What are we missing in the search for CP-violation at the LHC?

R. Santos

ISEL & CFTC-UL

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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 – $\mathrm{Re}(m^2_{12})$

h_{125} couplings measurements

Lightest Higgs coupling modifiers (to gauge bosons)

CP-VIOLATING 2HDM

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

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

"PSEUDOSCALAR" COMPONENT (DOUBLET)

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

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

ONLY TERM IN THE C2HDM AT TREE-LEVEL

Obtained 95% CL intervals on the *allowed* couplings of alternative, not SM-like, spin-zero states with respect to those of the SM scalar state.

		α/κ	β/κ	γ/κ
H→ZZ→4l	ATLAS	not tested	[−2.5, 0.75]	[−0.95, 2.9]
	CMS	[−1.2, 1.5]	[−∞, 0.69] [1.9, 2.3]	[−2.2, 2.1]
H→WW→2l2ν	ATLAS	not tested	[−0.4, 0.85] [1, 2.2]	[−5, 6]
	CMS	[−∞, +∞]	[−∞, 0.71] [1.2, +∞]	[−∞, +∞]
combined, assuming that ratios of "couplings" are the same for ZZ and WW	ATLAS	not tested	[−0.63, 0.73]	[−0.83, 2.2]
	CMS	[−1.7, 1.6]	[−0.76, 0.58]	[−1.6, 1.5]

CAN BE USED TO CONSTRAINT THE C2HDM AT LOOP-LEVEL

CP - what have ATLAS and CMS measured so far?

Correlations in the momentum distributions of leptons produced in the decays

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

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

S.Y. Choi, D.J. Miller, M.M. Muhlleitner and P.M. Zerwas, Phys. Lett. B 553, 61 (2003).

C. P. Buszello, I. Fleck, P. Marquard, J. J. van der Bij, Eur. Phys. J. C32, 209 (2004)

Conclusions:

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

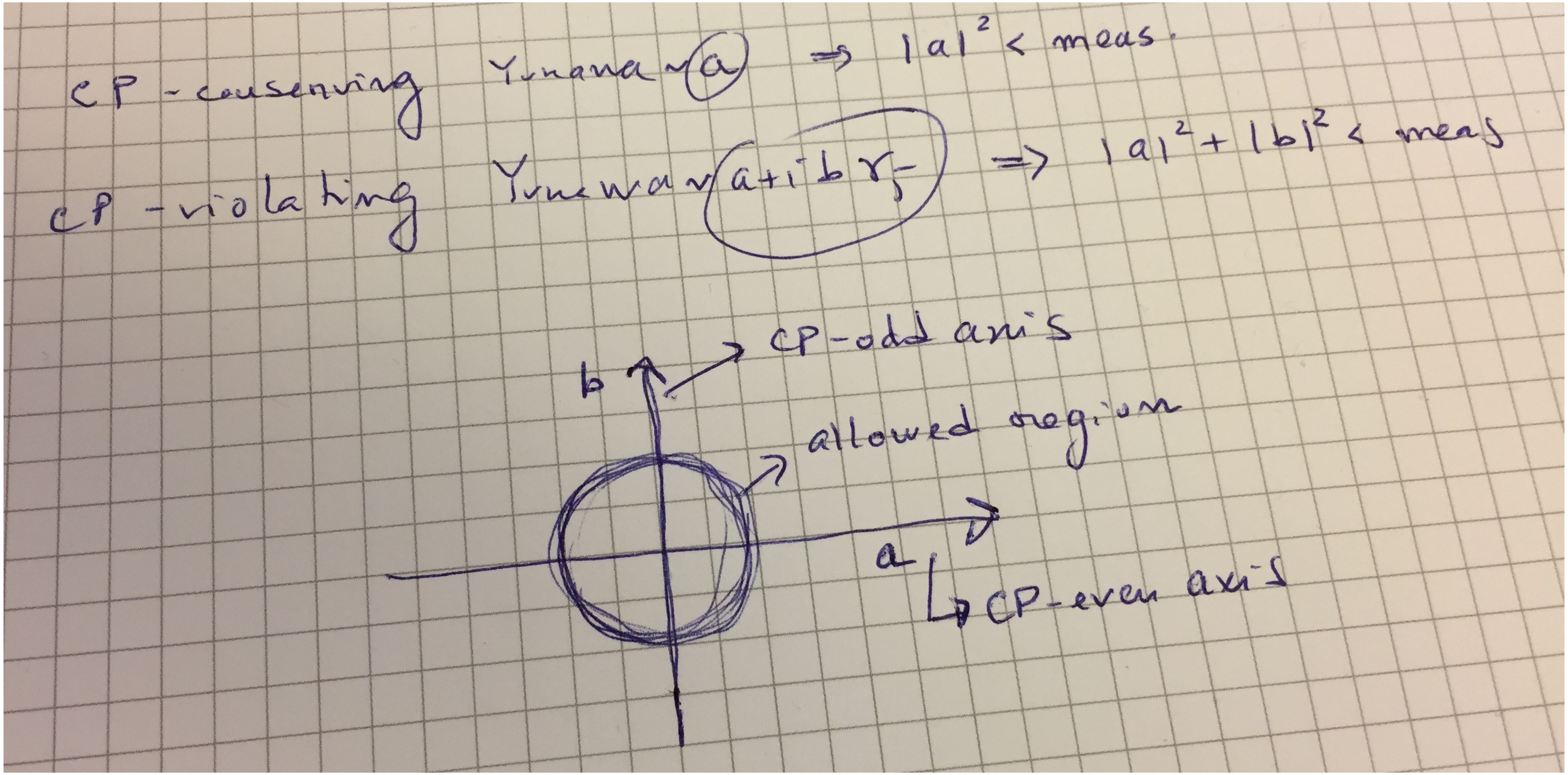
b) other terms in the effective Lagrangian can only be used to constraint the C2HDM at loop-level

We need to test the Yukawa couplings

$$Y^{TypeII}_{C2HDM} = c_2 Y^{TypeII}_{2HDM} - i\gamma_5 s_2 t_\beta \qquad \text{bottom, tau}$$

$$Y^{TypeII}_{C2HDM} = c_2 Y^{TypeII}_{2HDM} - i\gamma_5 \frac{s_2}{t_\beta} \qquad \text{top}$$

In the CP-odd vs. CP-even plane, the bounds on the Yukawa couplings look like rings.



Bounds on the Yukawa couplings

With the most relevant experimental and theoretical constraints

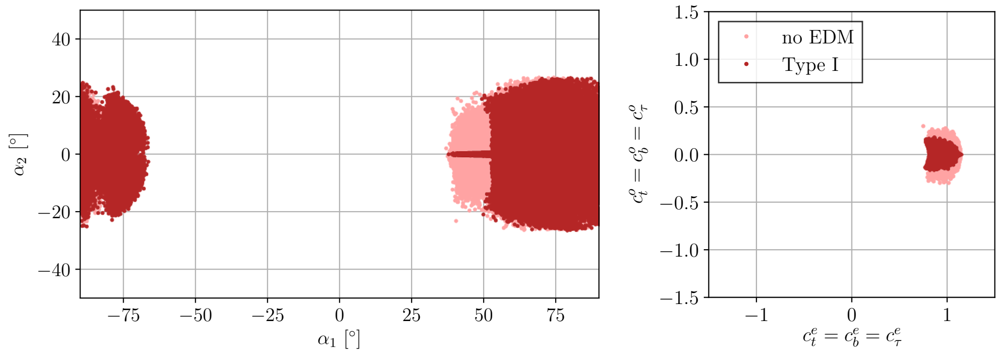


Figure 1. C2HDM Type I: for sample 1 (dark) and sample 2 (light) left: mixing angles α_1 and α_2 of the C2HDM mixing matrix R only including scenarios where $H_1 = h_{125}$; right: Yukawa couplings.

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

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

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

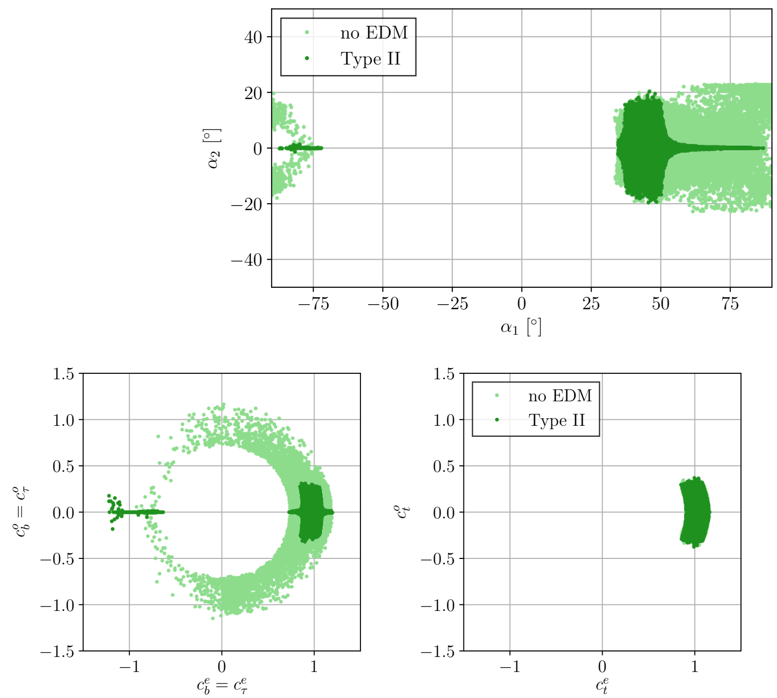


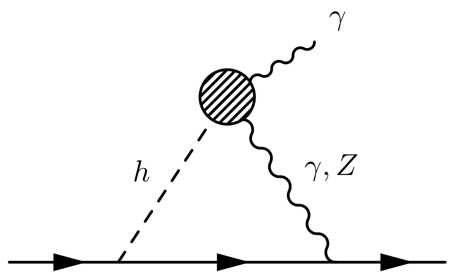
Figure 3. C2HDM Type II, $h_{125} = H_1$: Yukawa couplings to bottom quarks and tau leptons (left) and top quarks (right) for sample 1 (dark) and sample 2 (light).

