CP-violation at the LHC

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Outline

- A complex 2HDM
- CP-violation in the bosonic Higgs couplings
- CP-violation in the combination of Higgs decays
- Some variables to probe CP-violation
- CP-violation in the triple gauge boson couplings
- CP-violation in the Yukawa couplings
- CP-violation - a strange scenario
- Conclusions

A complex 2HDM

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

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 – Re(m^2_{12})

h_{125} couplings

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

CP-VIOLATING 2HDM

"PSEUDOSCALAR" COMPONENT (DOUBLET)

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

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

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

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

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

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

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

THREE NEUTRAL STATES MIX

CP-VIOLATING 2HDM $[h_i]_{mass} = [R_{ij}][h_j]_{gauge}$

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

CP-violation in bosonic decays

Correlations in the momentum distributions of leptons produced in the decays

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

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

Choi, Miller, Mühlleitner, Zerwas, PLB553, 61 (2003).

Buszello, Fleck, Marquard, van der Bij, EPJC32, 209 (2004)

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

Only term in the 2HDM at tree-level $\kappa = \sin(\beta - \alpha)$

Only term in the C2HDM at tree-level $\kappa = \cos\alpha_2 \sin(\beta - \alpha)$

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	
ATLAS	not tested	$[-2.5, 0.75]$	$[-0.95, 2.9]$	H→ZZ→4l
CMS	$[-1.2, 1.5]$	$[-\infty, 0.69]$ $[1.9, 2.3]$	$[-2.2, 2.1]$	
ATLAS	not tested	$[-0.4, 0.85]$ $[1, 2.2]$	$[-5, 6]$	H→WW→2l2ν
CMS	$[-\infty, +\infty]$	$[-\infty, 0.71]$ $[1.2, +\infty]$	$[-\infty, +\infty]$	
ATLAS	not tested	$[-0.63, 0.73]$	$[-0.83, 2.2]$	
CMS	$[-1.7, 1.6]$	$[-0.76, 0.58]$	$[-1.6, 1.5]$	

8 TeV results

Expected for the SM

$$\beta/\kappa < 10^{-2}; \quad \gamma/\kappa < 10^{-7}$$

karytov - talk at HiggsDays 2015

Sensitivity projections for Higgs boson properties measurements at the HL-LHC

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 $3000\,\mathrm{fb}^{-1}$. 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	$[2.0, 6.0]$

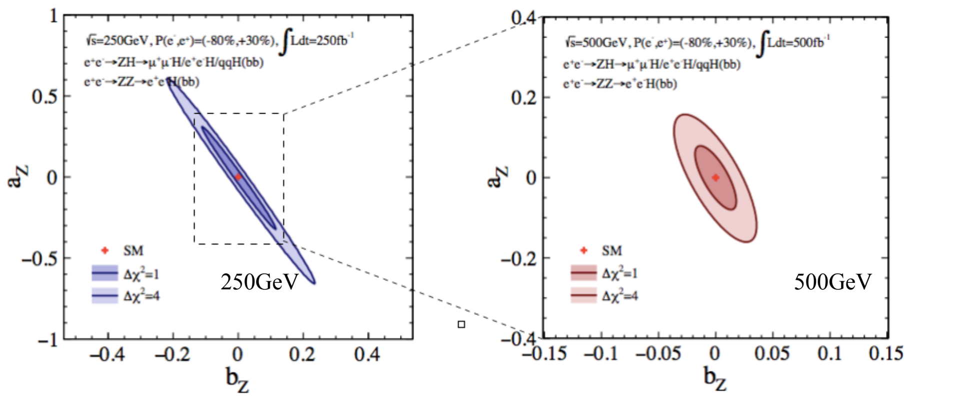
$$\gamma/\kappa \lessapprox 0.034$$

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)



$$\gamma/\kappa \lessapprox 0.022$$

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

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%

Can be used to constraint the C2HDM at loop-level

CP-violation in a combination of three decays

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

Combinations of three decays

Many other combinations

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

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

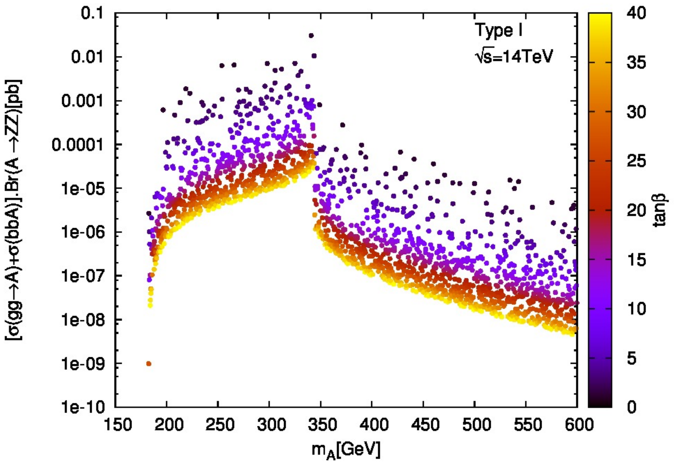
Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

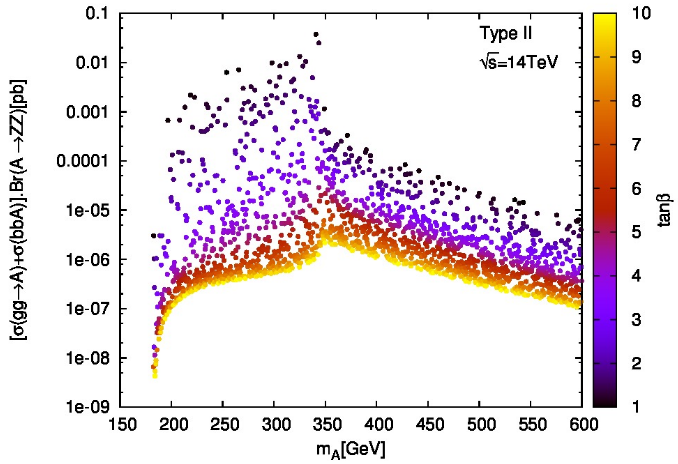
C2HDM – Fontes, Romão, RS, Silva, PRD92 (2015) 5, 055014

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

CP-violation in a combination of three decays

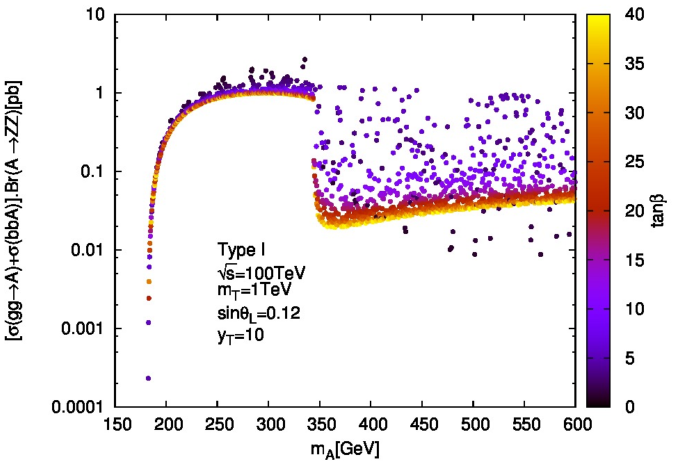
But if something is found, a more detail studied is needed

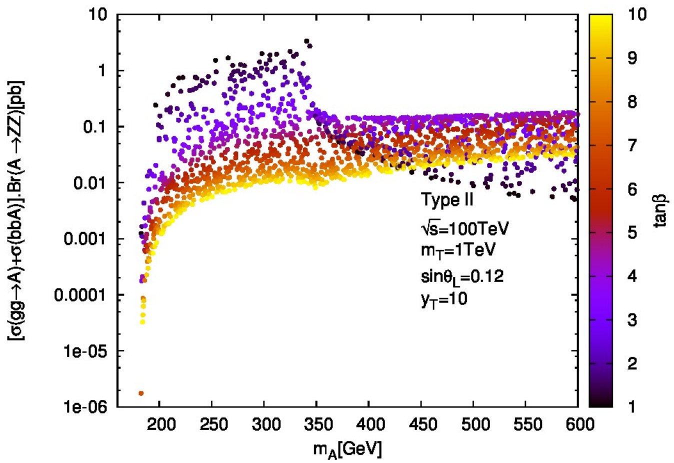




Problem 1 - scalar is found in ZZ with very low rates - it could be a pseudoscalar plus in the 2HDM, in the exact alignment limit:

$$\Gamma(A \to ZZ) \sim \Gamma(H \to ZZ)$$

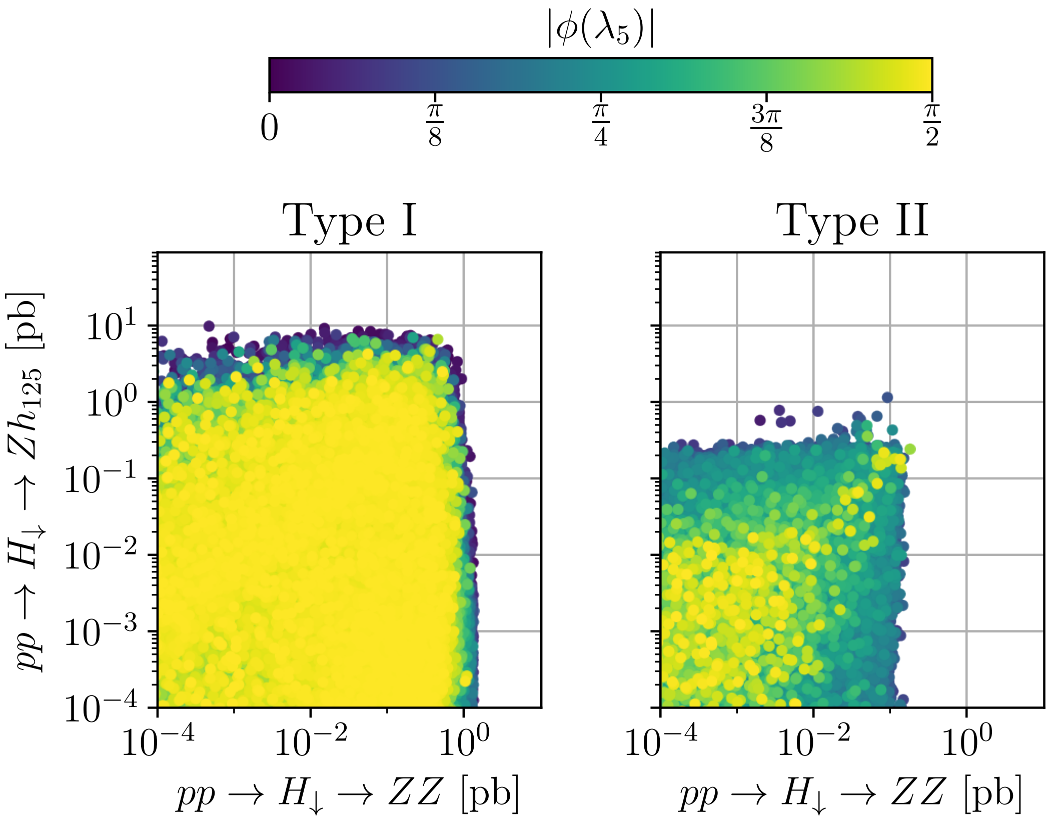




Problem 2 - with extra vector like quarks the rates could be higher even for a pseudoscalar

Arhrib, Benbrik, El Falaki, Sampaio, RS, to appear in PRD (1809.04805)

Variables to probe CP-violation



Compare variables that probe CP-violation with the set of processes that together could signal CP-violation.

