ISEL
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CP-violation measurements at the LHC

Where is the rest of it?

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ISEL & CFTC-UL

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FCT
Fundação para a Ciência e a Tecnologia
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Previously on "Searches for CPV at the LHC"

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

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

- ⊙ Season finale - 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

- ⊙ CP-violation in a dark sector

(if I have time because this is an episode from season 1)

- ⊙ 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**

➡ $\boxed{\tan\beta = \frac{v_2}{v_1}}$ 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

CP-violating 2HDM

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

"Pseudoscalar" component (doublet)

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

$\sin\alpha_2 = 0 \implies$ 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 $\kappa_U^I = \kappa_D^I = \kappa_L^I = \dfrac{\cos\alpha}{\sin\beta}$

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

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

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

For the C2HDM

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

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

With the most relevant experimental and theoretical constraints

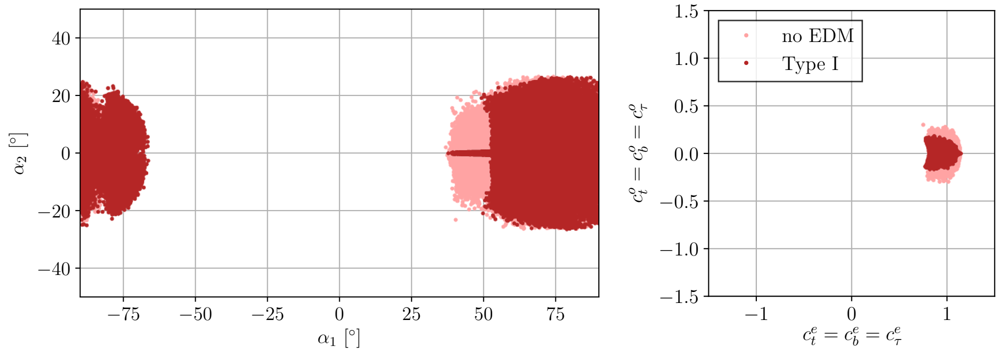
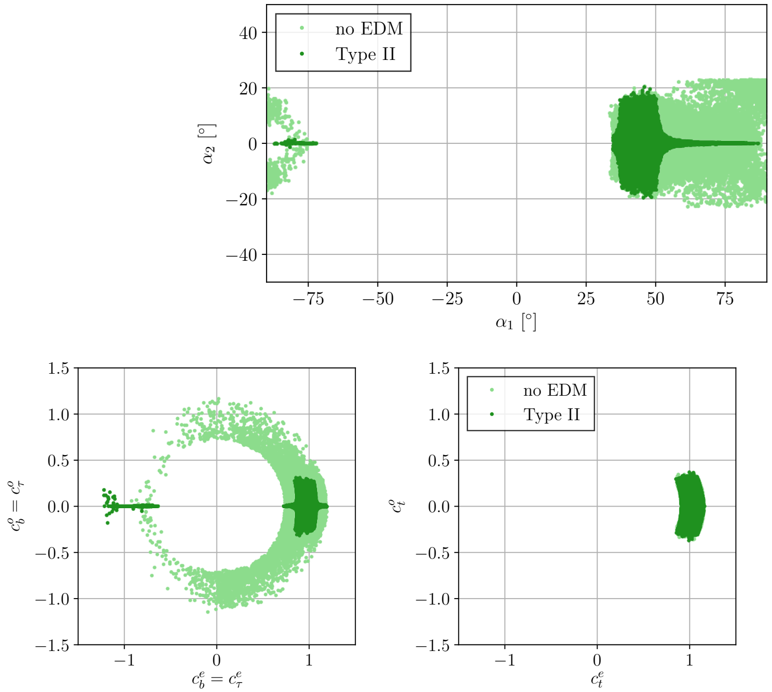


Figure 1. C2HDM Type I: for sample 1 (dark) and sample 2 (light) left: mixing angles α_1 and α_2 of the C2HDM mixing matrix R only including scenarios where $H_1 = h_{125}$; right: Yukawa couplings.

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

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

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

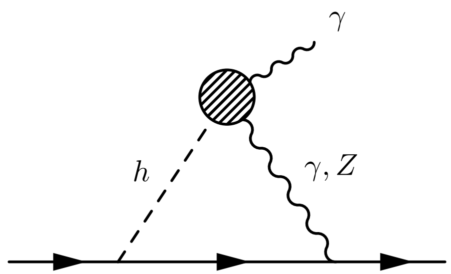


$$\boxed{\cos 20^o = 0.94 \qquad \sin 20^o = 0.34 \qquad \tan\beta > 1}$$

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

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).

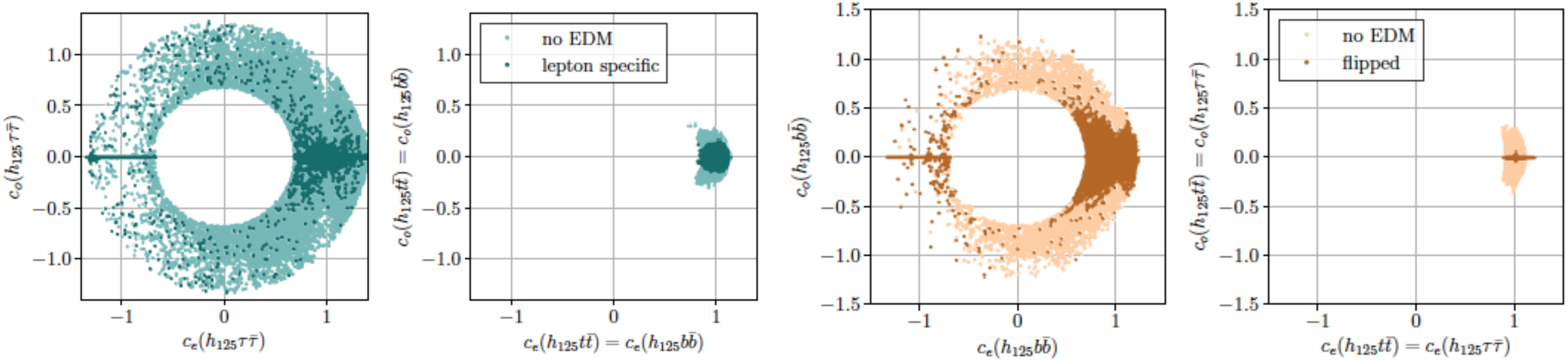
EDMs



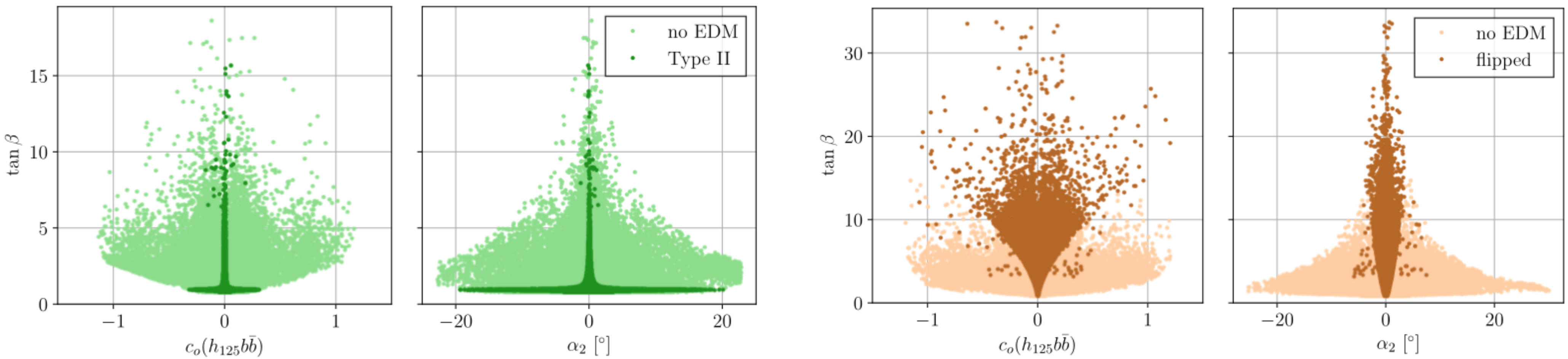
Fontes, Mühlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

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

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

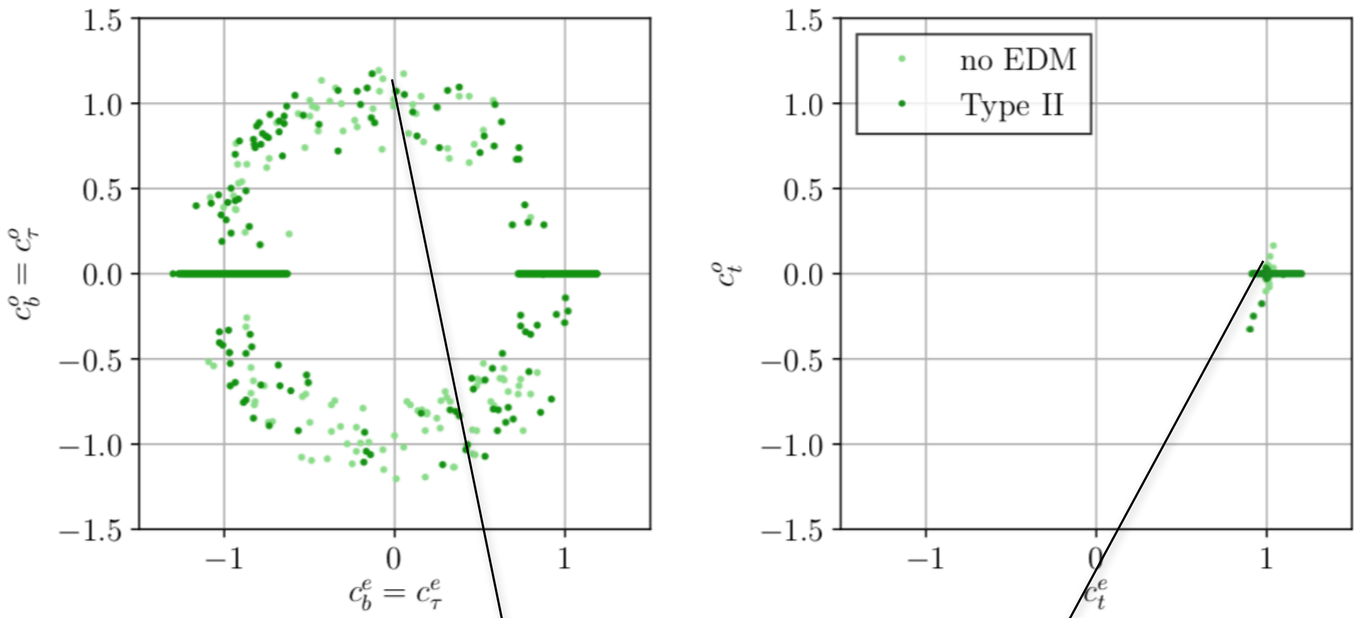


CP-odd coupling proportional to $\sin\alpha_2 \tan\beta$



EDMs act differently in the different Yukawa versions of the model.
Cancellations between diagrams occur.

