The C2HDM revisited

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CP - what have ATLAS and CMS measured so far?

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

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

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

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

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

The Higgs CP nature has been established by ATLAS and CMS assuming that h_{125} is a CP eigenstate.

Having a tree-level coupling HZZ(WW) that is the SM one modulo a constant, is inconclusive about the CP of the Higgs

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

CP - what have ATLAS and CMS measured so far?

- Effective Lagrangian (CMS notation)

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Having all extra couplings compatible with zero does not mean CP-conservation.

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

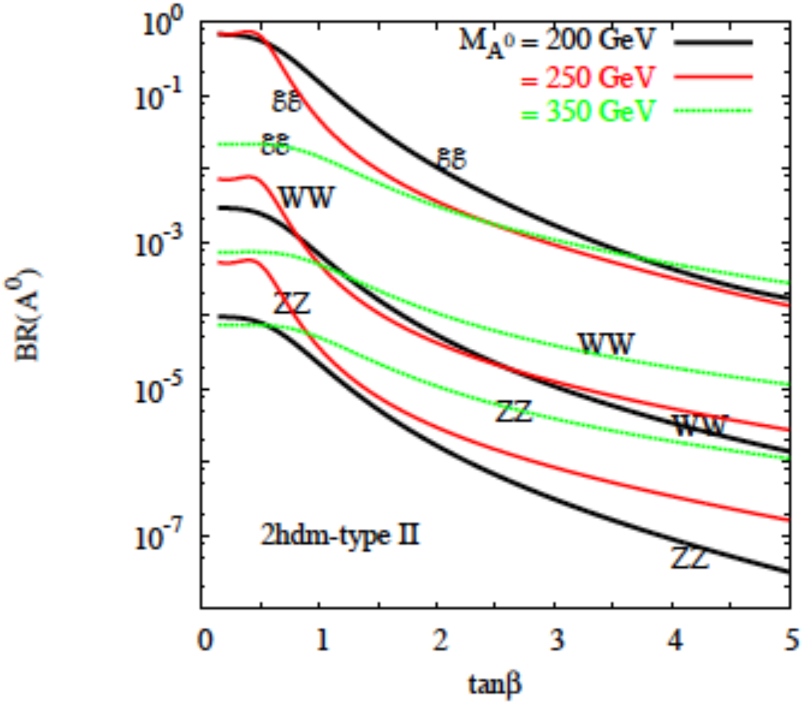
CMS, 1707.00541

ATLAS, 1506.05669

Radiative decays of A to ZZ (WW) in CP-conserving models

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

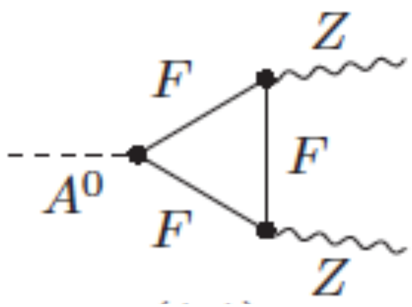
• ATLAS and CMS results have (will) shown that if these corrections exist they are small.



Arhrib, Benbrik, Field (2006).

For each particular model one should check

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



The C2HDM

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

• Interaction of each scalar with the Z (W) bosons comes exactly from the same kinetic term as the SM one

$$g_{C2HDM}^{hVV} = \cos(\alpha_2)\cos(\beta - \alpha_1)\; g_{SM}^{hVV} \quad (only\ g_{\mu\nu})$$

(for the lightest scalar)

• But Yukawa interactions are different

$$Y_{C2HDM} \equiv \left(c^e + i\gamma_5 c^o\right) Y_{SM} \overset{TII\ Lightest\ Hbb}{=} c_2 Y_{2HDM} + i\gamma_5 s_2 t_\beta Y_{SM}$$

• 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.

The (C)2HDM

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

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 λ_5 real** — **potential is CP-conserving (2HDM)**
- **m^2_{12} and λ_5 complex** — **potential is explicitly CP-violating (C2HDM)**

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

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

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

- 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 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 angle 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 $\kappa_U^I = \kappa_D^I = \kappa_L^I = \dfrac{\cos\alpha}{\sin\beta}$

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

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

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

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

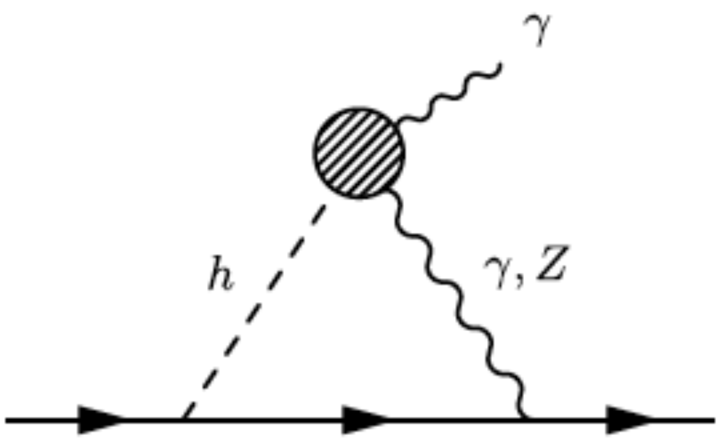
$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases}$$

when $s_2 \to 0$

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

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



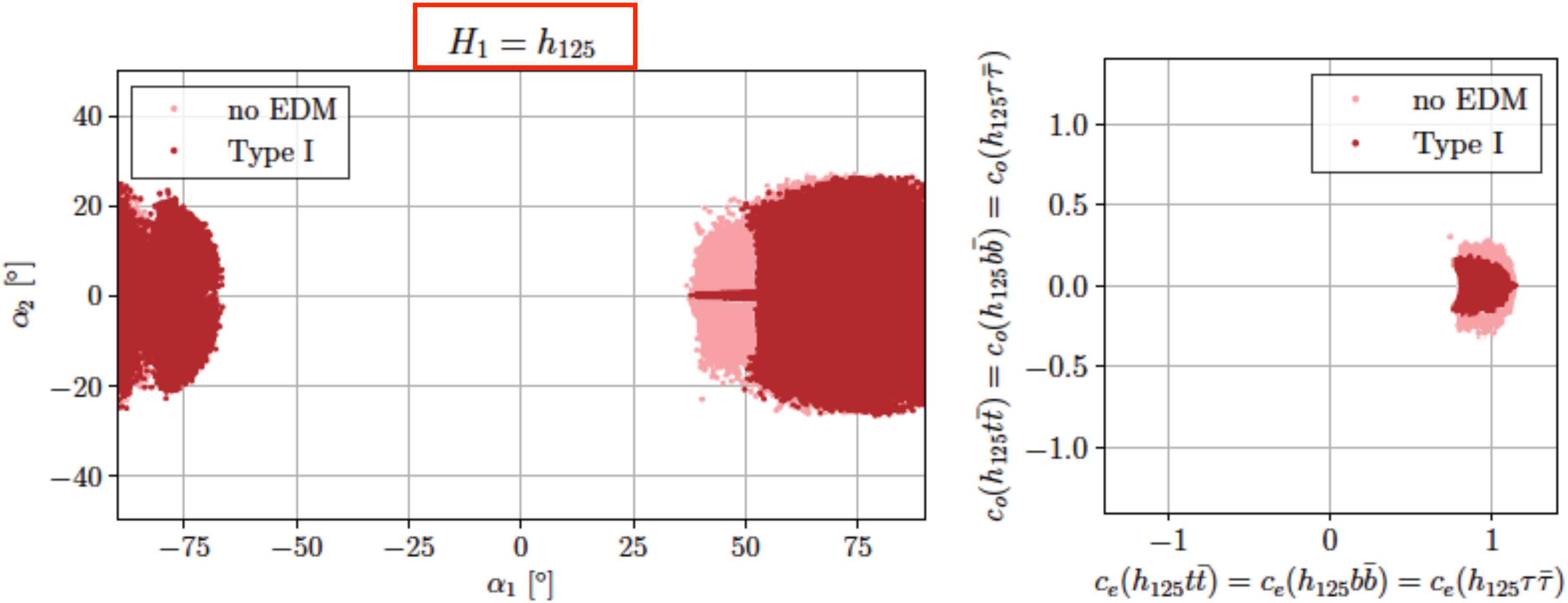
- Electric Dipole Moments are a probe of Yukawa CP-violating couplings

