# 3. CP-violation in Extended Higgs sectors

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Multi-Higgs day @ LIP

11 June 2018

# Where do we stand? (In CP-violation measurements)

# CP - what have ATLAS and CMS measured so far?

- Correlations in the momentum distributions of leptons produced in the decays

$$h \to ZZ^* \to (\bar{l}_1 l_1)\ (\bar{l}_2 l_2)$$

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

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)

The Higgs CP nature has only been established assuming that $h_{125}$ is a CP eigenstate.

ATLAS, 1307.1432

**If CP(H)=1, HZZ(WW) coupling is just a constant relative to the SM one, reverse not true!**

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

# CP - what have ATLAS and CMS measured so far?

- Effective Lagrangian (ATLAS notation) ATLAS, 1506.05669

$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]\Big\} X_0$$

Here $V^\mu$ represents the vector-boson field ($V = Z, W^\pm$), the $V^{\mu\nu}$ are the reduced field tensors and the dual tensor is defined as $\tilde{V}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}V_{\rho\sigma}$. The symbol $\Lambda$ denotes the EFT energy scale. The symbols $\kappa_{SM}$, $\kappa_{HVV}$ and $\kappa_{AVV}$ denote the coupling constants corresponding to the interaction of the SM, BSM CP-even or BSM CP-odd spin-0 particle, represented by the $X_0$ field, with $ZZ$ or $WW$ pairs. To ensure that the Lagrangian terms are Hermitian, these couplings are assumed to be real. The mixing angle $\alpha$ allows for production of CP-mixed states and implies CP-violation for $\alpha \neq 0$ and $\alpha \neq \pi$, provided the corresponding coupling constants are non-vanishing. The SM couplings, $g_{HVV}$, are proportional to the

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

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV}$$

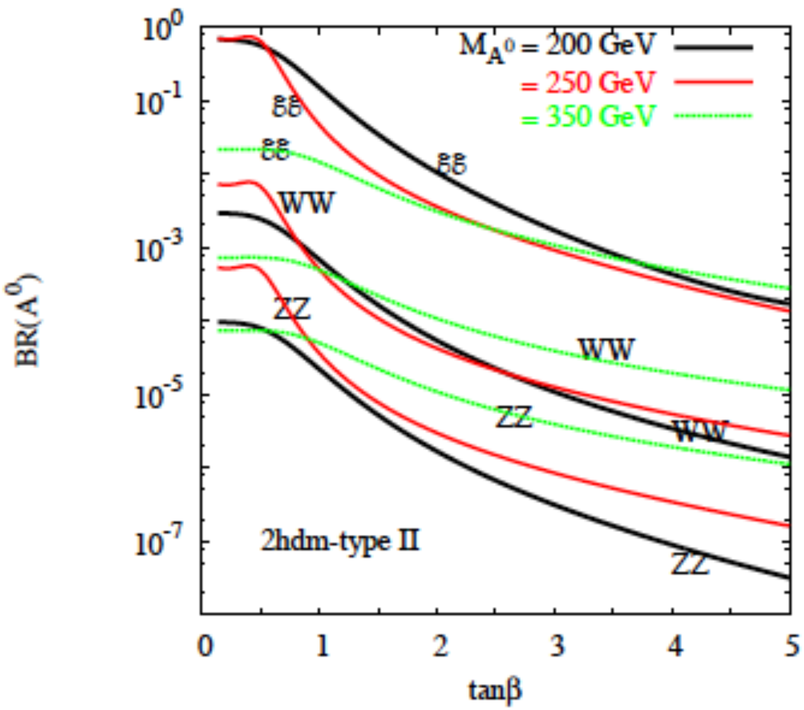
$$\tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$

| Coupling ratio | Best-fit value | 95% CL Exclusion Regions | |
|---|---|---|---|
| Combined | Observed | Expected | Observed |
| $\tilde{\kappa}_{HVV}/\kappa_{SM}$ | −0.48 | $(-\infty, -0.55] \bigcup [4.80, \infty)$ | $(-\infty, -0.73] \bigcup [0.63, \infty)$ |
| $(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$ | −0.68 | $(-\infty, -2.33] \bigcup [2.30, \infty)$ | $(-\infty, -2.18] \bigcup [0.83, \infty)$ |

# Radiative decays of A to ZZ (WW)

• AVV couplings can be generated at 1-loop - possible in extensions of the scalar sector such as 2HDMs.

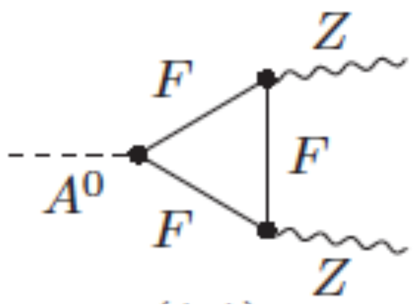
• ATLAS and CMS results have shown that if these corrections exist they are small.




Arhrib, Benbrik, Field (2006).

For each particular model one should check

$$A \to ZZ\ (W^+W^-)$$



## The C2HDM as a counterexample

- Complex 2HDM - three neutral scalars have indefinite CP.

- Interaction of each scalar with the Z bosons comes exactly from the same kinetic term as the SM one

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

- Analysis of the correlations in momenta will not allow to draw any conclusion on the scalar's CP. They show however that any radiate contribution to CP-violating terms in hZZ(WW) is small.

- Using again the C2HDM as a benchmark, if all neutral scalars have indefinite CP it is likely that we get the first hints in the study of the process

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

And later (in luminosity) possibly also using

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

# The Complex 2HDM as a benchmark model for CP-violation studies

# The (C)2HDM

$$V(\Phi_1,\ \Phi_2) = m_1^2\Phi_1^+\Phi_1 + m_2^2\Phi_2^+\Phi_2 - \left(m_{12}^2\Phi_1^+\Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^+\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^+\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^+\Phi_1\right)\left(\Phi_2^+\Phi_2\right) + \lambda_4\left(\Phi_1^+\Phi_2\right)\left(\Phi_2^+\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^+\Phi_2\right)^2 + \text{h.c.}\right]$$

**Softly broken $Z_2$ symmetric**

we choose a vacuum configuration

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix};\quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

- **$m^2_{12}$ and $\lambda_5$ real** — **potential is CP-conserving (2HDM)**
- **$m^2_{12}$ and $\lambda_5$ complex** — **potential is explicitly CP-violating (C2HDM)**

# Parameters

- $\tan\beta = \frac{v_2}{v_1}$ 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 – $\alpha$

  CP-violating - $\alpha_1$, $\alpha_2$ and $\alpha_3$

- soft breaking parameter

  CP-conserving – $m^2_{12}$

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

# Lightest Higgs couplings to gauge bosons

$$\alpha_1 = \alpha + \pi/2$$

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha)\ g_{SM}^{hVV} \qquad V = W, Z$$

$$g_{C2HDM}^{hVV} = (c_\beta R_{11} + s_\beta R_{12})\ g_{SM}^{hVV} = \cos(\alpha_2)\cos(\beta - \alpha_1)\ g_{SM}^{hVV} = \cos(\alpha_2) g_{2HDM}^{hVV}$$

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

Just an extra angle – Lorentz structure is the same

**The CP-violating phase is very constrained by the measurement of the Higgs couplings to vector bosons**

$$\mu_{VV} \geq 0.79 \Rightarrow \cos(\alpha_2) \geq 0.89 \Rightarrow \alpha_2 \leq 27^{\circ}$$

# Lightest Higgs Yukawa couplings

- No FCNC at tree-level

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

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

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

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

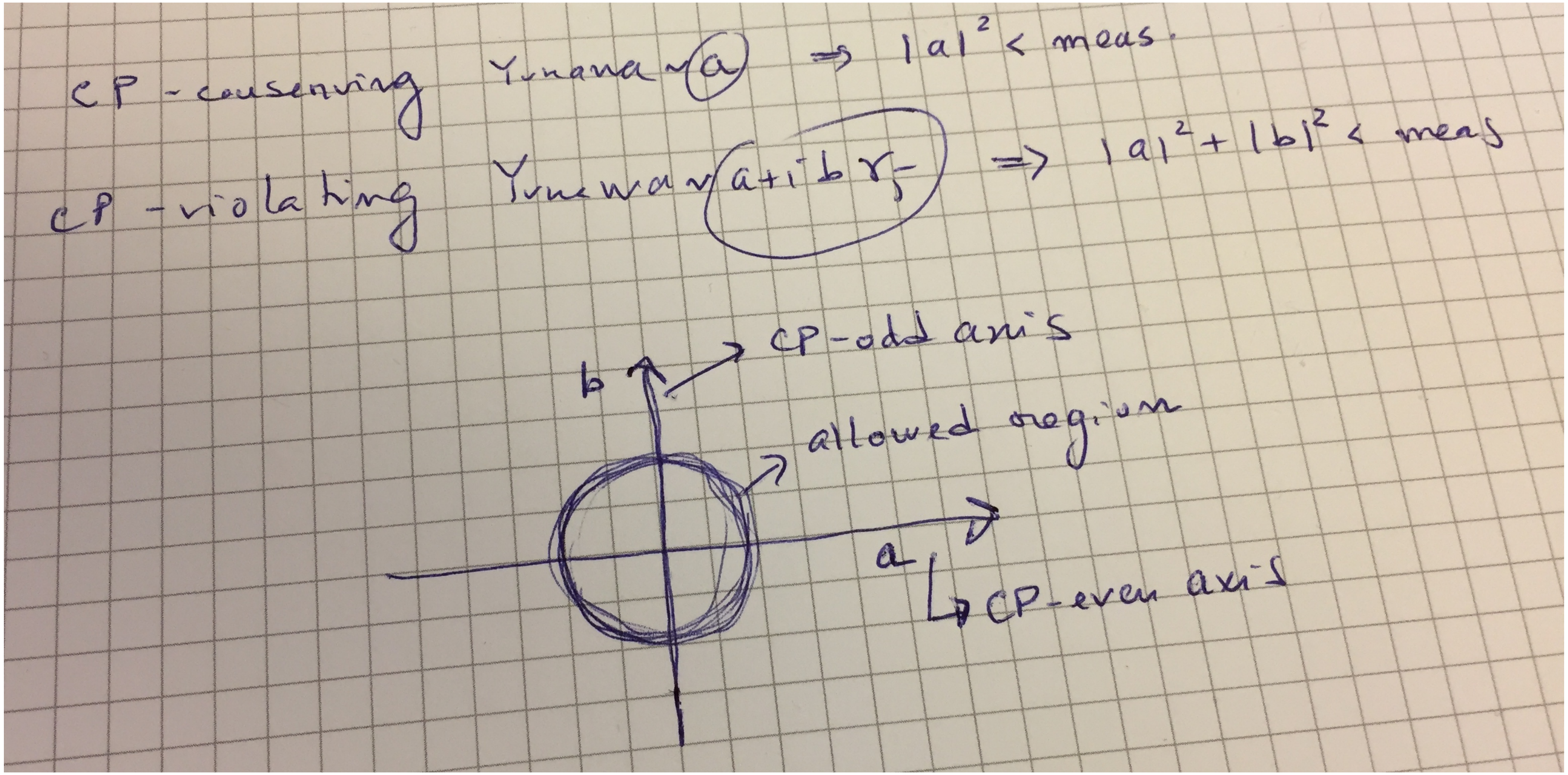
$c_i = \cos(\alpha_i);\ \ s_i = \sin(\alpha_i)$