The strange case of CP-violation in a complex 2HDM



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

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

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

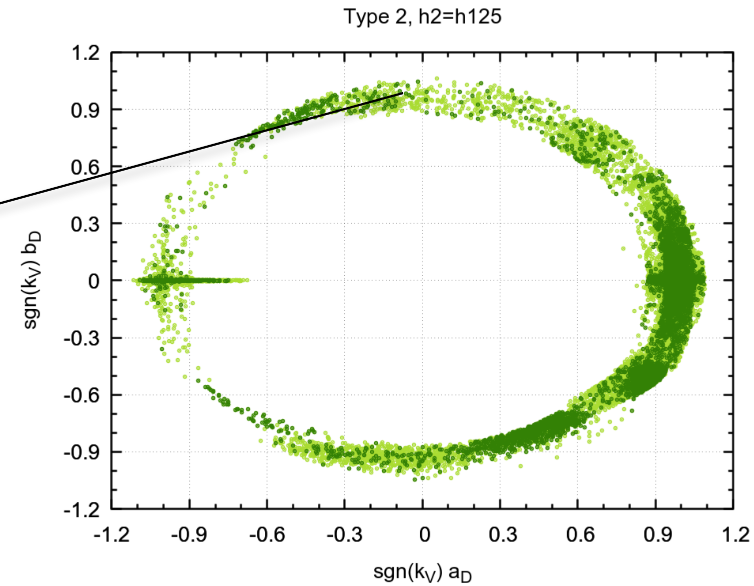
Find two particles of the same mass one decaying to tops as CP-even

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

and the other decaying to taus as CP-odd

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

With the new EDM result



Probing one Yukawa coupling is not enough!

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

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.

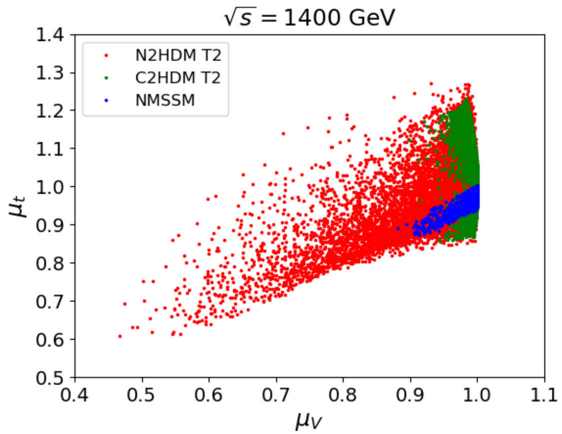
LHC today

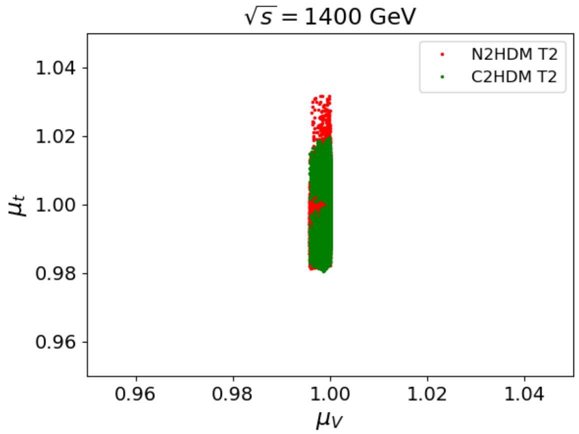
Model	CxSM	C2HDM II	C2HDM I	N2HDM II	N2HDM I	NMSSM
$(\Sigma \text{ or } \Psi)_{\text{allowed}}$	11%	10%	20%	55%	25%	41%

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

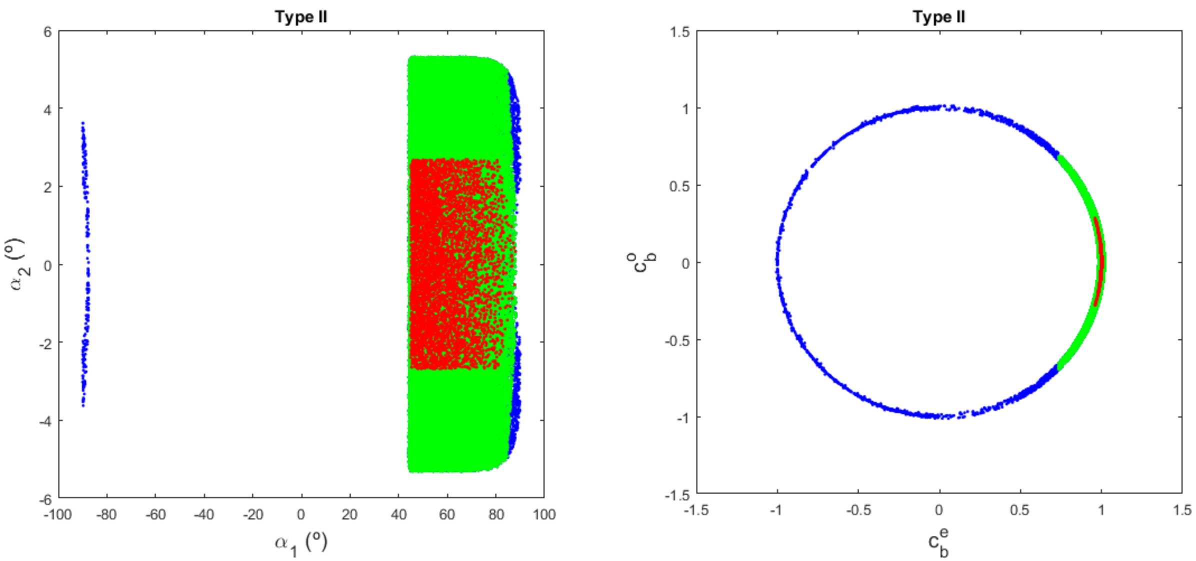


Figure 2: Mixing angles α_2 vs. α_1 (left) and c_b^o vs. c_b^e (right) for the C2HDM Type II. The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

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

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

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

Combinations of three decays

Many other combinations

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

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

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

Season 2

The Yukawa Couplings

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

Done!

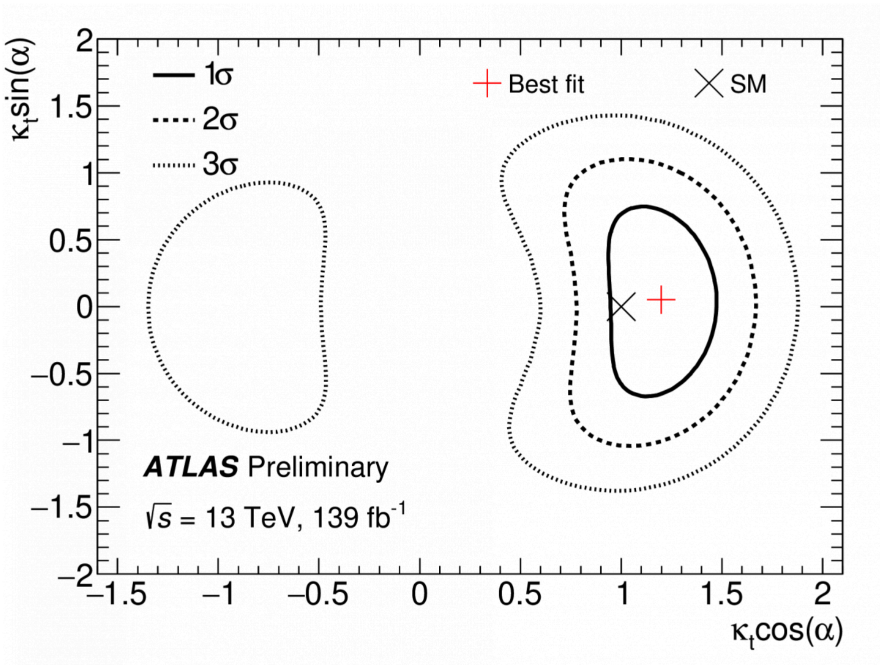
$$pp \to h \to \tau^+\tau^-$$

Great first episode - first appearance of a constraints on the top CPV angle!

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

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

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.



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

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

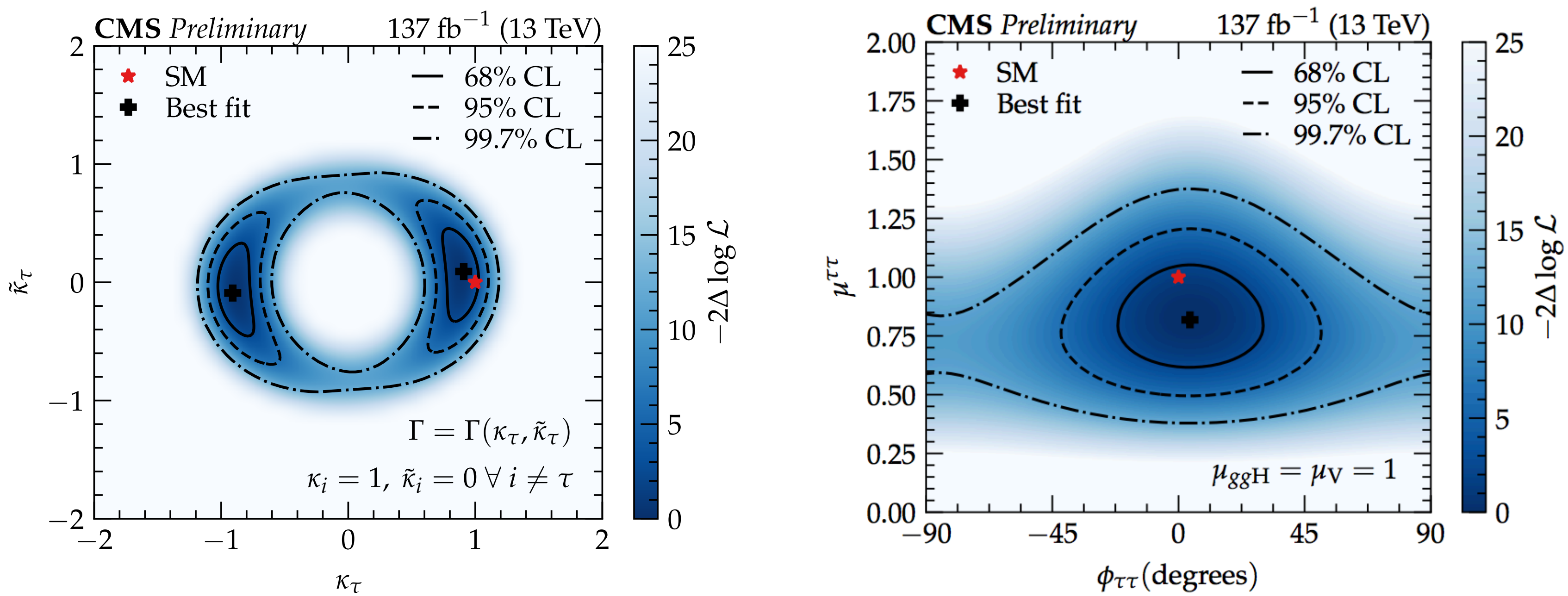
ATLAS COLLABORATION, PRL 125 (2020) 6, 061802

And also the first appearance of the tau CPV angle!

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

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

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)°.
Results compatible with SM predictions.



