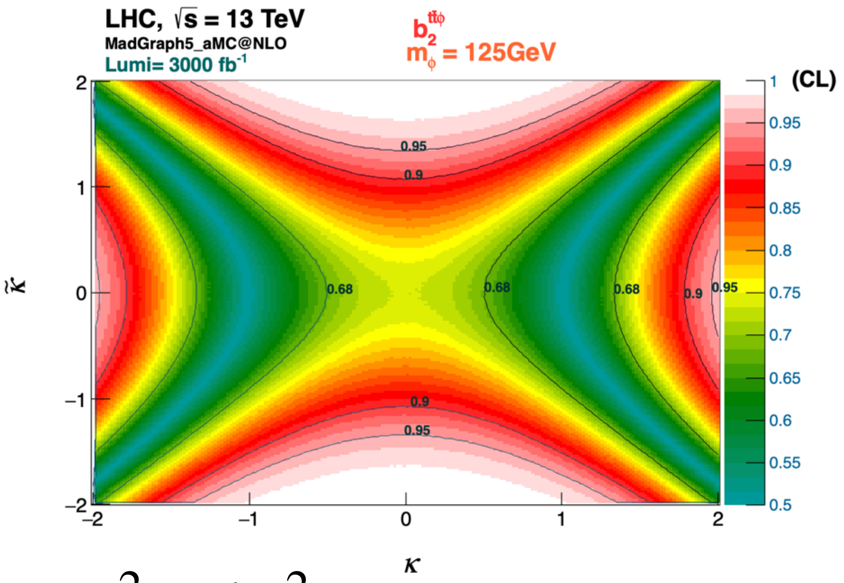
GUNION, HE, PRL77 (1996) 5172

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

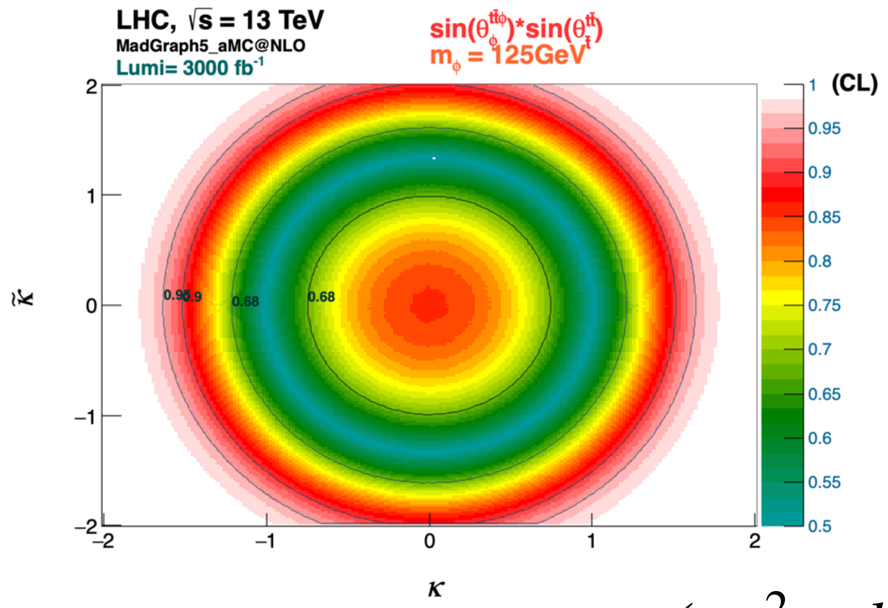




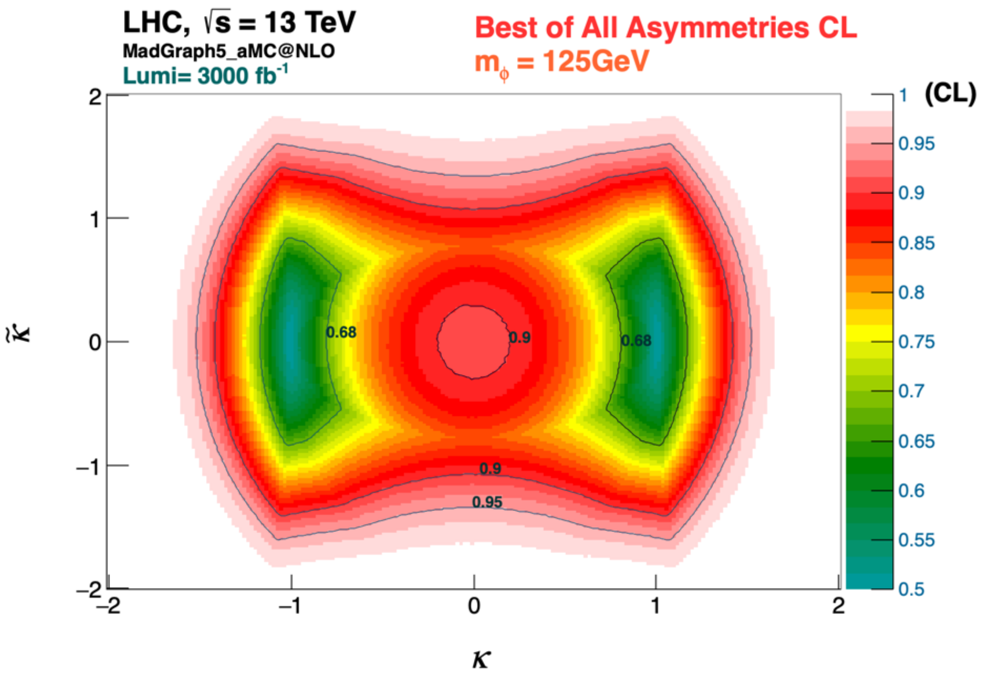
We are testing several variables, combining them, to improve the bounds