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

**when $s_2 \rightarrow 0$**

$$Y_{C2HDM} \equiv Y_{2HDM}$$

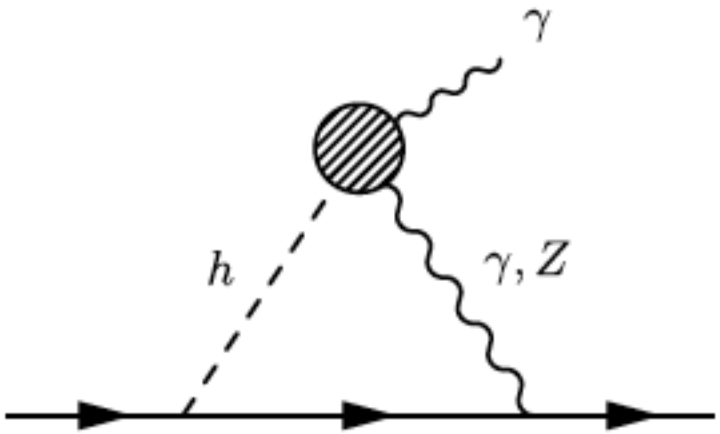
# Allowed parameter space is now a circle in the plane below




$$Y^{\text{Type II}}_{C2HDM} \equiv c_2 Y^{\text{Type II}}_{2HDM} + i\gamma_5 s_2 t_\beta$$

# Constraints

- Vacuum is stable and potential is bounded from below
- Perturbative unitarity
- Electroweak precision constraints (STU)
- B physics constraints
- Higgs searches bounds (HiggsBounds)
- Higgs bosons signal stregths
- Electron EDM

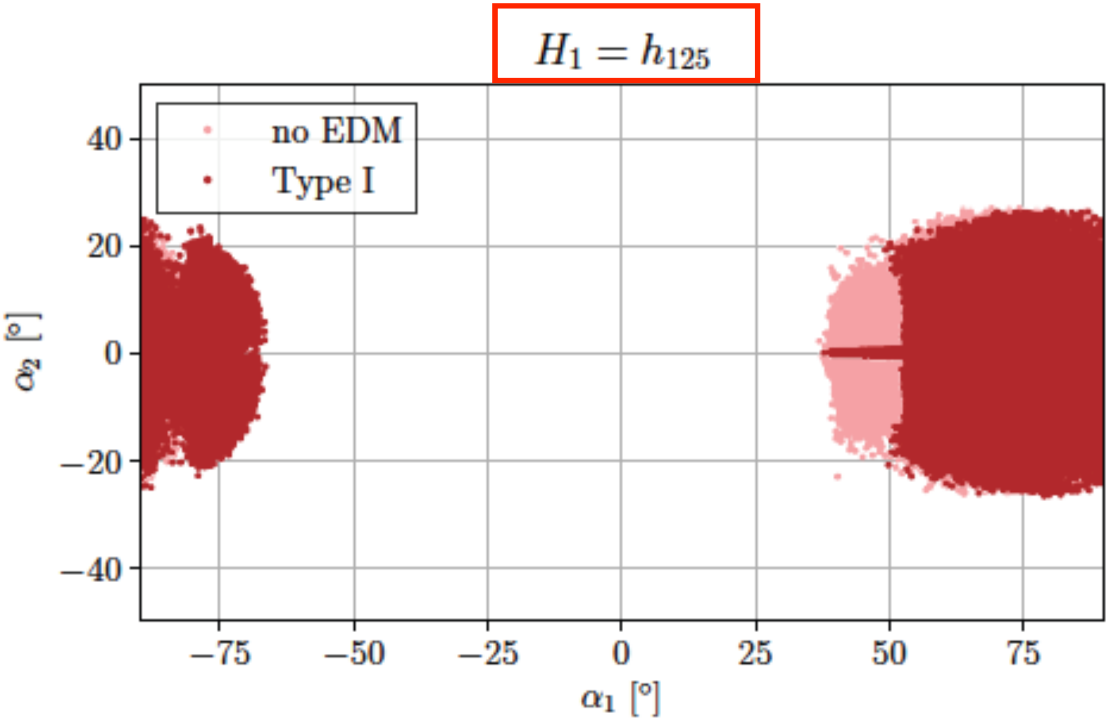


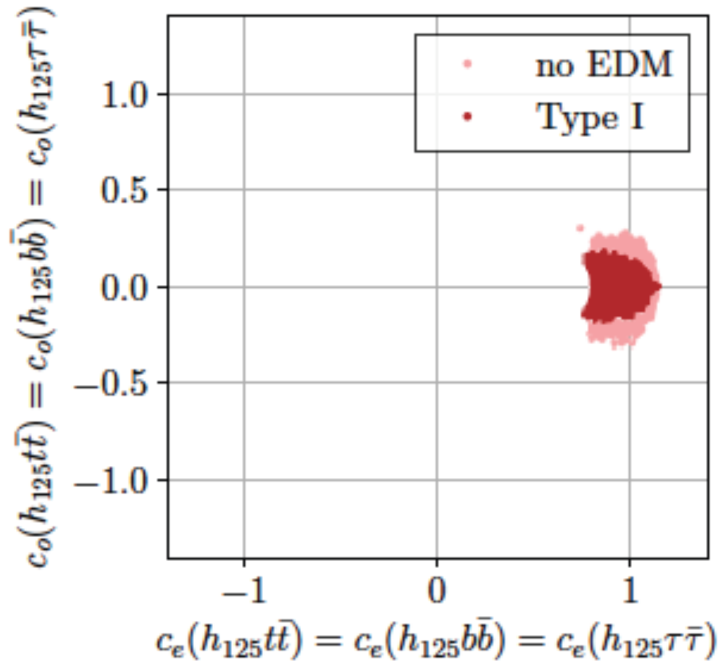

- Electric Dipole Moments are a probe of Yukawa CP-violating couplings
- Good limits on electron EDMs

$$d_e = 8.7 \times 10^{-29}\, e\,\mathrm{cm}$$

ACME, 1310.7534.

# The allowed parameter space in type I



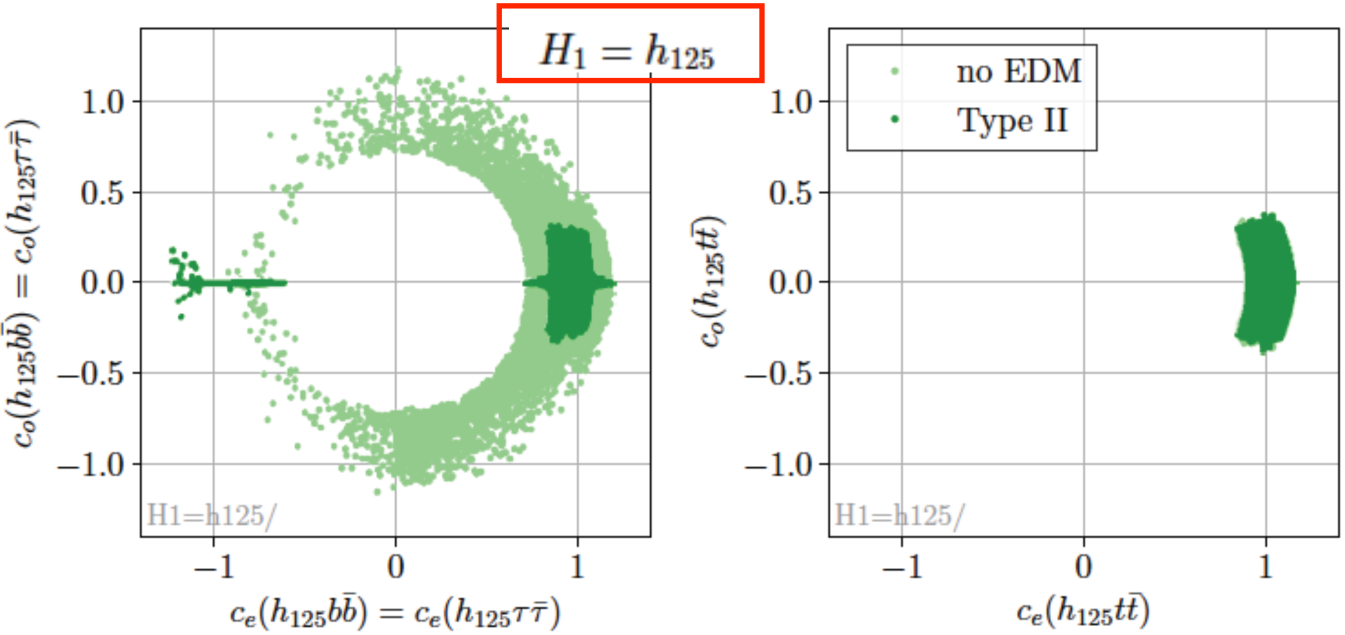




$$\mu_{VV} \geq 0.79 \Rightarrow \cos(\alpha_2) \geq 0.89 \Rightarrow \alpha_2 \leq 27^\circ \quad \text{and} \quad \tan(\beta) \geq 1$$

$$\alpha_2 \leq 27^\circ \Rightarrow \sin(\alpha_2) \leq 0.46 \Rightarrow c_o = \frac{\sin(\alpha_2)}{\tan(\beta)} \leq 0.46$$