$h_{125} \to ZZ$ MEASURED

The first variable is just the phase

$$\lambda_5 = |\lambda_5| e^{i\phi(\lambda_5)}$$

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

Variables to probe CP-violation

Variable involving Higgs couplings to gauge bosons

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

$$[R_{ij}] = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

Mendez, Pomarol, PLB272 (1991) 313.

c(HiVV) is the coupling relative to the SM Higgs coupling; variables are normalised

$$0 < \xi_V \leq 1$$

which is related with the simplest CP-odd invariant that can be build from the mass matrix

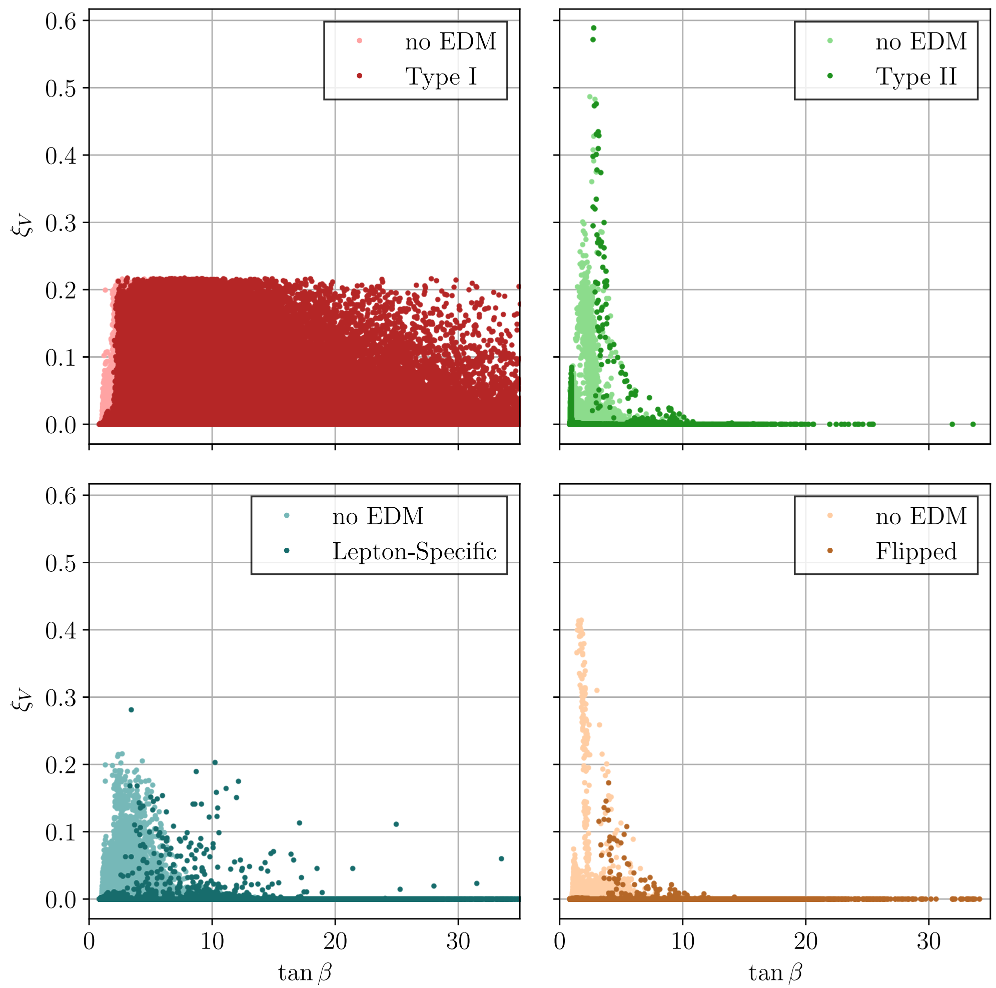
$$J_1^2 = [(m_2^2 - m_1^2)(m_3^2 - m_1^2)(m_3^2 - m_2^2)] \frac{\xi_V}{27}$$

Lavoura, Silva, PRD50 (1994) 4619.

Note that in the CP-conserving 2HDM,

$$c(AVV) = 0 \implies \xi_V = 0$$

Variables vs. tanβ



CP-violating parameter ξ_V as a function of tan β for all types.

Lighter points have passed all constraints except EDM, darker points have passed all constraints.

Type I: no special regions regarding the allowed values of tan β. Also, the maximum value for ξ_V is around 0.2 almost independently of tanβ.

Type II: ,after EDM, we end with two almost straight lines (one for tan β ≈ 1 and the other for ξ_V ≈ 0), as well as a region around tanβ ≈ 3 with ξ_V up to 0.6.

Points with significant CP-violation can occur for tan β ≈ 1 in the alignment limit or for large tan β for the wrong sign limit.

$$\kappa_D \kappa_W < 0 \quad \text{or} \quad \kappa_U \kappa_W < 0$$

The situation in Flipped is similar to Type II, with a maximum value of $\xi_V \sim 0.2$.

Ferreira, Gunion, Haber, RS, PRD89 (2014)

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

Let us consider now the Yukawa couplings. As an example consider a Type II up-quark coupling

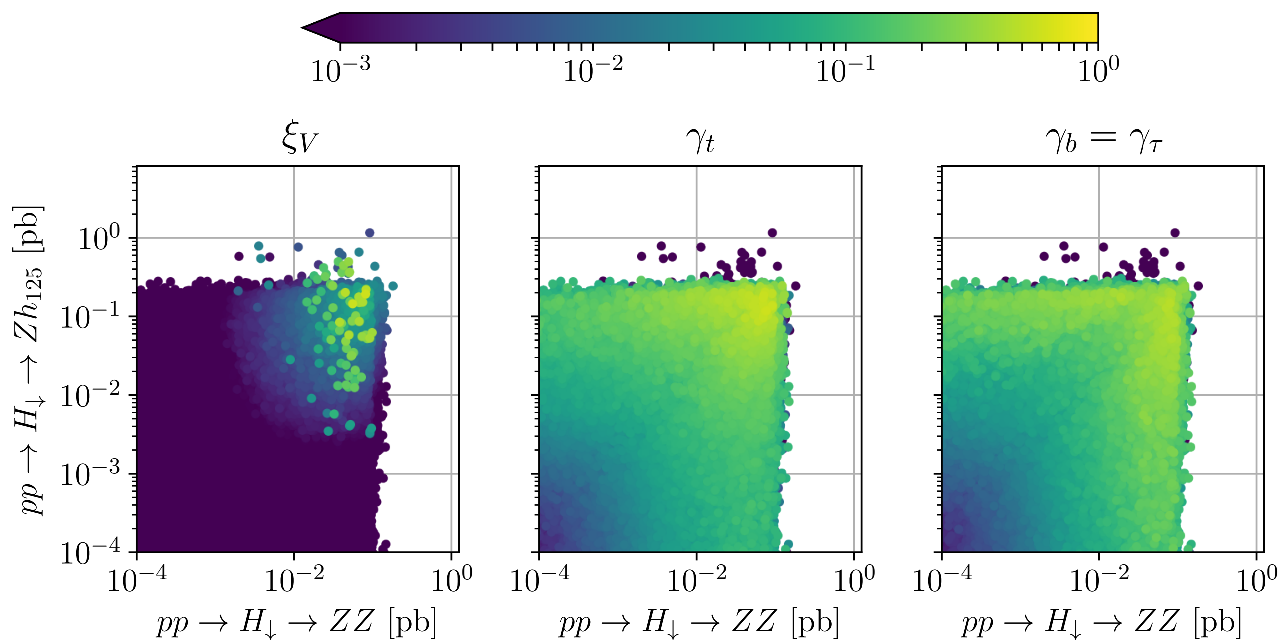
$$c(H_i\bar{t}t) = \frac{1}{s_\beta}(R_{i2} - i\gamma_5 R_{i3})$$

we defined the normalised variables

$$\gamma_t = 1024\prod_{i=1}^{3}(R_{i2}R_{i3})^2 \qquad \gamma_b = 1024\prod_{i=1}^{3}(R_{i1}R_{i3})^2$$

KHATER, OSLAND, APP B34 (2003) 4531.

Similar variables can be defined for the sum.



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

But in most cases we found no correlation.

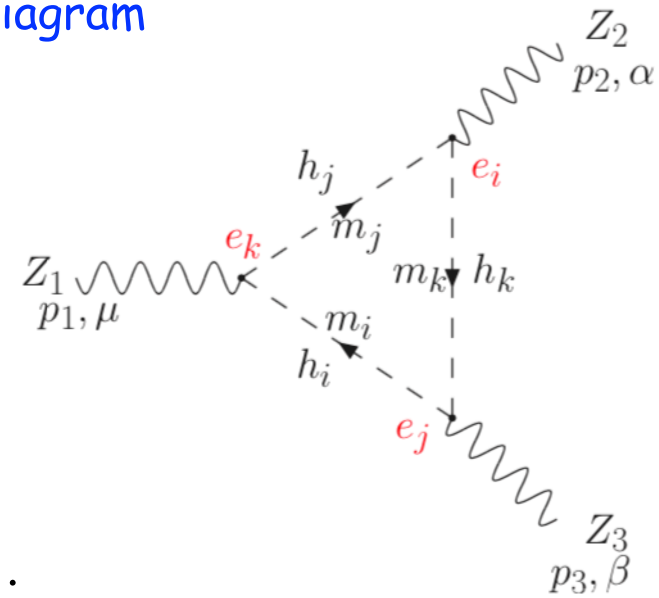
CP-violation in the triple gauge bosons coupling

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

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

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

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



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

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

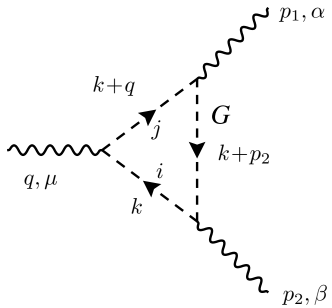
Gaemers, Gounaris, ZPC1 (1979) 259
Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB282 (1987) 253
Grzadkowski, Ogreid, Osland, JHEP 05 (2016) 025

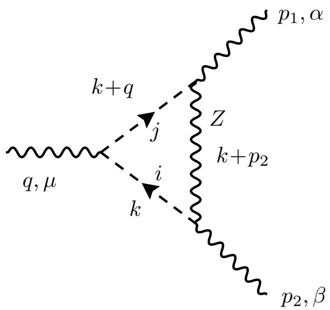
For a model with only this type of diagrams

DO NOT MISS
PEDRO FERREIRA'S CP IN THE DARK tomorrow at 10.45

In the C2HDM there are two more types of diagrams

PLOT FROM JHEP 04 (2018) 002

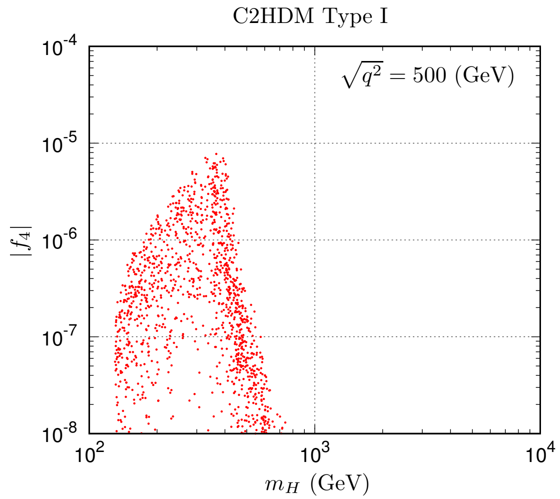




$$h_1 \to ZZ \quad CP(h_1) = 1$$

$$h_2 \to ZZ \quad CP(h_2) = 1$$

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



GRZĄDKOWSKI, OGREID, OSLAND, JHEP 05 (2016) 025.
BÉLUSCA-MAÏTO, FALKOWSKI, FONTES, ROMÃO, SILVA, JHEP 04 (2018) 002

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

Present measurements by ATLAS and CMS - still two orders of magnitude away

CMS COLLABORATION, EPJC78 (2018) 165.