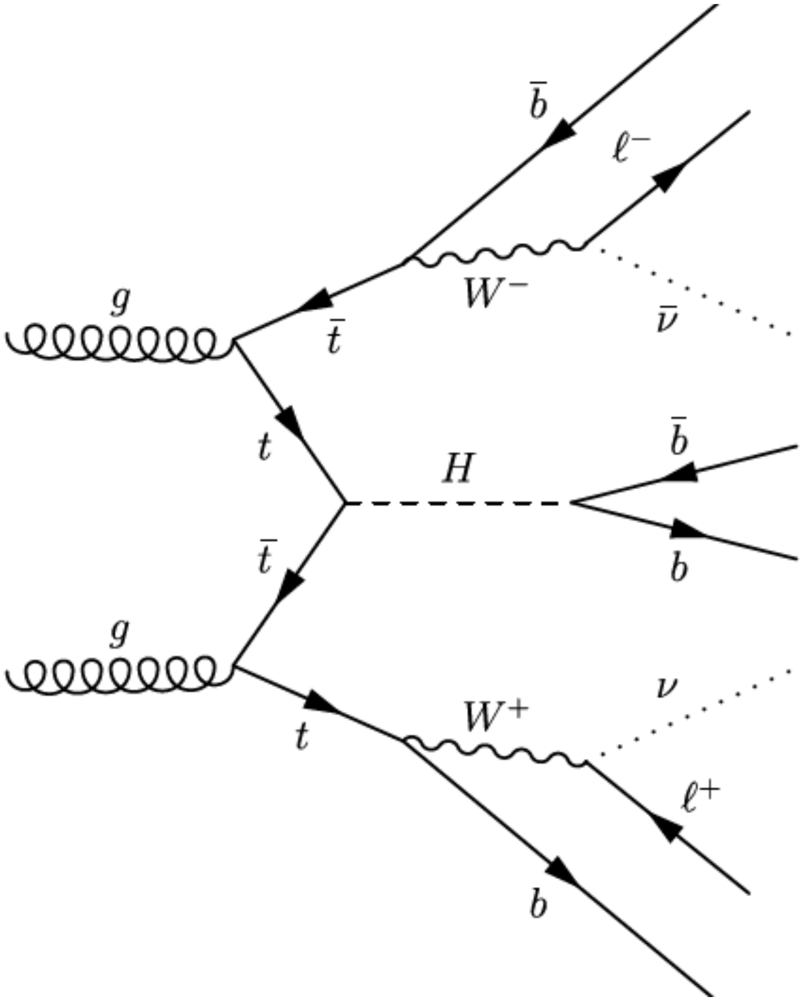
$$\phi_{\tau\tau} = \alpha$$

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

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

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

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



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

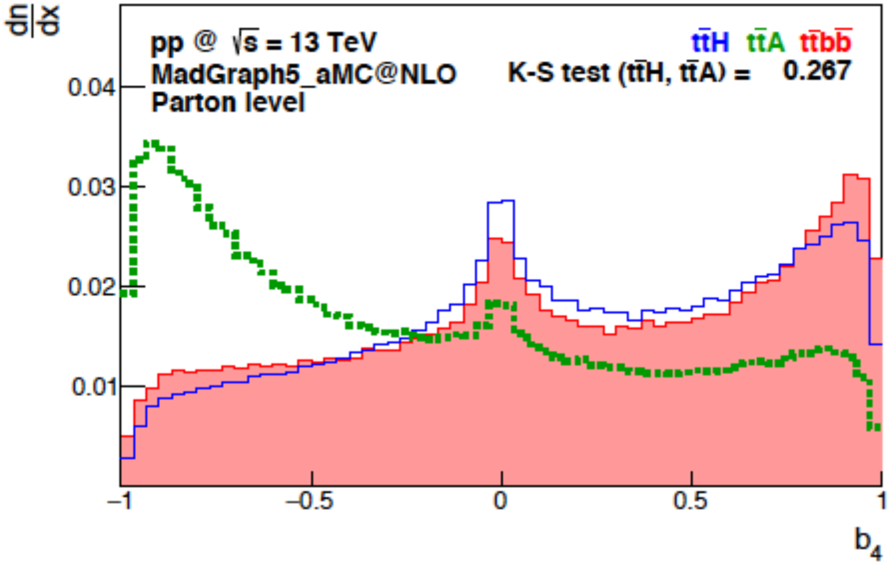
Signal: we consider the tt fully leptonic (but could add the or semi-leptonic case) and H -> bb

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.

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

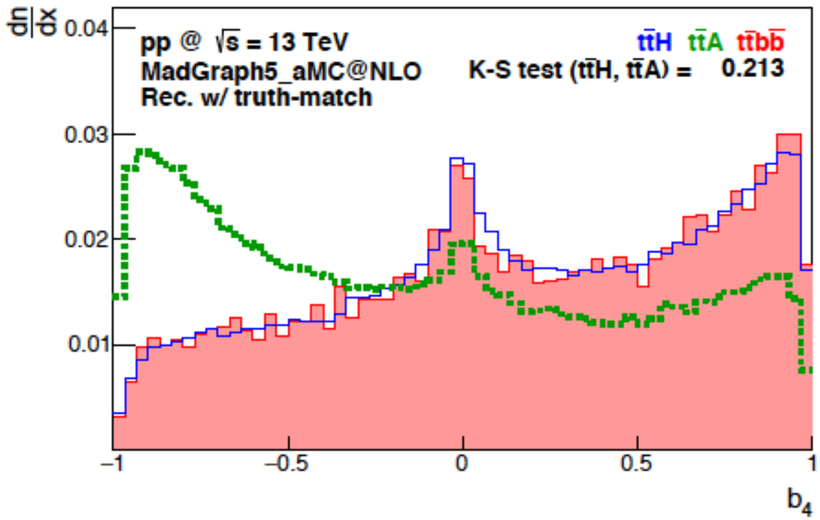
Like a good port wine!

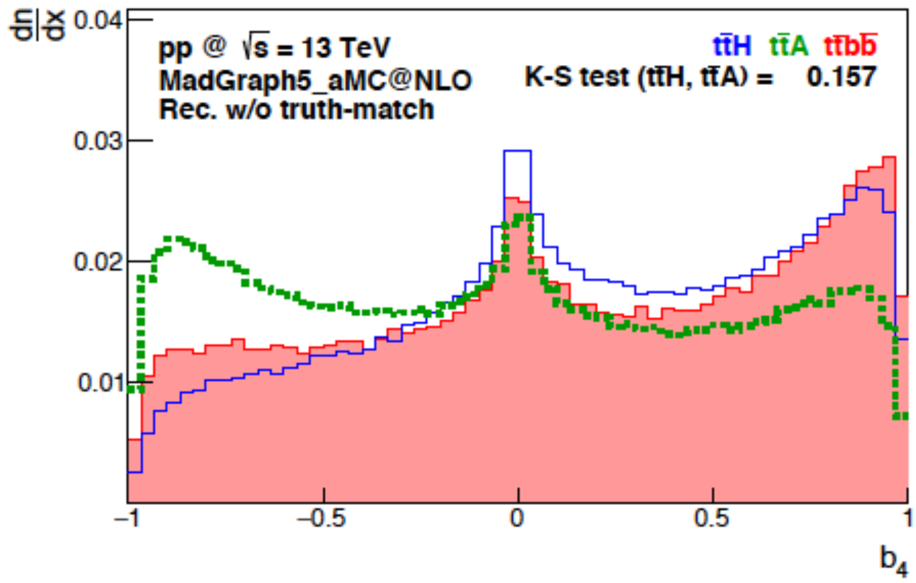


Gunion, He, PRL77 (1996) 5172

Boudjema, Godbole, Guadagnoli, Mohan, Phys.Rev.D 92 (2015) 1, 015019

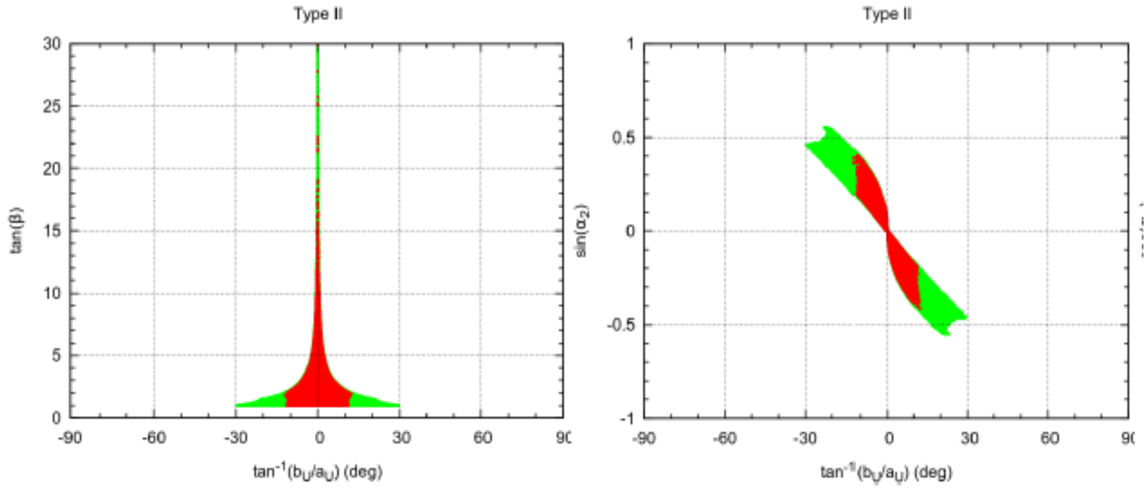
Amor dos Santos eal PRD96 (2017) 013004





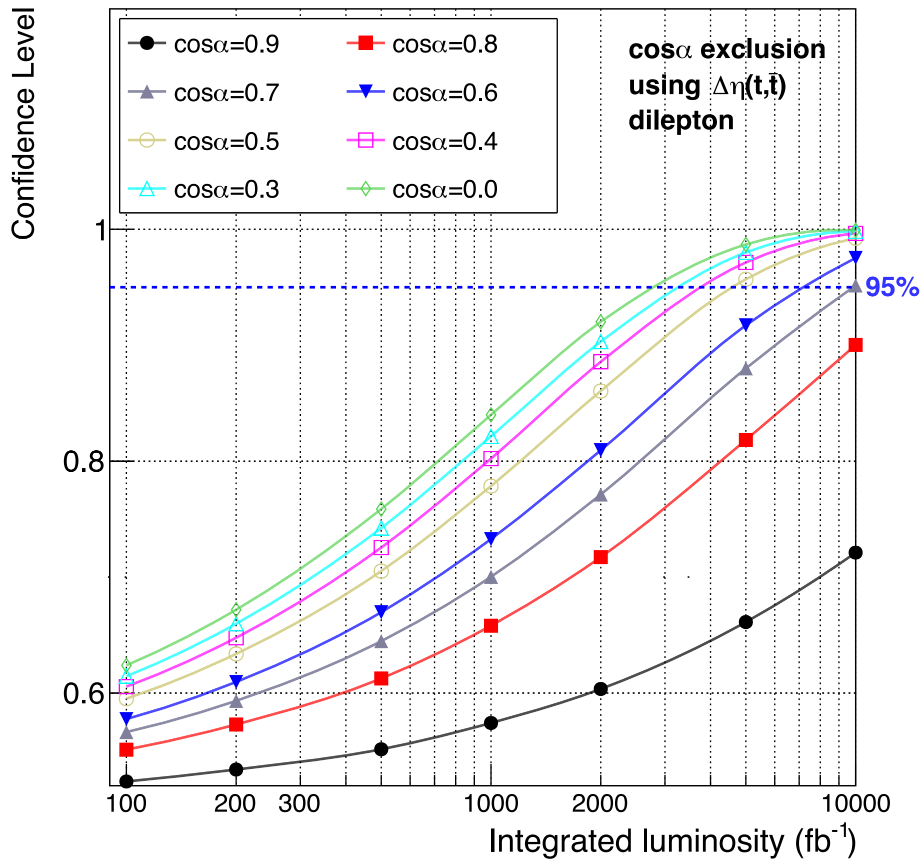
$$\mathscr{L}_{H\bar{t}t} = \kappa y_t \bar{t}(\cos\alpha + i\sin\alpha\gamma_5)th$$

$\cos\alpha = 1$ 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?