**All Yukawa couplings are the same – the bounds apply equally to all of them.**

# The allowed parameter space in type II C2HDM




$$c_o(h_{125}tt) = \frac{\sin(\alpha_2)}{\tan(\beta)}$$

$$c_o(h_{125}bb(\tau\tau)) = \sin(\alpha_2)\tan(\beta)$$

$$\tan(\beta) \geq 1$$

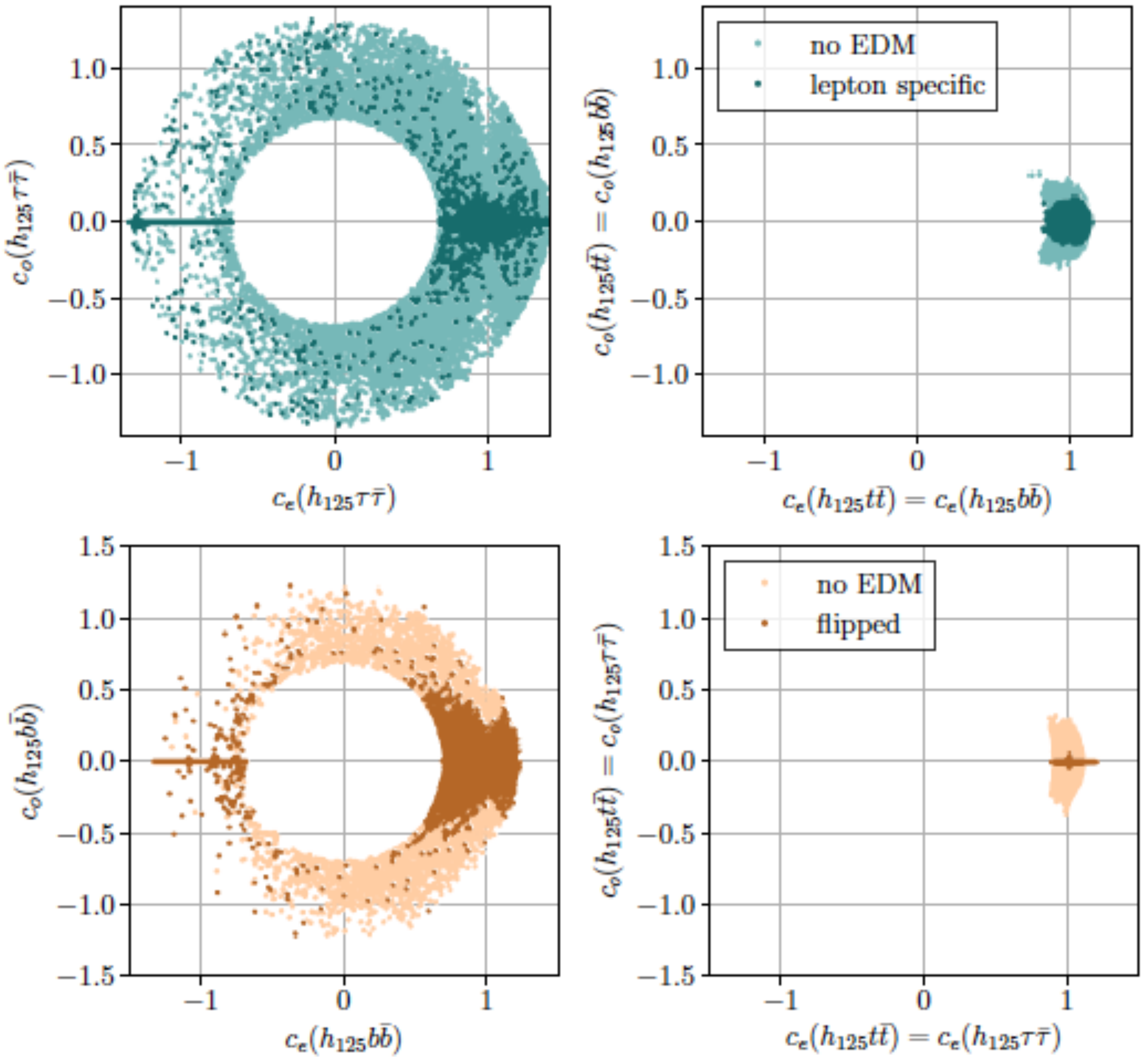
**Bounds are stronger for the up-quarks couplings. They come from $\mu_{VV}$ and the bound on tanβ. In type I all couplings are very constrained.**

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

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

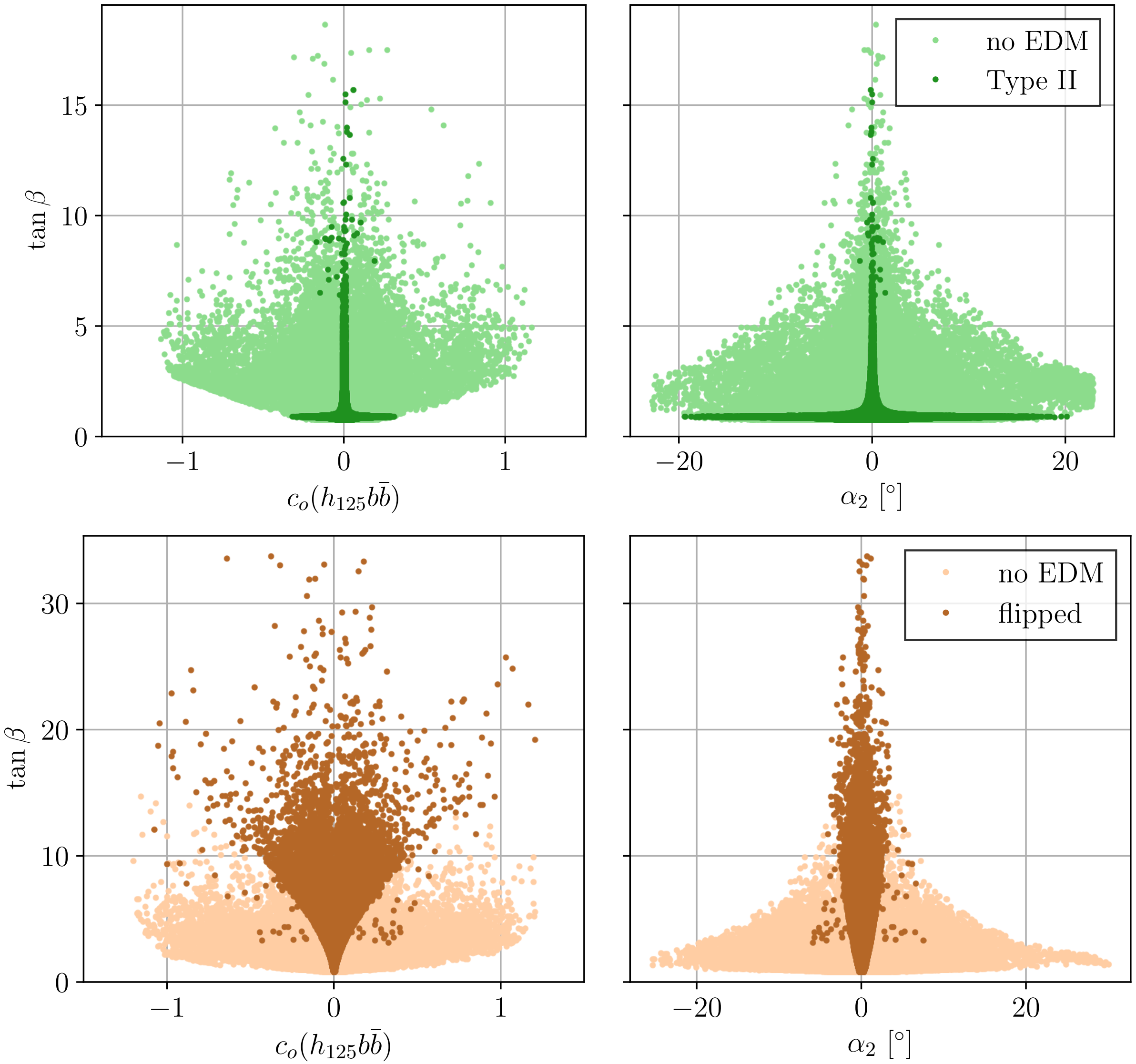
$$\begin{cases} a_U^2 = (1 - s_2^4) = (1 - 1/t_\beta^4) \\ b_U^2 = s_2^4 = 1/t_\beta^4 \end{cases} \qquad \left(\frac{g_{C2HDM}^{hVV}}{g_{SM}^{hVV}}\right)^2 = C^2 = \frac{t_\beta^2 - 1}{t_\beta^2 + 1} = \frac{1 - s_2^2}{1 + s_2^2}$$