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

$\tan\beta > 1$

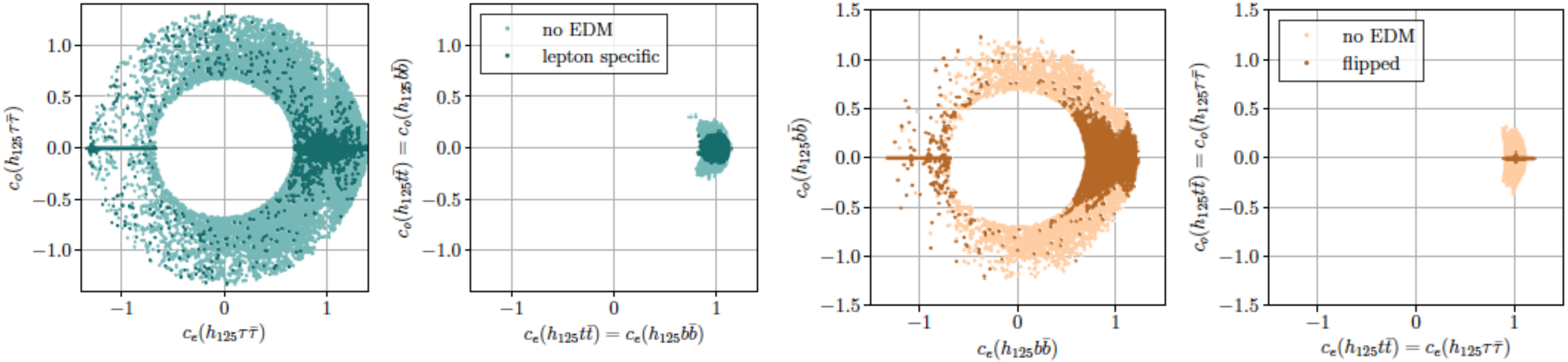
$$g^{hbb}_{C2HDM} = \left(\cos\alpha_2 \frac{\cos\alpha_1}{\cos\beta} - i \sin\alpha_2 \, \tan\beta \, \gamma_5 \right) g^{hff}_{SM}$$

EDMs

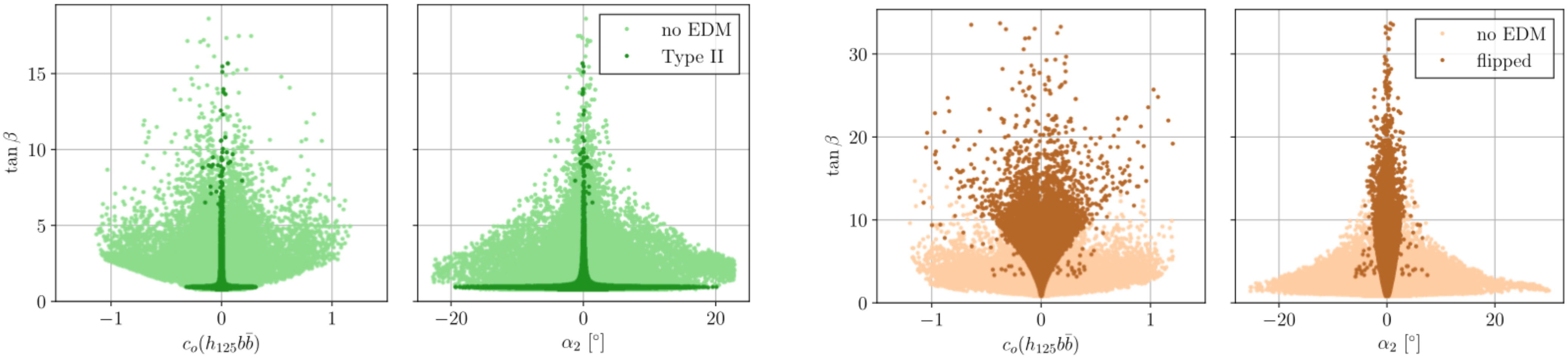


Fontes, Muhlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

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.

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.

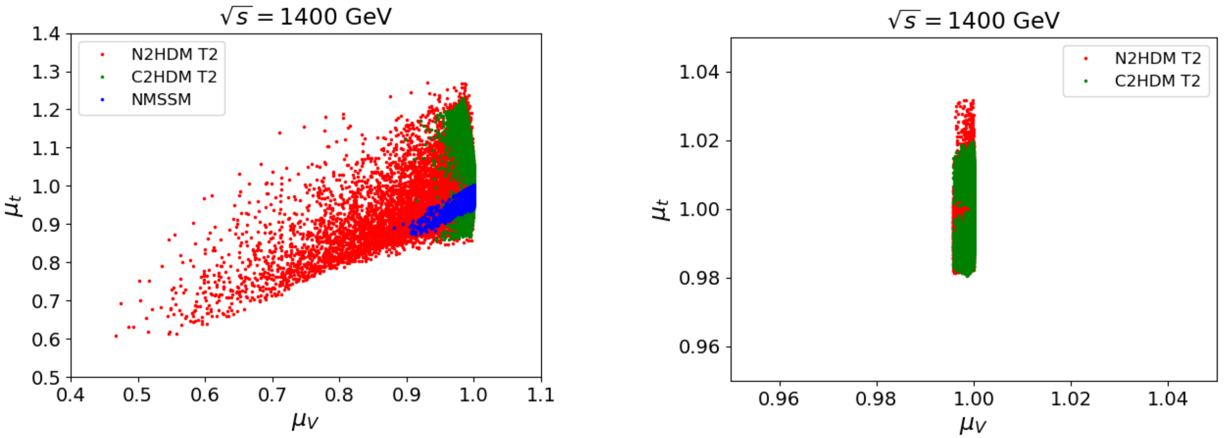
LHC today

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.



Azevedo, Ferreira, Muhlleitner, RS, Wittbrodt, 1808.00755

Beware of radiative corrections.

How will it look in the future?

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

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

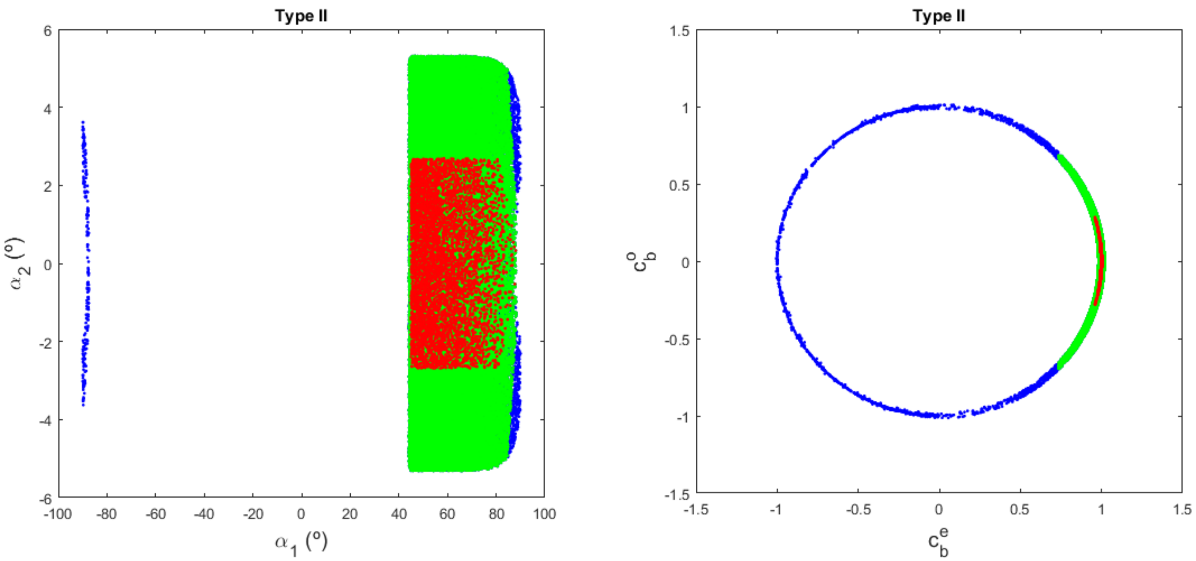


Figure 2: Mixing angles α_2 vs. α_1 (left) and c_b^o vs. c_b^e (right) for the C2HDM Type II. The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

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, Muhlleitner, RS, Wittbrodt, 1808.00755

What if the 125 GeV reveals different CP behaviour in two decay channels?