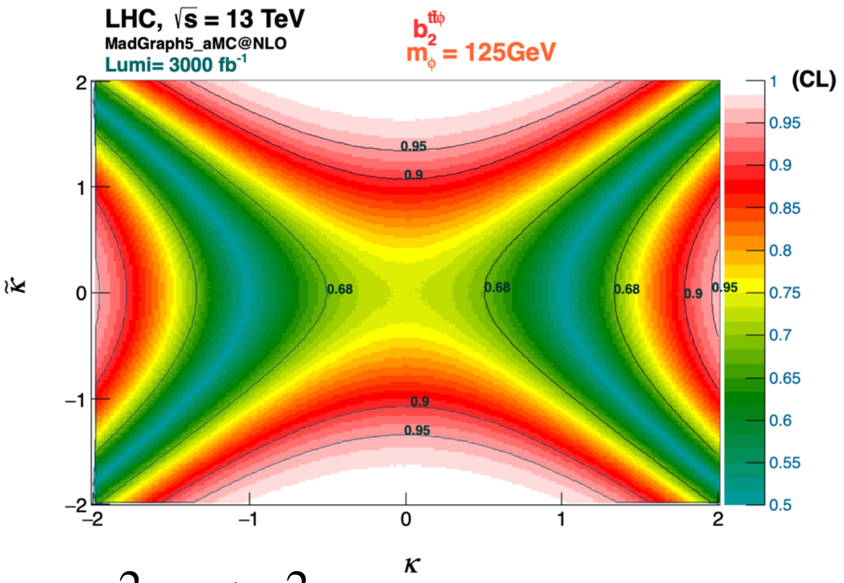


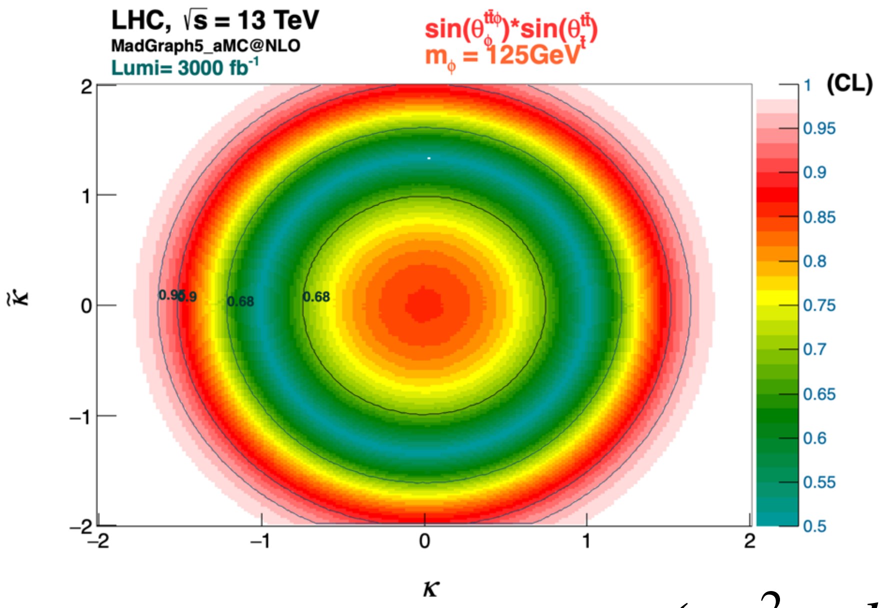
For cosα=0.7 the limit on α_2 is 46° for tanβ=1 while for cosα=0.9 is 26° - close to what we have today from indirect measurements.

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

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

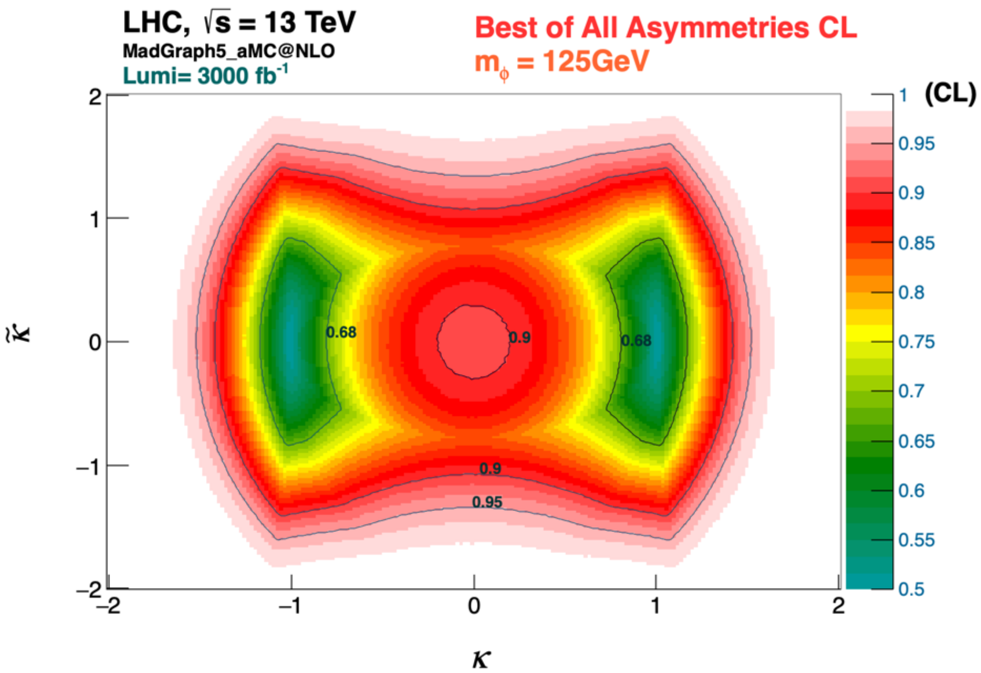
We are testing several variables, combining them, to improve the bounds





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

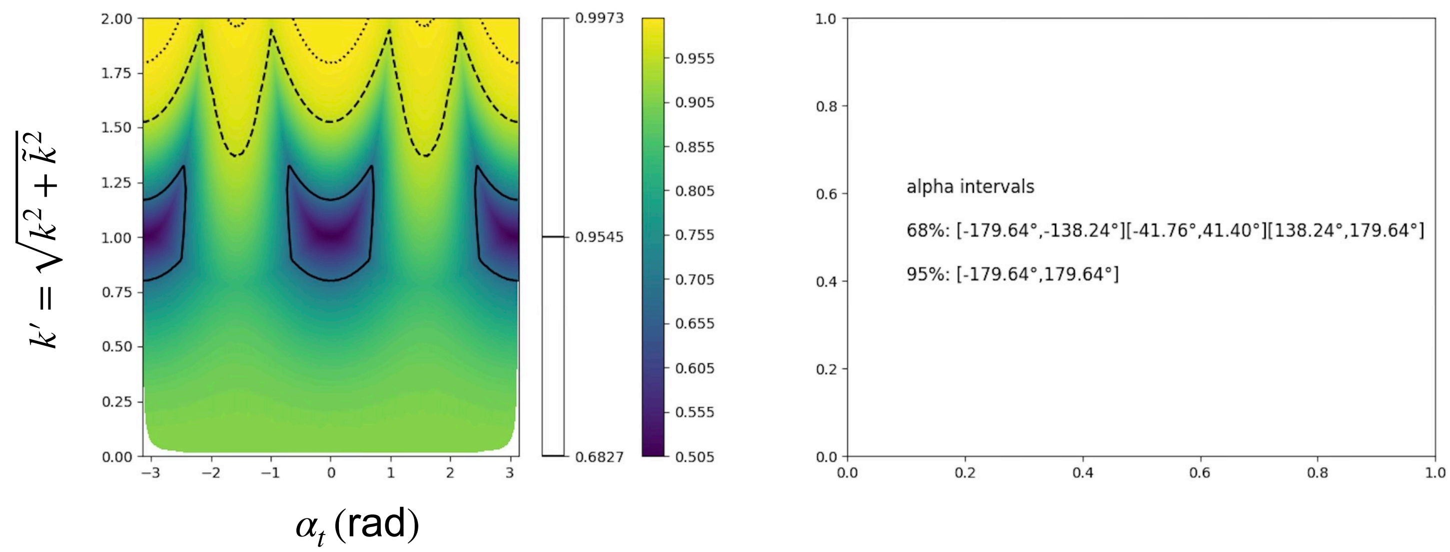
$$\propto (a\kappa_t^2 + b\tilde{\kappa}_t^2)$$

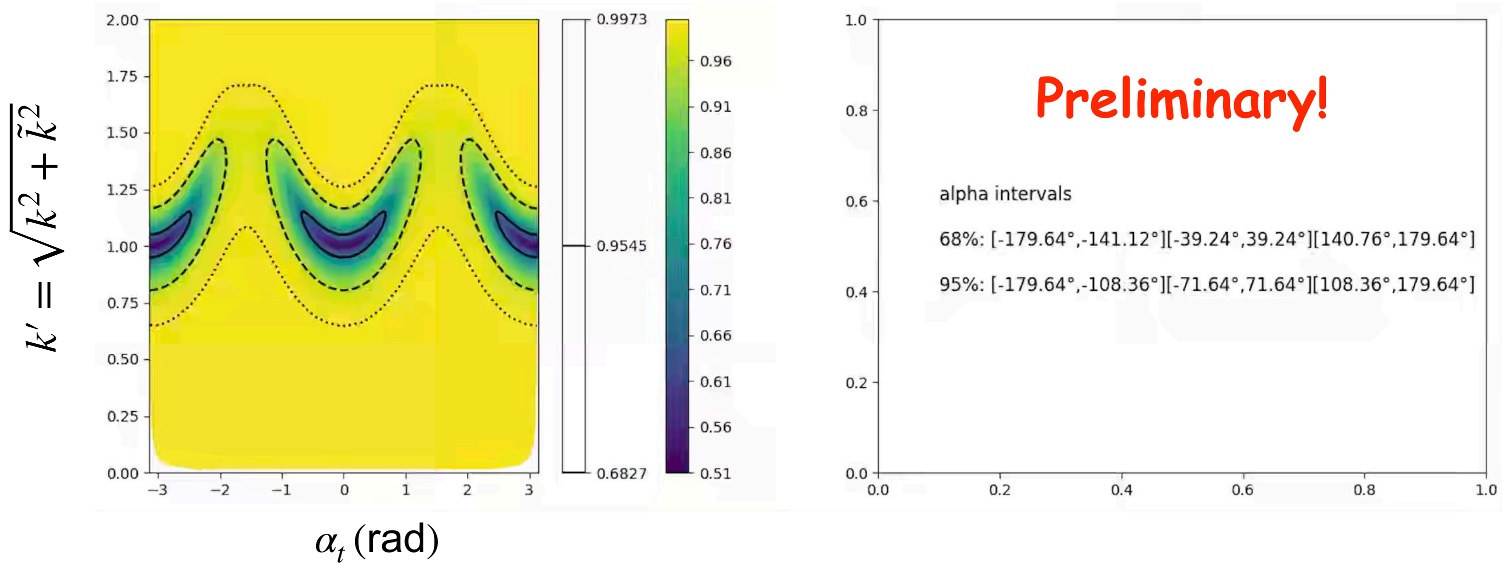


Preliminary! - The plug plot

Asymmetries - less systematics

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





More shapes?

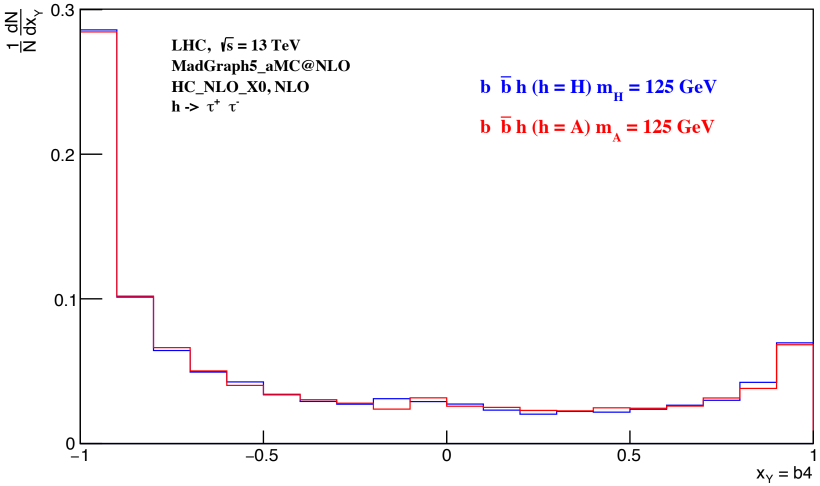
Ellis, Hwang, Sakurai, Takeuchi, JHEP 04 (2014) 004

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

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

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

Can we use the idea for bbh?