$\propto (a\kappa_t^2 - b\tilde{\kappa}_t^2)$



$\propto (a\kappa_t^2 + b\tilde{\kappa}_t^2)$

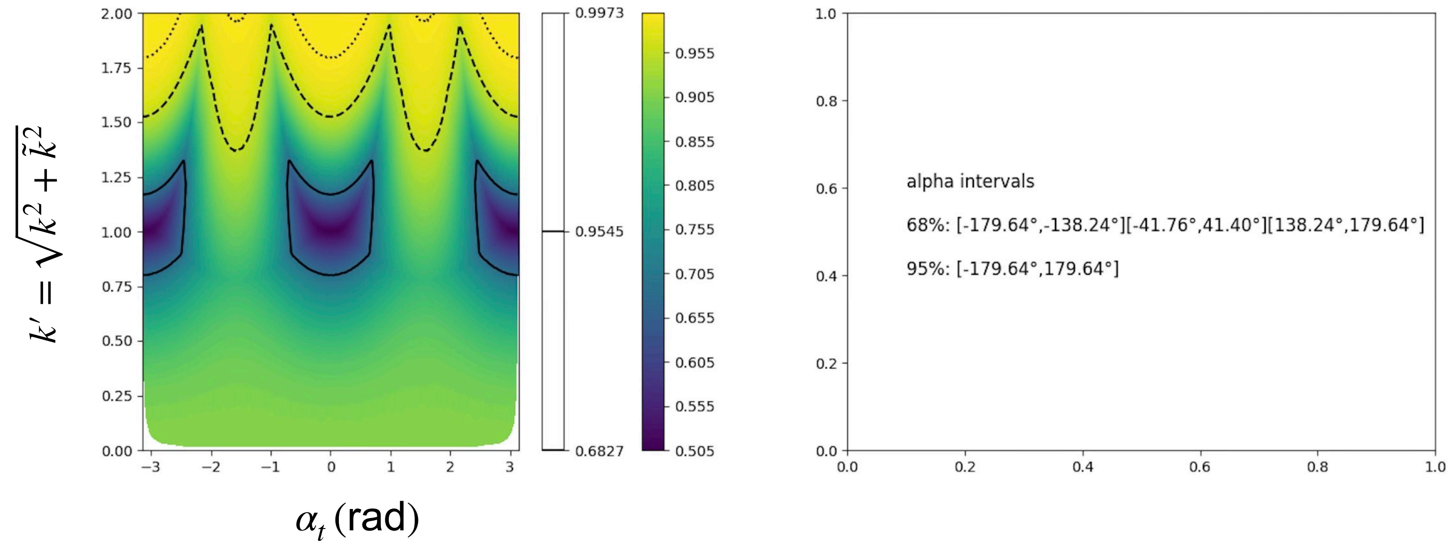


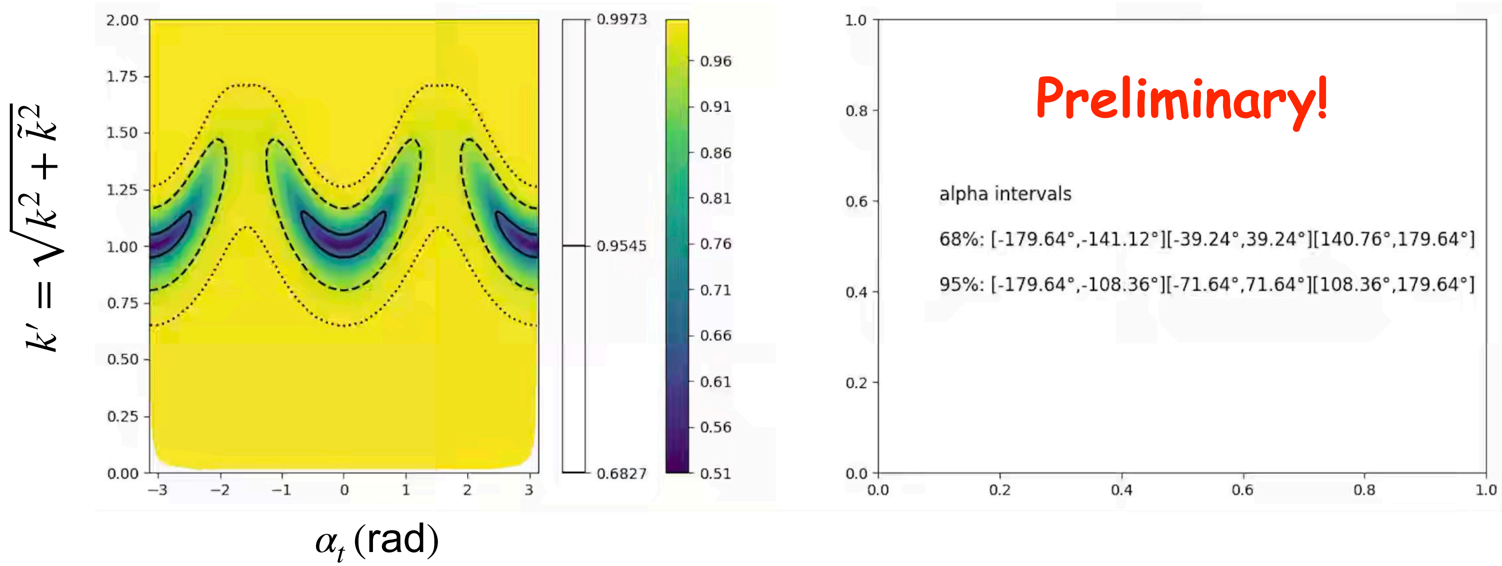
Preliminary! - The plug plot

Asymmetries - less systematics

Azevedo, Capucha, Gouveia, Onofre, RS, work in progress

Azevedo, Capucha, Gouveia, Onofre, RS, work in progress





More shapes?

Ellis, Hwang, Sakurai, Takeuchi, JHEP 04 (2014) 004

Mileo , Kiers , Szynkman , Crane, Gegner, JHEP 07 (2016) 056

$$\sigma_{\bar{t}t\phi} = \kappa^2 \sigma_{\bar{t}th} + \tilde{\kappa}^2 \sigma_{\bar{t}tA}$$

$$d\sigma(gg \to t(n_t)\bar{t}(n_{\bar{t}})H) = \kappa_t^2 f_1(p_i \cdot p_j) + \tilde{\kappa}_t^2 f_2(p_i \cdot p_j) + \kappa_t \tilde{\kappa}_t \sum_{l=1}^{15} g_l(p_i \cdot p_j)\, \epsilon_l$$

The Higgs Coupling to gauge bosons

Is it worth it?

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

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

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

TERM COMING FROM A CPV OPERATOR.

THE SM CONTRIBUTION SHOULD BE PROPORTIONAL TO THE JARLSKOG INVARIANT J = $\mathrm{Im}(V_{UD} V_{CD}^* V_{CS} V_{CD}^*) = 3.00\times 10^{-5}$. 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.