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

ATLAS COLLABORATION, PRD97 (2018) 032005.

$$-1.5 \times 10^{-3} < f_4^Z < 1.5 \times 10^{-3}$$

How far can we go in constraining f_4?

TABLE III. Simultaneous limits (10^{-3}) on anomalous couplings in ZZ production at LHC at $\sqrt{s} = 13$ TeV for various luminosity from MCMC

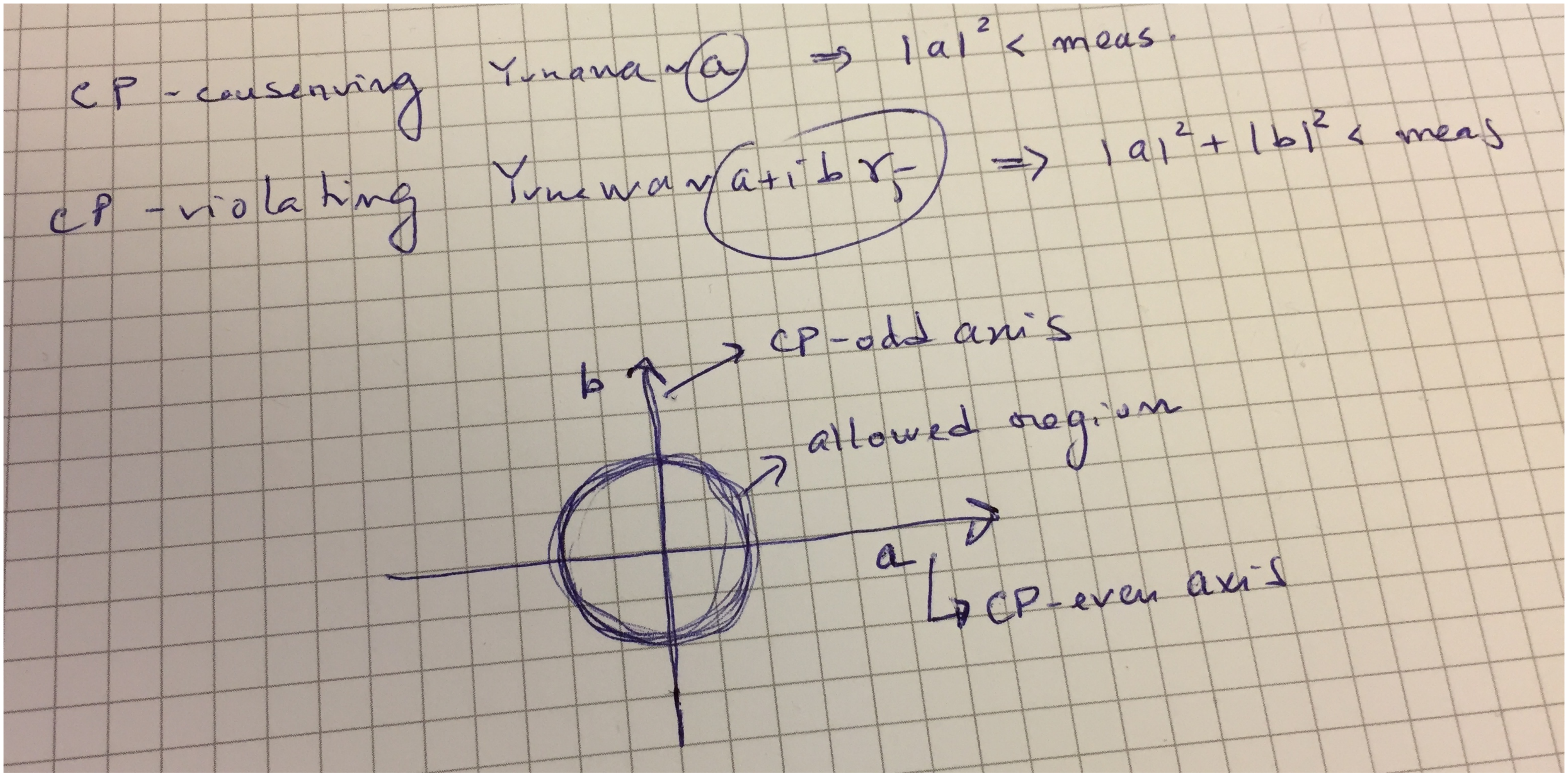
param / $\mathscr{L}$	35.9 fb^{-1}	150 fb^{-1}	300 fb^{-1}	1000 fb^{-1}
f_4^γ	$^{+1.12}_{-1.11}$	$^{+0.78}_{-0.78}$	$^{+0.66}_{-0.66}$	$^{+0.50}_{-0.50}$
f_5^γ	$^{+1.10}_{-1.13}$	$^{+0.77}_{-0.80}$	$^{+0.65}_{-0.67}$	$^{+0.47}_{-0.50}$
f_4^Z	$^{+0.95}_{-0.95}$	$^{+0.67}_{-0.67}$	$^{+0.57}_{-0.57}$	$^{+0.41}_{-0.41}$
f_5^Z	$^{+0.95}_{-0.97}$	$^{+0.67}_{-0.68}$	$^{+0.56}_{-0.58}$	$^{+0.41}_{-0.42}$

RAHAMAN, SINGH, 1810.11657.

CP-violation in the Yukawa couplings

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

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



Bounds on the Yukawa couplings

With the most relevant experimental and theoretical constraints

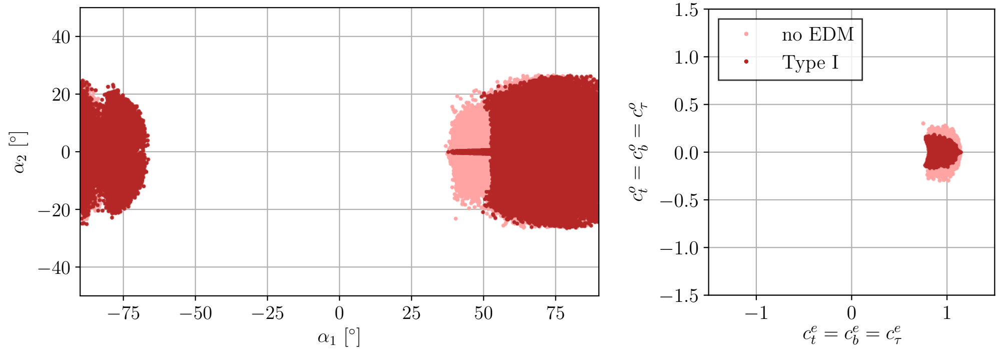


Figure 1. C2HDM Type I: for sample 1 (dark) and sample 2 (light) left: mixing angles α_1 and α_2 of the C2HDM mixing matrix R only including scenarios where $H_1 = h_{125}$; right: Yukawa couplings.

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

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

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

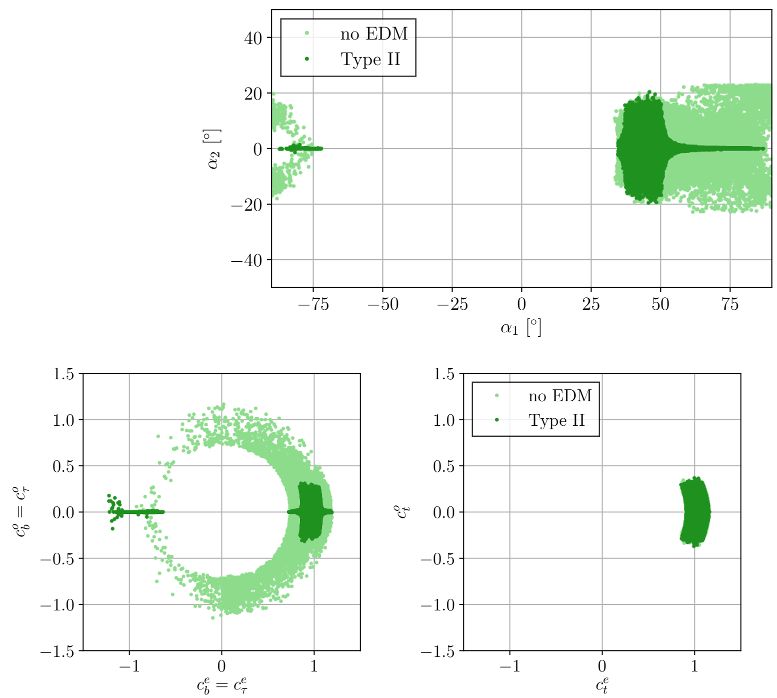


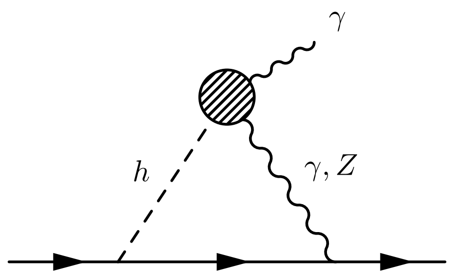
Figure 3. C2HDM Type II, $h_{125} = H_1$: Yukawa couplings to bottom quarks and tau leptons (left) and top quarks (right) for sample 1 (dark) and sample 2 (light).