The SM-like Higgs coupling to ZZ(WW) relative to the corresponding SM coupling is

$$\kappa_{C2HDM}^{h_{125}WW} = c_2 \sin(\beta - \alpha)$$

and c_2 cannot be far from 1. But α_2 is the CP-violating angle and therefore it should be small. However, the CP-odd component has an extra tanβ factor for down quarks and leptons, but not for the up quarks

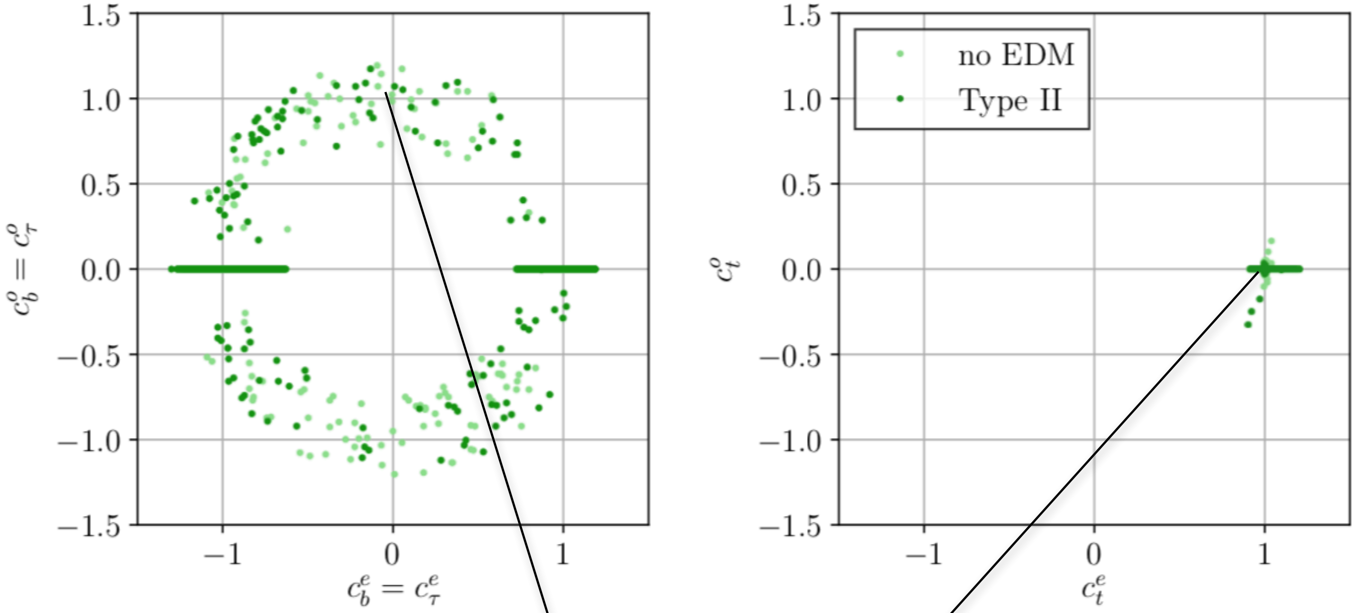
$$Y_{C2HDM}^{TypeII} = c_2 Y_{2HDM}^{TypeII} - i\gamma_5 s_2 t_\beta$$ bottom, tau

$$Y_{C2HDM}^{TypeII} = c_2 Y_{2HDM}^{TypeII} - i\gamma_5 \frac{s_2}{t_\beta}$$ top

Thus, the SM-like Higgs couplings to the tops could be mainly CP-even while couplings to the bottoms and taus could be mainly CP-odd.

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

And this brings a very interesting CP-violation scenario



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

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

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

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

$$h_2 = H \to t\bar{t}$$

and the other decaying to taus as CP-odd

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

Probing one Yukawa coupling is not enough!

Type II	BP2m	BP2c	BP2w
m_{H_1}	94.187	83.37	84.883
m_{H_2}	125.09	125.09	125.09
$m_{H^\pm}$	586.27	591.56	612.87
$\mathrm{Re}(m_{12}^2)$	24017	7658	46784
α_1	−0.1468	−0.14658	−0.089676
α_2	−0.75242	−0.35712	−1.0694
α_3	−0.2022	−0.10965	−0.21042
$\tan\beta$	7.1503	6.5517	6.88
m_{H_3}	592.81	604.05	649.7
$c_b^e = c_\tau^e$	0.0543	0.7113	−0.6594
$c_b^o = c_\tau^o$	1.0483	0.6717	0.6907
μ_V/μ_F	0.899	0.959	0.837
μ_{VV}	0.976	1.056	1.122
$\mu_{\gamma\gamma}$	0.852	0.935	0.959
$\mu_{\tau\tau}$	1.108	1.013	1.084
μ_{bb}	1.101	1.012	1.069

The LS and Flipped benchmark points

LS	BPLSm	BPLSc	BPLSw
m_{H_1}	125.09	125.09	91.619
m_{H_2}	138.72	162.89	125.09
$m_{H^\pm}$	180.37	163.40	199.29
$\mathrm{Re}(m_{12}^2)$	2638	2311	1651
α_1	-1.5665	1.5352	0.0110
α_2	0.0652	-0.0380	0.7467
α_3	-1.3476	1.2597	0.0893
$\tan\beta$	15.275	17.836	9.870
m_{H_3}	206.49	210.64	177.52
c_τ^e	-0.0661	0.6346	-0.7093
c_τ^o	0.9946	0.6780	-0.6460
μ_V/μ_F	0.980	0.986	0.954
μ_{VV}	1.014	1.029	1.000
$\mu_{\gamma\gamma}$	0.945	1.018	0.879
$\mu_{\tau\tau}$	1.007	0.880	0.943
μ_{bb}	1.013	1.020	1.025

Flipped	BPFm	BPFc	BPFw
m_{H_1}	125.09	125.09	125.09
m_{H_2}	154.36	236.35	148.75
$m_{H^\pm}$	602.76	589.29	585.35
$\mathrm{Re}(m_{12}^2)$	10277	8153	42083
α_1	-1.5708	1.5277	-1.4772
α_2	-0.0495	-0.0498	0.0842
α_3	0.7753	0.4790	-1.3981
$\tan\beta$	18.935	14.535	8.475
m_{H_3}	611.27	595.89	609.82
c_b^e	-0.0003	0.6269	-0.7946
c_b^o	-0.9369	0.7239	0.7130
μ_V/μ_F	0.927	0.964	0.844
μ_{VV}	1.154	1.091	0.998
$\mu_{\gamma\gamma}$	1.027	0.986	0.874
$\mu_{\tau\tau}$	1.148	1.084	1.039
μ_{bb}	1.001	0.992	1.170

Almost CP-odd in the coupling to taus. Almost CP-even in the coupling to quarks.

$$h_1 = A \to \tau^+\tau^-$$

$$h_1 = H \to \bar{t}t$$

Same but with a CP-odd coupling to b quarks.

$$h_1 = A \to \bar{b}b$$

$$h_1 = H \to \bar{t}t$$

The other scenarios are for maximal $c^o * c^e$ with all possible signs combination.

No scalar component

Can be achieved

$$a_i + i\gamma_5 b_i \ (i = U, D, L)$$

$$c_1 = 0 \Rightarrow R_{11} = 0$$

and

$$a_U^2 = \frac{c_2^2}{s_\beta^2}; \quad b_U^2 = \frac{s_2^2}{t_\beta^2}; \quad C^2 = s_\beta^2 c_2^2$$

Type I $\quad a_U = a_D = a_L = \dfrac{c_2}{s_\beta} \qquad b_U = -\,b_D = -\,b_L = -\,\dfrac{s_2}{t_\beta}$

Type II $\quad a_D = a_L = 0 \qquad b_D = b_L = -\,s_2 t_\beta$

Type F $\quad a_D = 0 \qquad b_D = -\,s_2 t_\beta$

Type LS $\quad a_L = 0 \qquad b_L = -\,s_2 t_\beta$

Even if the CP-violating parameter is small, large tanβ can lead to large values of b.

No scalar component

In Type II, if

$$a_i + i\gamma_5 b_i \; (i = U, D, L)$$

$$a_D = a_L \approx 0 \Rightarrow b_D = b_L \approx 1$$

and the remaining h_1 couplings to up-type quarks and gauge bosons are

$$a_U^2 = 1 - s_2^4 = 1 - \frac{1}{t_\beta^4}$$

$$b_U^2 = s_2^4 = \frac{1}{t_\beta^4}$$

$$\frac{g_{C2HDM}^{hVV}}{g_{SM}^{hVV}} = C = \frac{t_\beta^2 - 1}{t_\beta^2 + 1} = \frac{1 - s_2^2}{1 + s_2^2}$$

This means that the h_1 couplings to up-type quarks and to gauge bosons have to be very close to the SM Higgs ones.

Direct probing 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

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

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

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

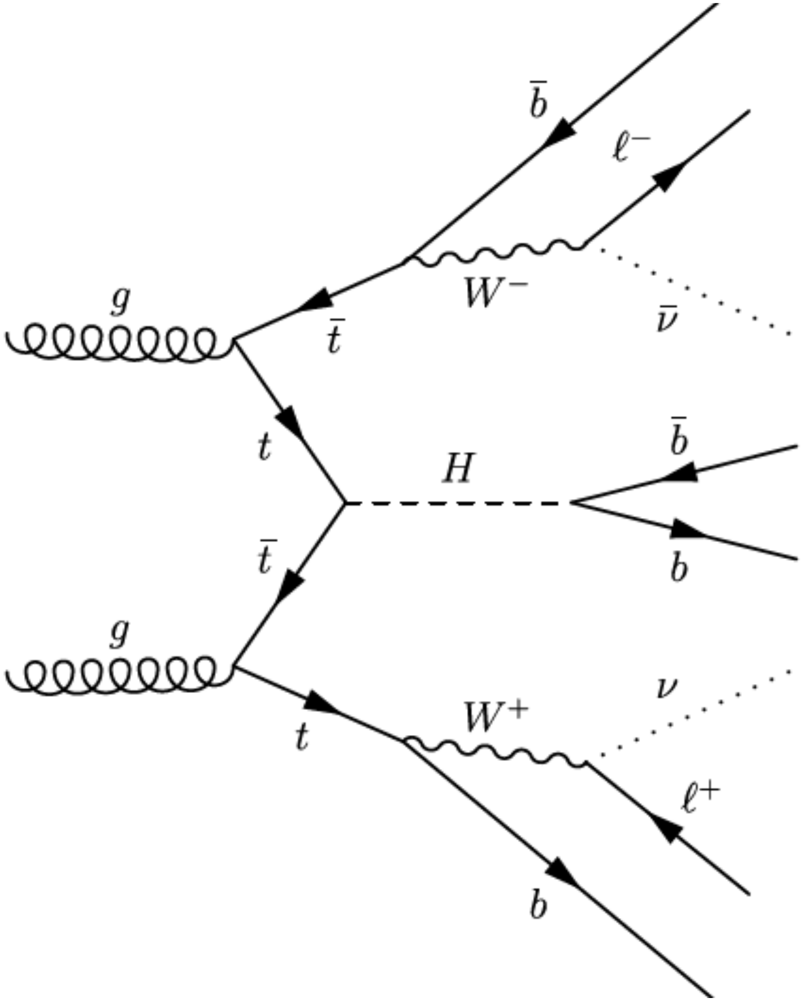
$$\tan\Phi_\tau = -\frac{\sin\beta}{\cos\alpha_1}\tan\alpha_2 \Rightarrow \tan\alpha_2 = -\frac{\cos\alpha_1}{\sin\beta}\tan\Phi_\tau$$