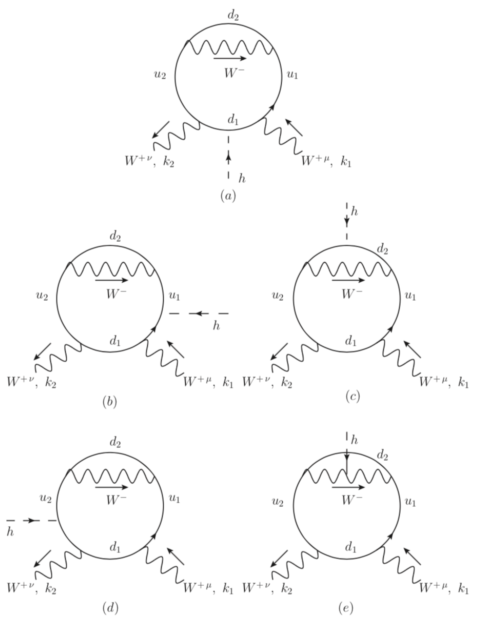


Figure 1. Feynman diagrams leading to the CPV hW^+W^- coupling in the SM.

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

SM ESTIMATE

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

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

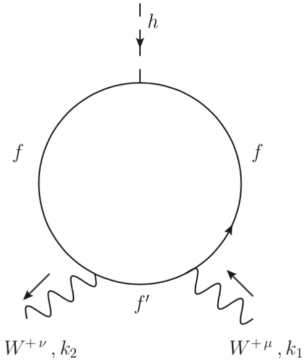
CMS COLLABORATION, PRD100 (2019) 112002.

ATLAS COLLABORATION, EPJC 76 (2016) 658.

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

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

We can now extract the operator for this case

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

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.

Sensitivity projections for future colliders

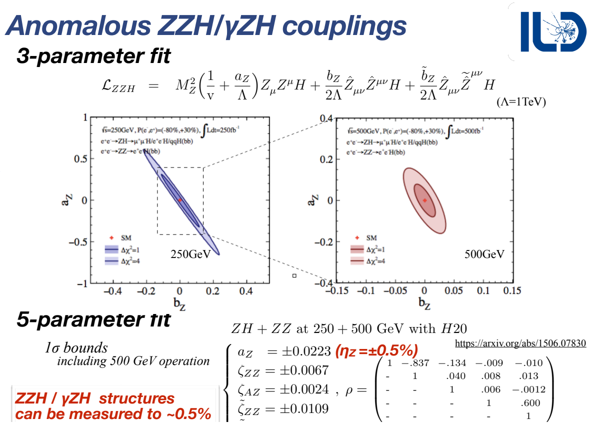
Table 10: Summary of the 95% CL intervals for $f_{a3}\cos(\phi_{a3})$, under the assumption $\Gamma_H = \Gamma_H^{SM}$, and for Γ_H under the assumption $f_{ai} = 0$ for projections at 3000 fb^{-1}. Constraints on $f_{a3}\cos(\phi_{a3})$ are multiplied by 10^4. Values are given for scenarios S1 (with 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 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

Conclusions

- Higgs and fermions - two ongoing direct measurements of Yukawa couplings - with top-quarks in the production and with tau-leptons in the decays. The other Yukawas are measured indirectly by the total rates. Ideas needed. EDMs play a major role.

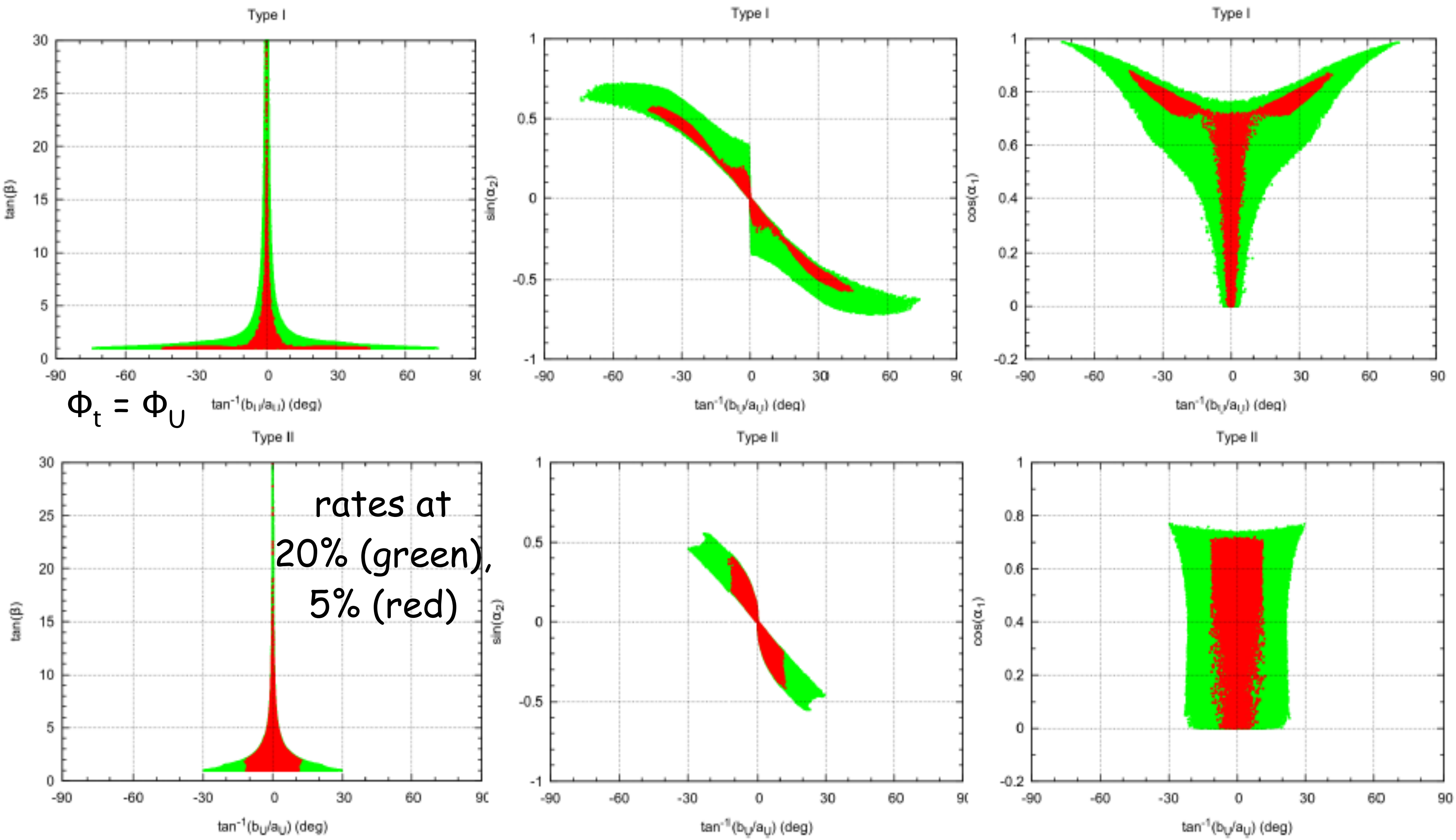
- Higgs and gauge bosons. CP-violating terms appear at the 2-loop level in the SM but at 1-loop in many other extensions. Coefficients are small but reachable in the (near?) future.