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

$$\tan\beta > 1$$

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

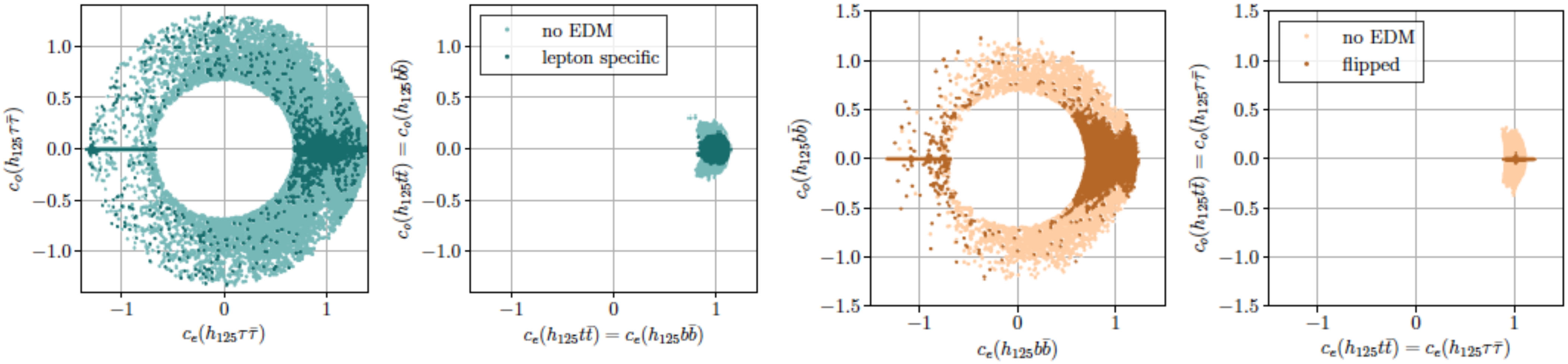
EDM



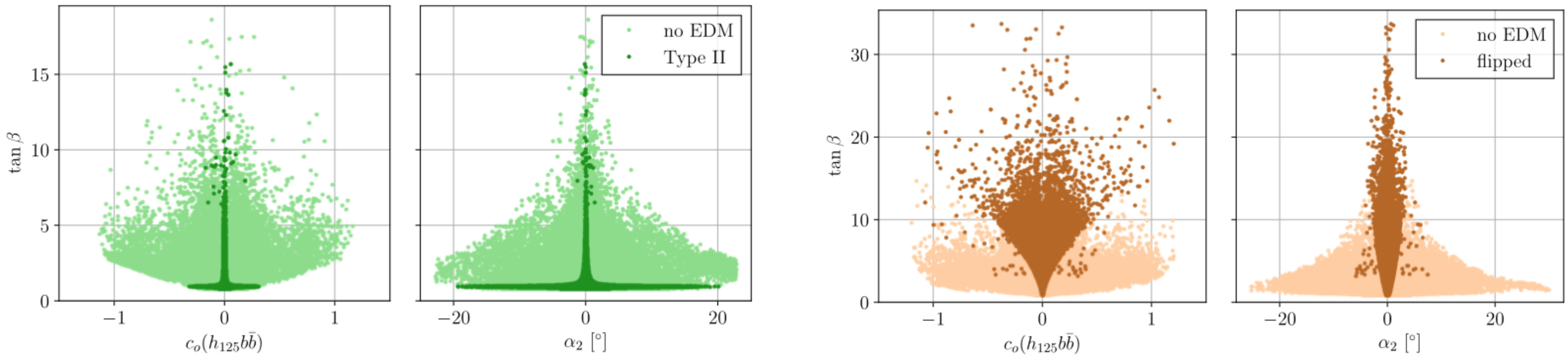
Fontes, Muhlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

EDM 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 relevant quantity for the pseudoscalar component is $c_o = \sin(\alpha_2)\tan(\beta)$

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

Ψ_i^{C2HDM} C2HDM - pseudoscalar component.

LHC today

$\Psi_i^{C2HDM} = R_{i3}^2$

C2HDM II	C2HDM I
10%	20%

CLIC@350GeV (500/fb)

$\Psi_i^{C2HDM} \leq 0.85\,\%$ from κ_{ZZ}

If no new physics is discovered and the measured values are in agreement with the SM predictions, the pseudoscalar components (from the C2HDM) will be below the % level.

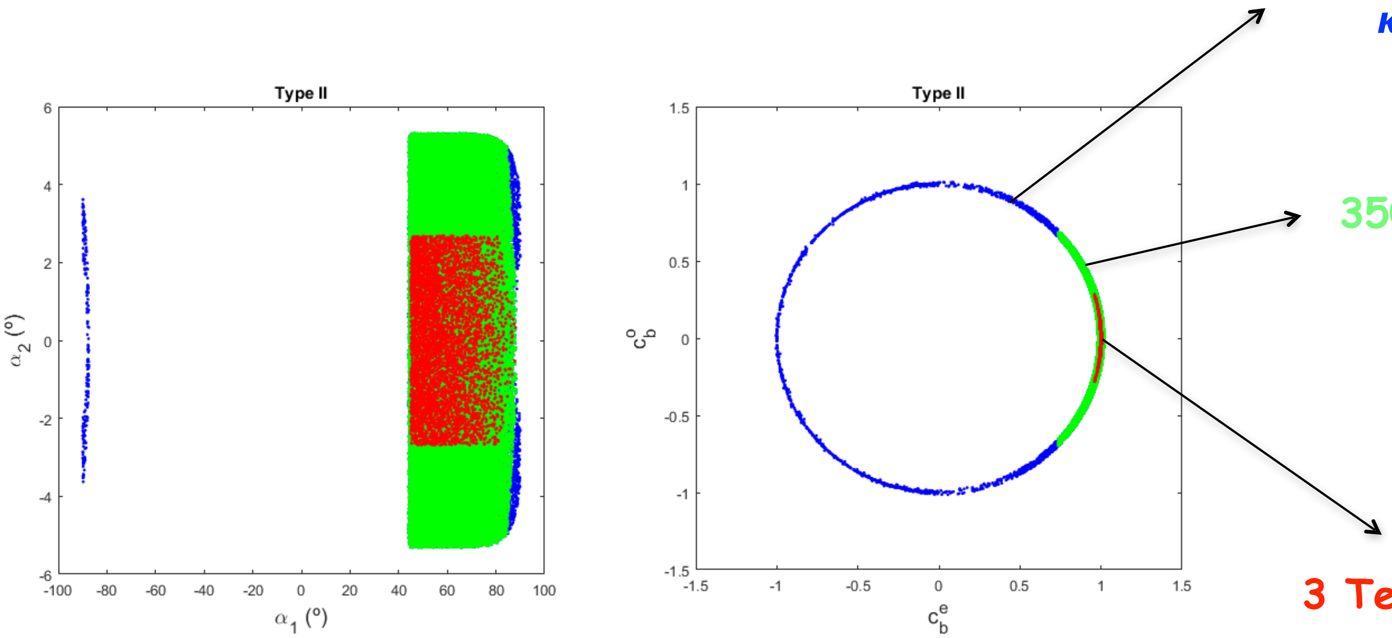
Not taking into account radiative corrections

Azevedo, Ferreira, Muhlleitner, RS, Wittbrodt, 1808.00755

How will it look in the future?

Using the bounds for κ_i the Yukawa allowed circle looks like

Unitarity $\Rightarrow \kappa^2_{ZZ,WW} + \Psi_i^{C2HDM} \leq 1$ $\qquad \Psi_i^{C2HDM} = R^2_{i3}$



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

CP-violation - a strange scenario

	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	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$

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

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

and for instance in type II

$$c_1 = 0 \implies R_{11} = 0 \implies a_D = a_L = 0$$

and

A scalar that is also a pseudoscalar

$$b_D = b_L = -s_2 t_\beta \qquad b_D^2 = b_L^2 \approx 1 \qquad 0 + i\gamma_5 b_D$$

for large $\tan\beta$

$$b_U = s_2 / t_\beta \qquad b_U \approx 0 \qquad a_U + i\gamma_5 \times 0$$

Possible for all Yukawa types except Type I

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 $a_U = a_D = a_L = \frac{c_2}{s_\beta}$ $\quad b_U = -b_D = -b_L = -\frac{s_2}{t_\beta}$

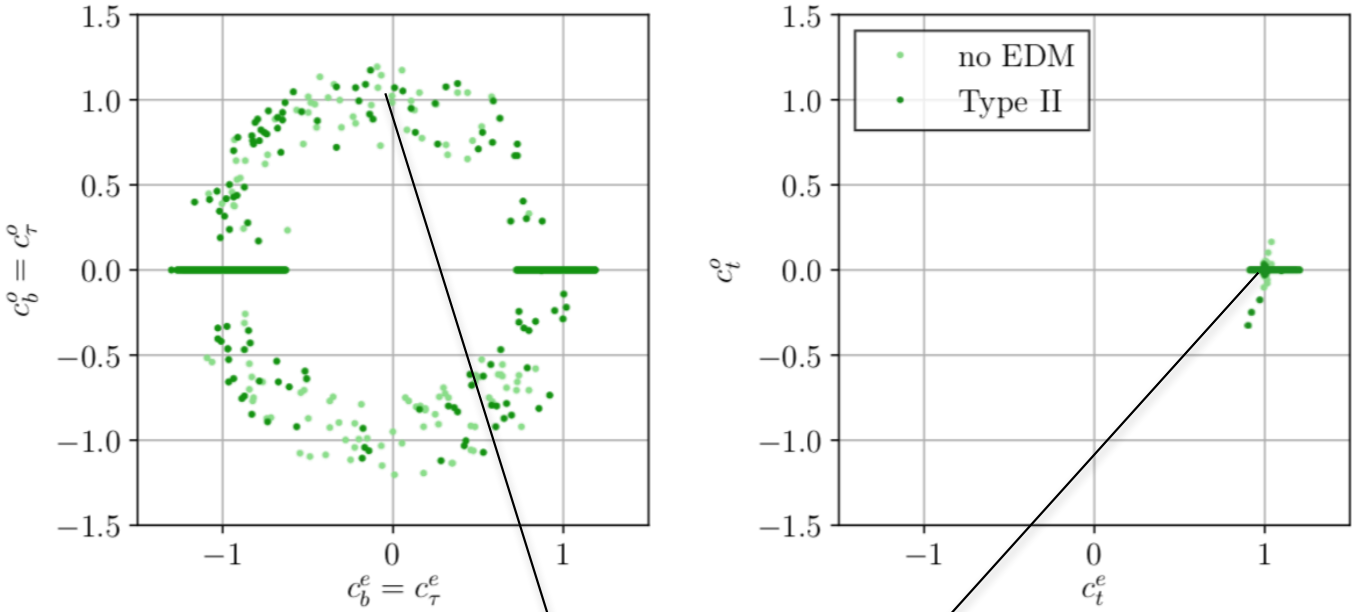
Type II $a_D = a_L = 0$ $\quad b_D = b_L = -s_2 t_\beta$

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

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

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

Which means CP-violation in a strange way



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

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

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

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

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!

The LS and F 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.