# Flipped and Lepton Specific



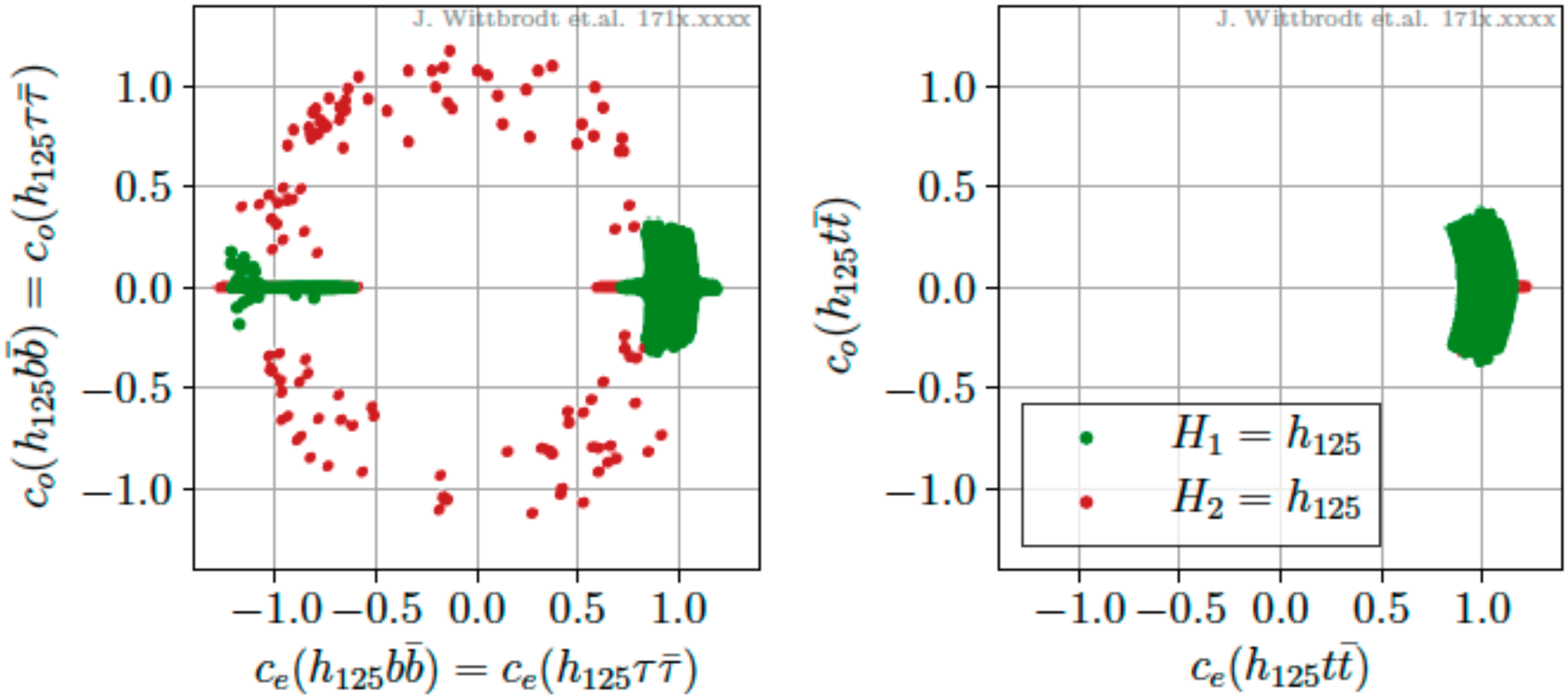

Although EDMs constraints completely kill large pseudoscalar components in Type II but not in Flipped and Lepton Specific.

# Type II and Flipped



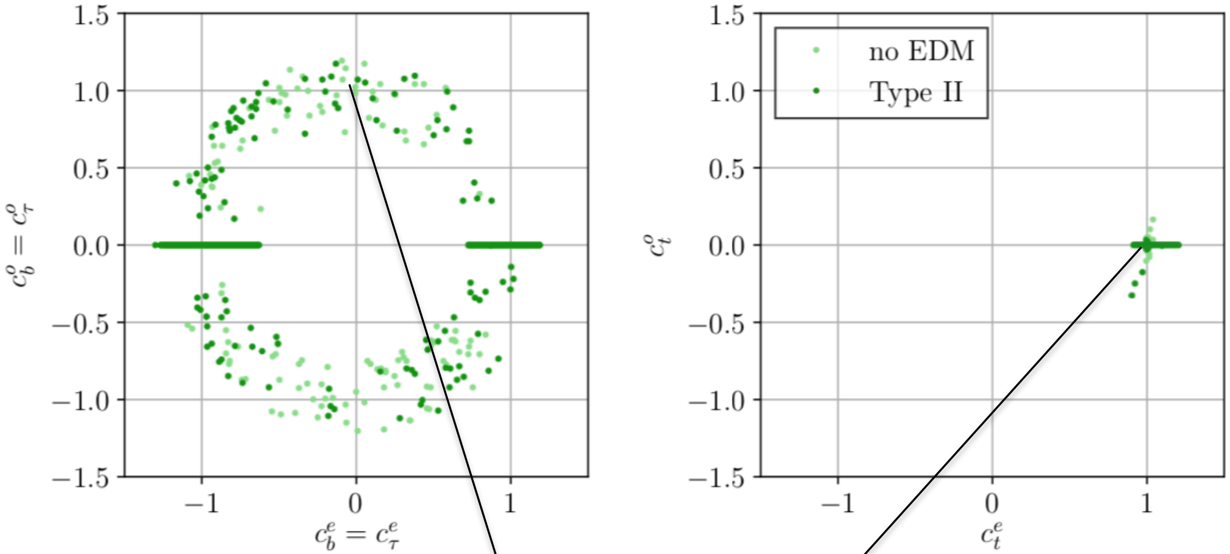

EDMs act differently in the different Yukawa versions of the model.

# Other scenarios in Type II




A Type II model and two scenarios: $H_1$ or $H_2$ is the SM-like Higgs.

# And this brings a very interesting CP-violation scenario




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

$$b_U \approx 0 \quad \text{and} \quad a_D \approx 0$$

**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**

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

**and the other decaying to taus as CP-odd**

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

**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 |
| $\alpha_1$ | −0.1468 | −0.14658 | −0.089676 |
| $\alpha_2$ | −0.75242 | −0.35712 | −1.0694 |
| $\alpha_3$ | −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 |
| $\mu_V/\mu_F$ | 0.899 | 0.959 | 0.837 |
| $\mu_{VV}$ | 0.976 | 1.056 | 1.122 |
| $\mu_{\gamma\gamma}$ | 0.852 | 0.935 | 0.959 |
| $\mu_{\tau\tau}$ | 1.108 | 1.013 | 1.084 |
| $\mu_{bb}$ | 1.101 | 1.012 | 1.069 |

# New probes of CP-violation

# Combinations of three decays

**Already observed**

$$h_1 \rightarrow ZZ \quad \Leftarrow \quad \mathrm{CP}(h_1) = 1$$

$$h_3 \rightarrow h_2 h_1 \quad \Rightarrow \quad \mathrm{CP}(h_3) = \mathrm{CP}(h_2)\ \mathrm{CP}(h_1) = \mathrm{CP}(h_2)$$

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


**C2HDM** - D. Fontes, J.C. Romão, RS, J.P. Silva; PRD92 (2015) 5, 055014.

**NMSSM** - S.F. King, M. Mühlleitner, R. Nevzorov, K. Walz; NPB901 (2015) 526-555.

# Classes of CP-violating processes

- ON GOING SEARCHES

| Classes | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|---|---|---|---|---|---|
| Decays | $h_3 \to h_2 Z$ | $h_2 \to h_1 Z$ | $h_3 \to h_1 Z$ | $h_3 \to h_2 Z$ | $h_3 \to ZZ$ |
| | $h_2 \to h_1 Z$ | $h_1 \to ZZ$ | $h_1 \to ZZ$ | $h_2 \to ZZ$ | $h_2 \to ZZ$ |
| | $h_3 \to h_1 Z$ | $h_2 \to ZZ$ | $h_3 \to ZZ$ | $h_3 \to ZZ$ | $h_1 \to ZZ$ |

IN 2HDMS ONLY

ONLY TWO TO GO

| Classes | $C_6$ | $C_7$ |
|---|---|---|
| Decays | $h_3 \to h_2 h_1$ | $h_{2,3} \to h_1 h_1$ |
| | $h_3 \to h_2 Z$ | $h_{2,3} \to h_1 Z$ |
| | $h_1 \to ZZ$ | $h_1 \to ZZ$ |

CLASSES INVOLVING SCALAR TO TWO SCALARS DECAYS



FONTES, ROMÃO, RS, SILVA (2015).