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

Direct probing at the LHC (tth)

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

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

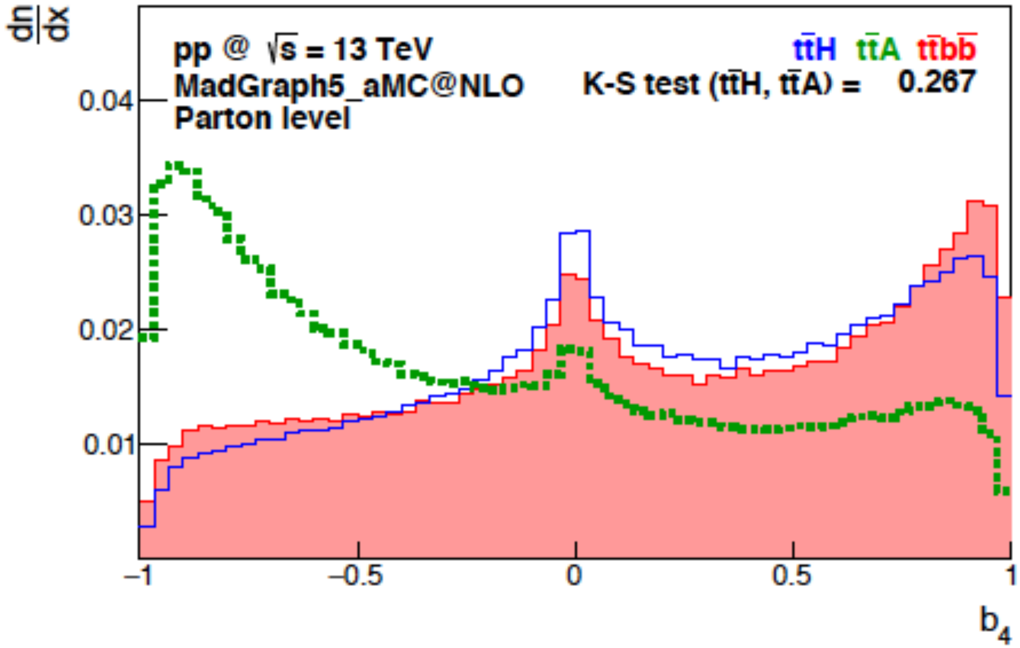


$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

Signal: tt fully leptonic and H -> bb

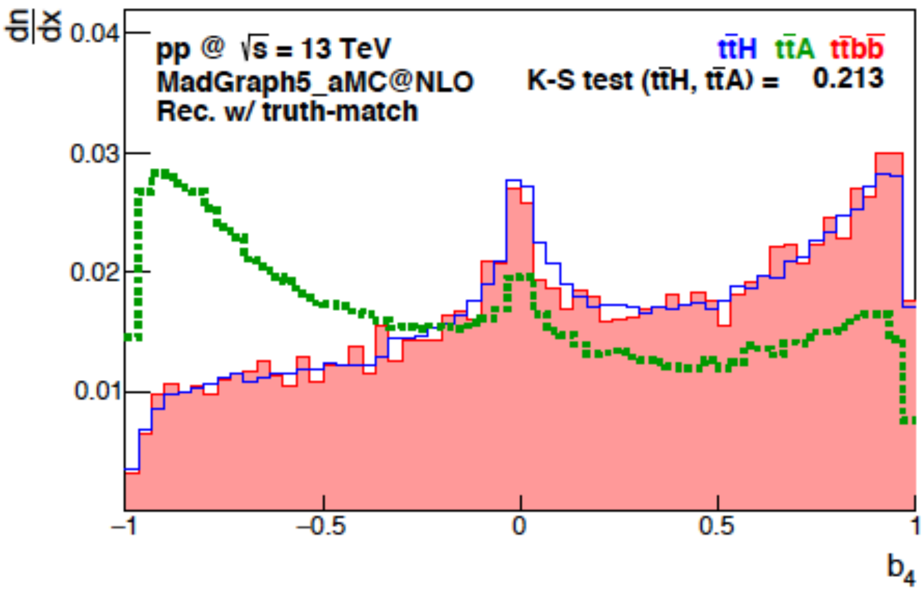
Background: most relevant is the irreducible tt background

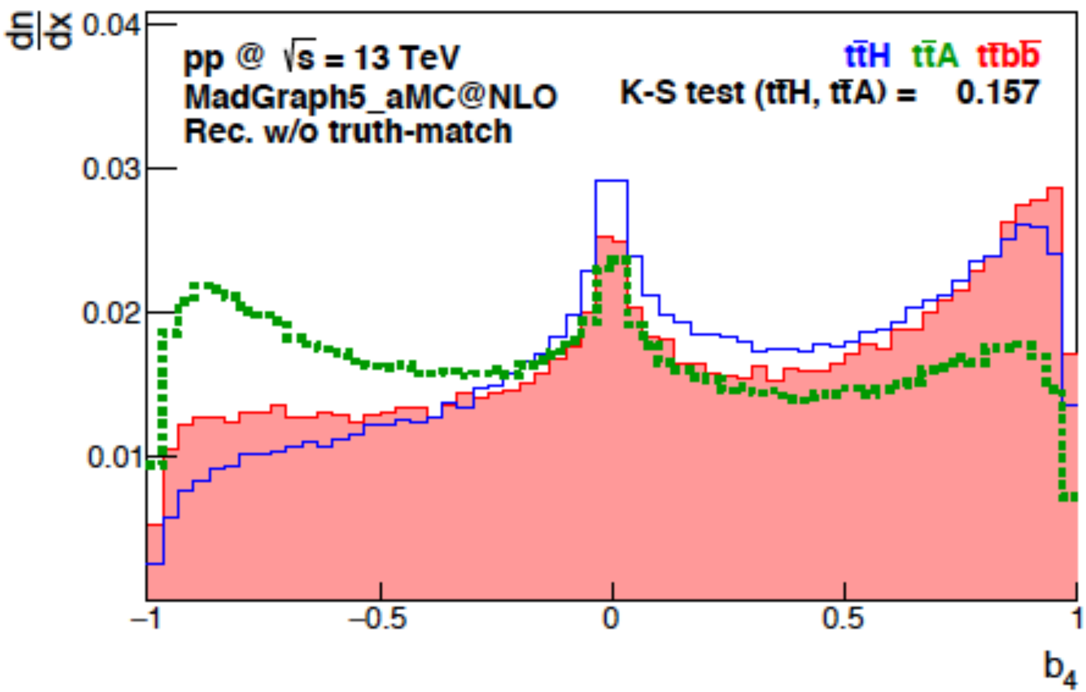
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$



Gunion, He, PRL77 (1996) 5172
Amor dos Santos eal PRD96 (2017) 013004

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





Direct probing at the LHC

- For the C2HDM we need three independent measurements

$$\tan\phi_i = \frac{b_i}{a_i}; \qquad i = U, D, L$$

- Just one measurement for type I (U = D = L), two for the other three types. At the moment there are studies for tth and ττh.

- If $\Phi_t \neq \Phi_\tau$ type I and F (Y) are excluded.

- To probe model F (Y) we need the bbh vertex.

CP violation - direct

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

Combinations of three decays

Many other combinations

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

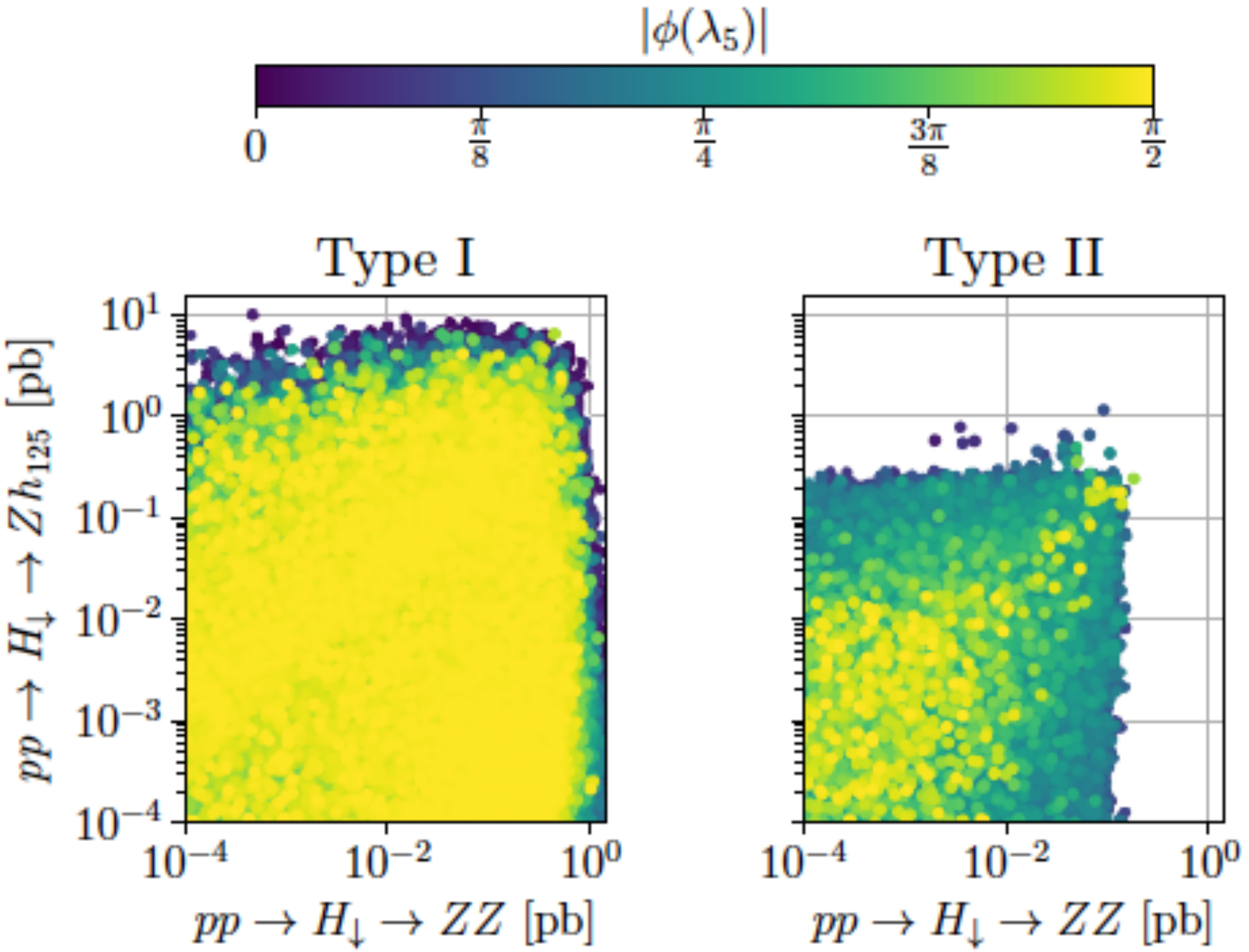
$$h_3 \to h_2 h_1 \;\Rightarrow\; CP(h_3) = CP(h_2)$$