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

$$h_1 = H; pp \to Ht\bar{t}$$

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

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

$$h_1 = H; pp \to Ht\bar{t}$$

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

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

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

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

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

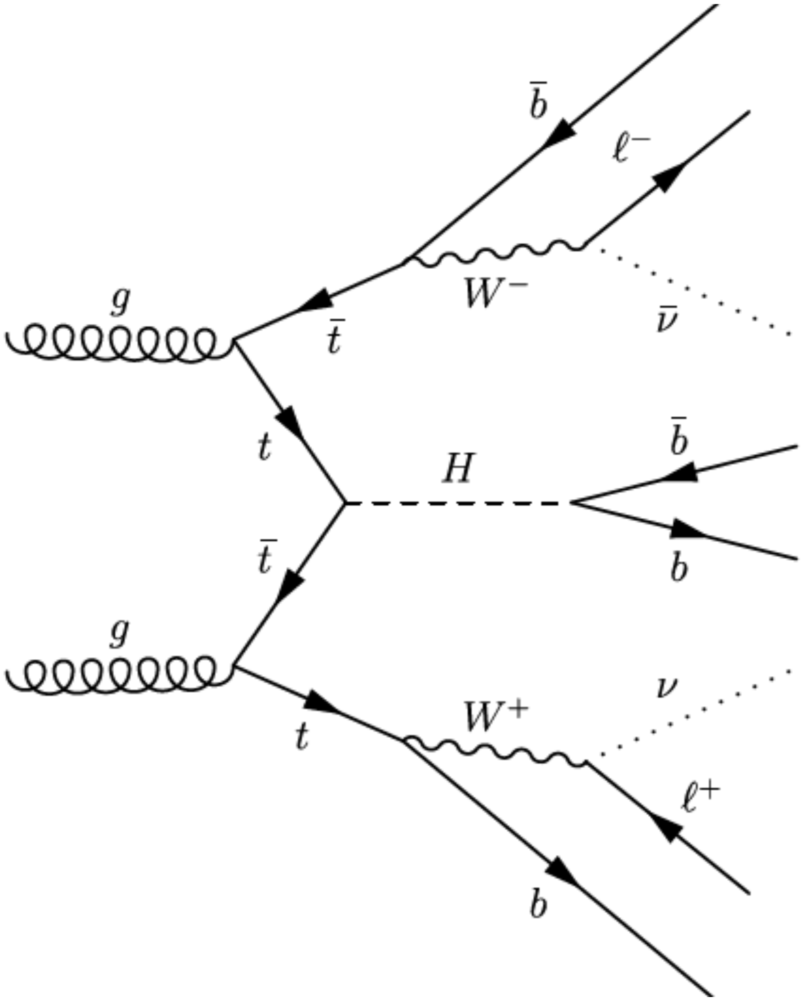
$$\tan\Phi_\tau = -\frac{\sin\beta}{\cos\alpha_1}\tan\alpha_2 \Rightarrow \tan\alpha_2 = -\frac{\cos\alpha_1}{\sin\beta}\tan\Phi_\tau$$

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

CP from direct measurements 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



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

Signal: tt fully leptonic (or semi-leptonic) and H -> bb

Background: most relevant is the irreducible tt background

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

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

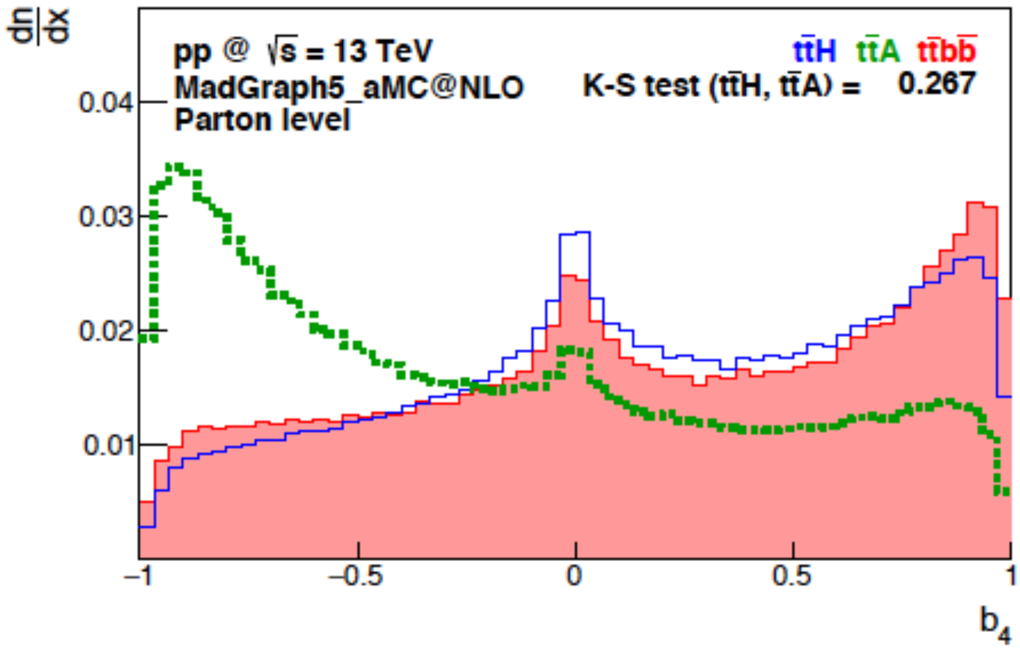
$$\mathcal{L}_{Ht\bar{t}} = -\frac{y_t}{\sqrt{2}}\bar{t}(a + ib\gamma_5)th$$

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

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

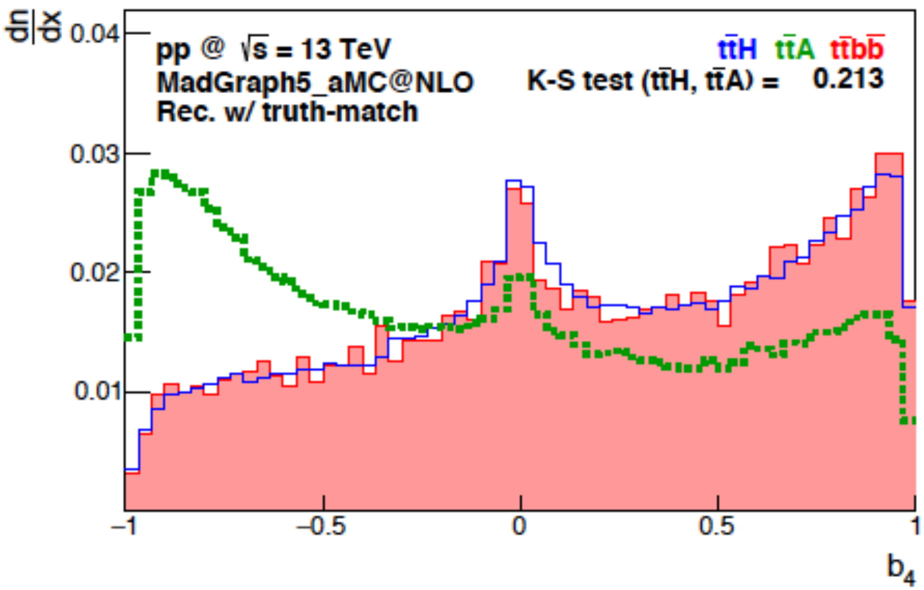
Gunion, He, PRL77 (1996) 5172

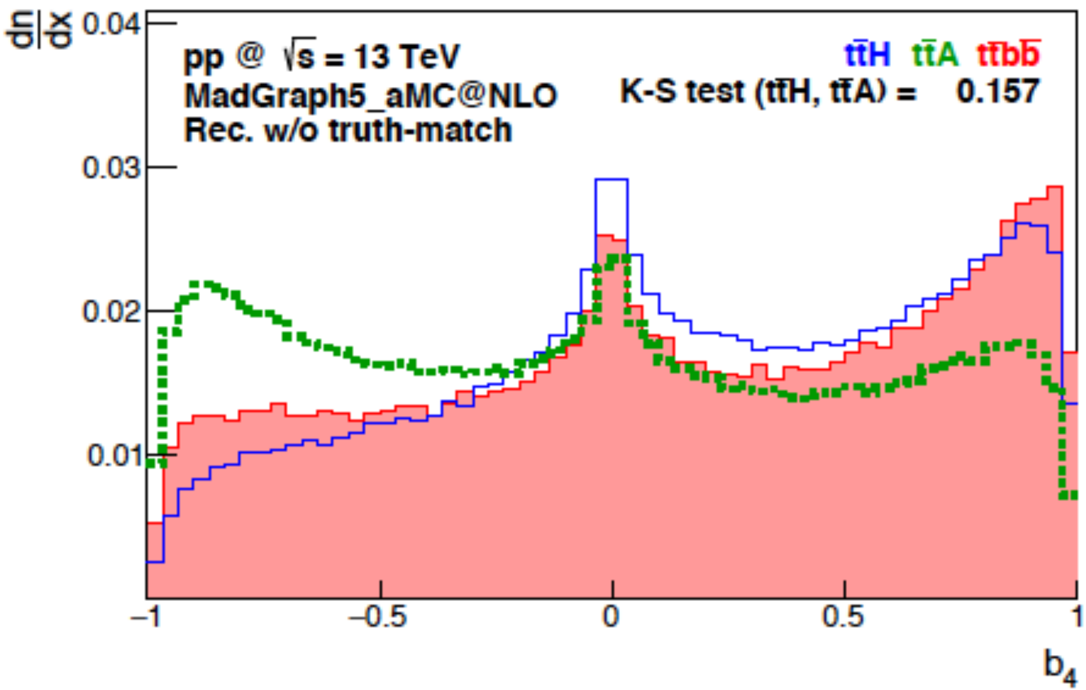
Another option is to use angular distributions for which the CP-even and the CP-odd terms behave differently.

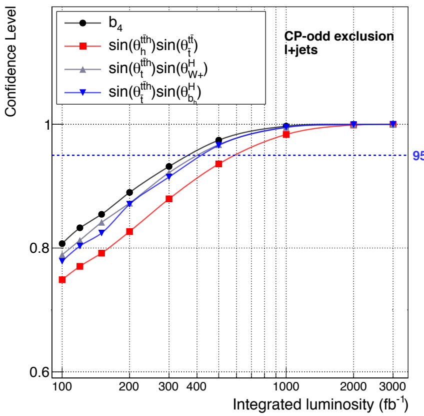


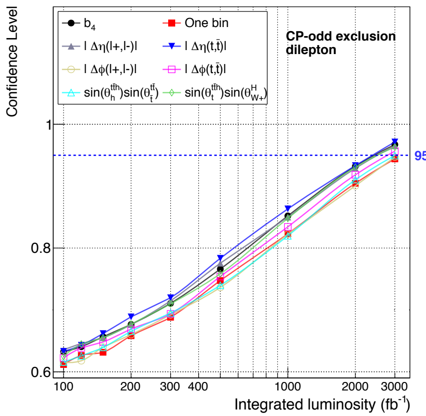
GUNION, HE, PRL77 (1996) 5172
AMOR DOS SANTOS EAL PRD96 (2017) 013004