TABLE VIII. Predictions for $\sigma \times \mathrm{BR}$ at $\sqrt{s} = 13$ TeV for the benchmark points $P5$ (Type I) and $P6$ (lepton specific).

| | $P5$ | $P6$ |
|---|---|---|
| $\sigma(h_1)$ 13 TeV | 55.144 [pb] | 53.455 [pb] |
| $\sigma(h_1)\mathrm{BR}(h_1 \to W^*W^*)$ | 10.657 [pb] | 11.069 [pb] |
| $\sigma(h_1)\mathrm{BR}(h_1 \to Z^*Z^*)$ | 1.093 [pb] | 1.136 [pb] |
| $\sigma(h_1)\mathrm{BR}(h_1 \to bb)$ | 33.118 [pb] | 32.152 [pb] |
| $\sigma(h_1)\mathrm{BR}(h_1 \to \tau\tau)$ | 3.825 [pb] | 2.845 [pb] |
| $\sigma(h_1)\mathrm{BR}(h_1 \to \gamma\gamma)$ | 119.794 [fb] | 122.579 [fb] |
| $\sigma_2 \equiv \sigma(h_2)$ 13 TeV | 1.620 [pb] | 4.920 [pb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to WW)$ | 1.032 [pb] | 0.542 [pb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$ | 0.427 [pb] | 0.232 [pb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to bb)$ | 0.012 [pb] | 0.097 [pb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$ | 0.001 [pb] | 0.109 [pb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$ | 0.123 [fb] | 0.344 [fb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z)$ | 0.140 [pb] | 0.075 [pb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to bbZ)$ | 0.084 [pb] | 0.045 [pb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to \tau\tau Z)$ | 9.683 [fb] | 3.982 [fb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$ | 0.000 [fb] | 3772.577 [fb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$ | 0.000 [fb] | 1364.787 [fb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$ | 0.000 [fb] | 241.505 [fb] |
| $\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$ | 0.000 [fb] | 10.684 [fb] |
| $\sigma_3 \equiv \sigma(h_3)$ 13 TeV | 9.442 [pb] | 10.525 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to WW)$ | 0.638 [pb] | 0.945 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$ | 0.293 [pb] | 0.406 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to bb)$ | 0.004 [pb] | 0.422 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$ | 0.432 [fb] | 407.337 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$ | 0.140 [fb] | 2.410 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z)$ | 0.383 [pb] | 0.691 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to bbZ)$ | 0.230 [pb] | 0.416 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to \tau\tau Z)$ | 26.554 [fb] | 36.779 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z)$ | 2.495 [pb] | 0.000 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to bbZ)$ | 0.019 [pb] | 0.000 [pb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to \tau\tau Z)$ | 2.188 [fb] | 0.000 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$ | 433.402 [fb] | 6893.255 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$ | 156.329 [fb] | 2493.740 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$ | 36.111 [fb] | 441.277 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$ | 2.085 [fb] | 19.521 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1)$ | 0.000 [fb] | 0.000 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bbbb)$ | 0.000 [fb] | 0.000 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bb\tau\tau)$ | 0.000 [fb] | 0.000 [fb] |
| $\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to \tau\tau\tau\tau)$ | 0.000 [fb] | 0.000 [fb] |

## Class C7

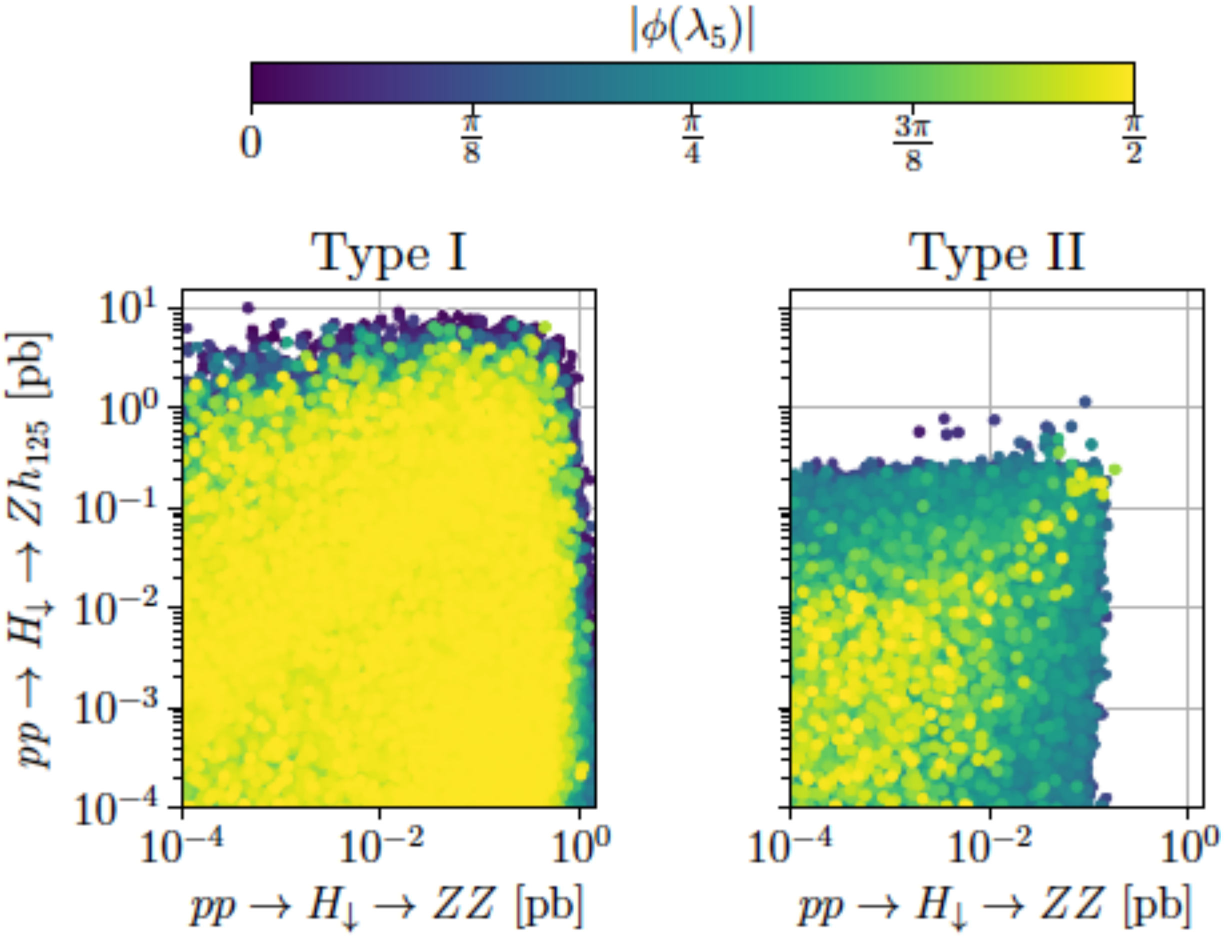
$$h_1 \to ZZ \quad \Leftarrow \quad \mathrm{CP}(h_1) = 1$$

$$h_3 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_3) = -\,\mathrm{CP}(h_1) = -1$$

$$h_3 \to h_1 h_1 \quad \Leftarrow \quad \mathrm{CP}(h_3) = 1$$

# Measures of CP-violation

# 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.**

# Other variables

- Variable involving Higgs couplings to gauge bosons

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

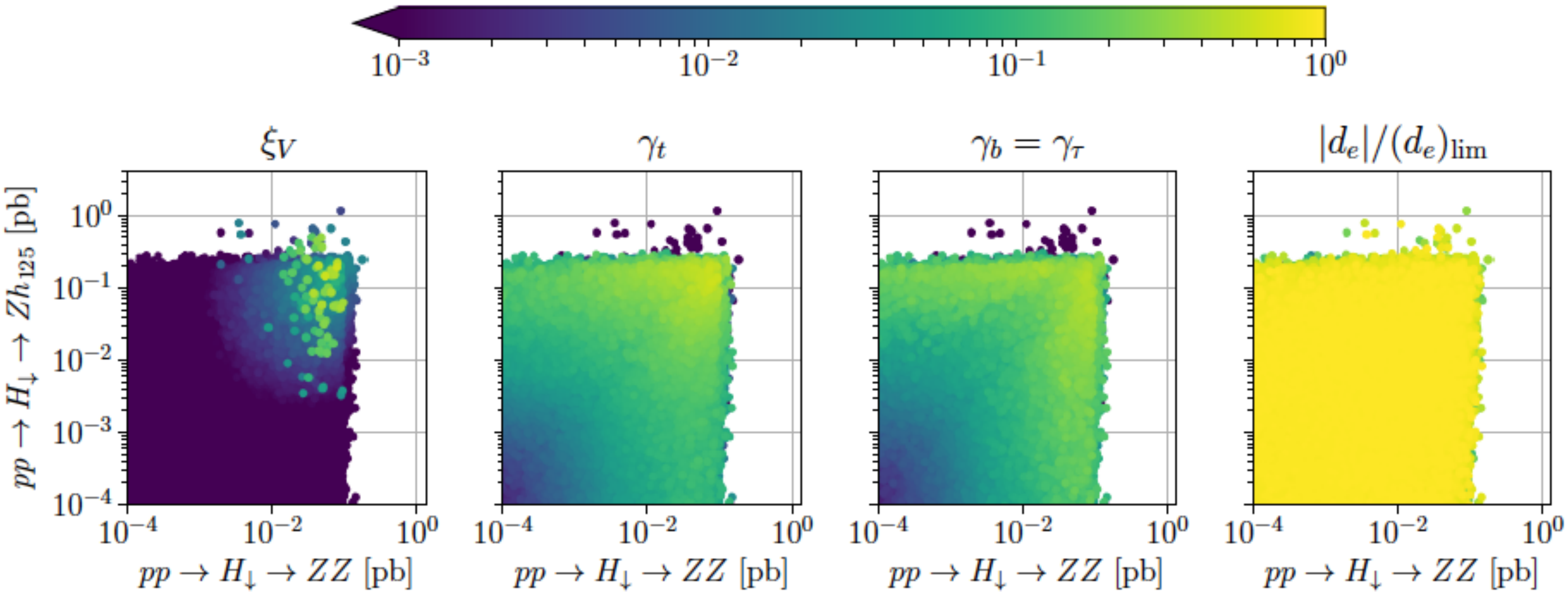
- Variables involving Higgs Yukawa couplings (for a Type II model)

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

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

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.**

# CP-violating angles vs. direct measurements

# Direct probing at the LHC (ττh)

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

Berge, Bernreuther, Ziethe 2008
Berge, Bernreuther, Niepelt, Spiesberger, 2011
Berge, Bernreuther, Kirchner 2014

- A measurement of the angle

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

can be performed with the accuracies

$$\begin{cases} \Delta\phi_\tau = 40^\circ & 150\ \text{fb}^{-1} \\ \Delta\phi_\tau = 25^\circ & 500\ \text{fb}^{-1} \end{cases}$$

Numbers from:
Berge, Bernreuther, Kirchner,
EPJC74, (2014) 11, 3164.

$$\tan\phi_\tau = -\frac{s_\beta}{c_1}\tan\alpha_2 \quad \Rightarrow \quad \tan\alpha_2 = -\frac{c_1}{s_\beta}\tan\phi_\tau$$

- It is not a measurement of the CP-violating angle $\alpha_2$. In fact if $c_1$=0 the particle seems to be a pure pseudoscalar but...