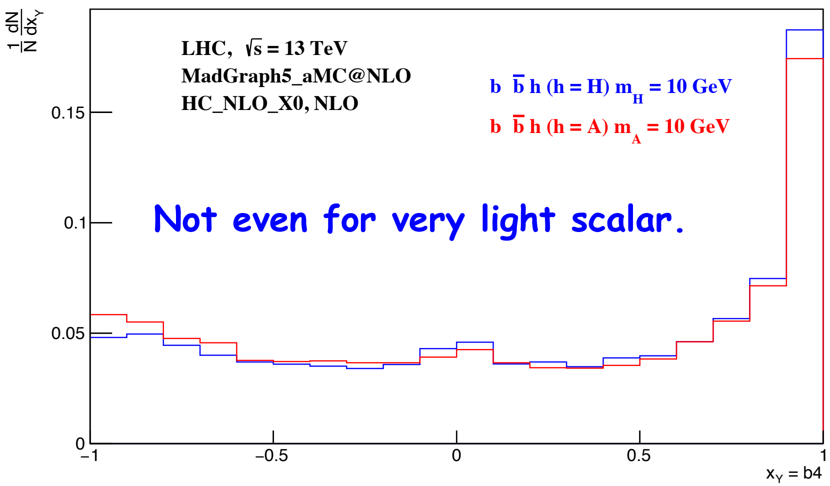


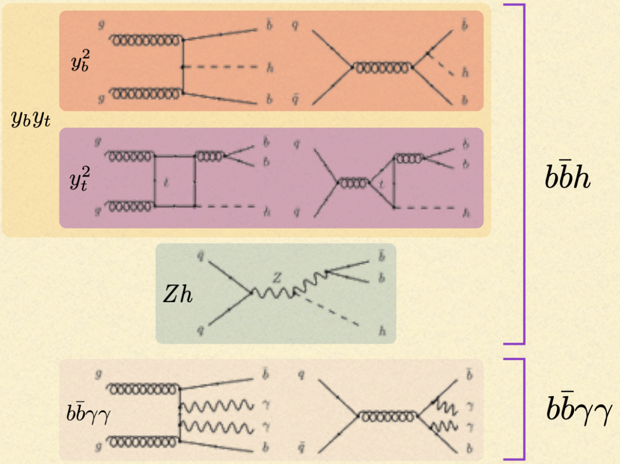
Figure 1: Parton level b_4 distributions at NLO, normalized to unity, for $m_\phi = 125$ GeV (left) and $m_\phi = 10$ GeV (right). Only events with $p_T(b) > 20$ GeV and $|\eta(b)| < 2.5$ were selected, with p_T and η being the transverse momentum and the pseudo-rapidity, respectively.

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

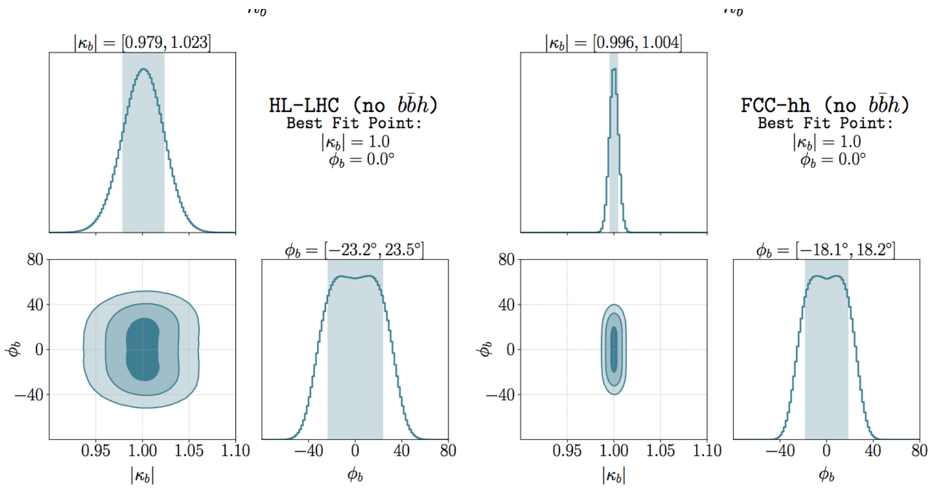
Basic selection (14 TeV HL-LHC): **signals**

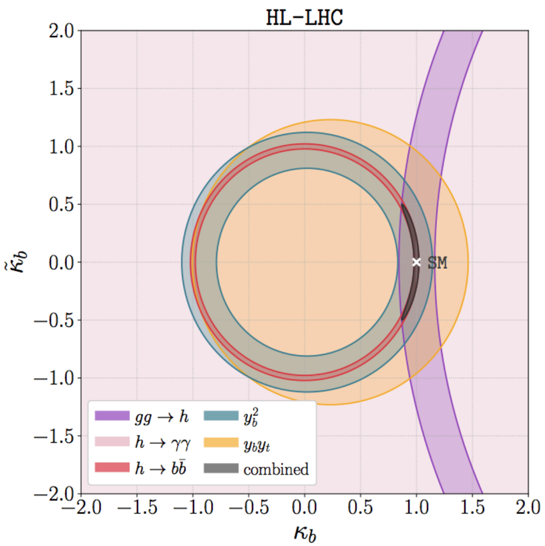
Channel	LO σ (fb)	NLO-k-fact	6 ab^{-1} [#evt]	2b-jets[%]
y_b^2	0.0648	1.5	583	7.7%
$y_b y_t$	-0.00829	1.9	-95	4.0%
y_t^2	0.123	2.5	1,840	12%
Zh	0.0827	1.3	645	21%
$\sum b\bar{b}h$	0.262	-	2,970	-
$b\bar{b}\gamma\gamma$	12.9	1.5	116,000	14%

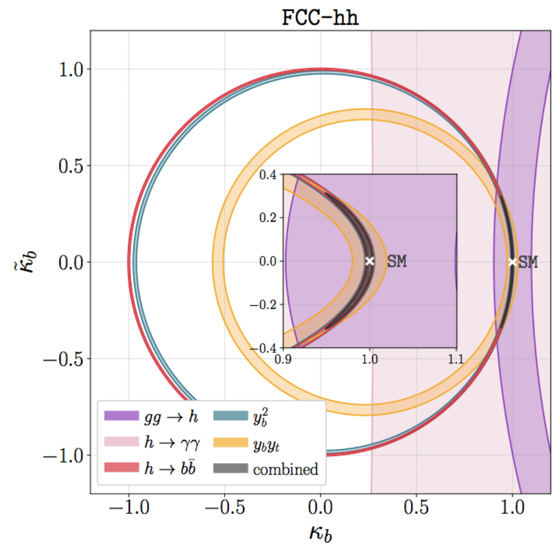
$b\bar{b}h$ background **QCD-QED background**

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

SLIDE FROM
Zhuoni Qian, HPNP2021
March 25th 2021



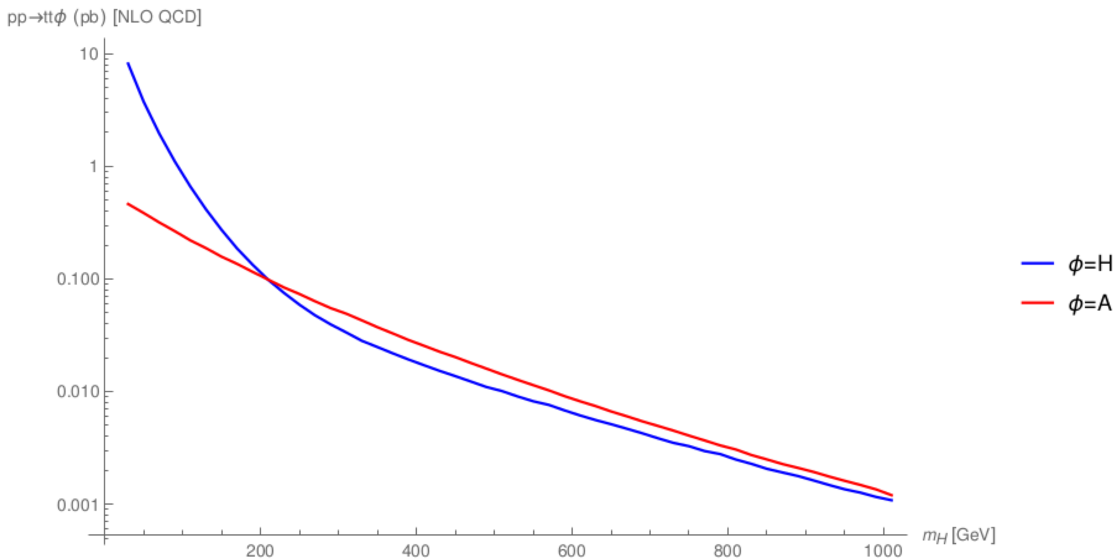


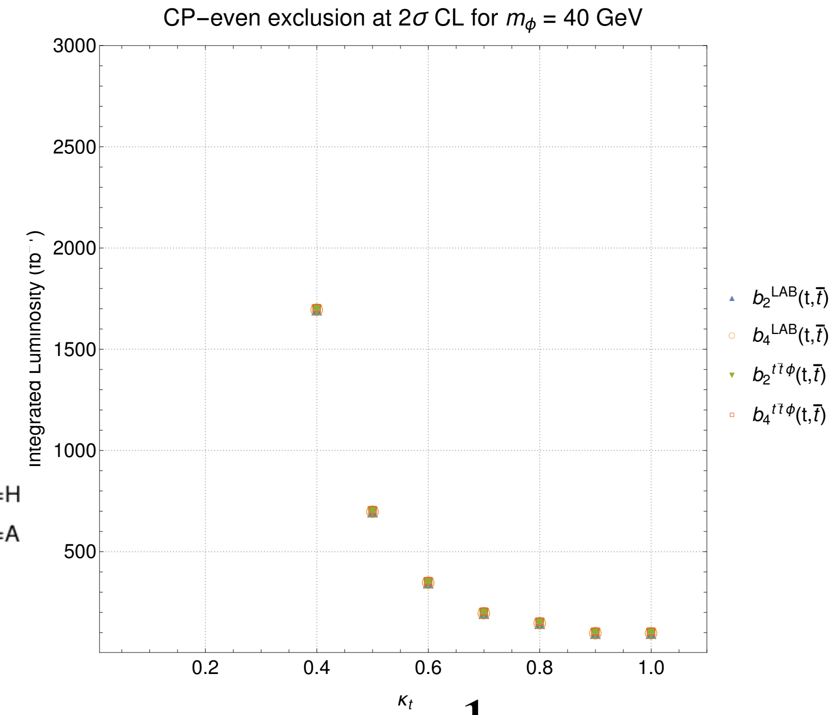


Finally the search for low/high mass scalars

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?