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...

C2HDM – Fontes, Romão, RS, Silva, PRD92 (2015) 5, 055014

CNMSSM – King, Mühlleitner, Nevzorov, Walz; NPB901 (2015) 526-555

The 3 decays vs. variables - the CP-violating angle



$h_{125} \to ZZ$ MEASURED

MORE YELLOW MEANS LARGER CP-VIOLATING PHASE

There is no correlation between the high rates of CP-violating decays and the CP-violating phase.

FONTES, MUHLLEITNER, ROMÃO, RS, SILVA, WITTBRODT, JHEP 1802 (2018) 073.

Other cool variables

- Variable involving Higgs couplings to gauge bosons

$$\xi_V = 27 \prod_{i=1}^{3} c(H_i VV)^2 \quad \text{with} \quad c(H_i VV) = R_{i1} c_\beta + R_{i2} s_\beta$$

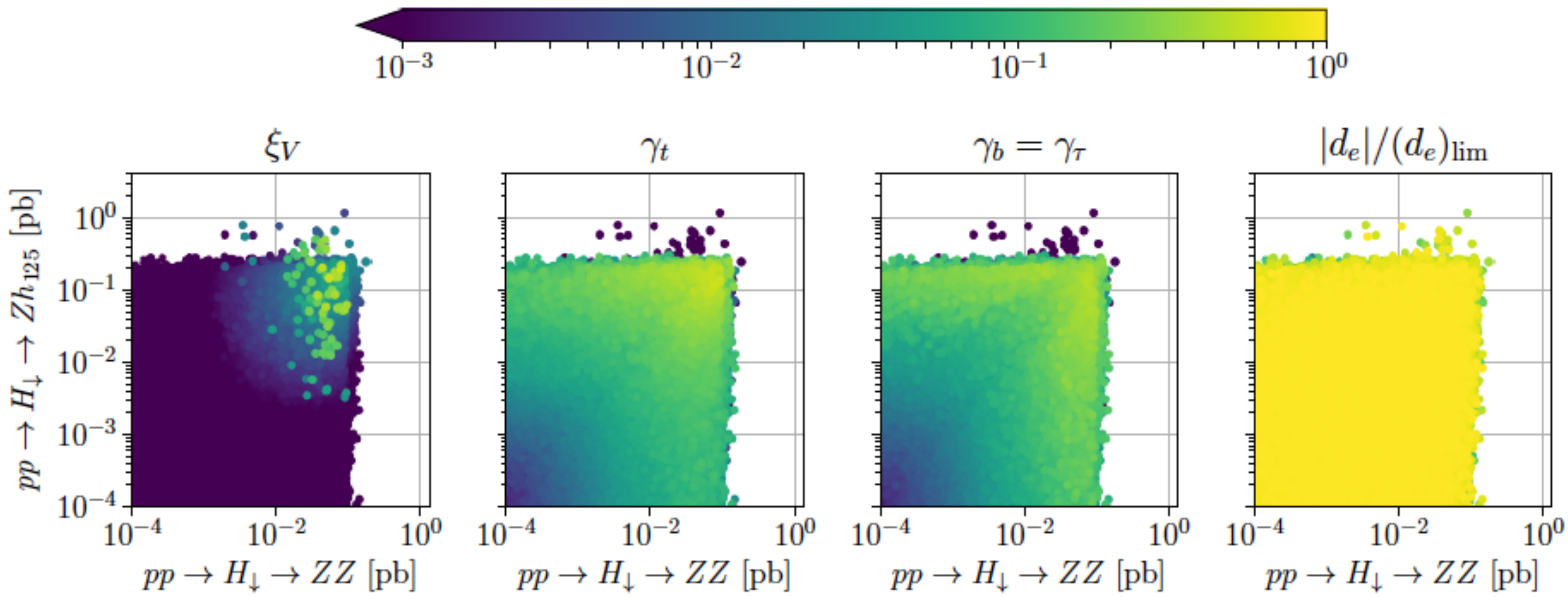
- Variables involving Higgs Yukawa couplings (for a Type II model)

$$\gamma_t = 1024 \prod_i (R_{i2} R_{i3})^2 ,$$
$$\gamma_b = 1024 \prod_i (R_{i1} R_{i3})^2 .$$

$$c(H_i t\bar{t}) = \frac{1}{s_\beta} \left(R_{i2} - i\gamma^5 \frac{R_{i3}}{c_\beta} \right)$$

which are normalized to be between 0 and 1. Variables for the sum can also be defined but they are useless.

Results for Type II (where some correlation seems to exist)



But in most cases there is no correlation.

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

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

and the vacuum preserves the symmetry

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

The potential is invariant under the CP-symmetry

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

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

Azevedo, Ferreira, Muehlleitner, 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.

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

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

Mono-Z and mono-Higgs events.

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

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

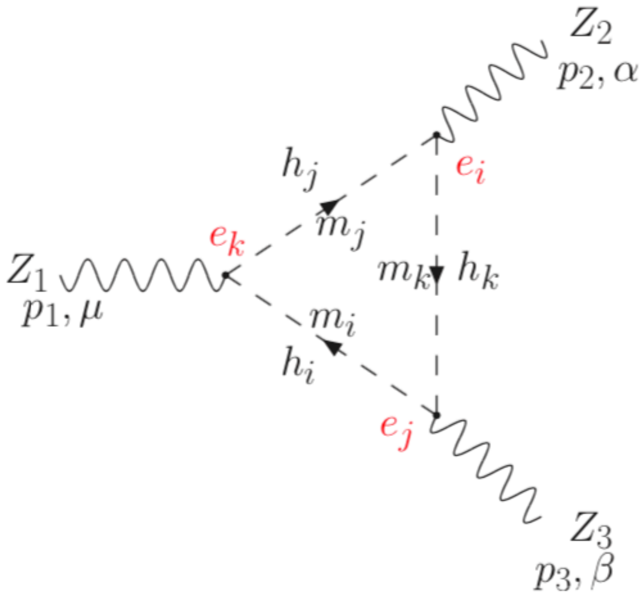
GAEMERS, GOUNARIS, ZPC1 (1979) 259

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

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

that comes from an effective operator (dim-6)

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

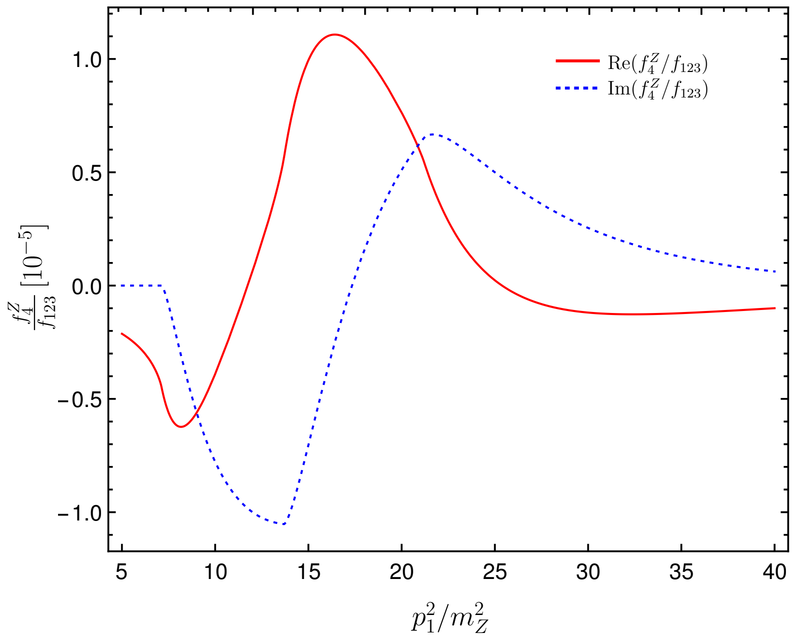


in our model it has the simple expression

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

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

Combining h_1h_2Z; h_1h_3Z and h_2h_3Z

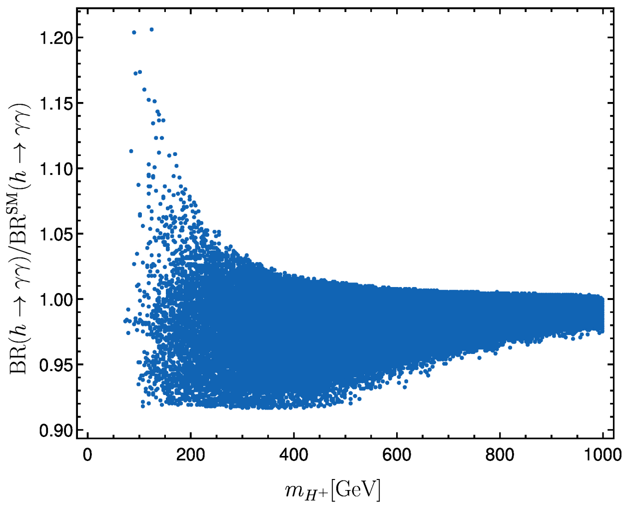


The form factor f_4 normalised to f_{123} for m_1=80.5 GeV, m_2=162.9 GeV and m_3=256.9 GeV as a function of the squared off-shell Z-boson 4-momentum, normalised to m_Z^2.