# Direct probing at the LHC

- For the C2HDM we need two 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.

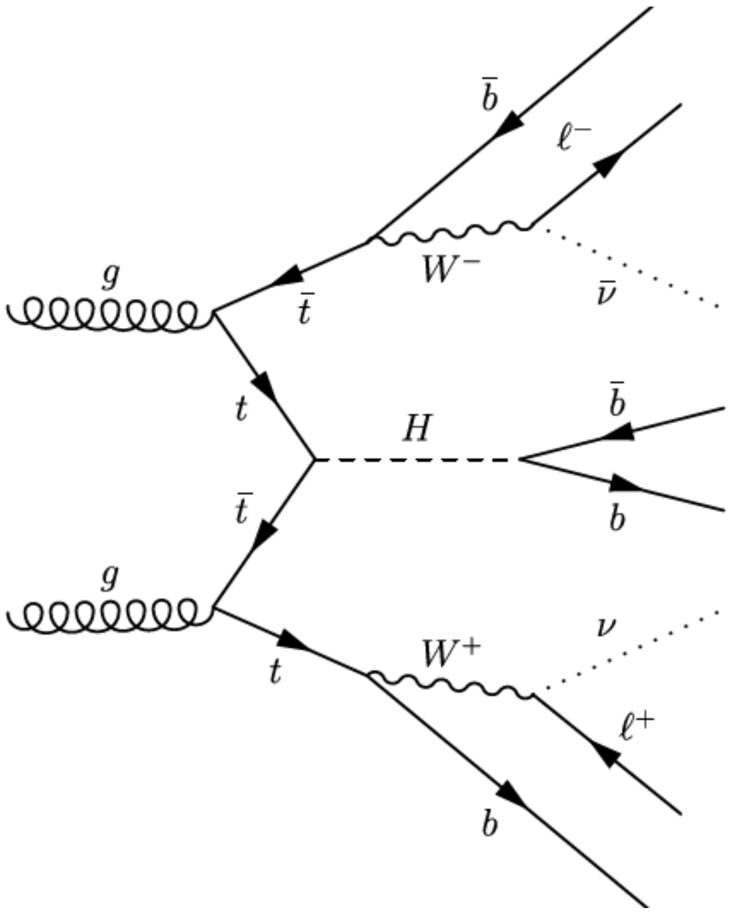
- If $\Phi_t \neq \Phi_\tau$ type I and F (Y) are excluded.

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

# Direct probing at the LHC (tth)

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

GUNION, HE 1996
BOUDJEMA, GODBOLE, GUADAGNOLI, MOHAN 2015
AMOR DOS SANTOS *EAL* 2015



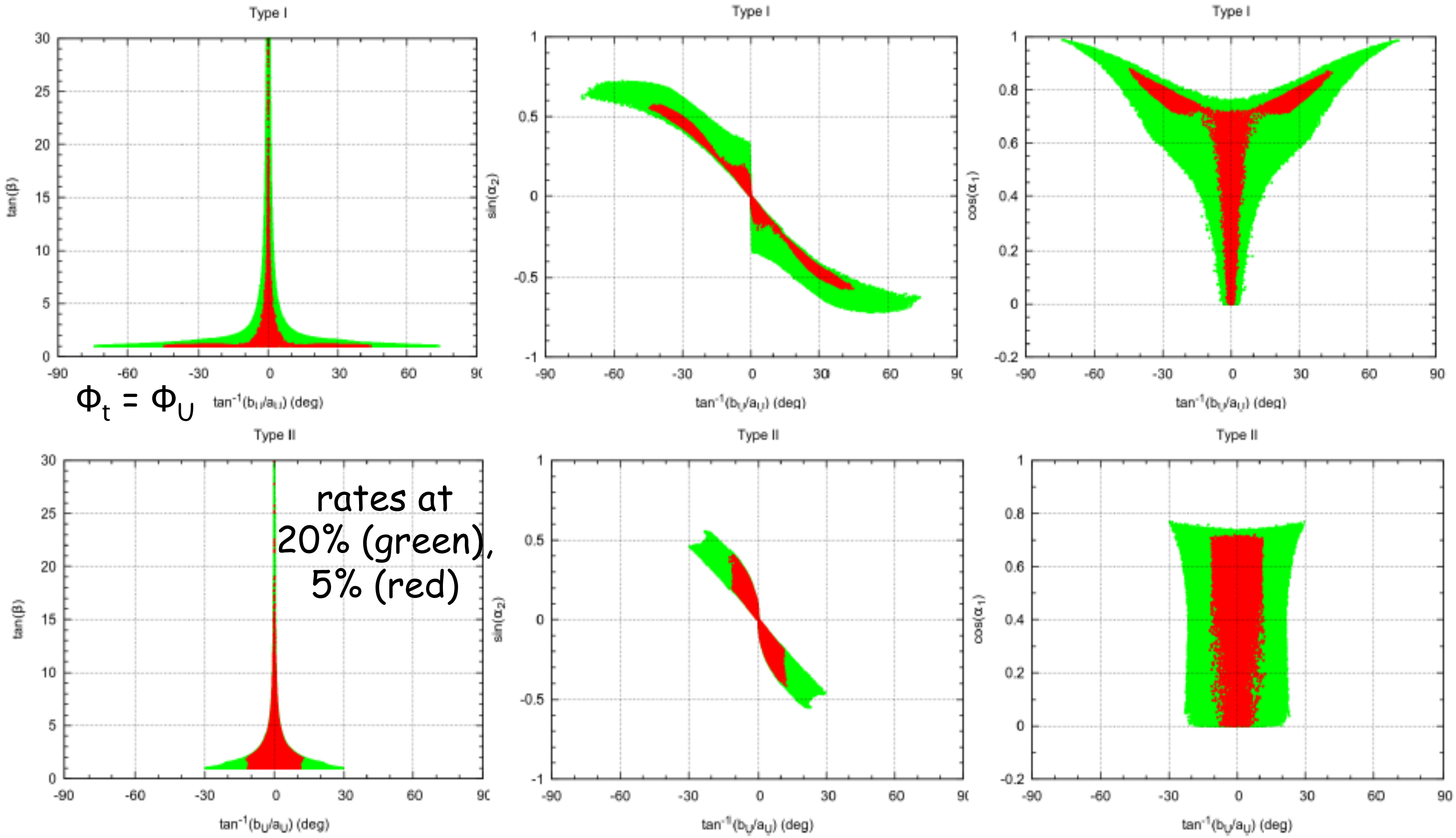

$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

Signal: tt fully leptonic and H -> bb

Background: most relevant is the irreducible tt background

Ask Ricardo G. et al

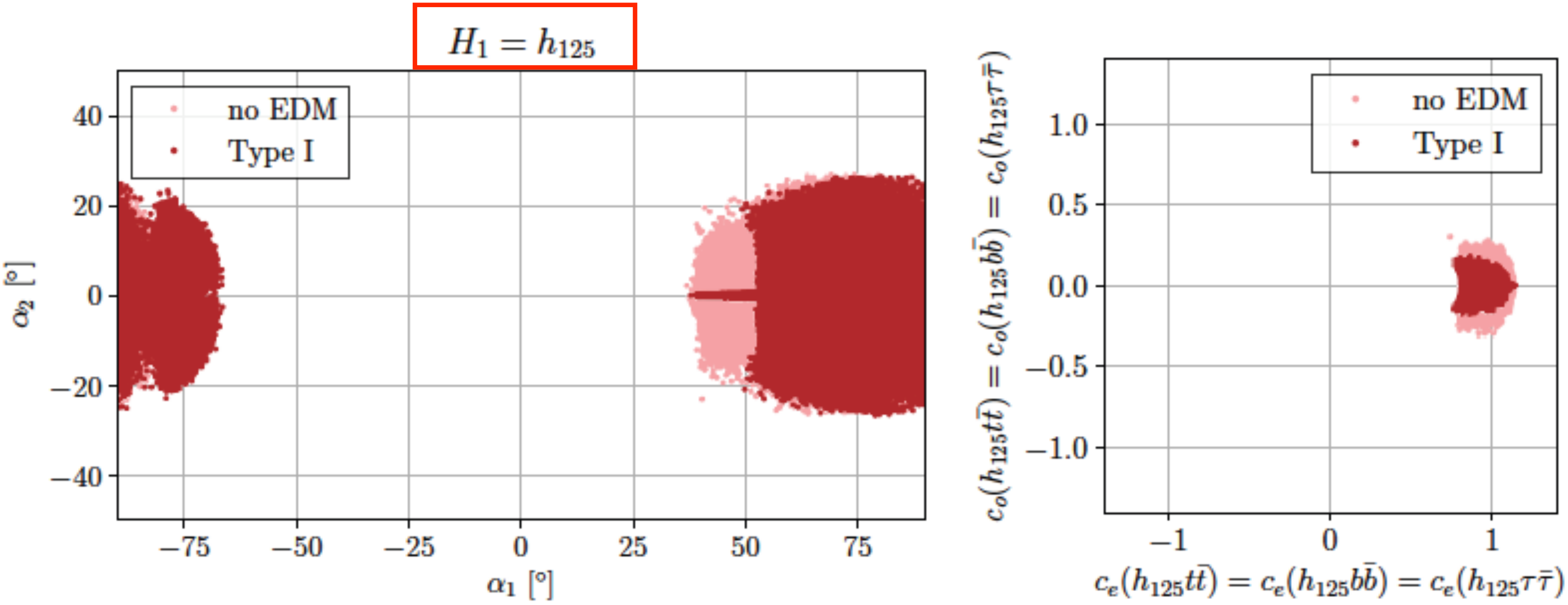
# Limits on $\Phi_t$ based on the rates only