- 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

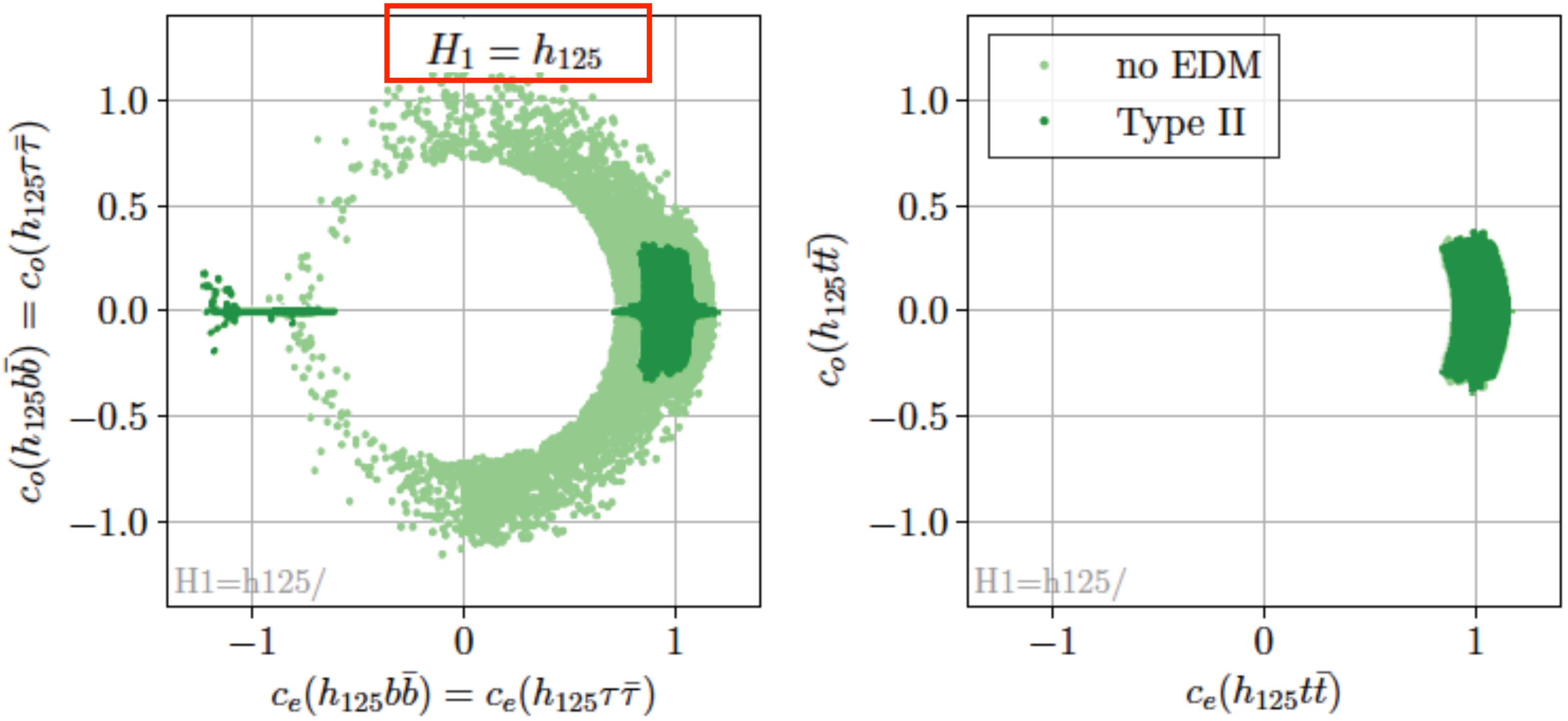


$$\mu_{VV} \geq 0.79 \Rightarrow \cos(\alpha_2) \geq 0.89 \Rightarrow \alpha_2 \leq 27^{\circ} \quad \text{and} \quad \tan(\beta) \geq 1$$

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

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

The allowed parameter space in Type II

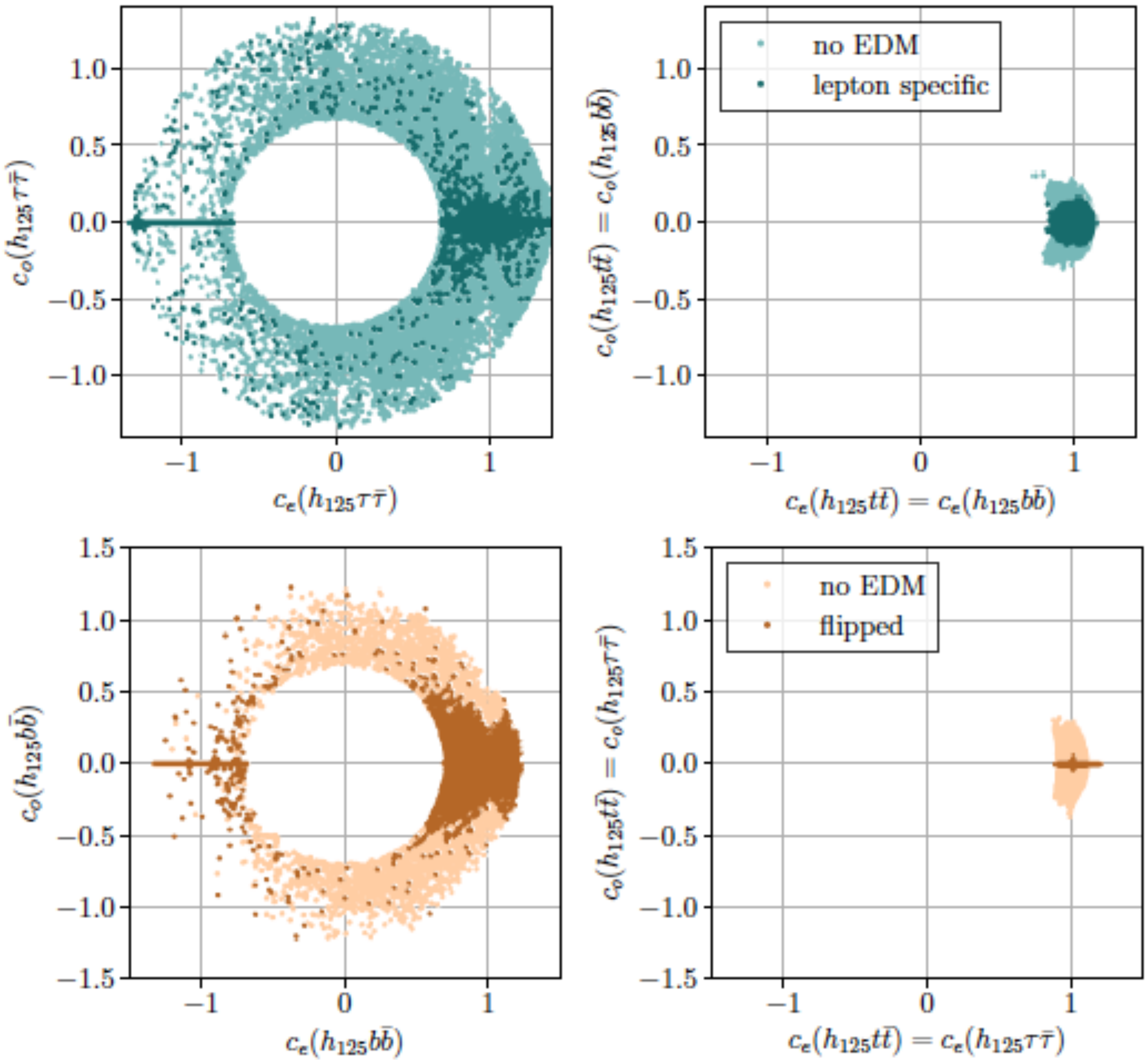


$$\alpha_2 \le 27^{\text{o}} \Rightarrow \sin(\alpha_2) \le 0.46 \Rightarrow c_o(h_{125}tt) = \frac{\sin(\alpha_2)}{\tan(\beta)} \le 0.46$$

$$c_o(h_{125}bb) = c_o(h_{125}\tau\tau) = \sin(\alpha_2)\tan(\beta) \le 0.46\tan(\beta)$$

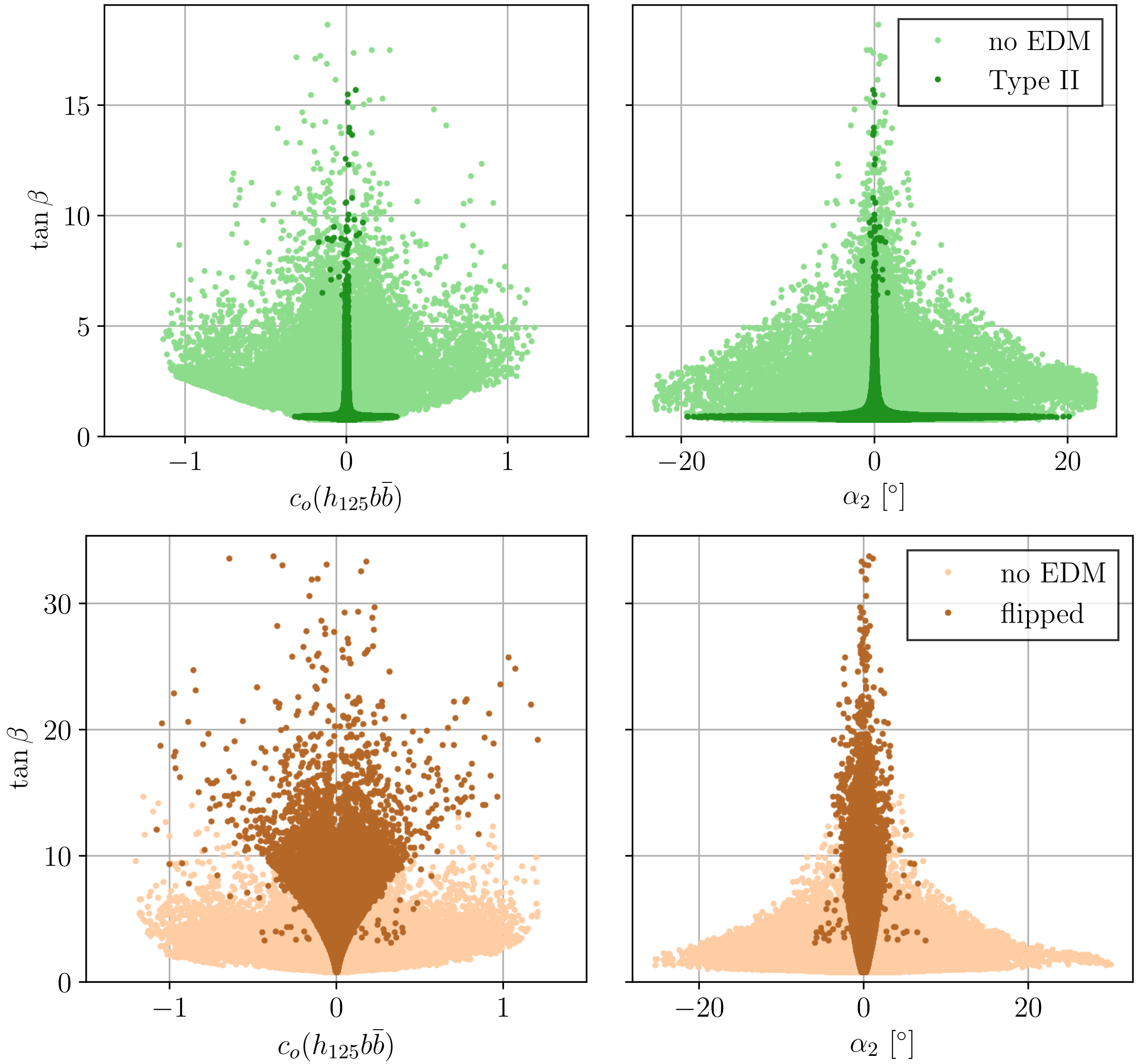
Yukawa couplings are different - the bounds are stronger for the up-quarks couplings.