- Invisible Higgs. If there is some invisible CPV around, perhaps it can be measured indirectly - like in anomalous triple gauge bosons couplings.

- The end of season 2 is coming with stunning revelations!

The End

Limits on Φ_t based on the rates only



Competitive for Type I but not for Type II

CP from direct measurements at the LHC (ττh)

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

Berge, Bernreuther, Ziethe PRL 100 (2008) 171605
Berge, Bernreuther, Niepelt, Spiesberger, PRD84 (2011) 116003

- A measurement of the angle

$$\tan\Phi_\tau = \frac{b_L}{a_L}$$

can be performed with the accuracies

$$\Delta\Phi_\tau = 15^o \Leftarrow 150\,\mathrm{fb}^{-1}$$

$$\Delta\Phi_\tau = 9^o \Leftarrow 500\,\mathrm{fb}^{-1}$$

Numbers from: Berge, Bernreuther, Kirchner PRD92 (2015) 096012

$$\tan\Phi_\tau = -\frac{\sin\beta}{\cos\alpha_1}\tan\alpha_2 \;\Rightarrow\; \tan\alpha_2 = -\frac{\cos\alpha_1}{\sin\beta}\tan\Phi_\tau$$

- It is not a direct measurement of the CP-violating angle α_2.

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

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

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

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

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

Gunion, He, PRL77 (1996) 5172

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

CP - what have ATLAS and CMS measured so far?

Correlations in the momentum distributions of leptons produced in the decays

$$pp \to h \to ZZ^* \to \bar{l}l\bar{l}l$$

$$pp \to h \to WW^* \to (l_1\nu_1)\,(l_2\nu_2)$$

More correlations in the momentum distributions

$$pp \to hV \to \tau^+\tau^- jj$$

How large can the pseudoscalar component in the Yukawa couplings

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

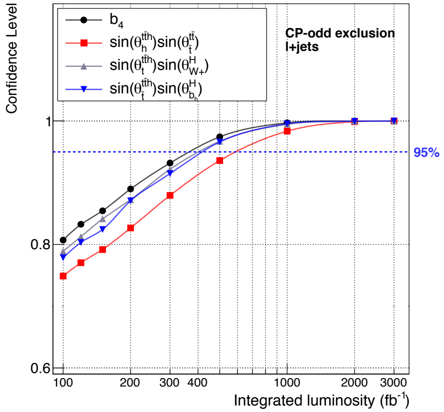
$$pp \to h \to \tau^+\tau^-$$

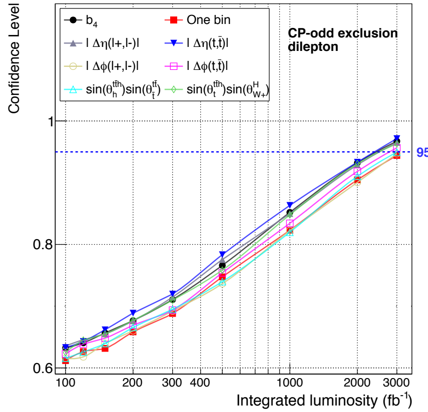
Conclusions:

a) If h is a CP-eigenstate it is not (really not!) CP-odd

b) Some Yukawa couplings are finally being directly probed

c) effective Lagrangian for hVV also probed

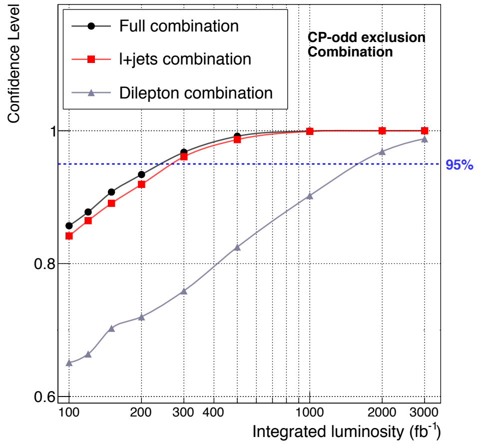


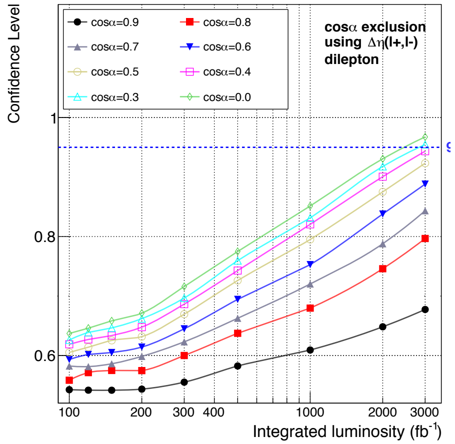


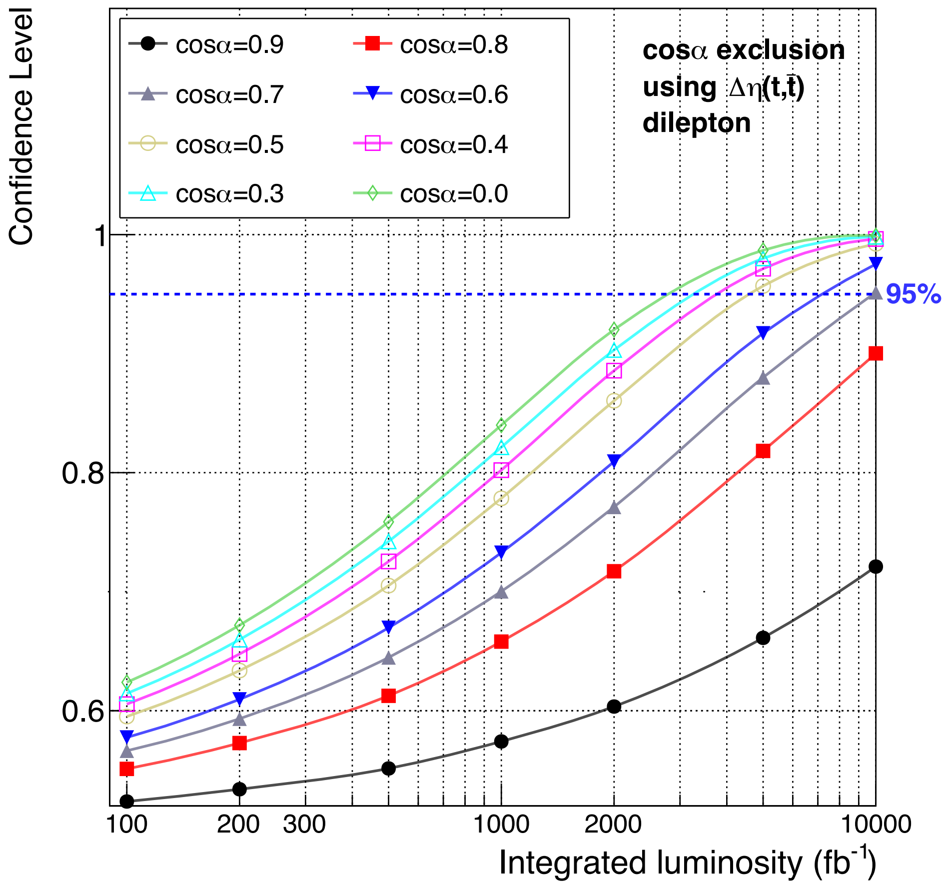
$$\mathscr{L}_{H\bar{t}t} = \kappa y_t \bar{t}(\cos\alpha + i \sin\alpha\gamma_5)th$$