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





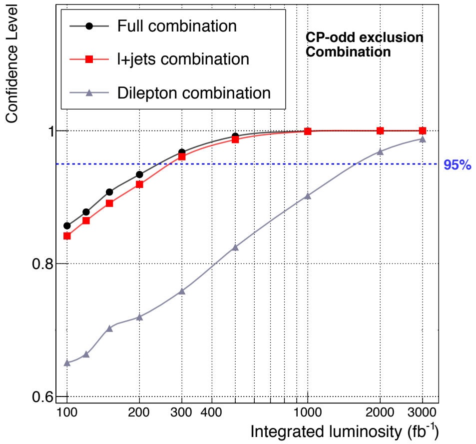


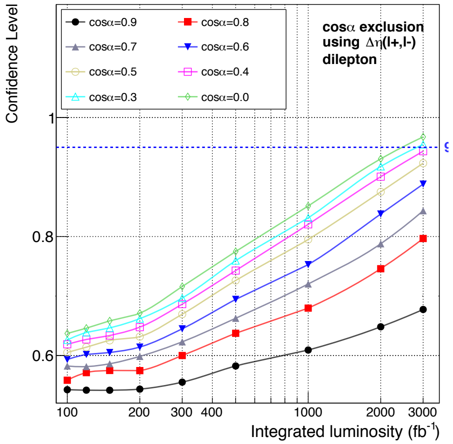


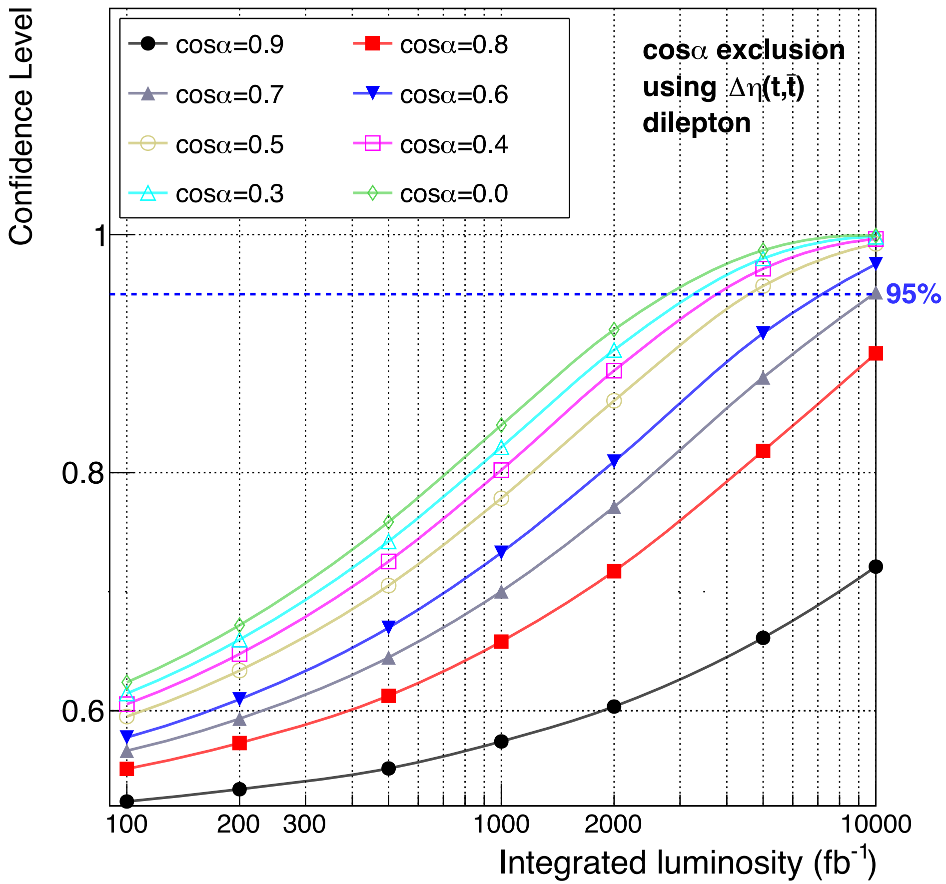
$$\mathcal{L}_{H\bar{t}t} = \kappa y_t \bar{t}(\cos\alpha + i\sin\alpha\gamma_5)th$$

$\cos\alpha = 1$ 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, 1902.00298

many other proposals...

HANKELE, KLAMKE, ZEPPENFELD, 0605117

$$pp \to jjh$$

Using the azimuthal angle between the two jets.

Corresponds to the C2HDM in the limit

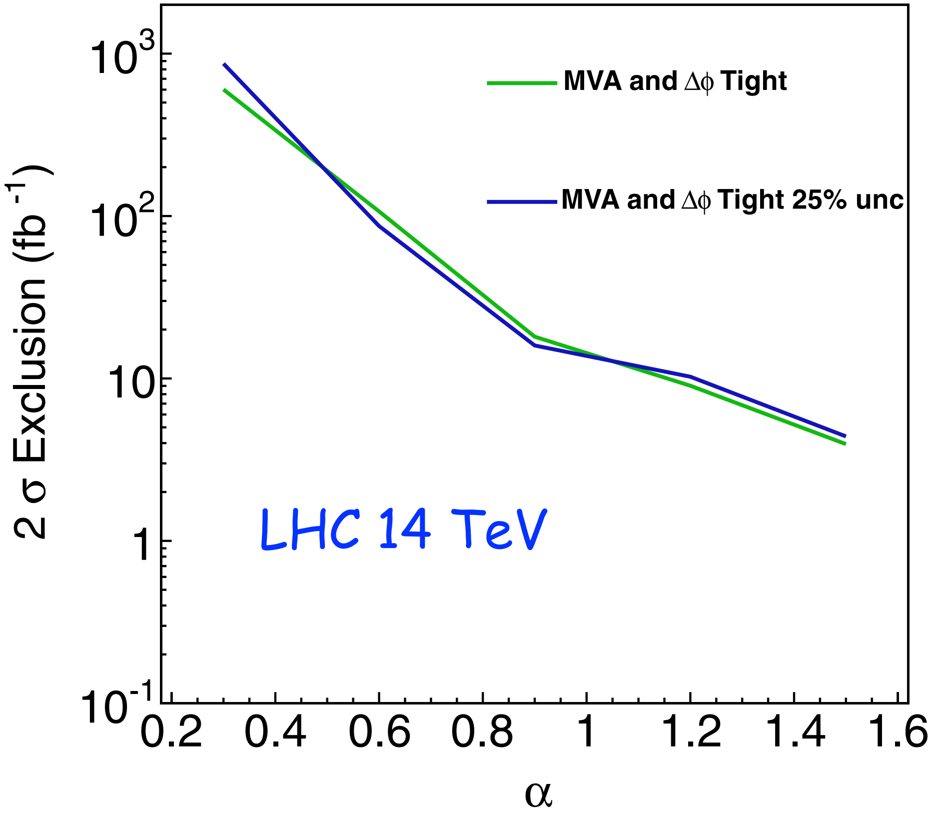
$$\cos(\beta - \alpha_1) = 1; \;\; \tan\beta = 1$$

In this case

$$\Phi_\tau = \alpha_2$$

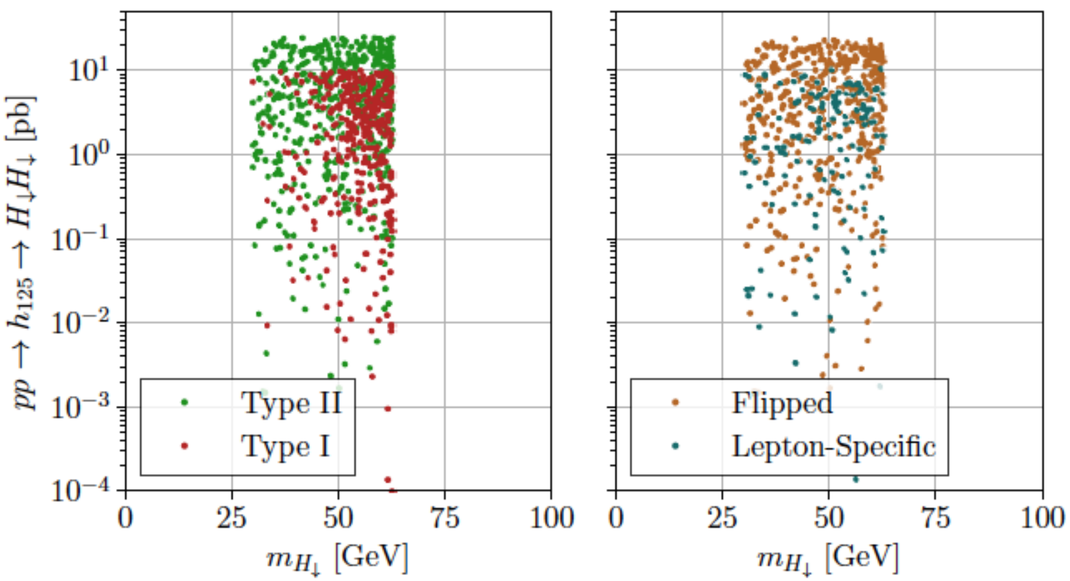
$$\Delta\Phi_\tau = 40^o \;\; \Leftarrow 50\,\text{fb}^{-1}$$

$$\Delta\Phi_\tau = 25^o \;\; \Leftarrow 300\,\text{fb}^{-1}$$

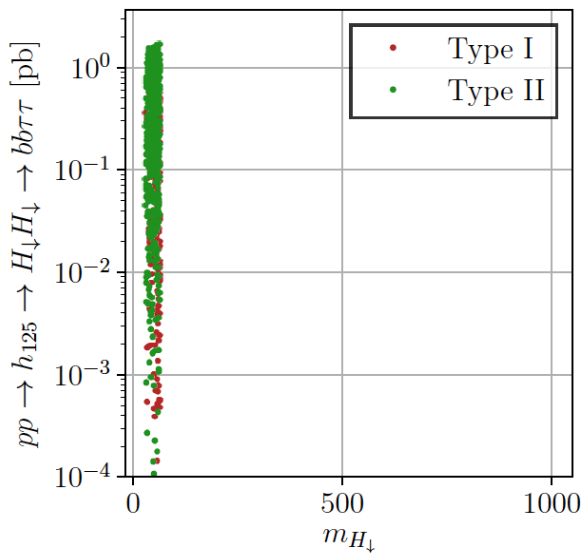


PLOT FROM: DOLAN, HARRIS, JANKOWIAK, SPANNOWSKY PRD90 (2014) 073008

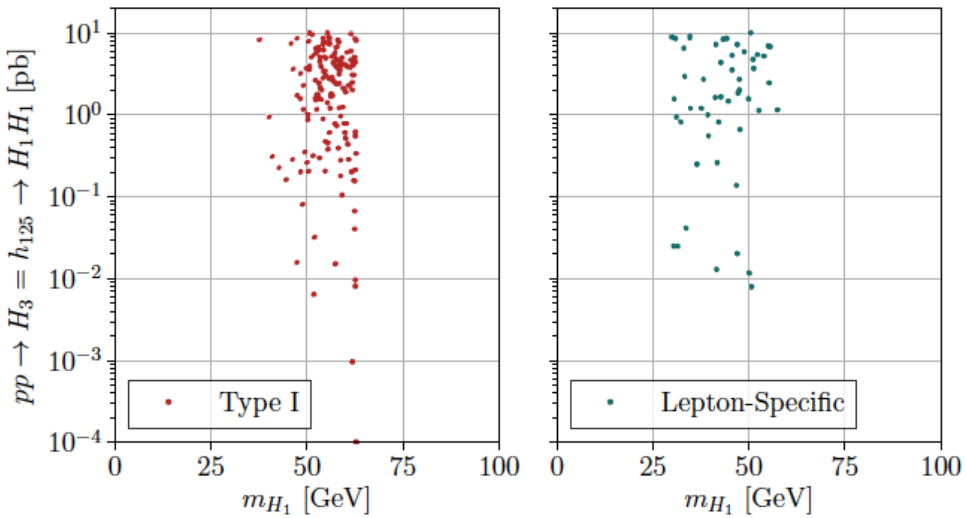
Signal rates - h_{125} (h_3 or h_2) to $H_\downarrow H_\downarrow$ for all types



Maximal rates range from 10 to 30 pb. As an example the final state bbττ is still above the pb level.