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.

The relevant quantity for the pseudoscalar component is

$$c_o = \sin(\alpha_2)\tan(\beta)$$

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.

$$h_1 = "A" \rightarrow \tau^+\tau^-$$

$$h_1 = "H" \rightarrow t\bar{t}$$

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

$$h_1 = "A" \rightarrow b\bar{b}$$

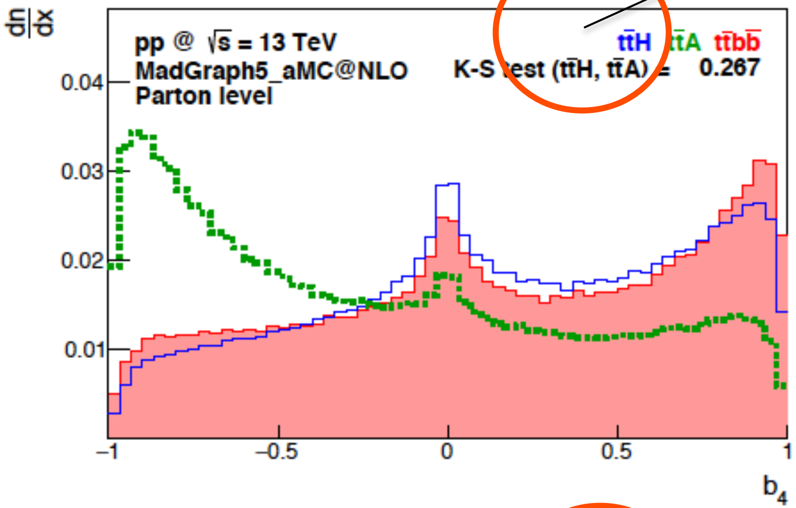
$$h_1 = "H" \rightarrow t\bar{t}$$

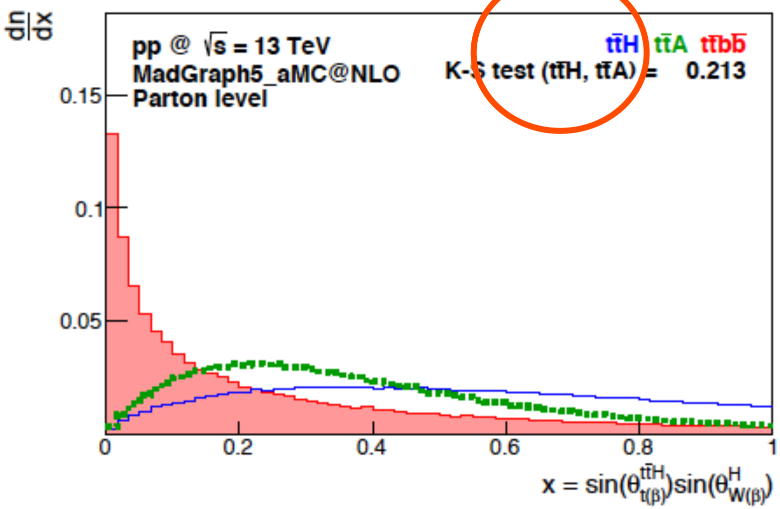
The other scenarios are for maximal $c^o * c^e$ with all possible signs combination.

$$h_1 = "H" \rightarrow t\bar{t}$$

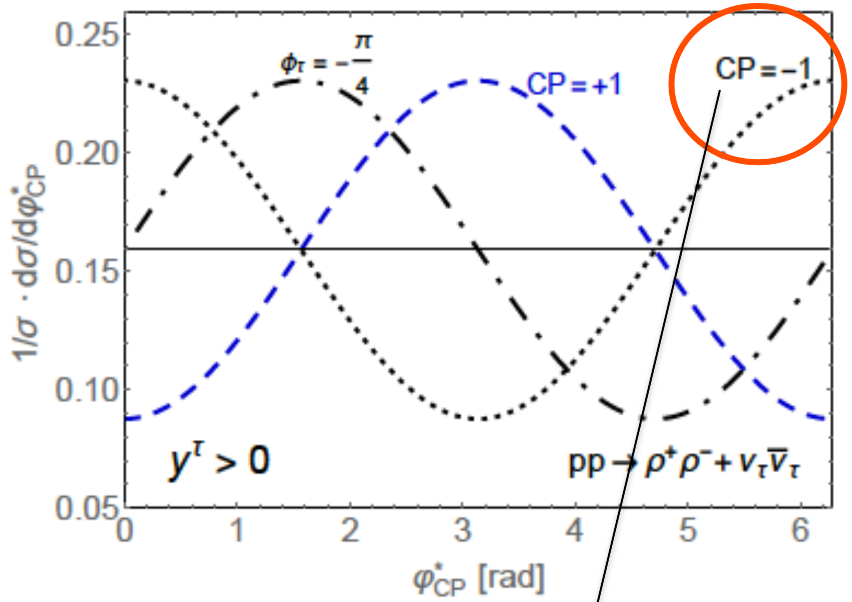
Is it CP-even?

Gunion, He 1996





Amor dos Santos *eal* 2015

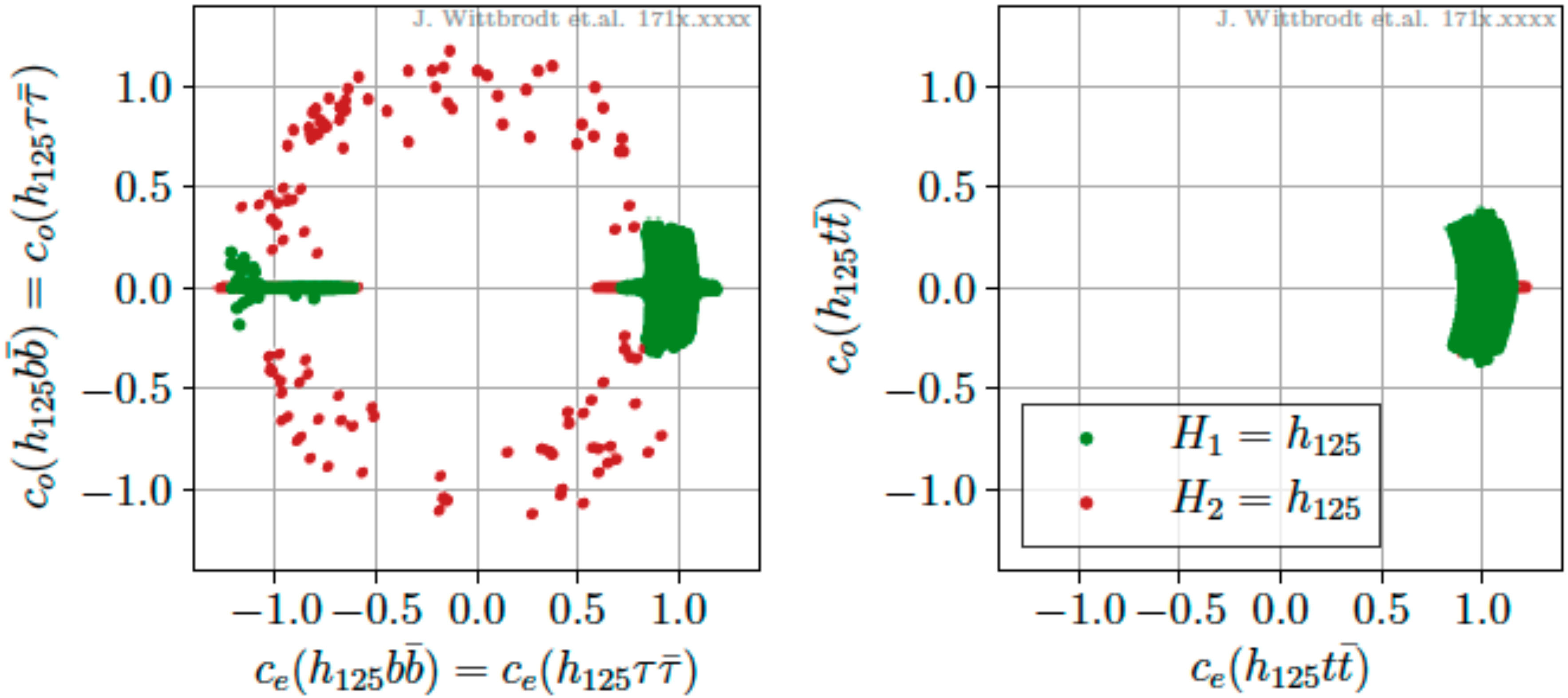


Berge, Bernreuther, kirchner, 2015

$$h_1 = "A" \rightarrow \tau^+\tau^-$$

Is it CP-odd?

Other scenarios in Type II



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

The Type II scenario with M_{h2} = 125 GeV

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

Almost CP-odd in the couplings to b-quarks and taus. Almost CP-even in the coupling to the top.

$$h_2 = "H" \rightarrow t\bar{t}$$

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

The other two scenarios are CP-even = + (-) CP-odd component.