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. $-1.2\times10^{-3} < f_4^Z < 1.0\times10^{-3}$

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



How far can we go in constraining f_4?

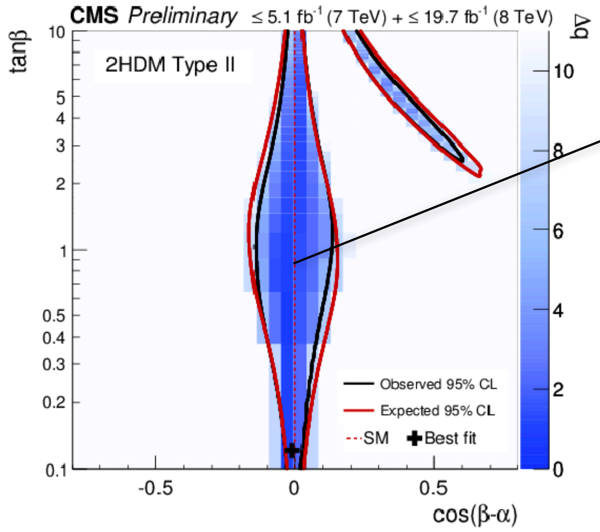
Finally: there are also charged particles that that can only decay to to another Z_2-odd particle. They also contribute to the decay of the SM-like Higgs into photons. But again no deviation was found so far.

The end

The alignment limit in the 2HDM

What about tanβ? All couplings of h125 with the other SM particles are SM-like (even hhh).

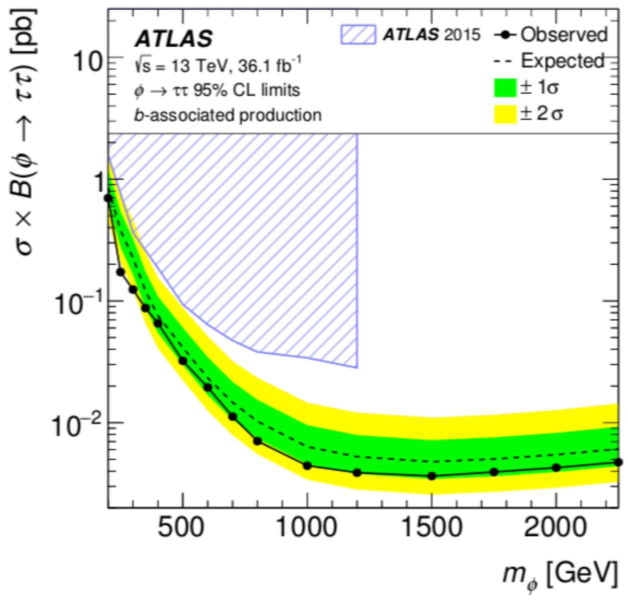
$$\begin{pmatrix} \\ V_1 \end{pmatrix} \begin{pmatrix} \\ V_2 \end{pmatrix}$$



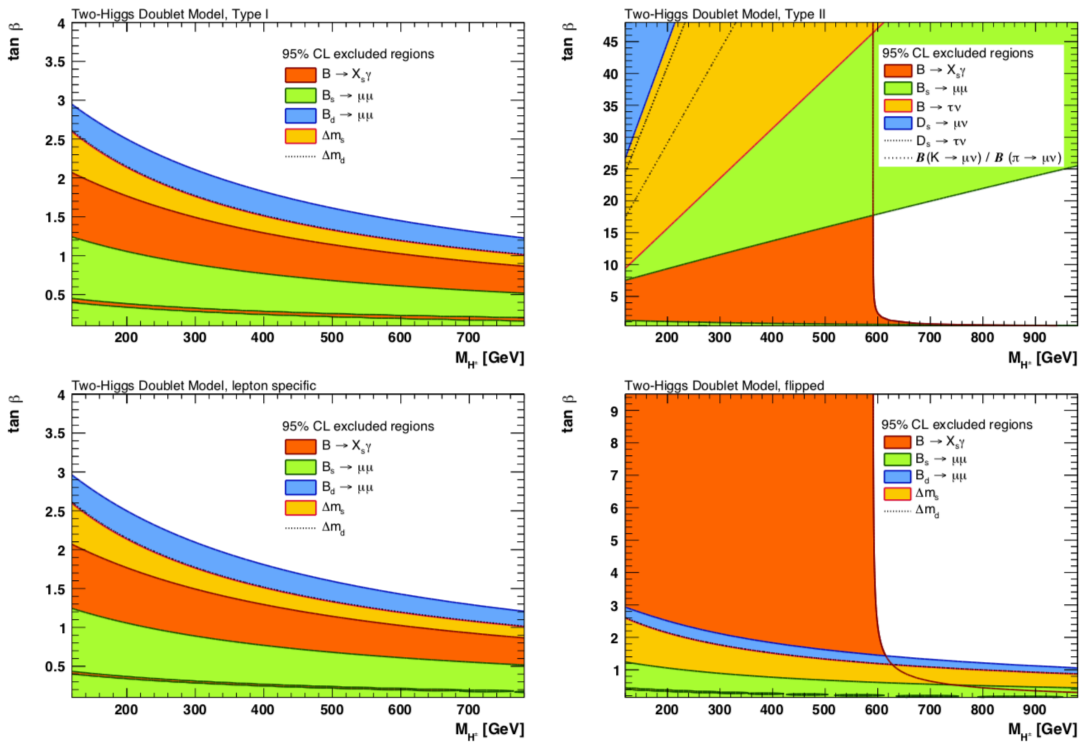
EVEN IF IN THE END WE WILL HAVE A LINE ONLY, THE MIXING BETWEEN VEVS CAN ONLY BE SEEN WITH NEW PHYSICS.

TWO EXAMPLES:

HALLER, HOECKER, KOGLER, PEIFFER, STELZER 1803.01853



(b) $\phi \to \tau\tau$ (b-associated production).



From the LHC: limit on the pseudoscalar mass, tanβ plane.

ATLAS, JHEP01(2018)055

From B-physics: Charged Higgs loops – constraint in the charged Higgs mass, tanβ plane

Direct probing at the LHC

- For the C2HDM we need three independent measurements

$$\tan\phi_i = \frac{b_i}{a_i}; \qquad i = U, D, L$$

- Just one measurement for type I (U = D = L), two for the other three types. At the moment there are studies for tth and ττh.

- If $\Phi_t \neq \Phi_\tau$ type I and F (Y) are excluded.

- To probe model F (Y) we need the bbh vertex.

Searching (almost) everywhere!

$$S_i \rightarrow S_j V \qquad H \rightarrow AZ\,(A \rightarrow HZ), h_2 \rightarrow h_1 Z$$

2HDM, C2HDM…

- $H \rightarrow AZ$, $A \rightarrow ZH$ and $A \rightarrow Zh_{125}$, ATLAS and CMS

$$S_i \rightarrow S_j S_k \qquad H_i \rightarrow H_j H_j (A_j A_j)$$

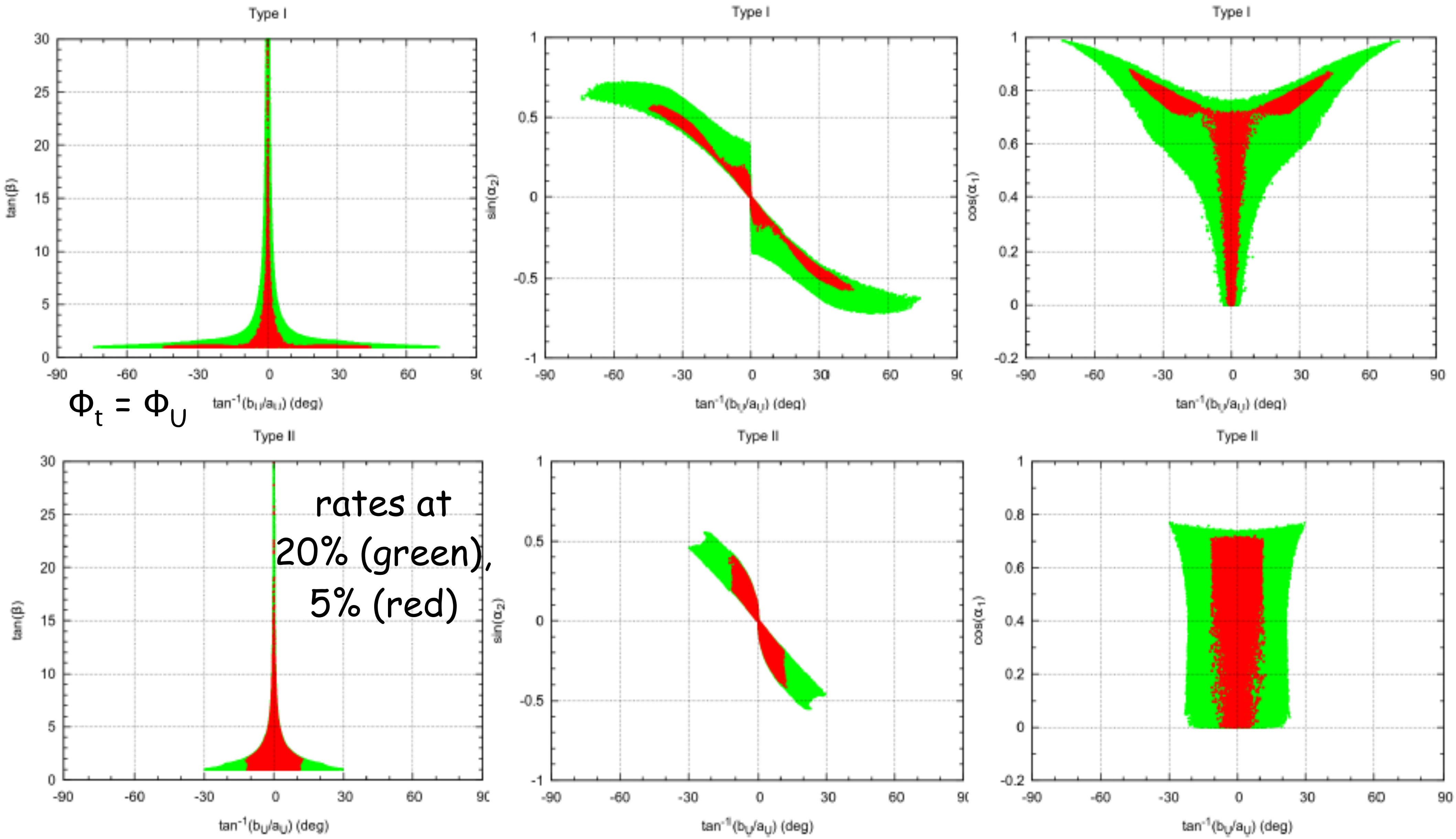
R(C)xSM, 2HDM, NMSSM, C2HDM, C-NMSSM, 3HDM…