$\cos\alpha = 1$ pure scalar

So, what is bound on the pseudoscalar component of the tth coupling at the end of the high luminosity LHC?







For cosα=0.7 the limit on α_2 is 46° for tanβ=1 while for cosα=0.9 is 26° - close to what we have today from indirect measurements.
The difference is that the bound is now directly imposed on the Yukawa coupling.

Azevedo, Gonçalo, Gouveia, Onofre, TOP2018 arXiv:1902.00298

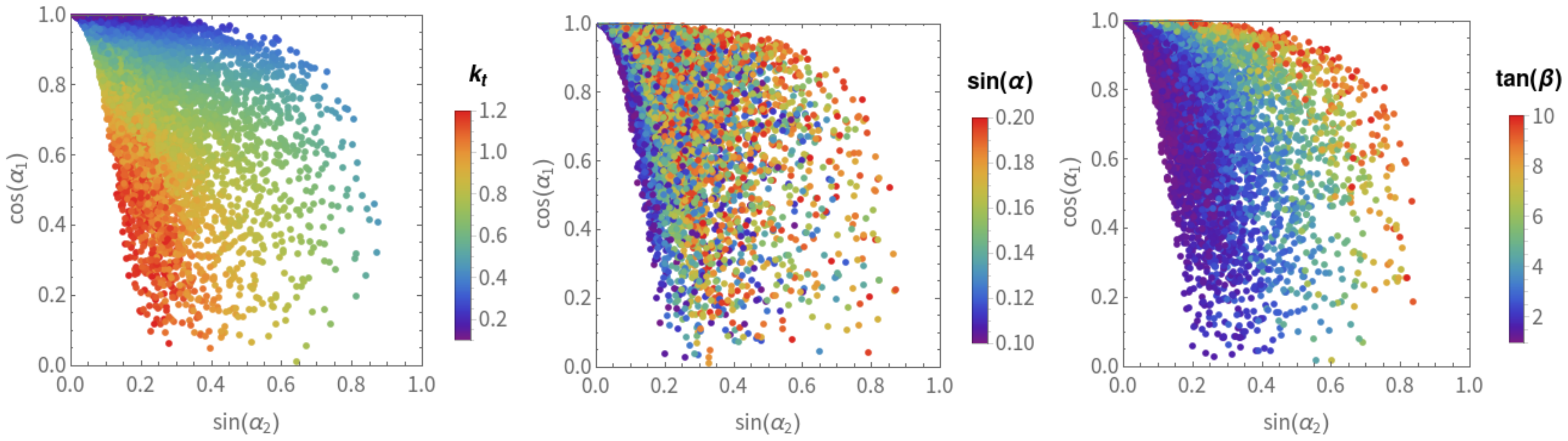


Figure 19: Points allowed in the plane c_1 vs. s_2 for $0.1 \leq \kappa_t \leq 1.2$ and $0.1 \leq \sin\alpha \leq 0.2$ and $1 \leq \tan\beta \leq 10$. In the left plot we see the variation with κ_t, in the middle with $\sin\alpha$ and on the right with $\tan\beta$.

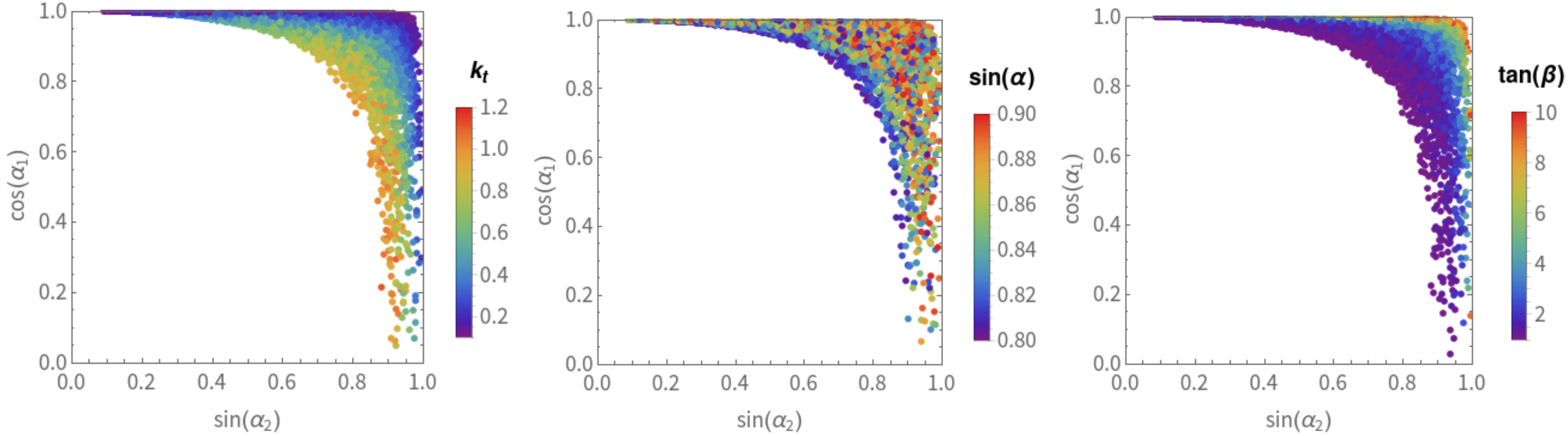


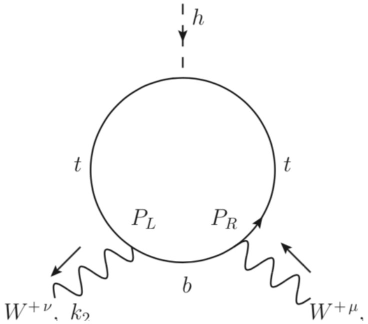
Figure 20: Points allowed in the plane c_1 vs. s_2 for $0.1 \leq \kappa_t \leq 1.2$ and $0.8 \leq \sin\alpha \leq 0.9$ and $1 \leq \tan\beta \leq 10$. In the left plot we see the variation with κ_t, in the middle with $\sin\alpha$ and on the right with $\tan\beta$.