CP-violation: rates vs. CPV variables

Combinations of three decays

Already observed

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

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

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

- ONGOING SEARCHES

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

IN 2HDMS ONLY

ONLY TWO TO GO

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

CLASSES INVOLVING SCALAR TO TWO SCALARS DECAYS

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

Class C7

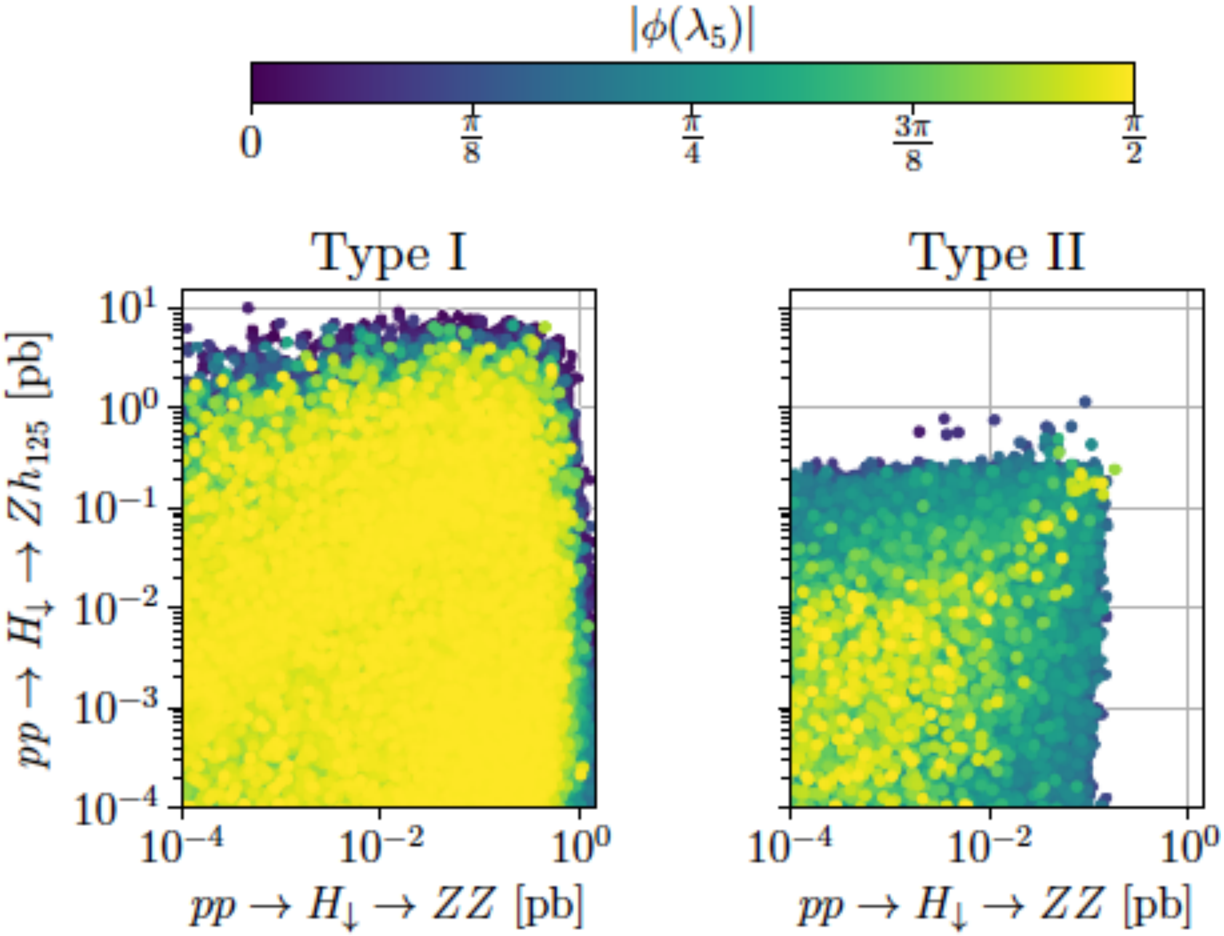
$$h_1 \to ZZ \quad \Leftarrow \quad \text{CP}(h_1) = 1$$

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

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

Yellow Report 4, 2017.

The CP-violating angle



So let us the take the observed h -> ZZ with two other decays that probe CP-violation.

Check if there are correlations between the amount of CP-violation and the rates of the processes.

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

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

MENDEZ, POMAROL, PLB272, (1991) 313.

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

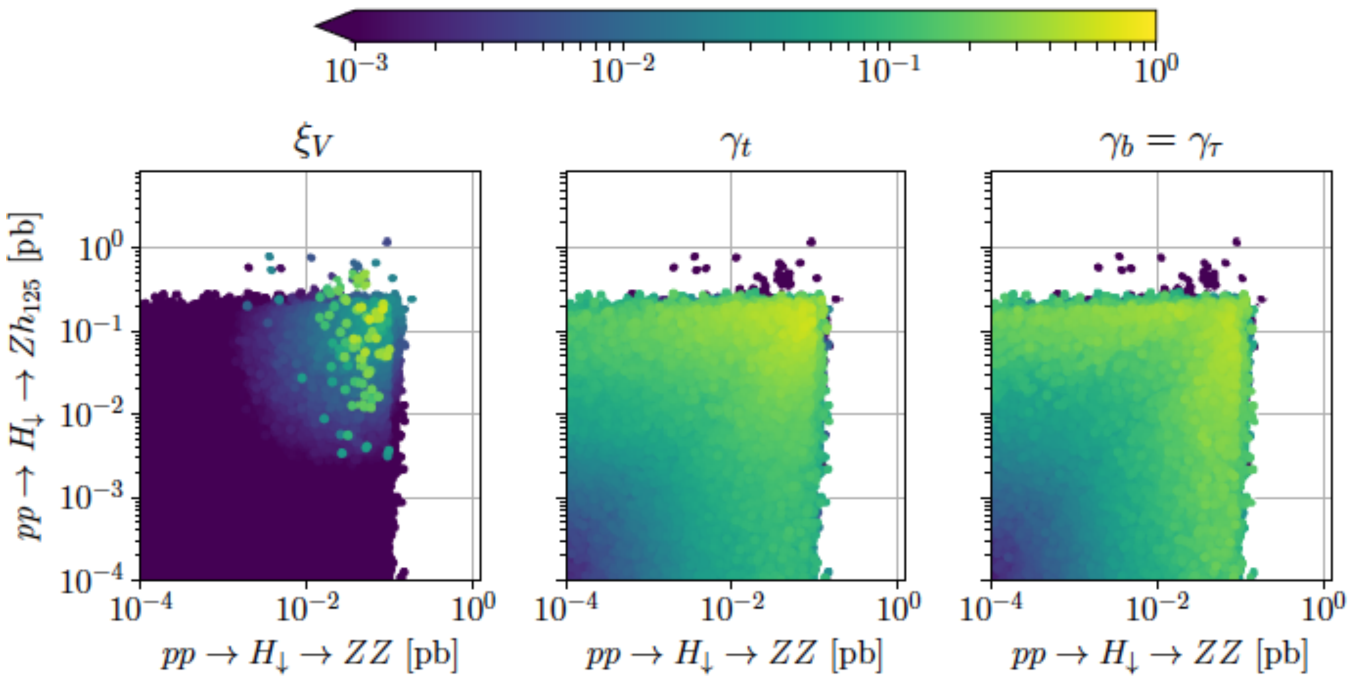
$$\gamma_t = 1024 \prod_i (R_{i2} R_{i3})^2 \,, \qquad \gamma_b = 1024 \prod_i (R_{i1} R_{i3})^2 \,.$$

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

KHATER, OSLAND, APPB34, (2003) 4531.

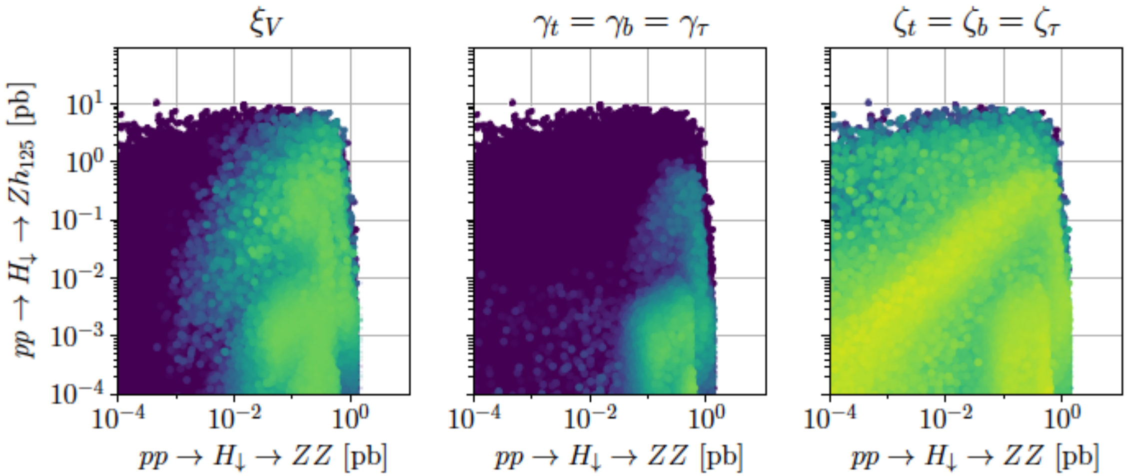
which are normalized to be between 0 and 1. Variables for the sum can also be defined but they are useless.