- $h_{125} \rightarrow AA$ and $H \rightarrow h_{125}\, h_{125}$, ATLAS and CMS but still no $H_i \rightarrow h_{125} H_k (j \neq k)$

$$S_i \rightarrow f_i \bar{f}_j \qquad H_i / A_i \rightarrow b\bar{b}, t\bar{t}, \tau^+\tau^-, \mu^+\mu^- \qquad h_{125} \rightarrow \tau\mu, e\mu, e\tau$$

Still, the CP-nature of the Higgs not probed (but it is not CP-odd). Attempts in tth (production) and ττh (decay) starting (many theory papers).

Limits on Φ_t based on the rates only



Competitive for Type I but not for Type II

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 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**

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

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

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

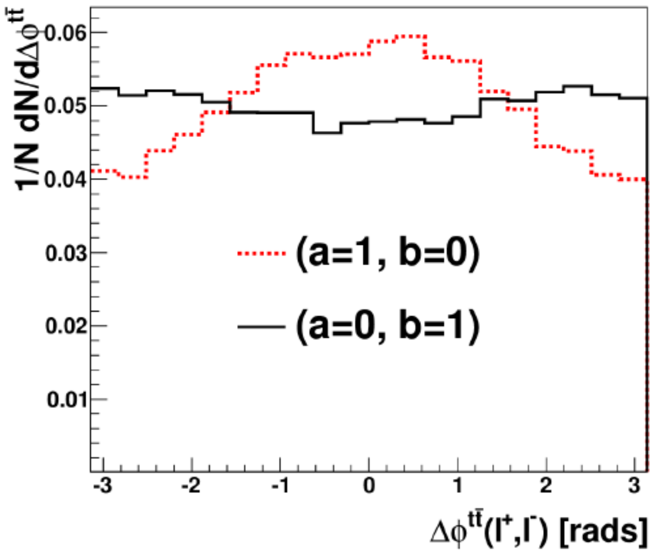
Type LS $\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta}$ $\qquad \kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$

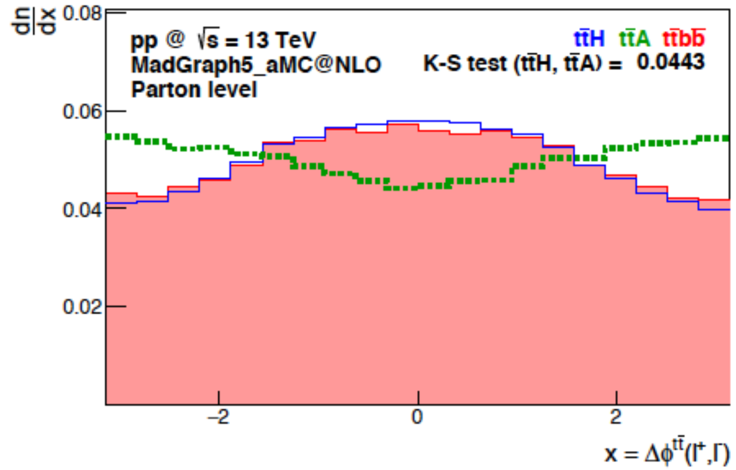
$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases} = Y_{N2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases}$$

III = I' = Y = Flipped = 4... IV = II' = X = Lepton Specific= 3...

Review of tth

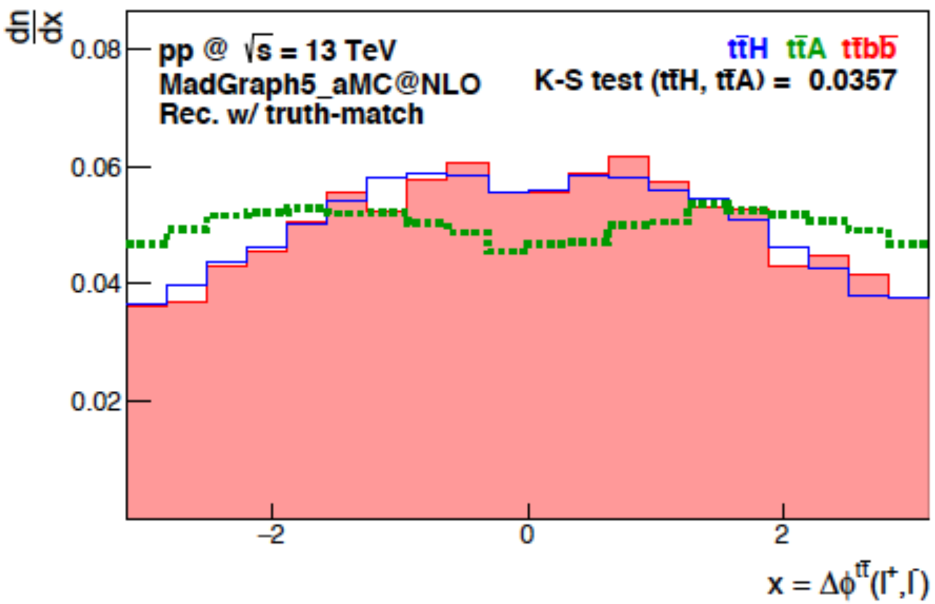
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

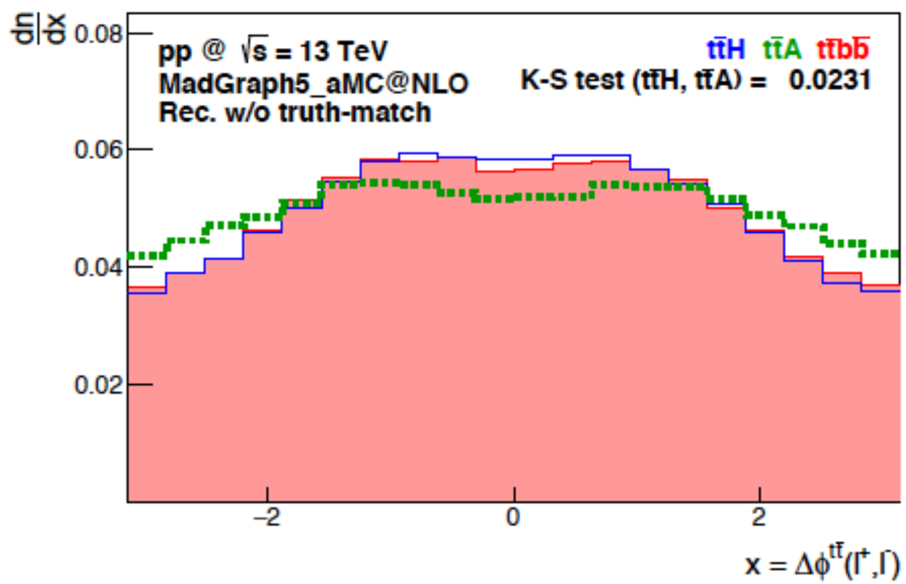




Boudjema, Godbole, Guadagnoli, Mohan 2015

Azimuthal difference between l+ in the t rest frame and l- in the tbar rest frame