Competitive for Type I but not for Type II

# The end and extra slides

# The allowed parameter space in type I




$$\mu_{VV} \geq 0.79 \Rightarrow \cos(\alpha_2) \geq 0.89 \Rightarrow \alpha_2 \leq 27^\circ \quad \text{and} \quad \tan(\beta) \geq 1$$

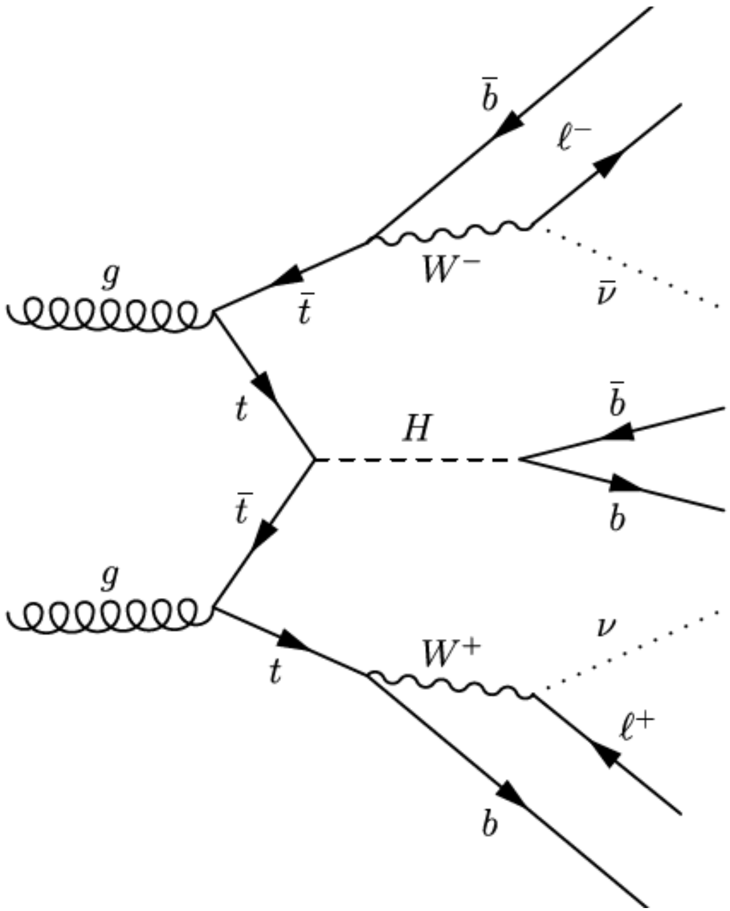
$$\alpha_2 \leq 27^\circ \Rightarrow \sin(\alpha_2) \leq 0.46 \Rightarrow c_o = \frac{\sin(\alpha_2)}{\tan(\beta)} \leq 0.46$$

**All Yukawa couplings are the same – the bounds apply equally to all of them.**

# Direct probing at the LHC (tth)

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

Gunion, He 1996
Boudjema, Godbole, Guadagnoli, Mohan 2015
Amor dos Santos *eal* 2015

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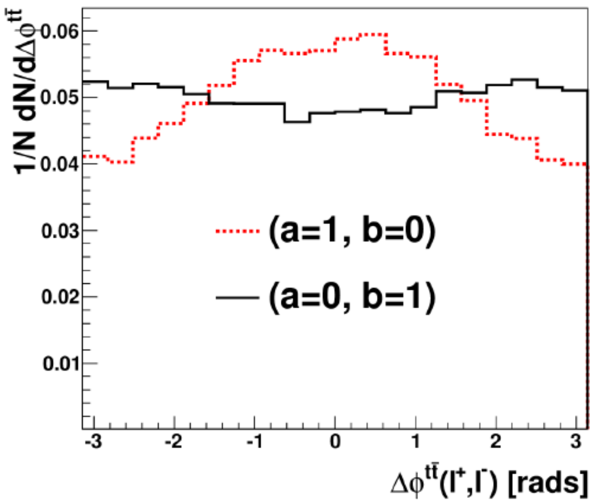
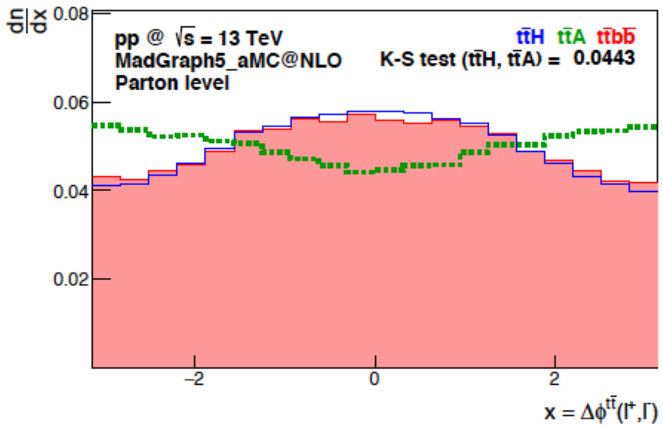
Signal: tt fully leptonic and H -> bb

Background: most relevant is the irreducible tt background

# Review of tth

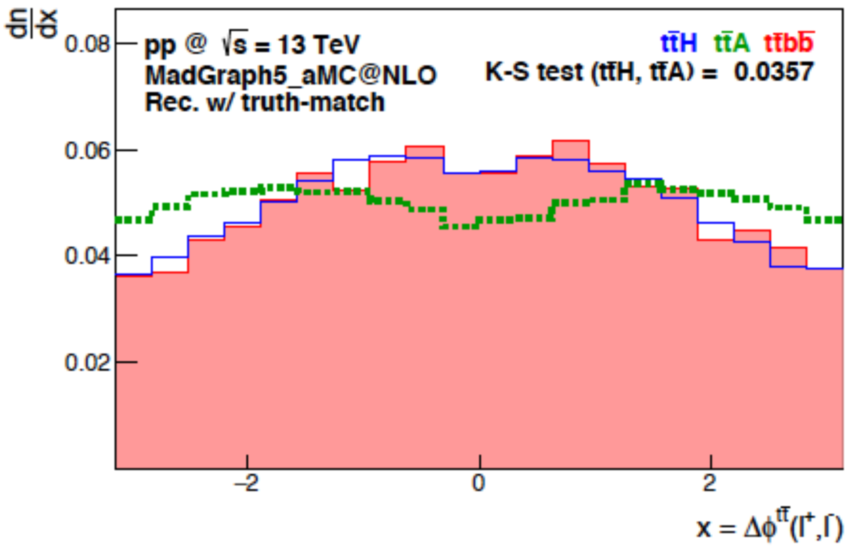
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

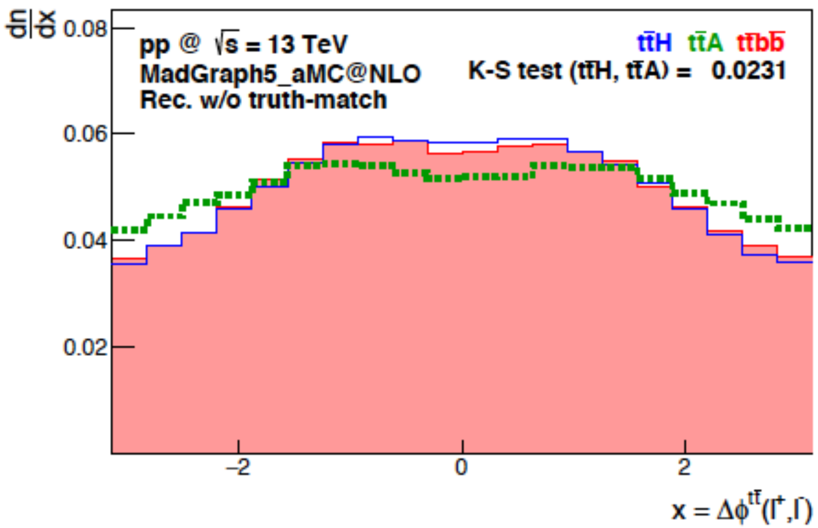



Boudjema, Godbole, Guadagnoli, Mohan 2015

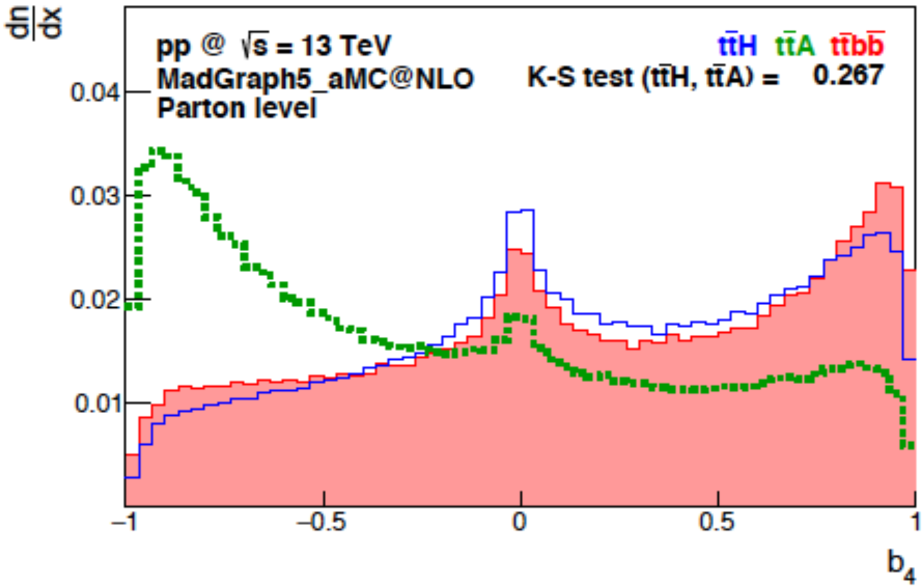
Azimuthal difference between $l^+$ in the t rest frame and $l^-$ in the tbar rest frame