Correlation between CPV variables and rates



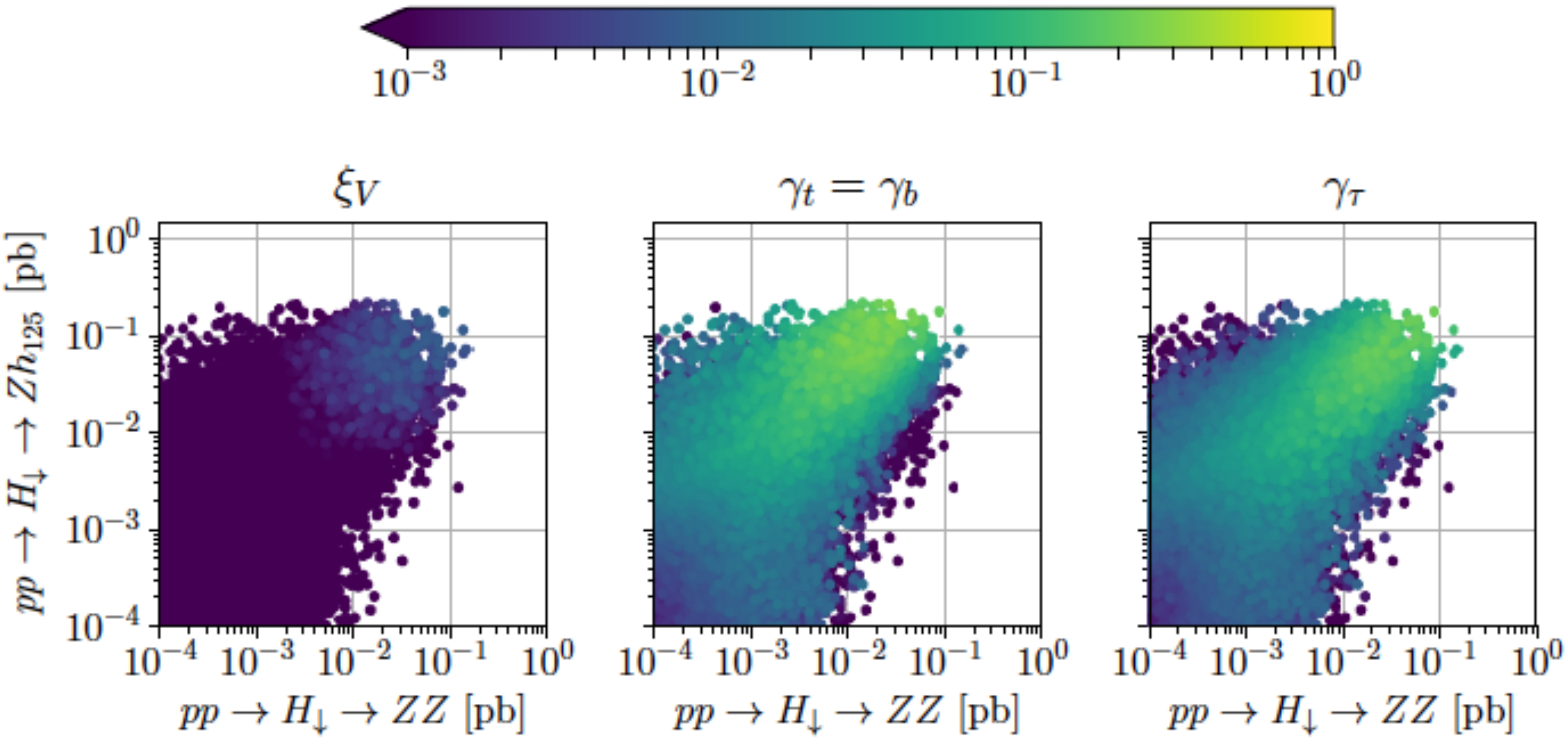
Results for Type II.
Both maximal rates above 100 fb.

It is not easy to find correlations. This is one of our best plots.



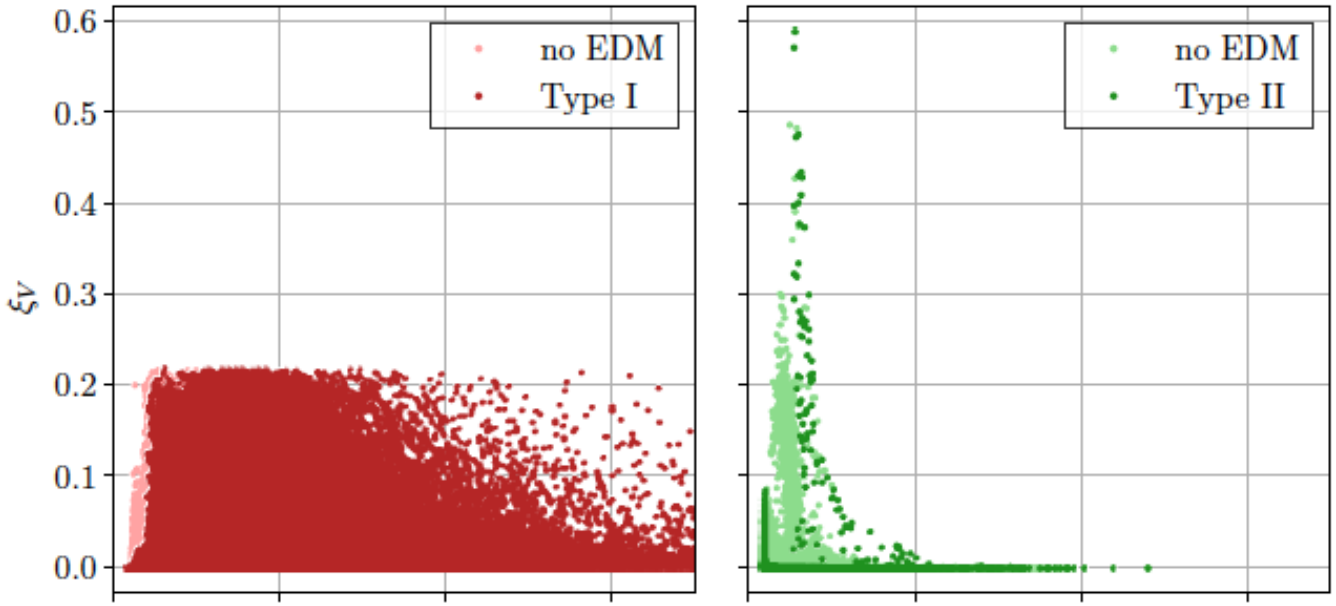
Results for Type I.
Rates can both reach the pb level.

Results for Type II (now considering that all rates measured are within 5 % of the SM)



Rates are reduced but still above 100 fb

Maximal ξ_V



For Type II tan β can only be large on when approaching the CP-conserving limit. Otherwise it is either close to 1 or if large in the wrong sign regime where the CP-violating variable can reach about 0.6.

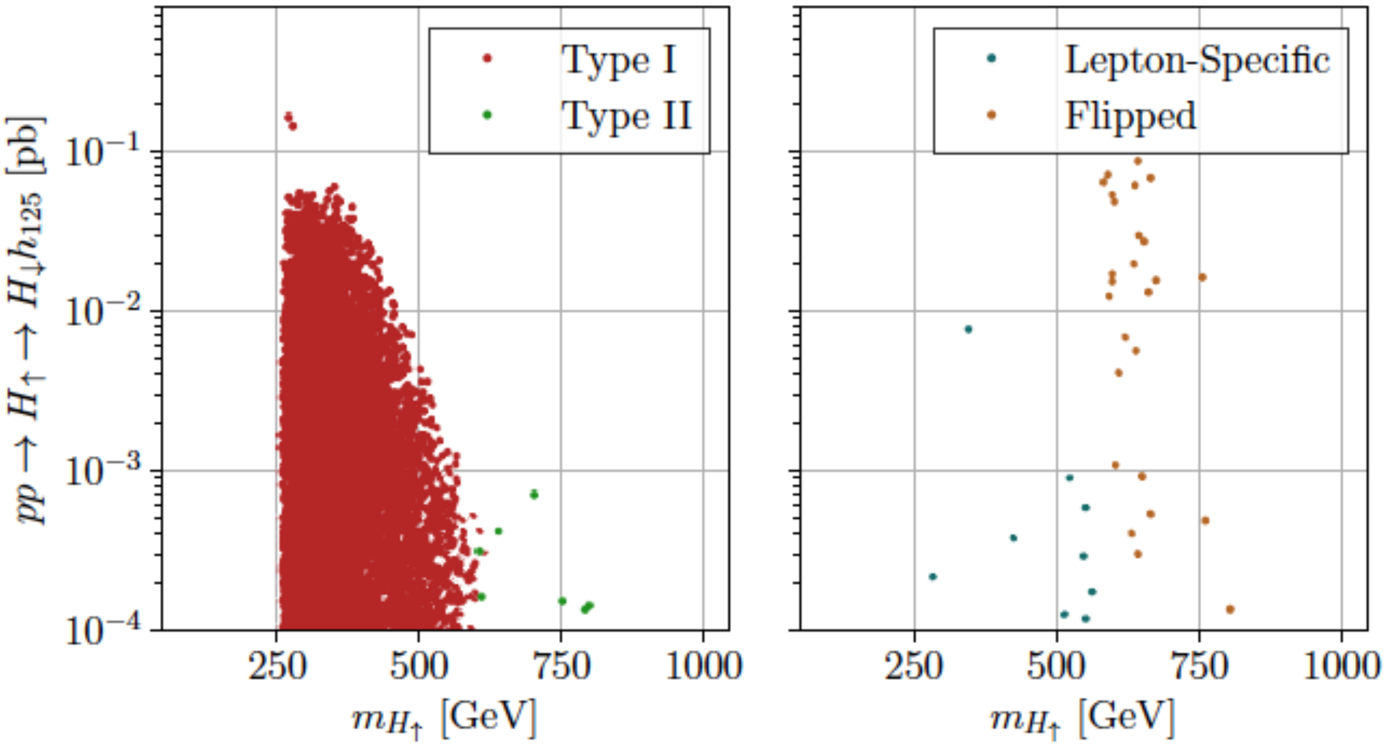
Wrong-sign Yukawa coupling – at least one of the couplings of h to down-type and up-type fermion pairs is opposite in sign to the corresponding coupling of h to VV (in contrast with SM).