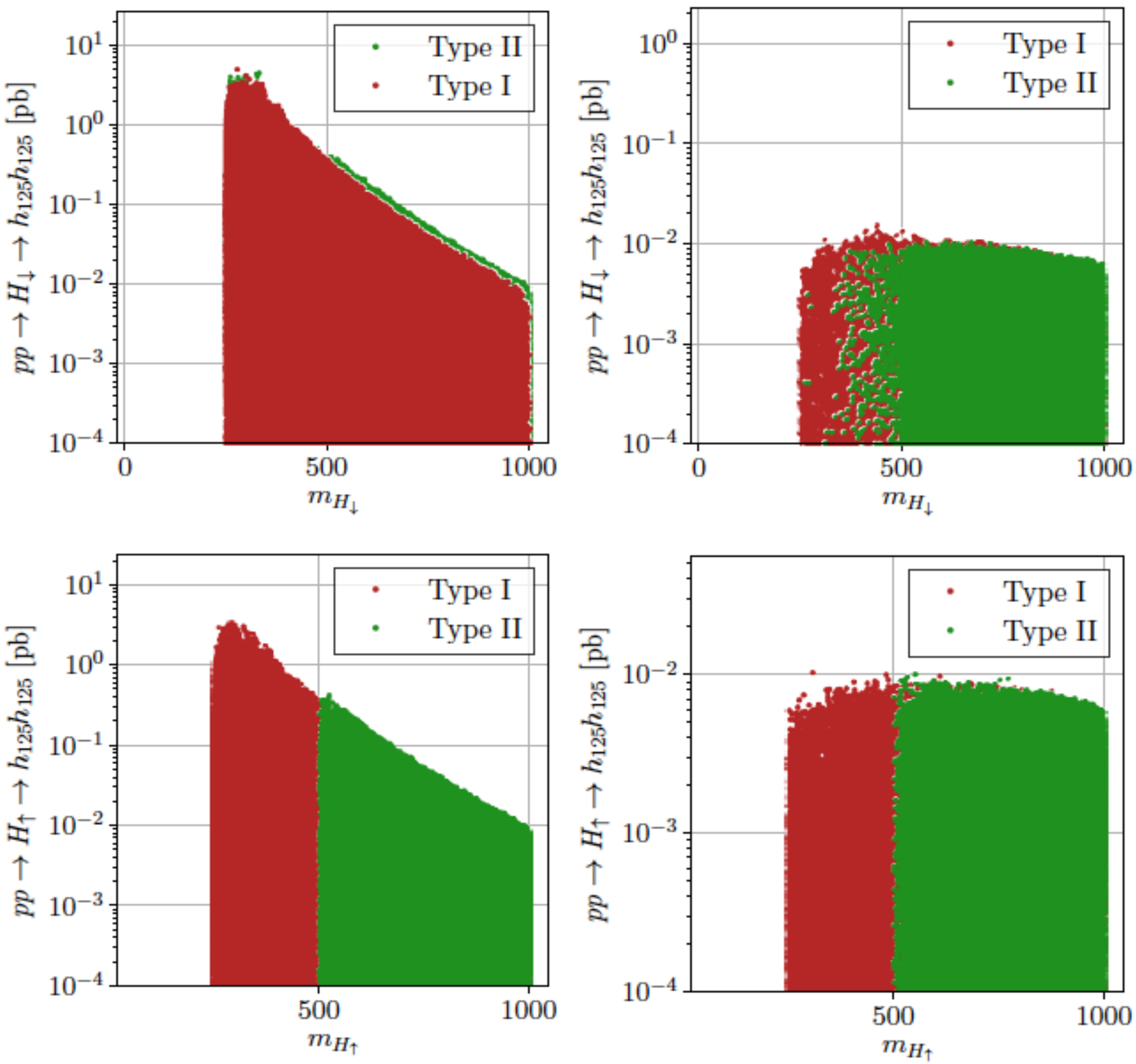


Decays of h_{125} (just h_3) to $H_\downarrow H_\downarrow$ for all types



In the case of the heaviest being the 125 GeV Higgs, signal rates can still be large but only for Type I and LS due to a combination of the bound on the charged Higgs mass and STU.

Decays to h_{125} h_{125} in Types I and II



<u>Left</u> - Signal rates for the production of $H_\downarrow$ (upper) and $H_\uparrow$ (lower) decaying to h_{125} h_{125} for 13 TeV as a function of m_H.

<u>Right</u> – Same as left with the extra conditions

$$\sigma(pp \to H_\downarrow \to ZZ) < 1\,\text{fb}$$

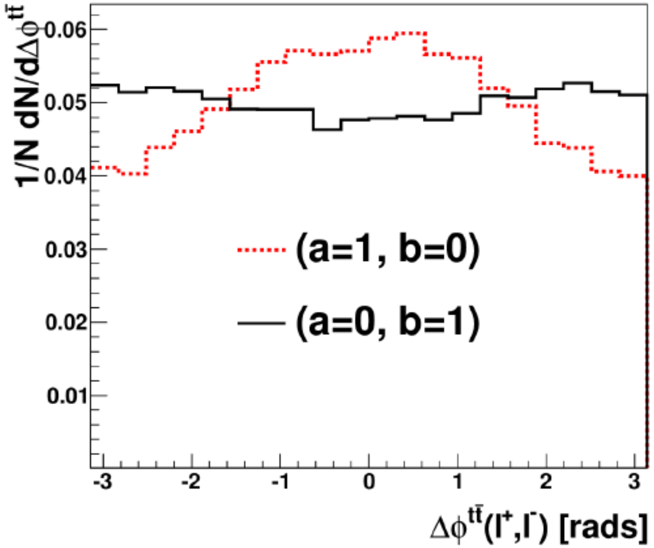
$$\sigma(pp \to H_\uparrow \to ZZ) < 1\,\text{fb}$$

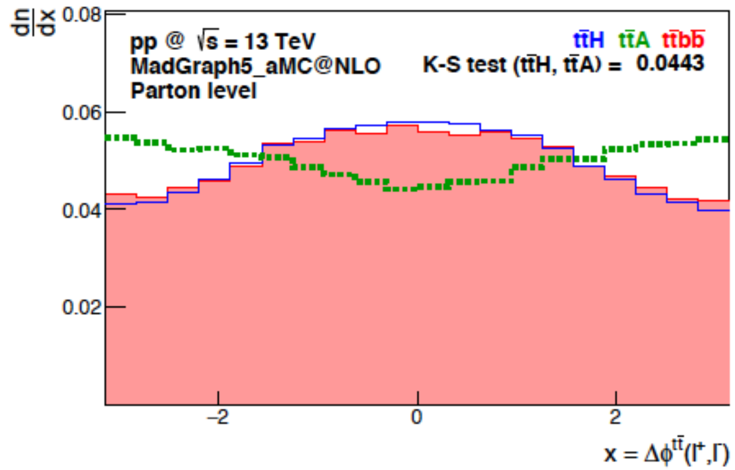
Rates can be above the pb level but are at most 10 fb if we restrict the decays to ZZ to be below 1 fb. Reference cross section for the SM di-Higgs production is about 30 fb.

Conclusions

- The closer we get to the situation where the Higgs couplings to fermions and gauge bosons are very SM-like, the harder will be to probe CP-violation using decays to Z bosons, if a new scalar is found.
- Anomalous triple Z couplings would be an important measurement in the future if we could increase precision.
- There is still a lot to do in the Yukawa sector…
- … and if not at the LHC, perhaps at the future ILC.
- There are still scalars to be discovered with very large production rates.