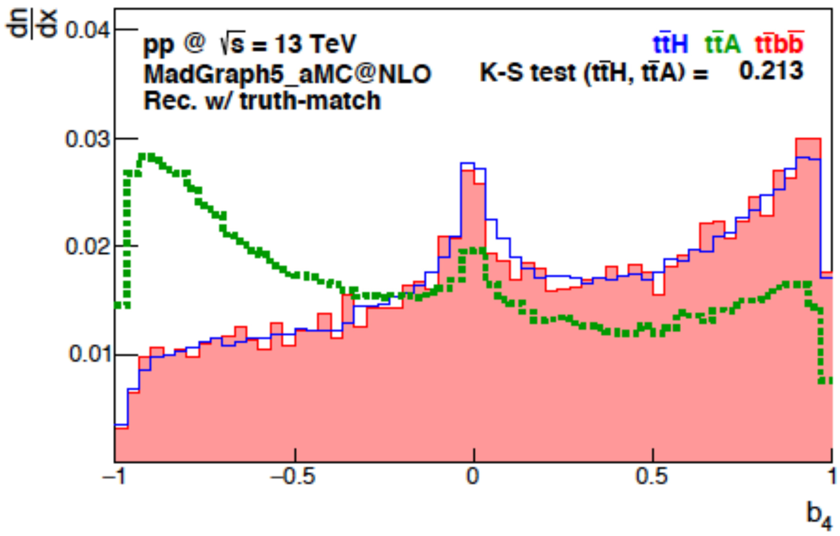
# Review of tth

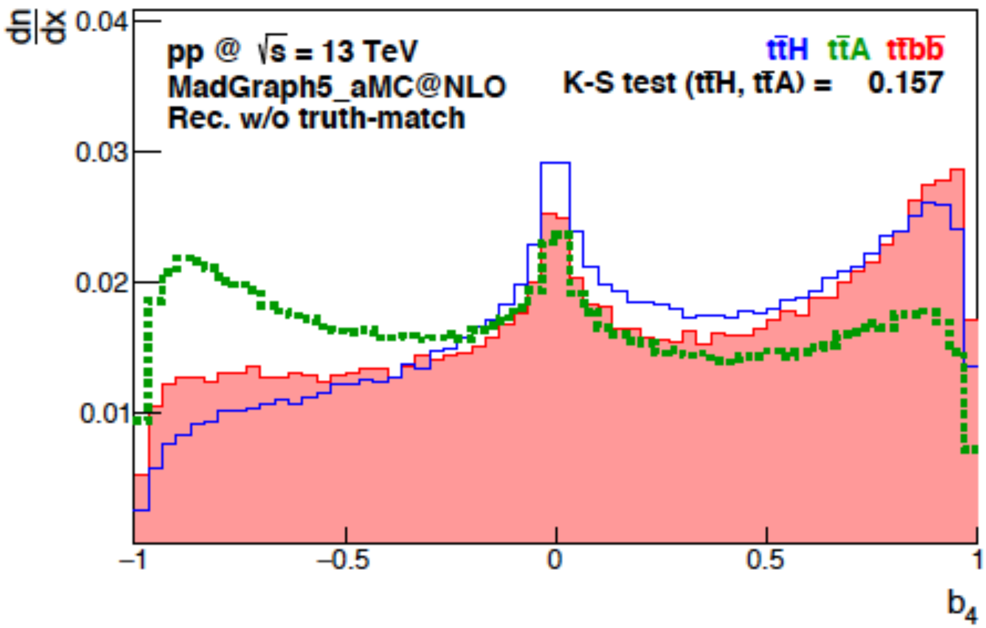
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$




Gunion, He 1996

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

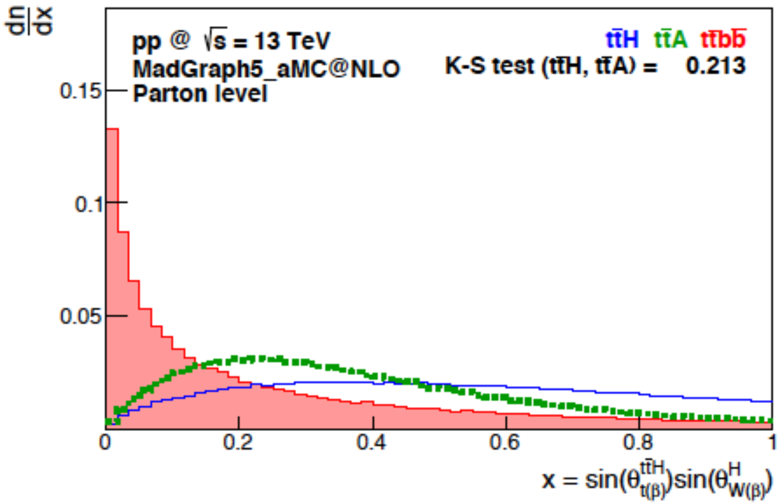


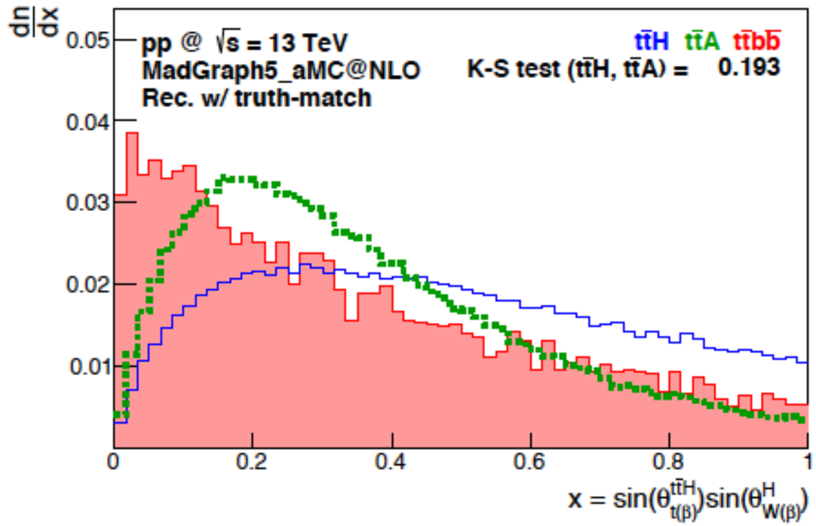



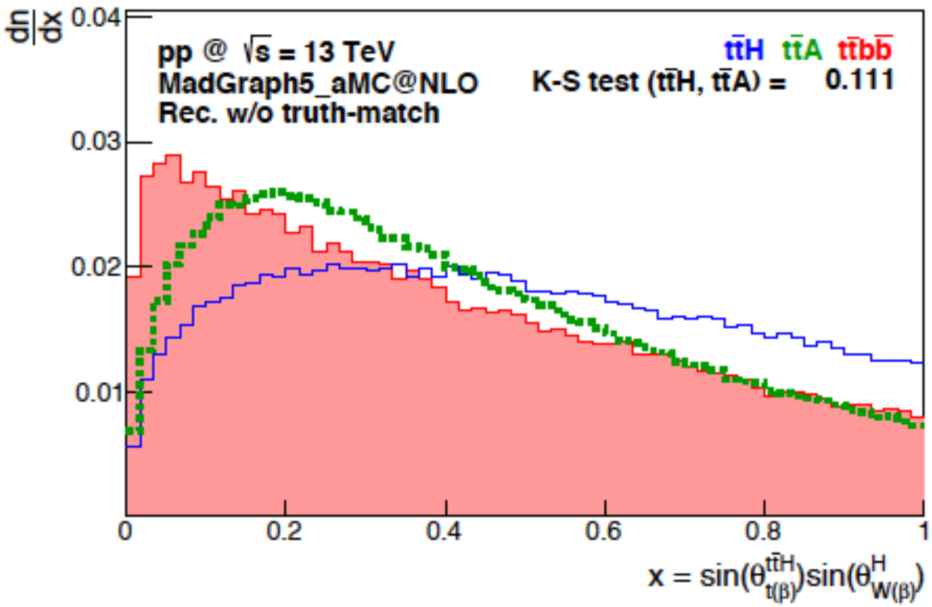
# Review of tth

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

Amor dos Santos *eal* 2015




Combinatorial background plays a very important role.

# The zero scalar scenarios

In Type II, if

$$a_D = a_L \approx 0 \quad \Rightarrow \quad \mathrm{b}_D = \mathrm{b}_L \approx 1$$

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

$$\begin{cases} a_U^2 = (1 - s_2^4) = (1 - 1/t_\beta^4) \\ b_U^2 = s_2^4 = 1/t_\beta^4 \end{cases} \qquad \left( \frac{g_{C2HDM}^{hVV}}{g_{SM}^{hVV}} \right)^2 = C^2 = \frac{t_\beta^2 - 1}{t_\beta^2 + 1} = \frac{1 - s_2^2}{1 + s_2^2}$$

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.

## 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

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

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

→ $c_1 = 0$ **allowed**

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

**excluded**

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

# The zero scalar scenarios

- So, taking

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

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

**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.