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

FERREIRA, GUNION, HABER, RS, PRD89 (2014)

Rates of scalars to scalars only

Decays of $H_{\uparrow}$ to $H_{\downarrow}$ h_{125} in all types



$H_{\uparrow}$ heaviest scalar
$H_{\downarrow}$ lightest scalar

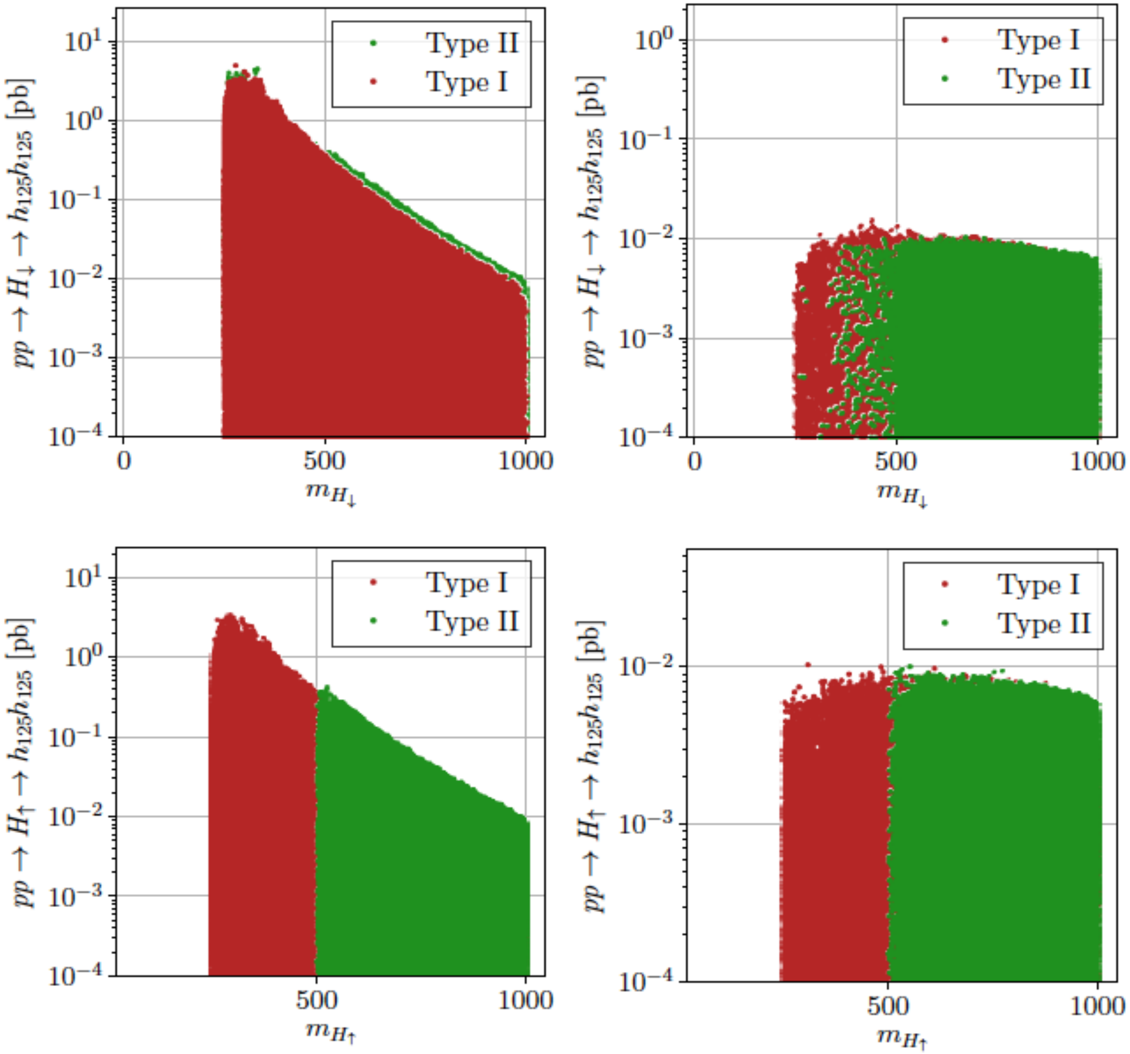
Can be both heavier or both lighter than h_{125}

Decays involving three scalars with different masses exclude some classes of models (eg: 2HDM).

Signal rates for the production of $H_{\uparrow}$ decaying to $H_{\downarrow}$ h_{125} for 13 TeV as a function of m_H for the four Yukawa types.

Hopeless for heavy Higgs. Maximum rates of about 100 fb.

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



Left - 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.

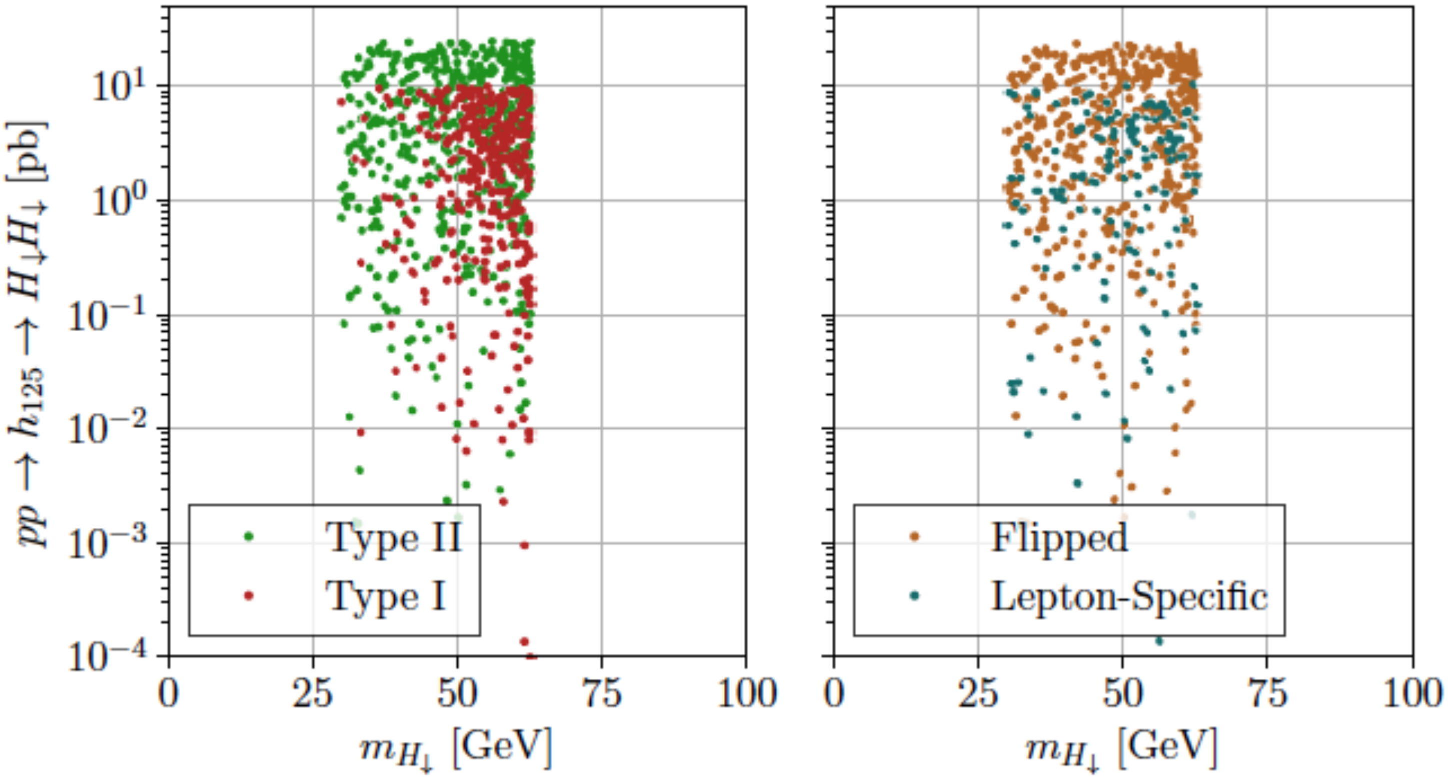
Right – Same as left with the extra conditions

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

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

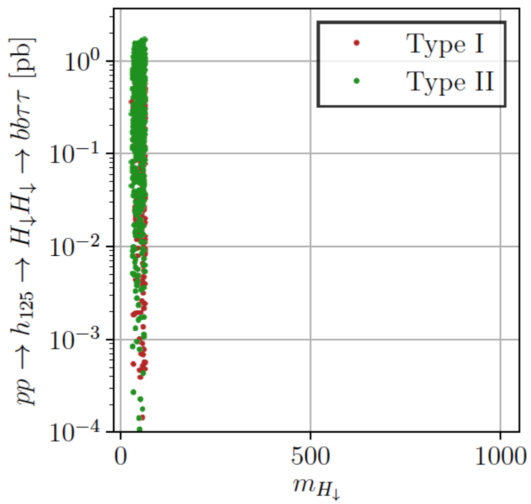
Rates can be above the pb level but are at most 10 fb if we restrict the decays to ZZ to be below 1 fb. Reference cross section for the SM di-Higgs production is about 30 fb.

Decays of h_{125} (h_3 or h_2) to $H_\downarrow H_\downarrow$ for all types



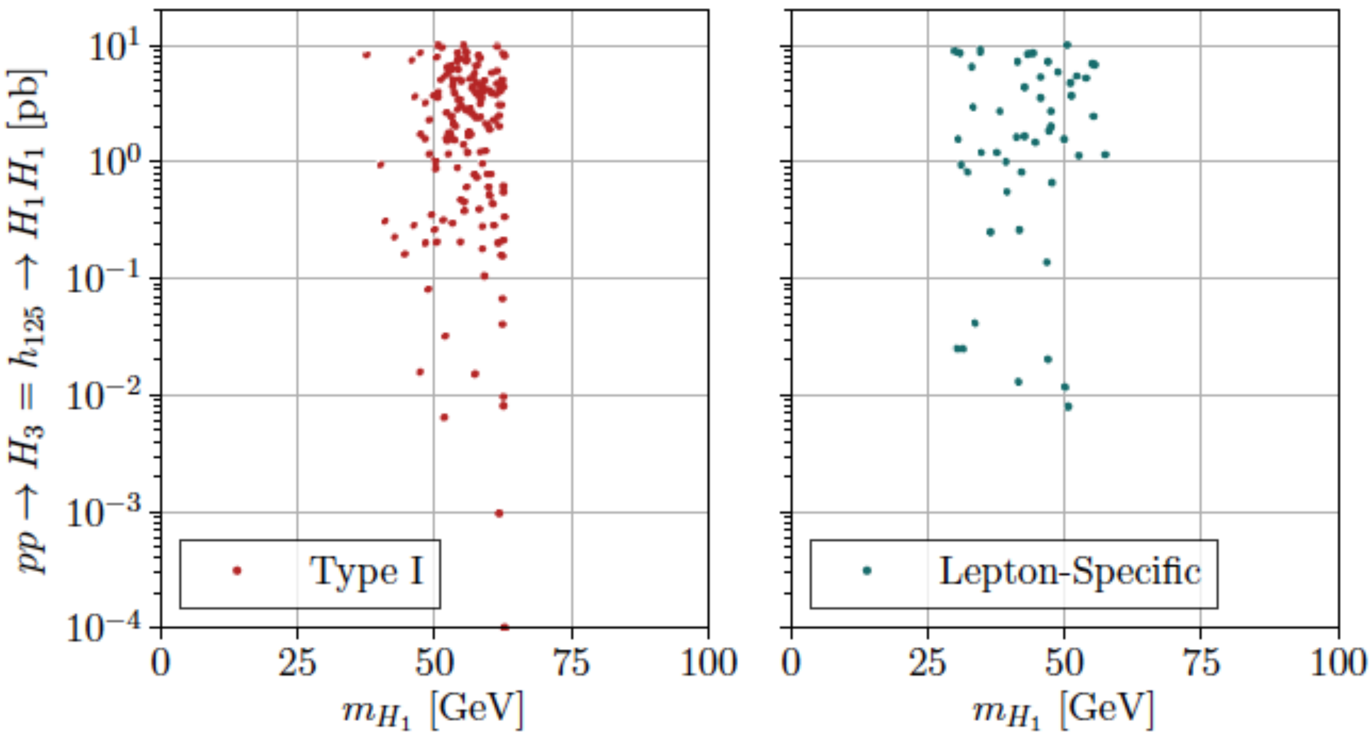
Maximal rates range from 10 to 30 pb.