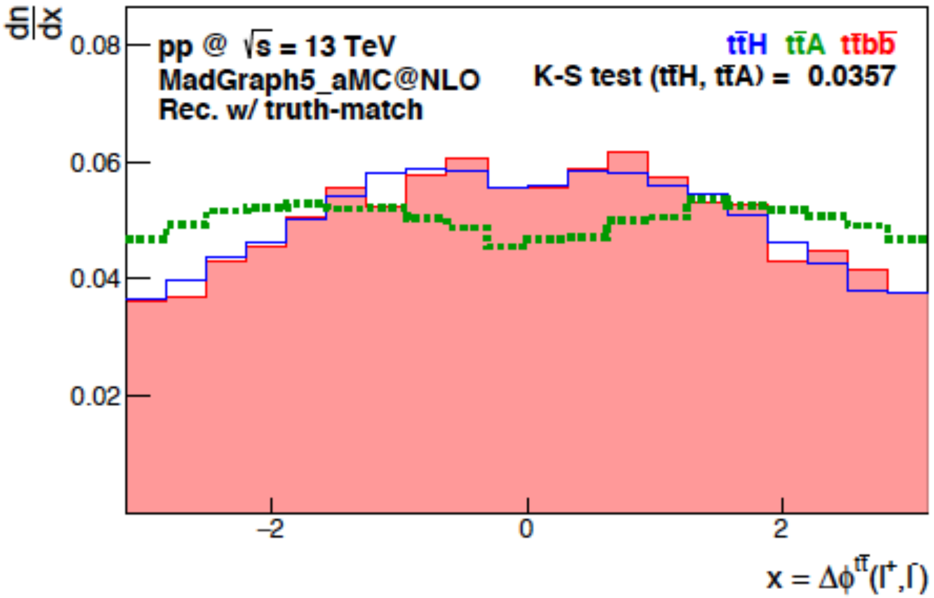
The end

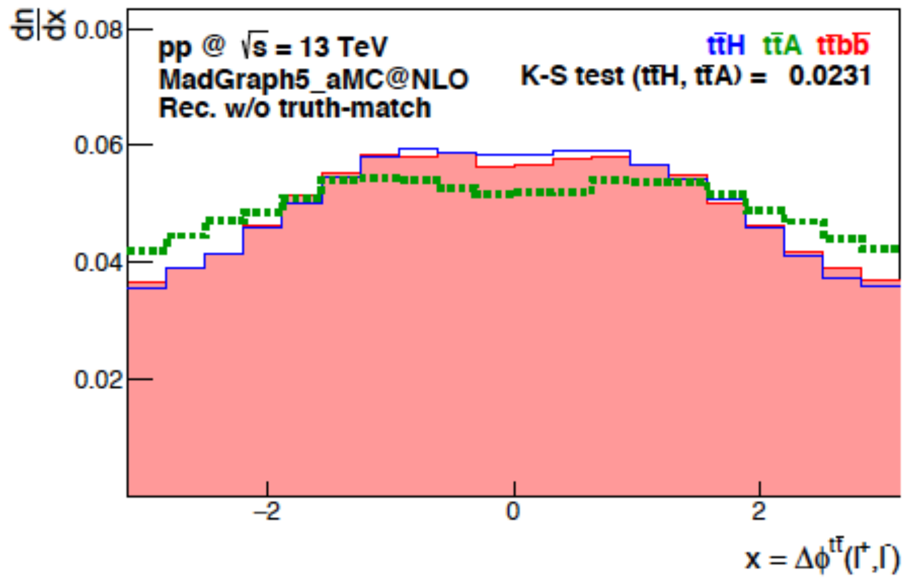


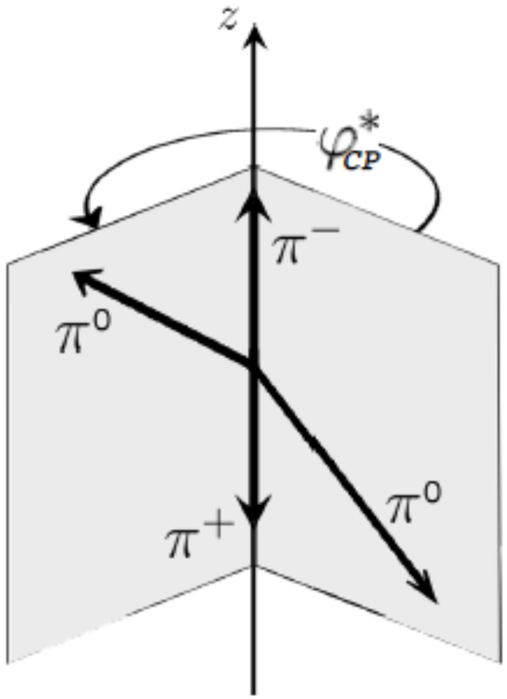


Boudjema, Godbole, Guadagnoli, Mohan 2015

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







Berge, Bernreuther, Kirchner PRD92 (2015) 096012

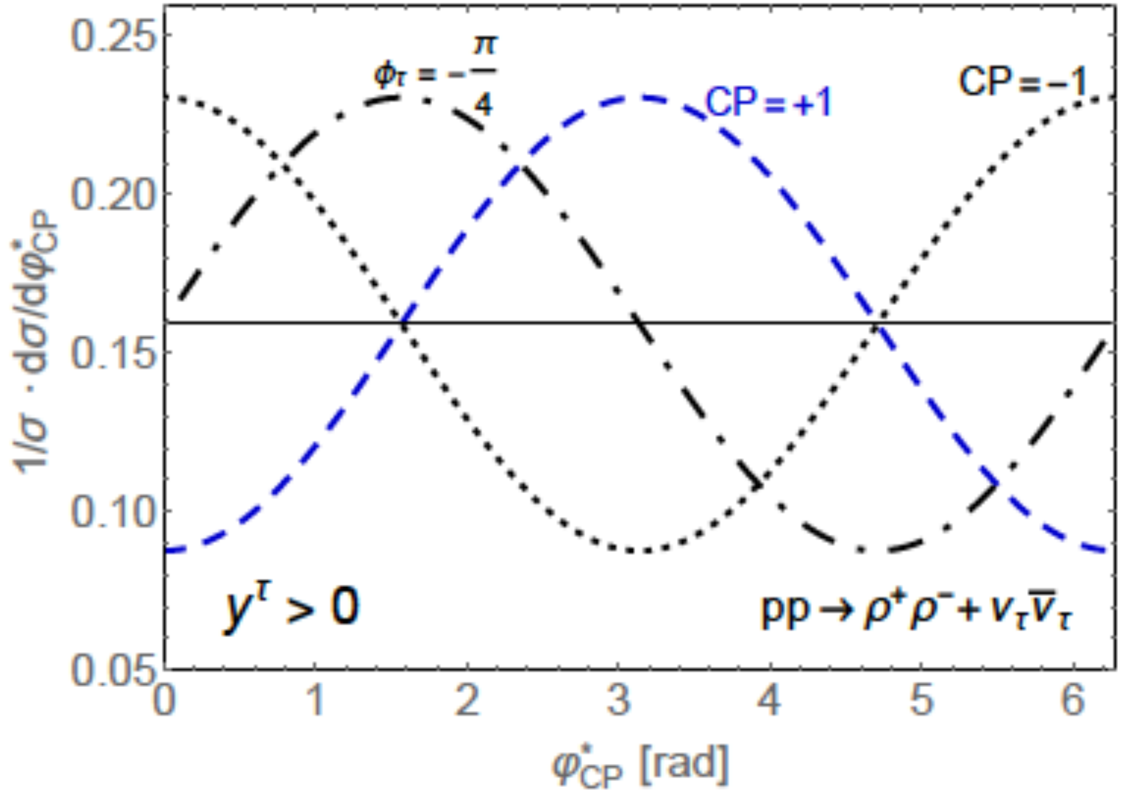


Illustration of φ^*_{CP} in the ρ decay-plane method as defined in (14) for $pp \to h^0 \to \tau^-\tau^+ \to \ \rho^-\rho^+ + 2\nu$.

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.

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

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

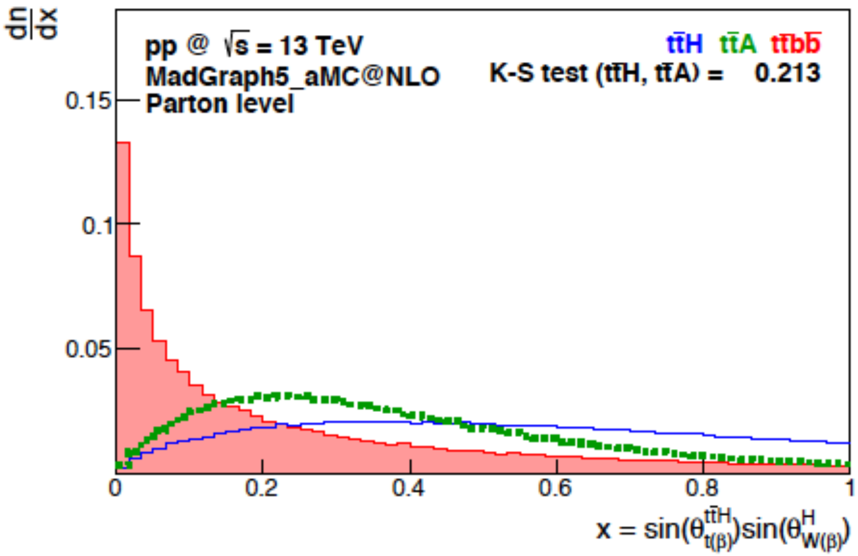
and c_2 cannot be far from 1. But α_2 is the CP-violating angle and therefore it should be small. However, the CP-odd component has an extra tanβ factor for down quarks and leptons, but not for the up quarks

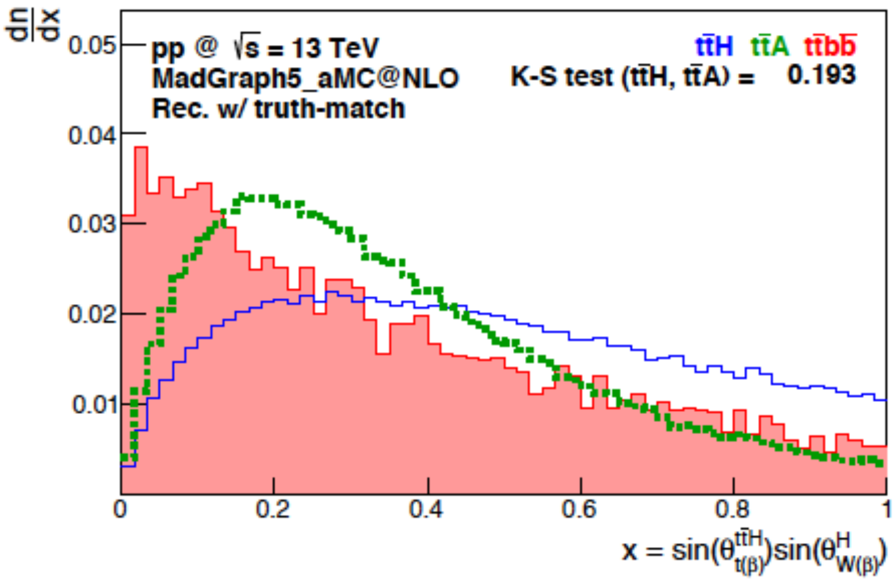
$$Y_{C2HDM}^{TypeII} = c_2 Y_{2HDM}^{TypeII} - i\gamma_5 s_2 t_\beta$$ bottom, tau

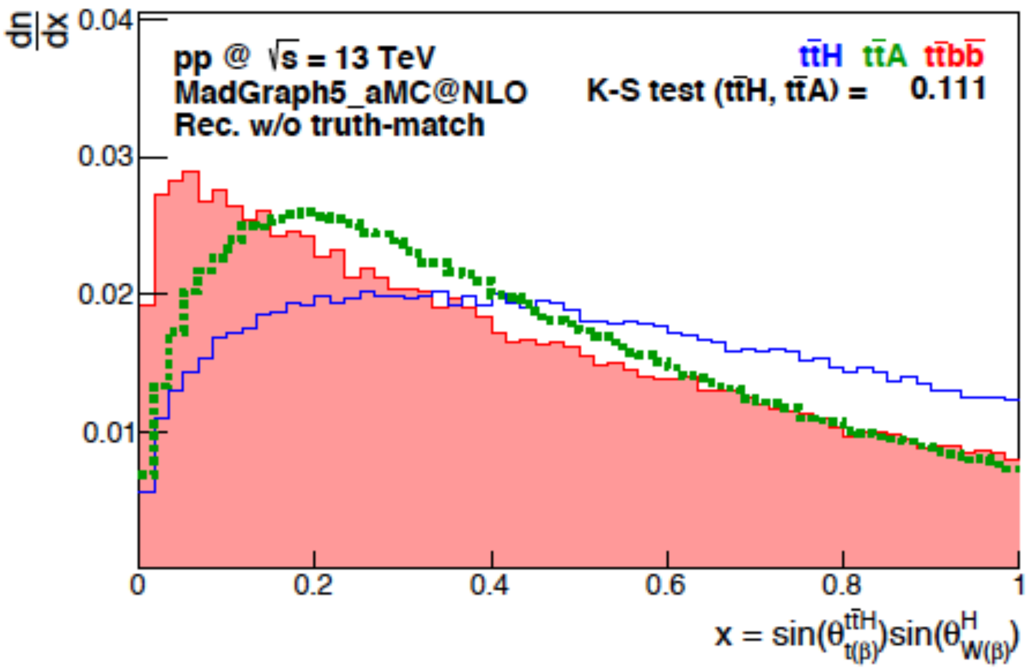
$$Y_{C2HDM}^{TypeII} = c_2 Y_{2HDM}^{TypeII} - i\gamma_5 \frac{s_2}{t_\beta}$$ top

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.







Amor dos Santos eal 2015

Combinatorial background plays a very important role.