See poster by Rodrigo Capucha

Interpretation in the framework of the C2HDM

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

$$\mathcal{L}_{Y\,i} = -\frac{m_f}{v}\bar{\psi}_f \left[\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5\right]\psi_f H_i$$ C2HDM parametrisation

"Facts are simple and facts are straight … Facts all come with points of view"
- David Byrne

This leads to

$$\begin{cases} \kappa_t \cos\alpha = \dfrac{s_1\, c_2}{s_\beta} \\ \kappa_t \sin\alpha = \dfrac{s_2}{t_\beta} \end{cases}$$

$$s_\beta^2 \kappa_t^2 = s_1^2 c_2^2 + s_2^2 c_\beta^2$$ Yukawa type independent

In the two CP-conserving limits we get

$$\begin{cases} \cos\alpha = 0 \implies \kappa_t = \dfrac{s_2}{t_\beta}\ (\text{if } s_1 = 0) \quad \text{or} \quad \kappa_t = \dfrac{1}{t_\beta}\ (\text{if } c_2 = 0) \\ \sin\alpha = 0 \implies \kappa_t = \dfrac{s_1}{s_\beta}\,, \end{cases}$$

Experimentally we obtain a limit on κ_t. For this model the maximum value of κ_t is $\sqrt{2}$ (due to already known constraints on tanβ). The bound on κ_t translates in a bound on the angles.

In the most general scenario (CP not defined) how does the C2HDM parameter space looks like? And in particular what happens if we are close to the CP-even or to the CP-odd scenario?

And so?

On the negative side even with high luminosity in can happen that the constraints will not look great when applied to a specific model like the C2HDM.

On the positive side if we measure a non-zero α this implies a direct evidence of a CP-violating interaction.

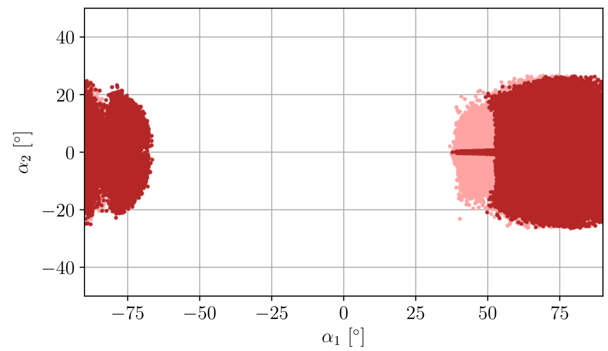
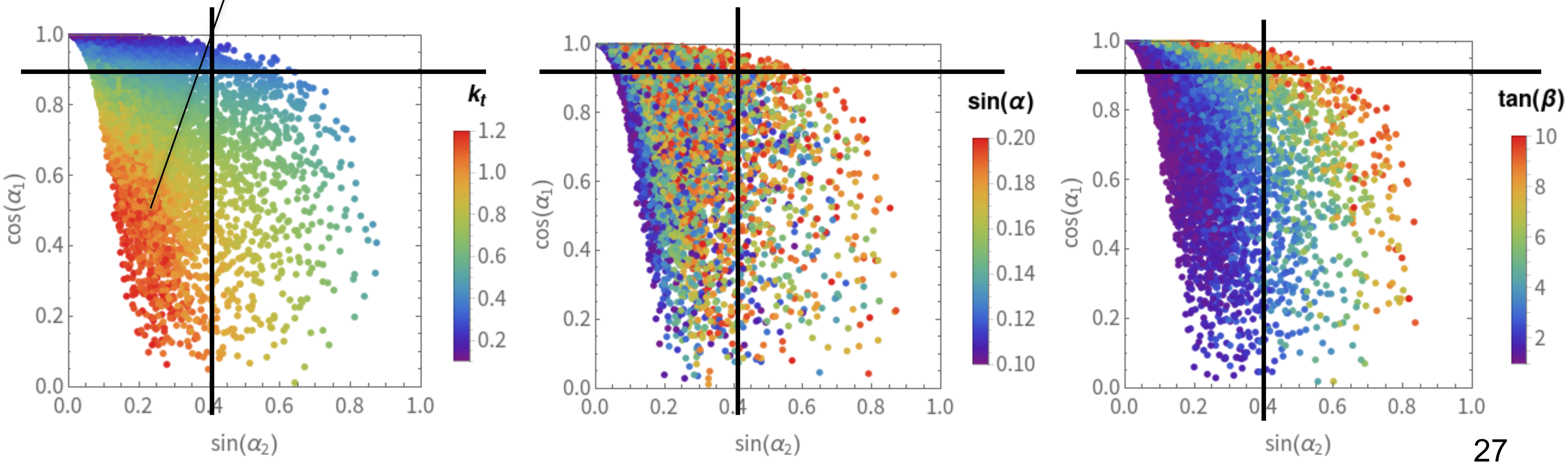


Figure 1. C2HDM Type I: for sample 1 (dark) and sample 2 the C2HDM mixing matrix R only including scenarios wher

Where we are in the 125 GeV Higgs.

$$0 < \cos\alpha_1 < 0.9$$

$$0 < \sin\alpha_2 < 0.4$$



The Higgs Coupling to gauge bosons

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?

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

EFFECTIVE LAGRANGIAN (CMS NOTATION)

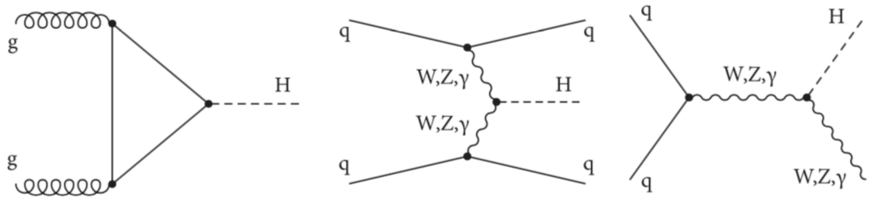


FIG. 1. Examples of leading-order Feynman diagrams for H boson production via the gluon fusion (left), vector boson fusion (middle), and associated production with a vector boson (right). The HWW and HZZ couplings may appear at tree level, as the SM predicts. Additionally, HWW, HZZ, $HZ\gamma$, $H\gamma\gamma$,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

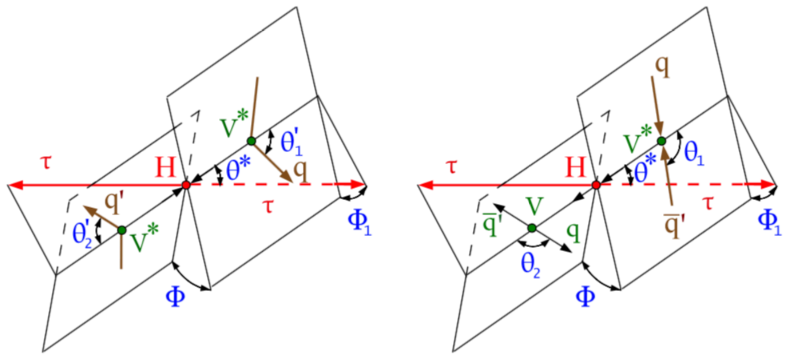


FIG. 2. Illustrations of H boson production in $qq' \to gg(qq') \to H(qq') \to \tau\tau(qq')$ or VBF $qq' \to V^*V^*(qq') \to H(qq') \to \tau\tau(qq')$ (left) and in associated production $q\bar{q}' \to V^* \to VH \to q\bar{q}'\tau\tau$ (right). The $H \to \tau\tau$ decay is shown without further illustrating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

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

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

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

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

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

Is it worth it?

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

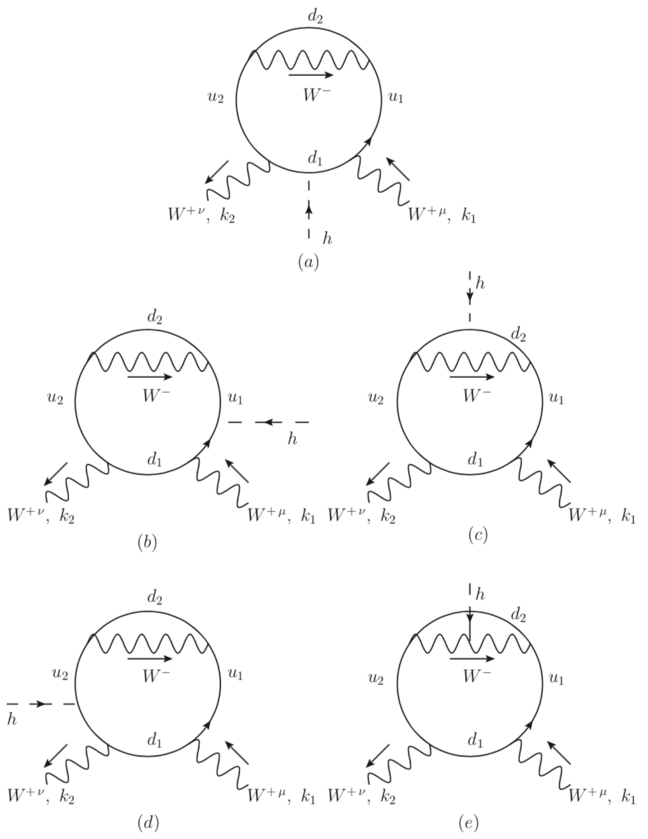


Figure 1. Feynman diagrams leading to the CPV hW^+W^- coupling in the SM.

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

Very complicated, so you estimate

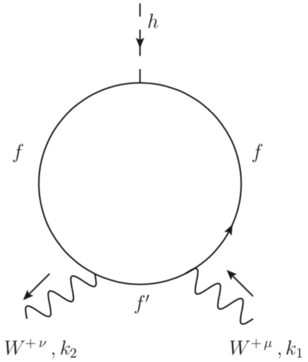
SM estimate

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

Is it worth it?

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

THE C2HDM



Starting with f=t and f'=b

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

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

We can now extract the operator for this case

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

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

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

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

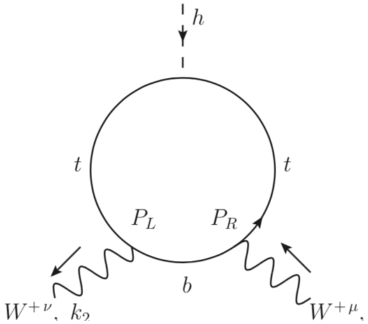
Using the bounds calculated before.

Is it worth it?

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

The left-right symmetric model

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



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

The effective operator coefficient for this case is

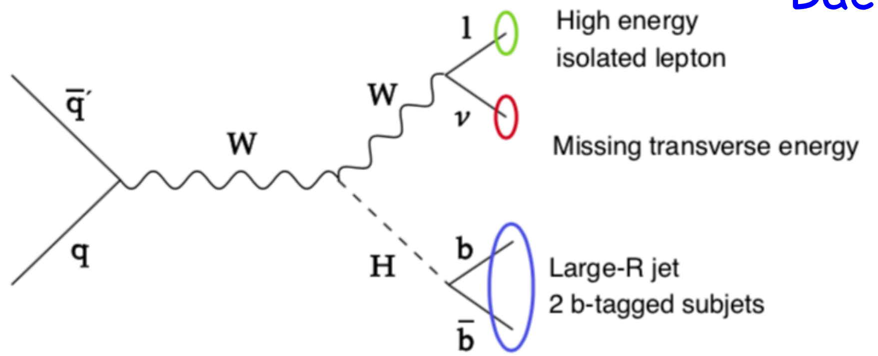
$$c_{\rm CPV}^{\rm LR} \approx \frac{N_c g^2}{8\pi^2} \frac{m_t m_b}{m_W^2} \mathcal{I}\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) {\rm Im}(V_{tb} U_{tb}^*) \qquad \mathcal{I}(x,y) \equiv \int_0^1 d\alpha \frac{\alpha(1-\alpha)}{\alpha x + (1-\alpha) y - \alpha(1-\alpha)}\,.$$

Using the constraint

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

Dekens, Boer, NPB889 (2014) 727

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



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

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

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

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

CMS PAS FTR-18-011

Table 10: Summary of the 95% CL intervals for $f_{a3}\cos(\phi_{a3})$, under the assumption $\Gamma_{\rm H} = \Gamma_{\rm H}^{\rm SM}$, and for $\Gamma_{\rm H}$ under the assumption $f_{ai} = 0$ for projections at $3000\,{\rm fb}^{-1}$. 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	$[-1.6, 1.6]$
$\Gamma_{\rm H}$ (MeV)	S1	$[2.0, 6.1]$
$\Gamma_{\rm H}$ (MeV)	S2	$[2.0, 6.0]$