As an example the final state bbττ is still above the pb level.



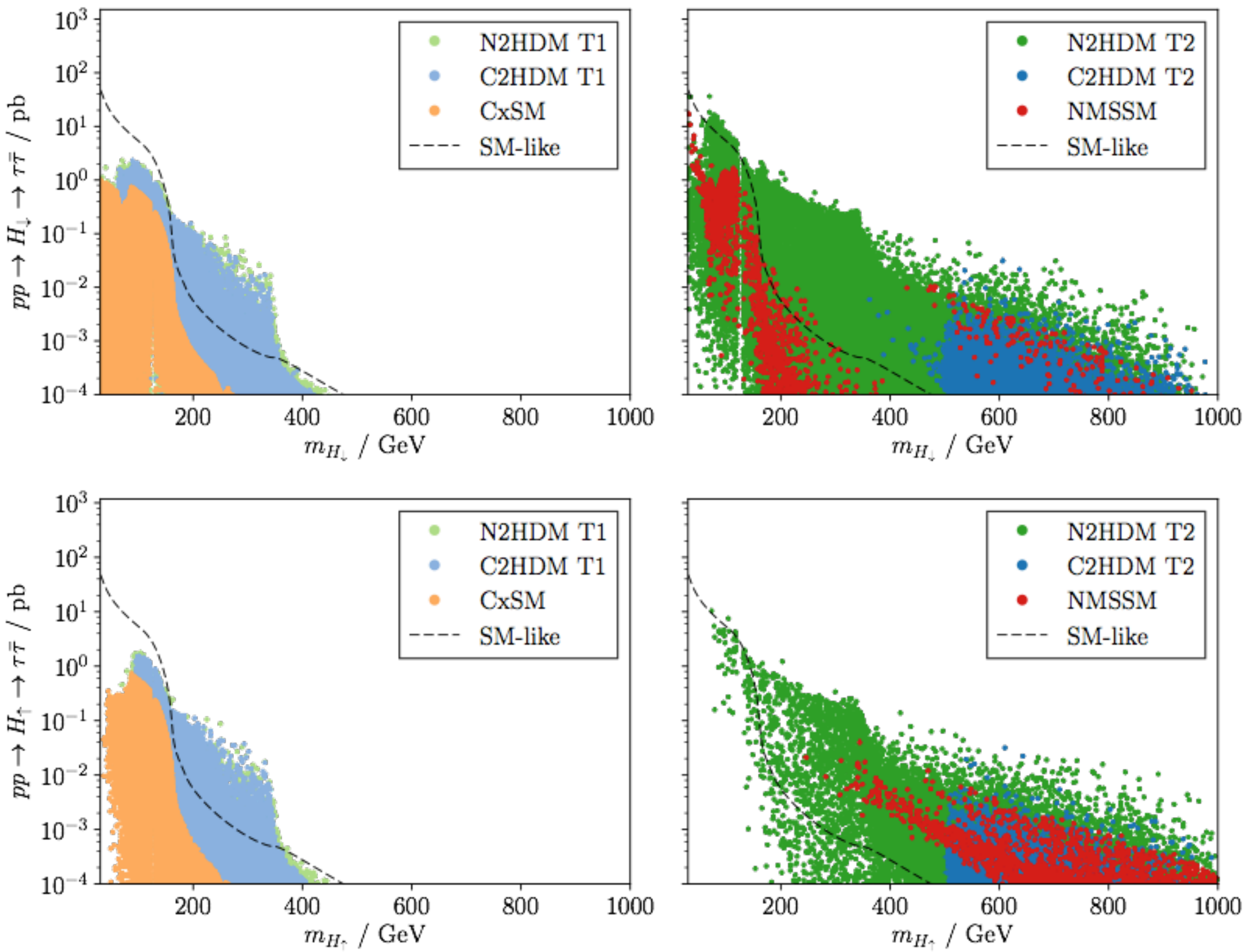
Signal rates for the production of h_{125} decaying to $H_\downarrow H_\downarrow$ for 13 TeV as a function of m_H for all types.

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.

Non-125 to ττ



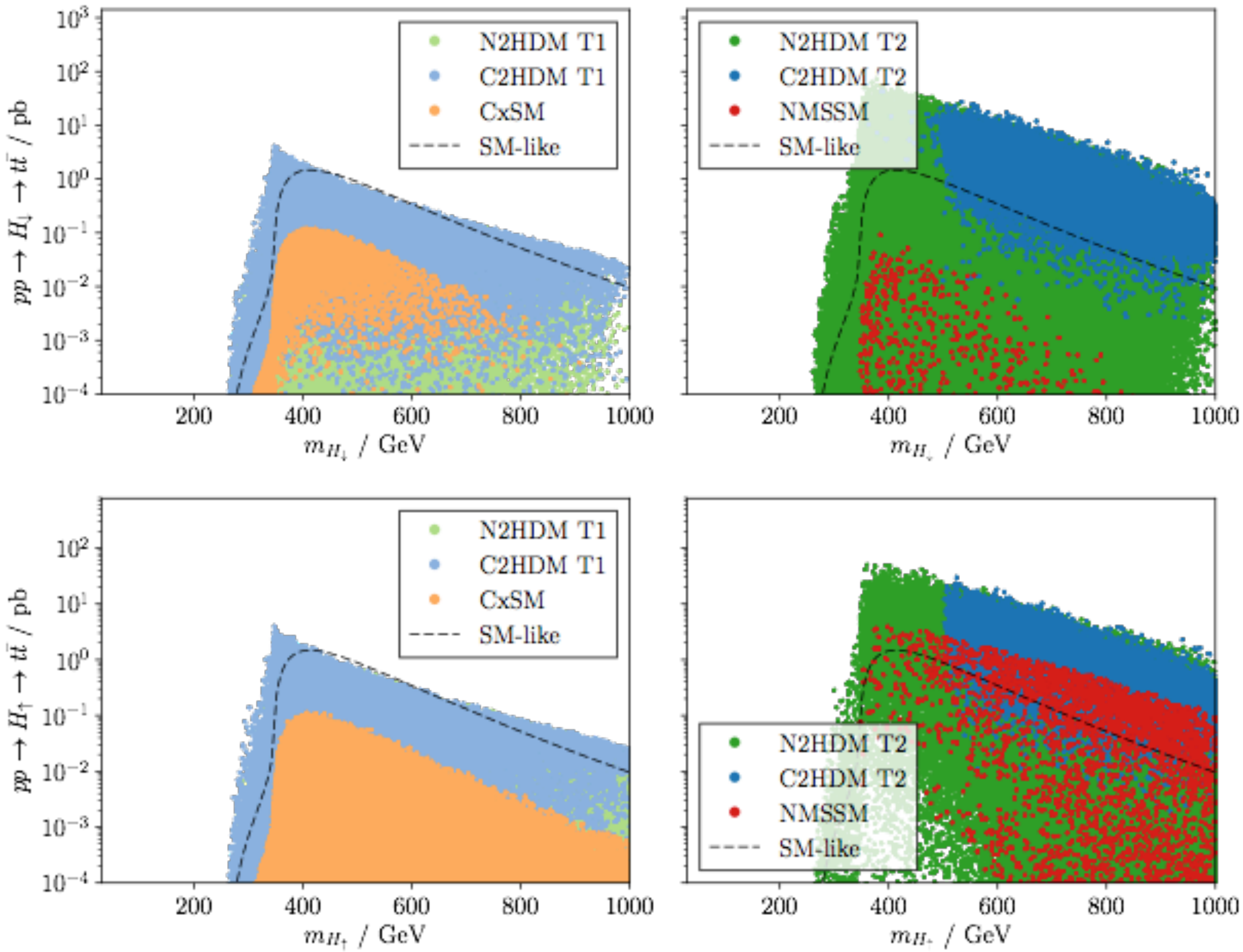
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

Rates can be well above the SM line.

Muhlleitner, Sampaio, RS, Wittbrodt, JHEP 1703 (2017) 094

Non-125 to tt



Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

C2HDM_HDECAY

The program C2HDM_DHECAY is a modified version of HDECAY 6.51.
It allows for the calculation of the partial decay widths and branching ratios of the Higgs bosons in the complex 2HDM

Released by:	Duarte Fontes, Margarete Mühlleitner, Jorge C. Romão, Rui Santos, João P. Silva and Jonas Wittbrodt
Program:	C2HDM_HDECAY obtained from extending HDECAY 6.51

When you use this program, please cite the following references:

C2HDM_HDECAY:	D. Fontes, M. Mühlleitner, J.C. Romão, R. Santos, J.P. Silva and J. Wittbrodt, arXiv:1711.abcd [hep-ph]
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput. Phys. Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Code based on HDECAY available

HTTPS://WWW.ITP.KIT.EDU/~MAGGIE/C2HDM/

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to margarete.muehlleitner@kit.edu, jonas.wittbrodt@desy.de.
- Modifs/corrected bugs are indicated explicitly in this file (25 July 2017).