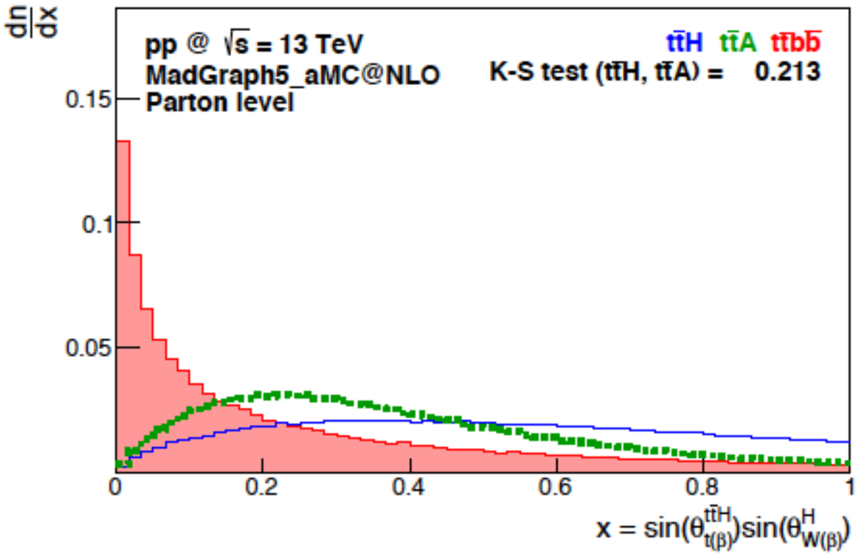


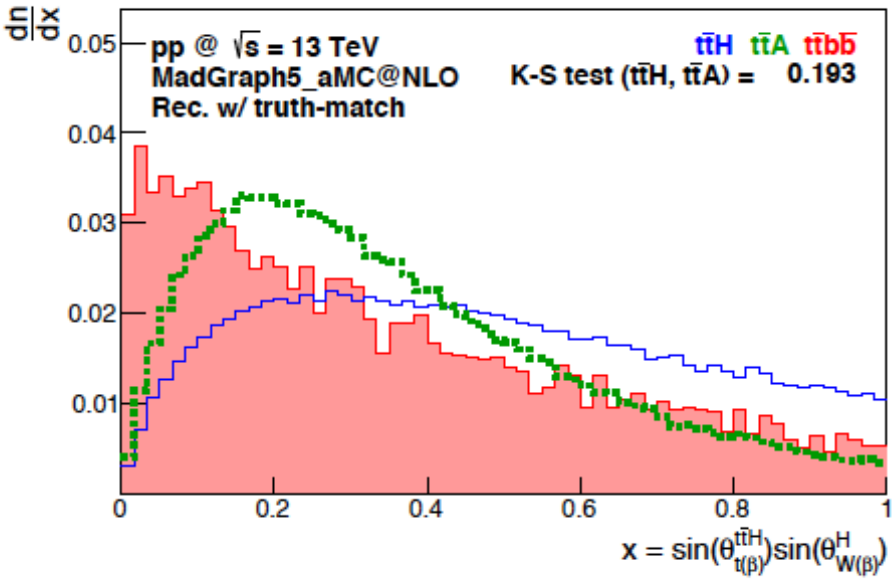


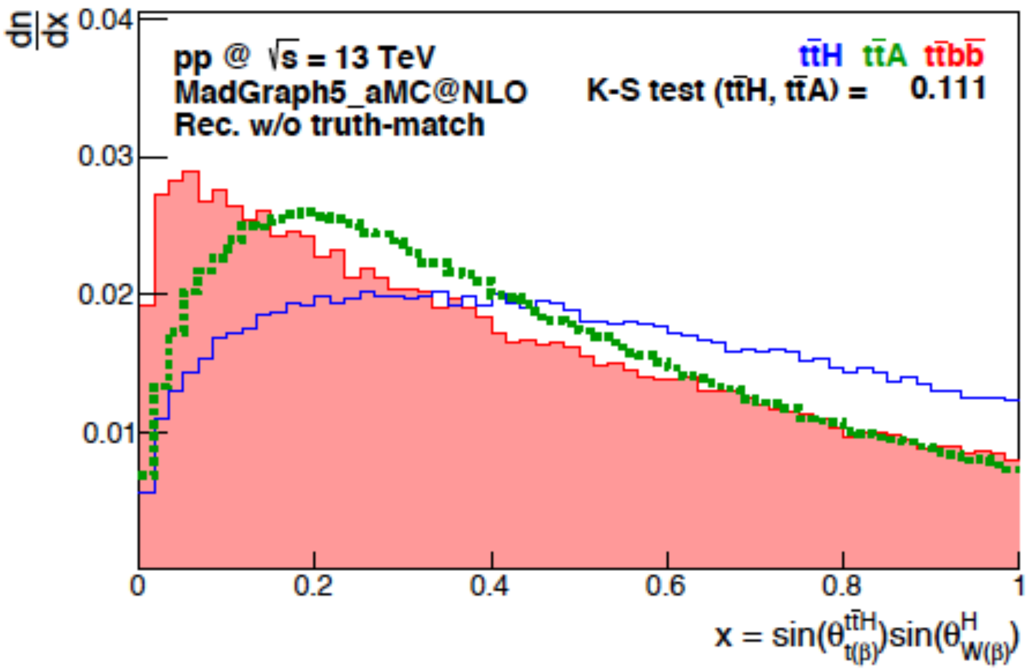
Review of tth

$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

AMOR DOS SANTOS EAL 2015







Combinatorial background plays a very important role.

CP - what have ATLAS and CMS measured so far?

- Effective Lagrangian (CMS notation)

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

HAVING ALL EXTRA COUPLINGS COMPATIBLE WITH ZERO DOES NOT MEAN CP-CONSERVATION.

Parameter	Observed	Expected
$f_{a3} \cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2} \cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f_{\Lambda 1}^{Z\gamma} \cos(\phi_{\Lambda 1}^{Z\gamma})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$

CMS, 1707.00541

ATLAS, 1506.05669

The zero scalar scenarios

- There is only one way to make the pseudoscalar component to vanish

$$R_{13} = 0 \quad \Rightarrow \quad s_2 = 0$$

and they all vanish (for all types and all fermions).

- There are two ways of making the scalar component to vanish

$$R_{11} = 0 \quad \Rightarrow \quad c_1 c_2 = 0$$

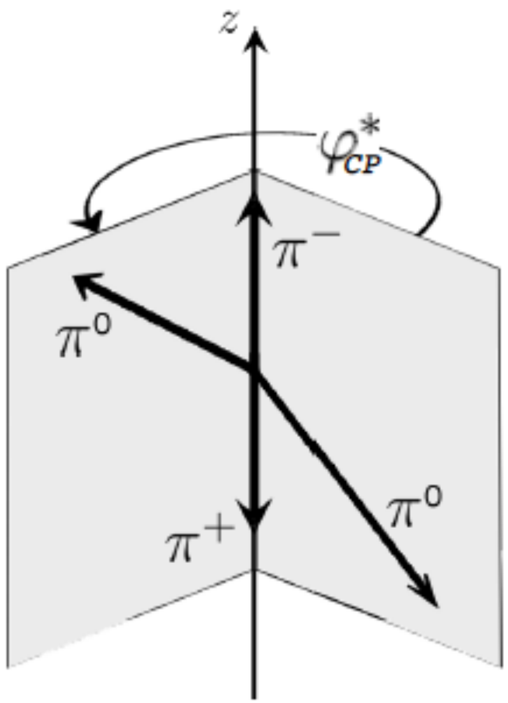
$\rightarrow$ $c_2 = 0 \quad \Rightarrow \quad g_{h1VV} = 0$ **excluded**

$\rightarrow$ $c_1 = 0$ **allowed**

$$R_{12} = 0 \quad \Rightarrow \quad s_1 c_2 = 0$$

excluded

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$



Berge, Bernreuther, Kirchner PRD92 (2015) 096012

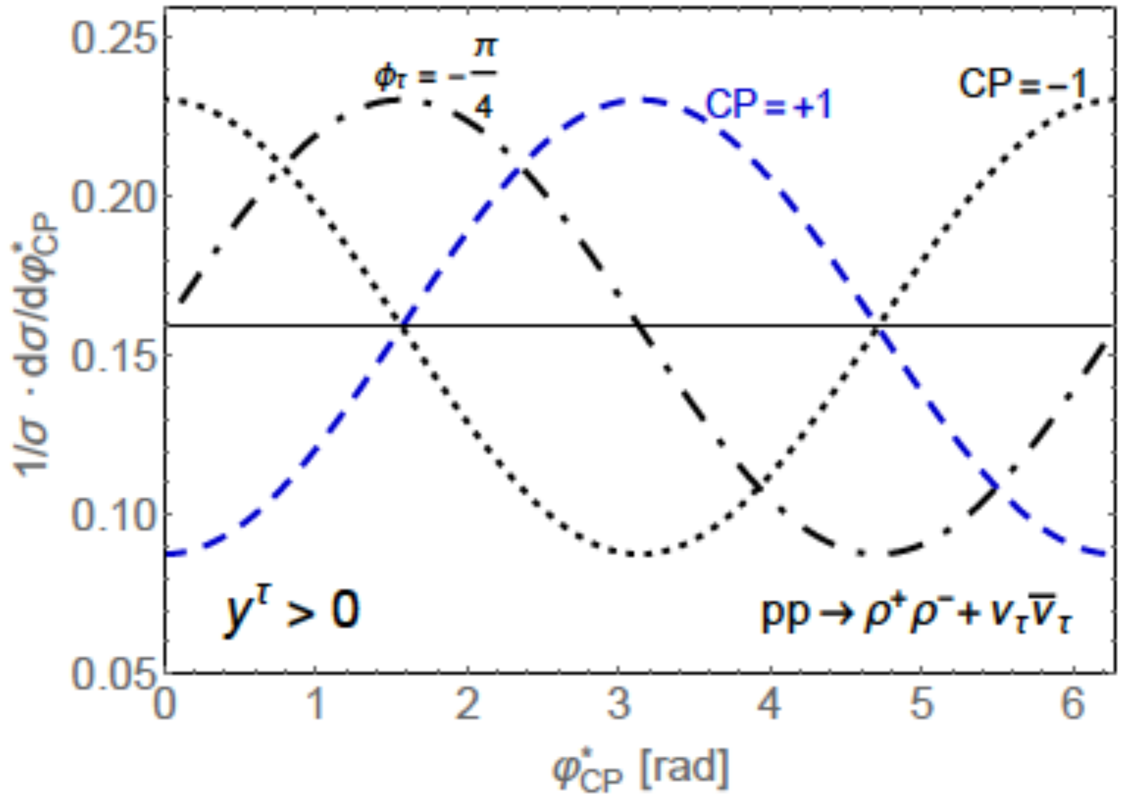


Illustration of φ^*_{CP} in the ρ decay-plane method as defined in (14) for $pp \to h^0 \to \tau^-\tau^+ \to \rho^-\rho^+ + 2\nu$.