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

The fraction as defined below is related to the effective coupling

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

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

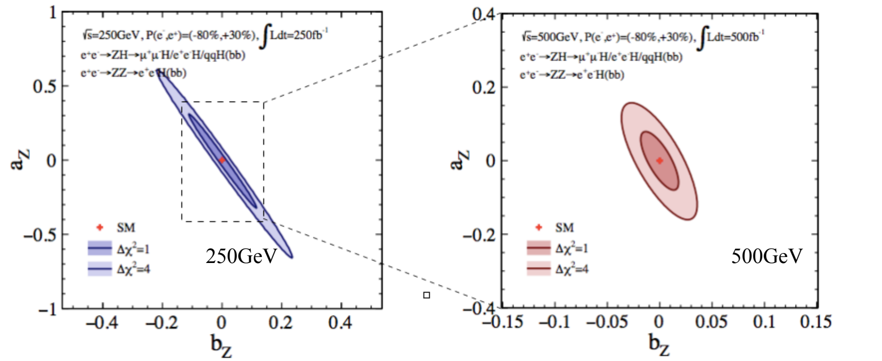
$\tilde{\sigma}_{\Lambda 1}$ = (cross section for the Λ_1-term with $\Lambda_1 = 1$ TeV) $\times$ [TeV]^4

Anomalous ZZH/γZH couplings

3-parameter fit

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

(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

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

ZZH / γZH structures can be measured to ~0.5%

SLIDE FROM KEISUKE FUJII'S PRESENTATION AT HIGGS COUPLINGS 2018, TOKYO

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

OGAWA, PHD THESIS (2018)

THEREFORE MODELS SUCH AS THE C2HDM MAY BE WITHIN THE REACH OF THESE MACHINES. CAN BE USED TO CONSTRAINT THE C2HDM AT LOOP-LEVEL

Dark sector and CP-violation

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

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

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 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

Dark CP-violating sector

The Z_2 symmetry is exact - all particles are dark except the SM-like Higgs. The couplings of the SM-like Higgs to all fermions and massive gauge bosons are exactly the SM ones.

The model is Type I - only the first doublet couples to all fermions

The neutral mass eigenstates are h_1, h_2, h_3

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

But now how do we see signs of CP-violation?

Missing energy signals are similar to some extent for all dark matter models. They need to be combined with a clear sign of CP-violation.

$$q\bar{q}(e^+e^-) \to Z^* \to h_1 h_2 \to h_1 h_1 Z$$

Mono-Z and mono-Higgs events.

$$q\bar{q}(e^+e^-) \to Z^* \to h_1 h_2 \to h_1 h_1 h_{125}$$

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

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

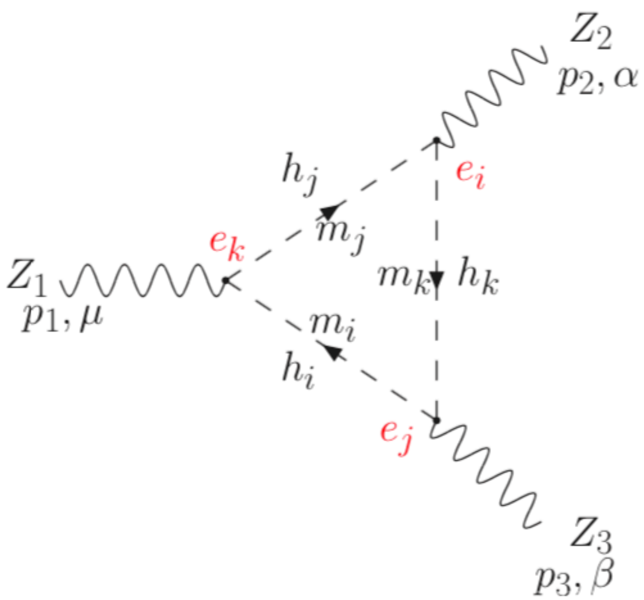
Gaemers, Gounaris, ZPC1 (1979) 259

Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB282 (1987) 253

that comes from an effective operator (dim-6)

Grzadkowski, Ogreid, Osland, JHEP 05 (2016) 025

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



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

CPV in the triple gauge bosons couplings

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

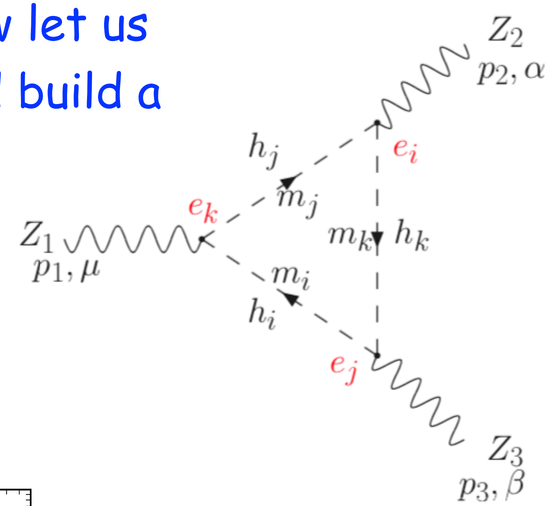
Combinations of three decays

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

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

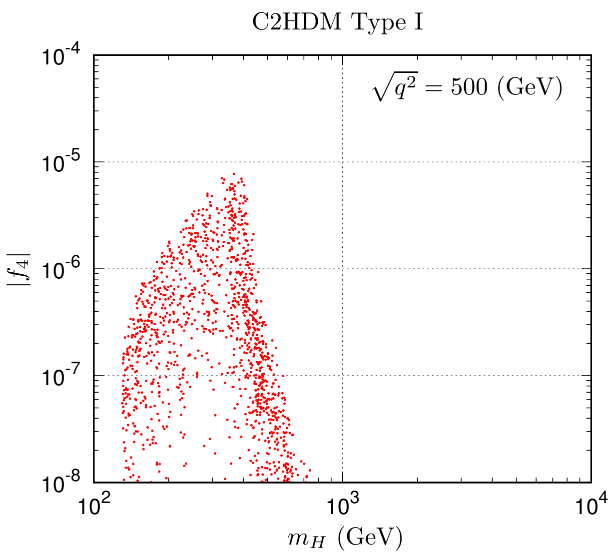
$$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$$

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

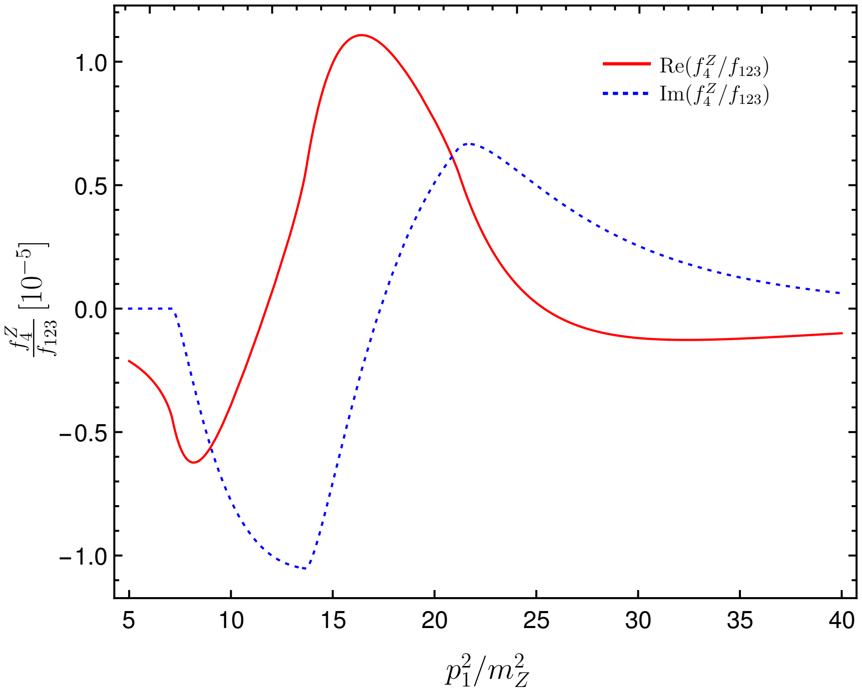
$$i\Gamma_{\mu\alpha\beta} = -e\frac{p_1^2 - m_Z^2}{m_Z^2} f_4^Z (g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$



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

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.

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. $-1.2\times 10^{-3} < f_4^Z < 1.0\times 10^{-3}$

ATLAS collaboration, PRD97 (2018) 032005. $-1.5\times 10^{-3} < f_4^Z < 1.5\times 10^{-3}$

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. EDMs play a major role.

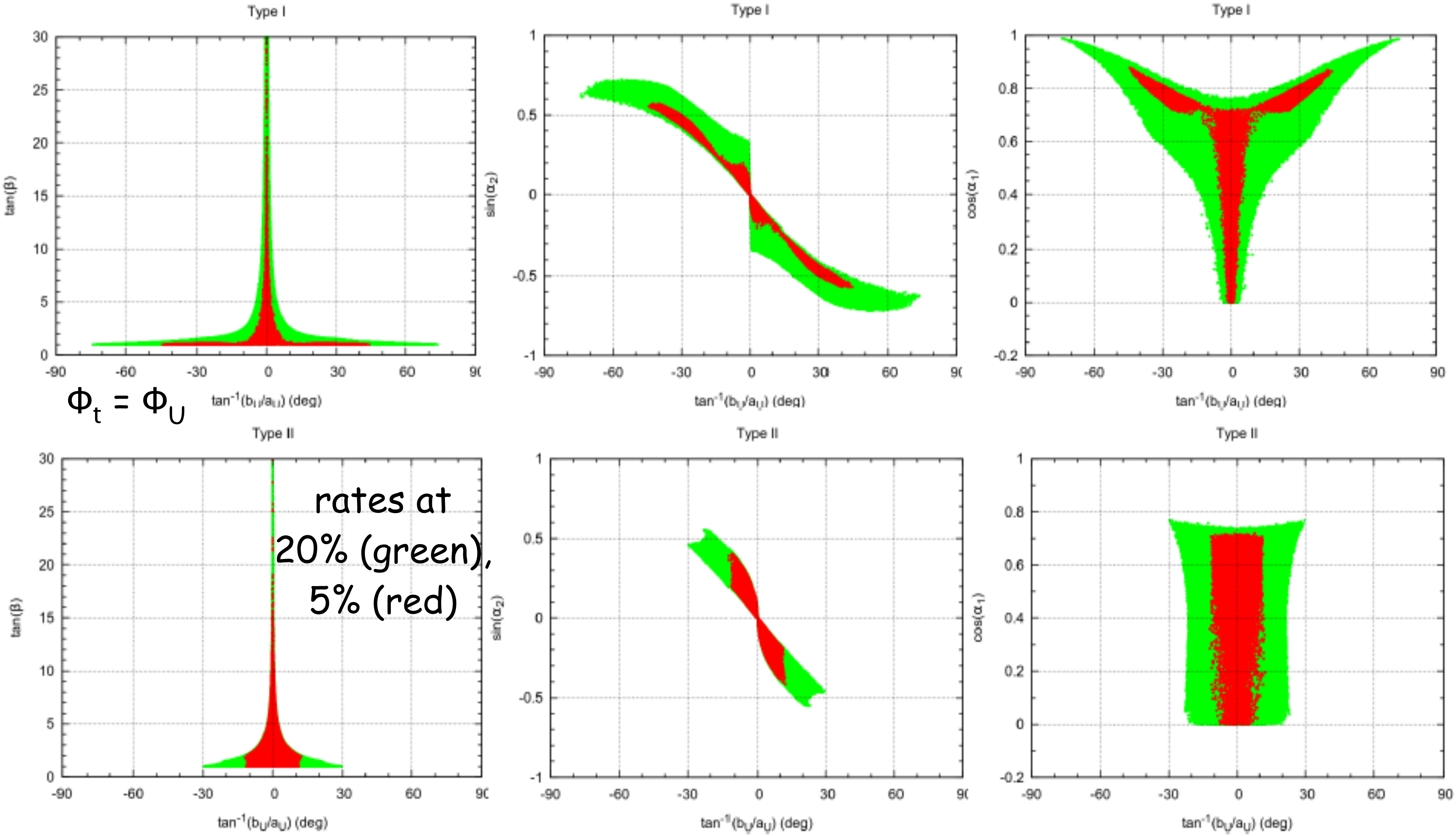
- Higgs and gauge bosons. CP-violating terms appear at the 2-loop level in the SM but at 1-loop in many other extensions. Coefficients are small but reachable in the (near?) future.