Is it worth it?

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

The left-right symmetric model

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



$$\mathcal{L}^{\mathrm{LR}} \supset -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{i,j} \bar{u}_i \gamma^\mu (V_{u_i d_j} P_L + U_{u_i d_j} P_R) d_j + \mathrm{h.c.}\,,$$

The effective operator coefficient for this case is

$$c_{\mathrm{CPV}}^{\mathrm{LR}} \approx \frac{N_c g^2}{8\pi^2} \frac{m_t m_b}{m_W^2} \mathcal{I}\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) \mathrm{Im}(V_{tb} U_{tb}^*) \qquad \mathcal{I}(x,y) \equiv \int_0^1 d\alpha \frac{\alpha(1-\alpha)}{\alpha x + (1-\alpha) y - \alpha(1-\alpha)}\,.$$

Using the constraint

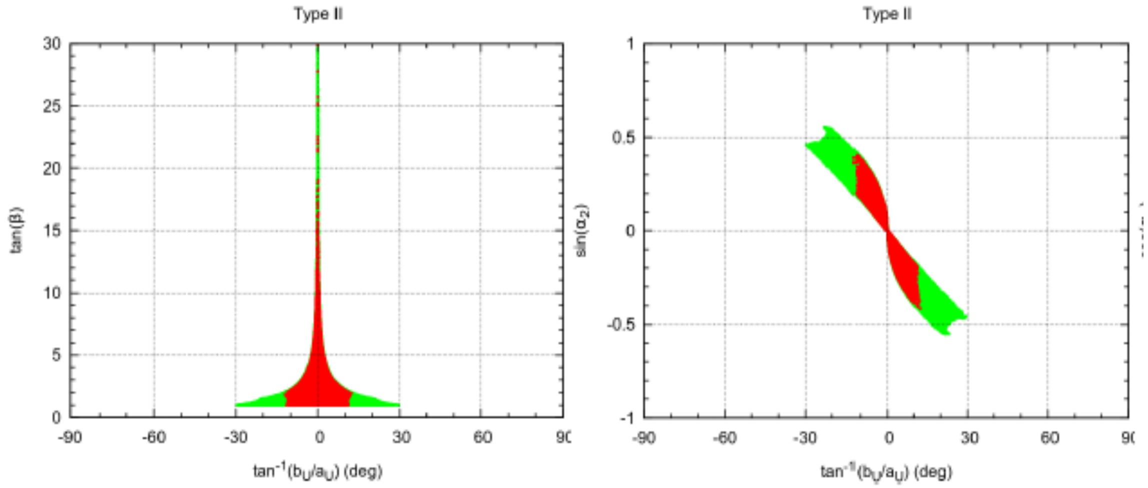
$$\mathrm{Im}(V_{tb} U_{tb}^*) \leq 4 \times 10^{-6}\,,$$

Dekens, Boer, NPB889 (2014) 727

$$c_{\mathrm{CPV}}^{\mathrm{LR}} \simeq 9.1 \times 10^{-10} \sim \mathcal{O}(10^{-9})$$

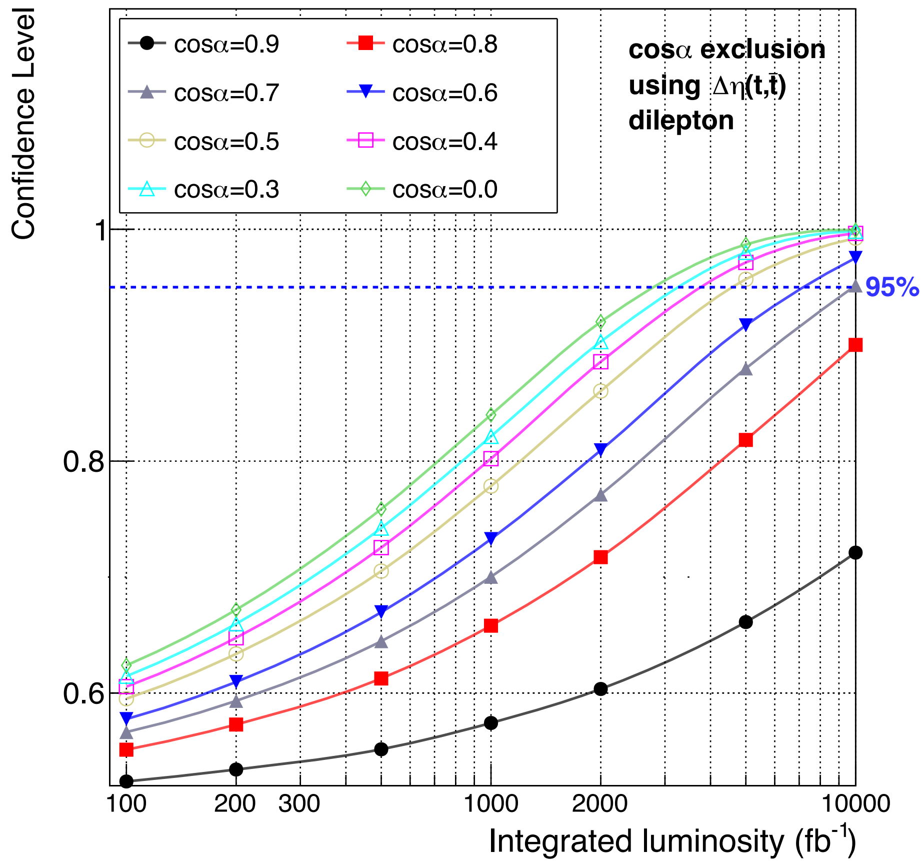
$$\mathcal{L}_{H\bar{t}t} = \kappa y_t \bar{t}(\cos\alpha + i\sin\alpha\gamma_5)th$$

$\cos\alpha = 1$ pure scalar



rates at 20% (green), 5% (red)

So, what is bound on the pseudoscalar component of the tth coupling at the end of the high luminosity LHC?



For cosα=0.7 the limit on α_2 is 46° for tanβ=1 while for cosα=0.9 is 26° - close to what we have today from indirect measurements.

The difference is that the bound is now directly imposed on the Yukawa coupling.