- 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)

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

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

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

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

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.

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

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

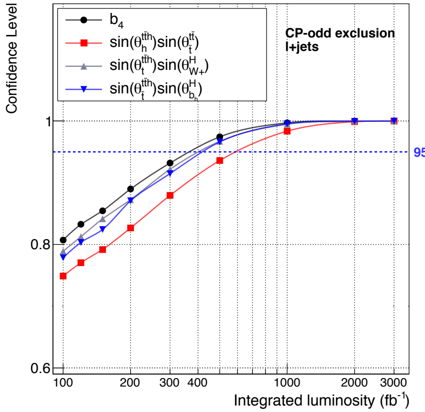
$$pp \to h \to \tau^+\tau^-$$

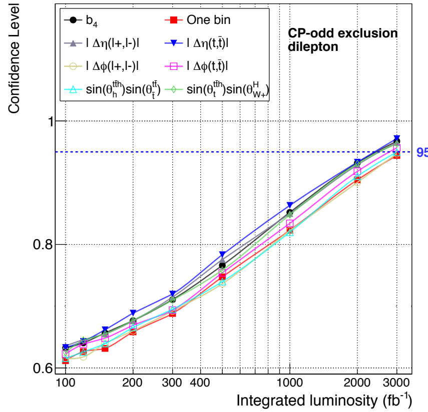
Conclusions:

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

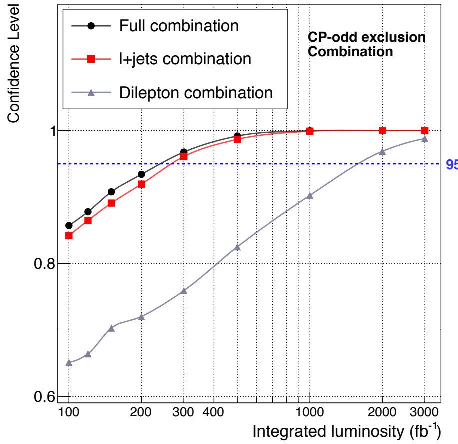


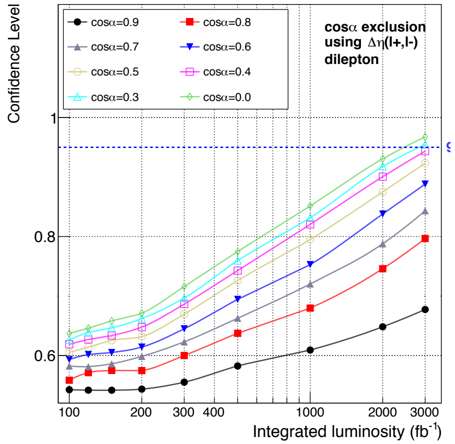


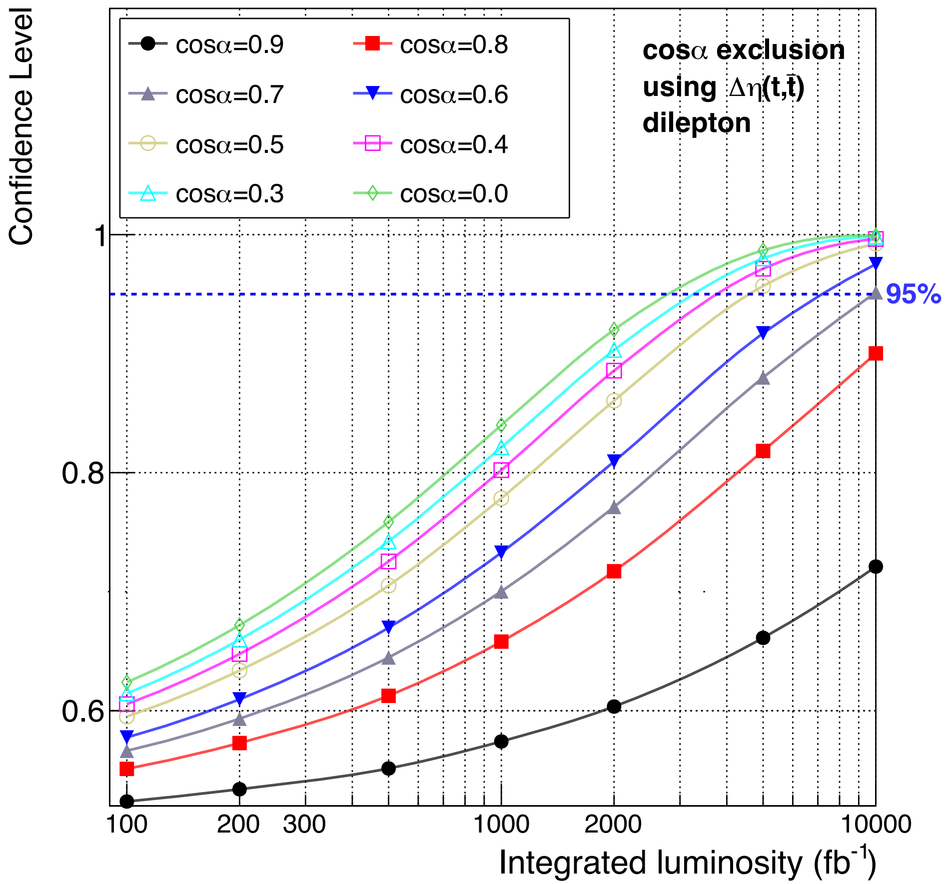
$$\mathscr{L}_{Ht\bar{t}} = \kappa y_t \bar{t}(\cos\alpha + i\sin\alpha\gamma_5)th$$

$$\cos\alpha = 1$$ 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

Interpretation in the framework of the C2HDM

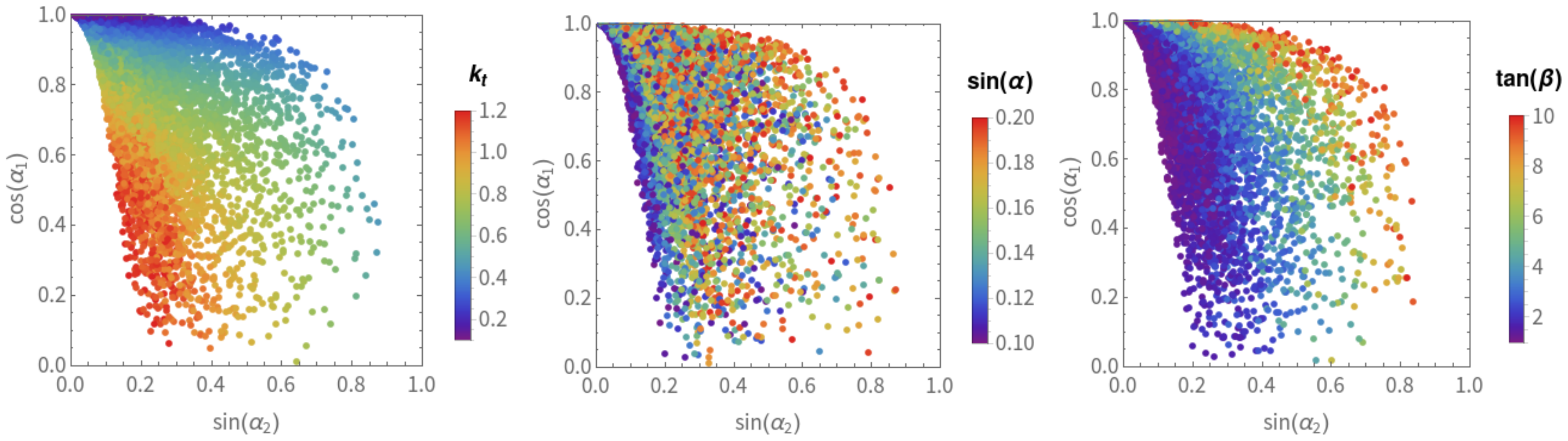


Figure 19: Points allowed in the plane c_1 vs. s_2 for $0.1 \leq \kappa_t \leq 1.2$ and $0.1 \leq \sin\alpha \leq 0.2$ and $1 \leq \tan\beta \leq 10$. In the left plot we see the variation with κ_t, in the middle with $\sin\alpha$ and on the right with $\tan\beta$.

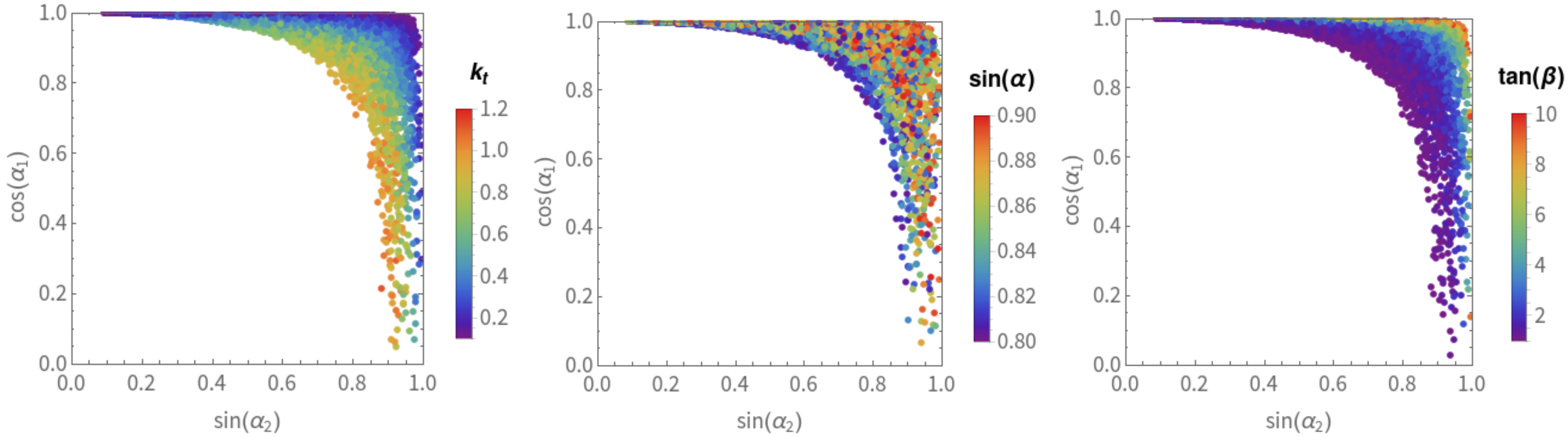


Figure 20: Points allowed in the plane c_1 vs. s_2 for $0.1 \leq \kappa_t \leq 1.2$ and $0.8 \leq \sin\alpha \leq 0.9$ and $1 \leq \tan\beta \leq 10$. In the left plot we see the variation with κ_t, in the middle with $\sin\alpha$ and on the right with $\tan\beta$.