Azevedo, Gonçalo, Gouveia, Onofre, TOP2018 arXiv:1902.00298

How will it look in the future?

Abramowicz eal, 1307.5288.
CLICdp, Sicking, NPPP, 273-275, 801 (2016)

Parameter	Relative precision [76, 77]		
	350 GeV 500 fb^{-1}	+1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
κ_{HZZ}	0.43%	0.31%	0.23%
κ_{HWW}	1.5%	0.15%	0.11%
κ_{Hbb}	1.7%	0.33%	0.21%
κ_{Hcc}	3.1%	1.1%	0.75%
κ_{Htt}	–	4.0%	4.0%
$\kappa_{H\tau\tau}$	3.4%	1.3%	<1.3%
$\kappa_{H\mu\mu}$	–	14%	5.5%
κ_{Hgg}	3.6%	0.76%	0.54%
$\kappa_{H\gamma\gamma}$	–	5.6%	< 5.6%

Predicted precision for CLIC

All models become very similar and hard to distinguish.

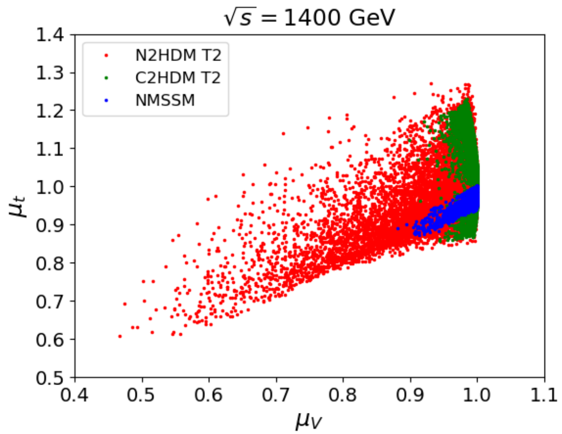
LHC today

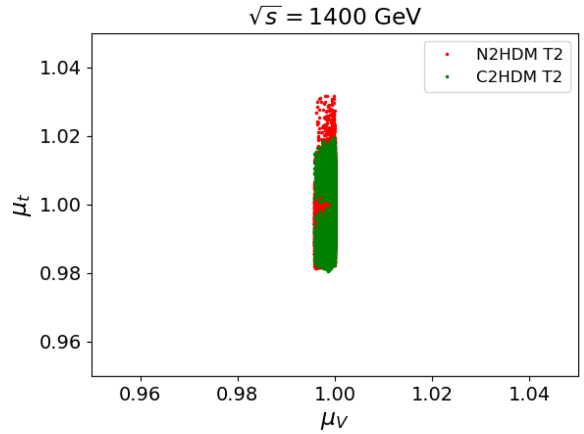
Model	CxSM	C2HDM II	C2HDM I	N2HDM II	N2HDM I	NMSSM
$(\Sigma \text{ or } \Psi)_{\text{allowed}}$	11%	10%	20%	55%	25%	41%

CLIC@350GeV (500/fb)

$$\Psi_i(\Sigma_1) \leq 0.85\,\% \text{ from } \kappa_{ZZ}$$

If no new physics is discovered and the measured values are in agreement with the SM predictions, the singlet and pseudoscalar components will be below the % level.





Beware of radiative corrections.

Azevedo, Ferreira, Mühlleitner, RS, Wittbrodt, PRD99 (2019) 5, 055013

How will it look in the future?

$\Psi_i^{C2HDM} = R_{i3}^2$ **C2HDM - pseudoscalar component.**

Unitarity $\Rightarrow \kappa_{ZZ,WW}^2 + \Psi_i(\Sigma_1) \leq 1$

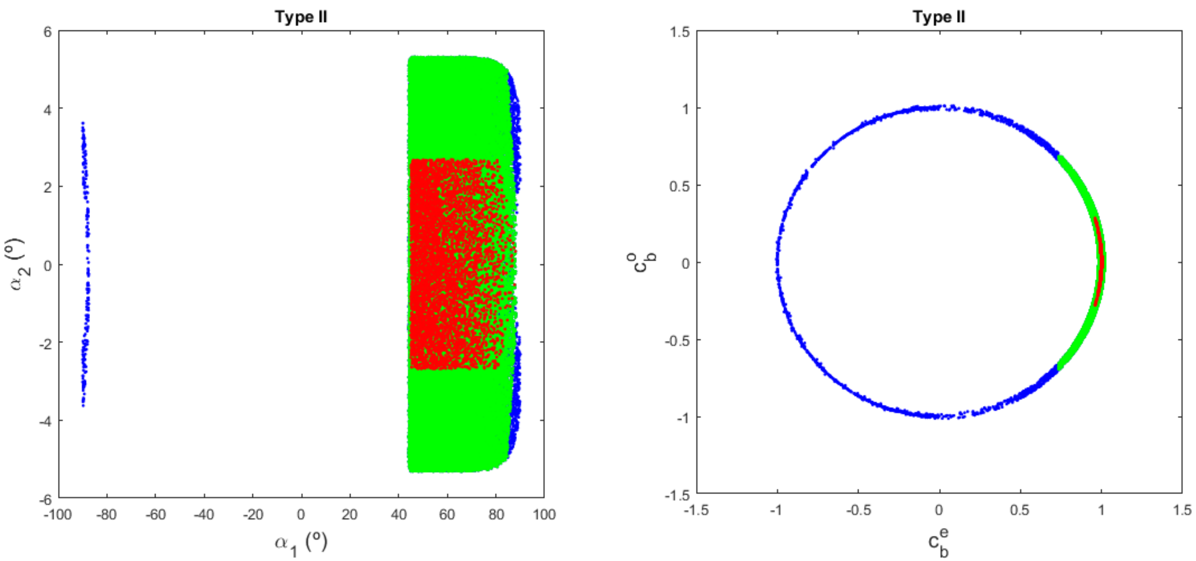


Figure 2: Mixing angles α_2 vs. α_1 (left) and c_b^o vs. c_b^e (right) for the C2HDM Type II. The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

The deviations can be written in terms of the rotation matrix from gauge to mass eigenstates.

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho \\ \eta \\ \rho_S \end{pmatrix} \qquad R = [R_{ij}] = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

Azevedo, Ferreira, Mühlleitner, RS, Wittbrodt, PRD99 (2019) 5, 055013

But what if the three scalars are invisible?

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

Azevedo, Ferreira, Mühlleitner, Patel, RS, Wittbrodt, JHEP 1811 (2018) 091

With one Z off-shell the most general ZZZ vertex has a CP-odd term of the form

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

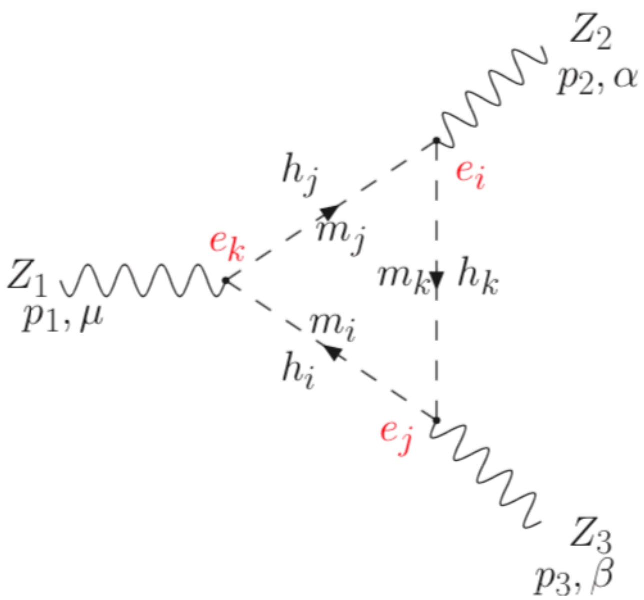
GAEMERS, GOUNARIS, ZPC1 (1979) 259

HAGIWARA, PECCEI, ZEPPENFELD, HIKASA, NPB282 (1987) 253

GRZADKOWSKI, OGREID, OSLAND, JHEP 05 (2016) 025

that comes from an effective operator (dim-6)

$$\frac{\tilde{k}_{ZZ}}{m_Z^2}\partial_\mu Z_\nu \partial^\mu Z^\rho \partial_\rho Z^\nu$$



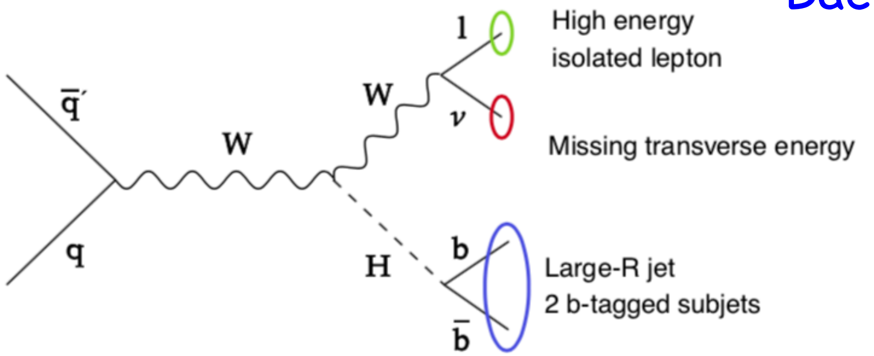
in our model it has the simple expression

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

$$f_{123} = R_{13}R_{23}R_{33}$$

Combining h_1h_2Z; h_1h_3Z and h_2h_3Z

Back to experiment



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

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

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

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

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

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

Pre-Preliminary!

Slide from Ricardo Barrué MSc thesis.

$\cos\delta^+$ asymmetry

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

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

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

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

Can we use the idea for bbh?

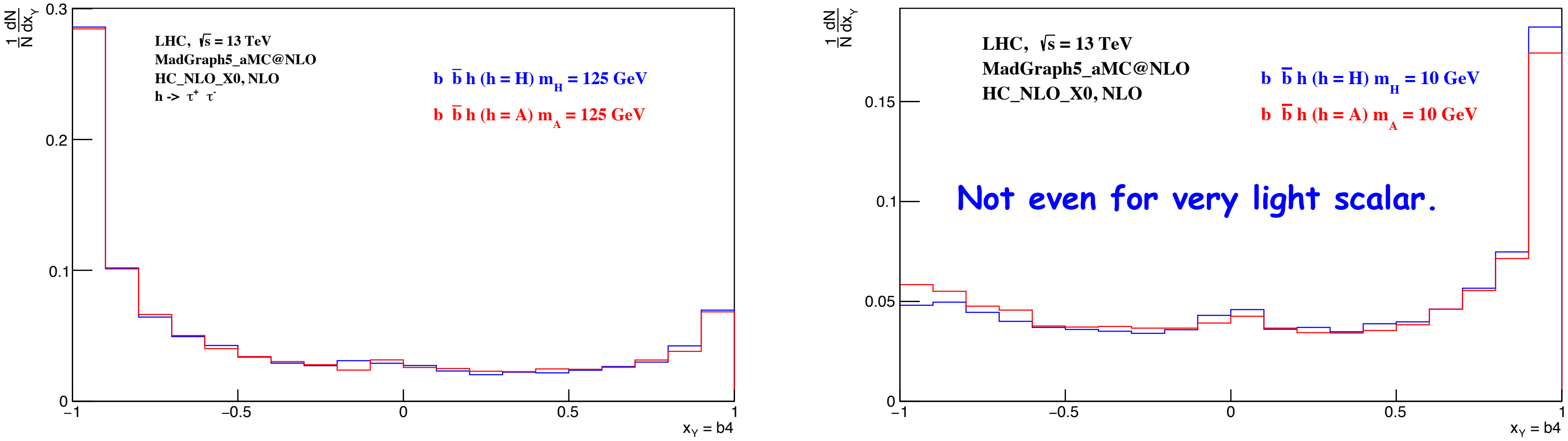


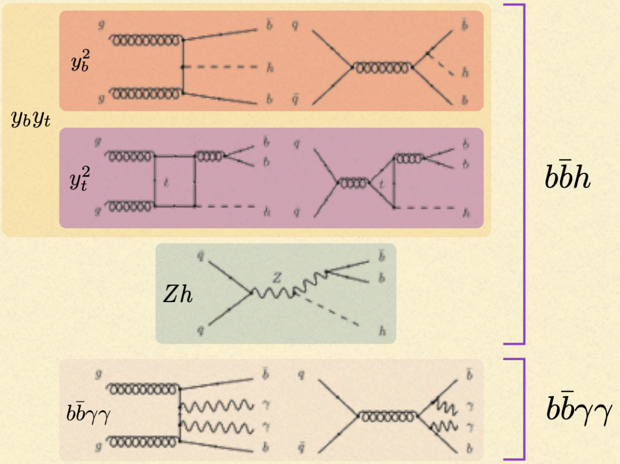
Figure 1: Parton level b_4 distributions at NLO, normalized to unity, for $m_\phi = 125$ GeV (left) and $m_\phi = 10$ GeV (right). Only events with $p_T(b) > 20$ GeV and $|\eta(b)| < 2.5$ were selected, with p_T and η being the transverse momentum and the pseudo-rapidity, respectively.

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.

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