Downloading the files needed for C2HDM_HDECAY (last modif: 25 July 2017) :

- chdecay.tar.gz contains the program package files: the input file hdecay.in; hdecay.f, dmb.f, elw.f, feynhiggs.f, haber.f, hgaga.f, hgg.f, hsqsq.f, susylha.f.
- makefile for the compilation.

Previous versions:

- chdecay12April2017.tar.gz
- chdecay19May2017.tar.gz
- chdecay11July2017.tar.gz

Example for an output file:

The input file hdecay.in provides the output files br.H1a_C2HDM, br.H1b_C2HDM, br.H1c_C2HDM, br.H2a_C2HDM, br.H2b_C2HDM, br.H2c_C2HDM, br.H3a_C2HDM, br.H3b_C2HDM, br.H3c_C2HDM, br.H3d_C2HDM, br.c1_C2HDM, br.c2_C2HDM, and br.c3_C2HDM.

For additional information, comments, complaints or suggestions please e-mail to: Margarete Mühlleitner, Jonas Wittbrodt

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- **General:** Based on implementation in HDECAY

  [Douadi,Spira,Kalinowski+Muhlleitner(2010), Comput.Phys.Commun. 108 (1998) 56]

- **Features:** Stand-alone codes; inclusion of relevant QCD corrections and off-shell decays, EW corrections consistently neglected

- **sHDECAY** http://www.itp.kit.edu/~maggie/sHDECAY/

  [R.Costa,M.Muhlleitner,M.O.P.Sampaio,R.Santos, JHEP 06 (106) 034]

  ⋆ Real-extended SM in symmetric (dark) phase, RxSM-dark: 1 Higgs + 1 Dark ($\mathbb{Z}_2$)

  ⋆ Real-extended SM in broken phase, RxSM-broken: 2 mixing Higgs bosons ($\mathbb{Z}_2$ spont. broken)

  ⋆ Complex-extended SM in symmetric (dark) phase, CxSM-dark: 2 mixing Higgs + 1 Dark

  ⋆ Complex-extended SM in broken phase, CxSM-broken: 3 mixing Higgs bosons

- **N2HDECAY for N2HDM** http://www.itp.kit.edu/~maggie/N2HDECAY/

  [M.Muhlleitner,M.O.P.Sampaio,R.Santos,J.Wittbrodt, JHEP 1703 (2017) 094]

  ⋆ 2DHM + real singlet $\mathbb{Z}_2$ spont. broken: 3 scalars $H_{1,2,3}$, 1 pseudocalar A, charged pair $H^\pm$

  ⋆ 2HDM + real singlet $\mathbb{Z}_2$: in preparation

Conclusions

> All scenarios regarding which of the scalars is the h_{125} are allowed.

> All scalar to scalar decays are within LHC reach.

> Even in a minimal model, different CP-violating quantities are not necessarily strongly correlated.

> Measurements of the Higgs couplings and constraints on EDMs provide the strongest bounds on CP-violating Higgs sectors.

> Large pseudoscalar couplings of $h125$ might be observable at LHC.

The end

Extra slides

ScannerS

ScannerS alows general scalar potential with automatic:

- Analysis of tree level local minimum/stability
- Detection of tree level scalar spectrum and mixing
- Tree level unitarity test

Interfaces to:

- HDECAY, sHDECAY, N2HDECAY, C2HDECAY
- HIGGSBOUNDS/SIGNALS (collider bounds/measurements)
- MICROMEGAS (dark matter observables)
- SUSHI (+ internal numerical tables for gluon fusion)
- SUPERISO (flavour physics observables)

User/model defined functions to:

- Check boundedness from below
- Check global stability
- Implement phenomenological analysis for each point

- Real and Complex Scalar Singlet Extensions:
  R. Costa, M. Mühlleitner, M.O.P. Sampaio, R. Santos, JHEP 1606 (2016) 034 + see YR4
  R. Coimbra, M.O.P. Sampaio, R. Santos, EPJ C73 (2013) 2428
  R. Costa, A. Morais, M.O.P. Sampaio, R. Santos, Phys.Rev. D92 (2015) 2, 025024
  - **RxSM-dark**: 1 Higgs + 1 Dark ($\mathbb{Z}_2$)
  - **RxSM-broken**: 2 Higgs mixing ($\mathbb{Z}_2$ spont.broken)
  - **CxSM-dark**: 2 Higgs mixing + 1 Dark
  - **CxSM-broken**: 3 Higgs mixing

  New: Input files allow *Scan* or *Check* point mode.
  see → *How to run scalar singlet extensions in ScannerS* (`indico.cern.ch/event/640710`)
- Scalar Doublet Extensions
  - **2HDM**: *Scan* or *Check* point modes available.
    P.M. Ferreira, R. Guedes, M.O.P. Sampaio, R. Santos, JHEP 12 (2014) 067
  - **N2HDM-broken**: 2HDM + Real singlet $\mathbb{Z}_2$ spont. broken. *Scan* mode (*Check* mode available soon . . .)
    M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, JHEP 1703 (2017) 094
  - **N2HDM-dark**: 2HDM + Real singlet $\mathbb{Z}_2$ (under dev.)
  - **C2HDM**: To be publicly released soon.
    M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, arXiv:1703.07750

The Neutron EDM

$$\frac{d_n}{e} = \Big\{ (1.0 \pm 0.5) \left[-5.3\, \kappa_q \tilde{\kappa}_t + 5.1 \cdot 10^{-2}\, \kappa_t \tilde{\kappa}_t \right] + (22 \pm 10)\, 1.8 \cdot 10^{-2}\, \kappa_t \tilde{\kappa}_t \Big\} \cdot 10^{-25}\, \text{cm}\,.$$

Constraints on CP-violating Higgs couplings to the third generation
Joachim Brod, Ulrich Haisch, Jure Zupan, JHEP 1311 (2013) 180

Alignment and wrong-sign Yukawa

The Alignment (SM-like) limit – all tree-level couplings to fermions and gauge bosons are the SM ones.

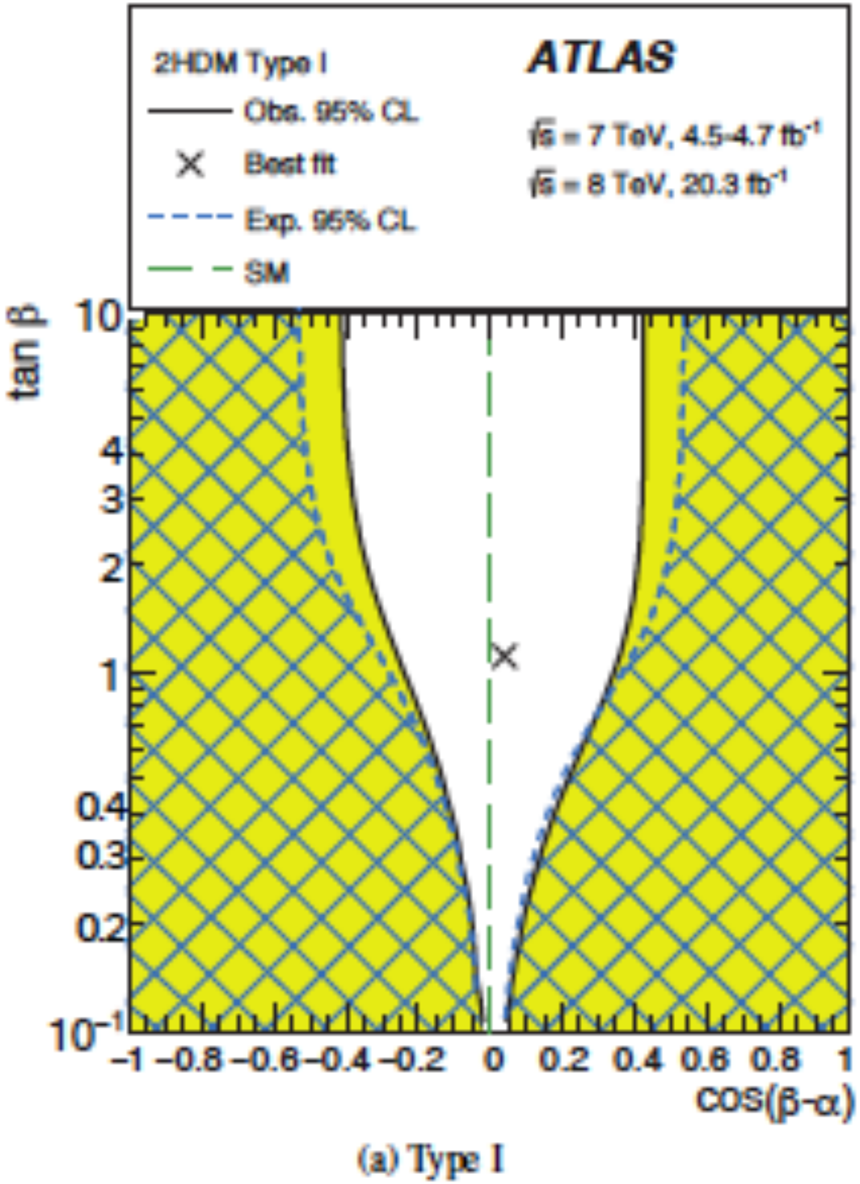
$$\sin(\beta-\alpha)=1 \quad \Rightarrow \quad \kappa_D=1; \quad \kappa_U=1; \quad \kappa_W=1$$

Wrong-sign Yukawa coupling – at least one of the couplings of h to down-type and up-type fermion pairs is opposite in sign to the corresponding coupling of h to VV (in contrast with SM).

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

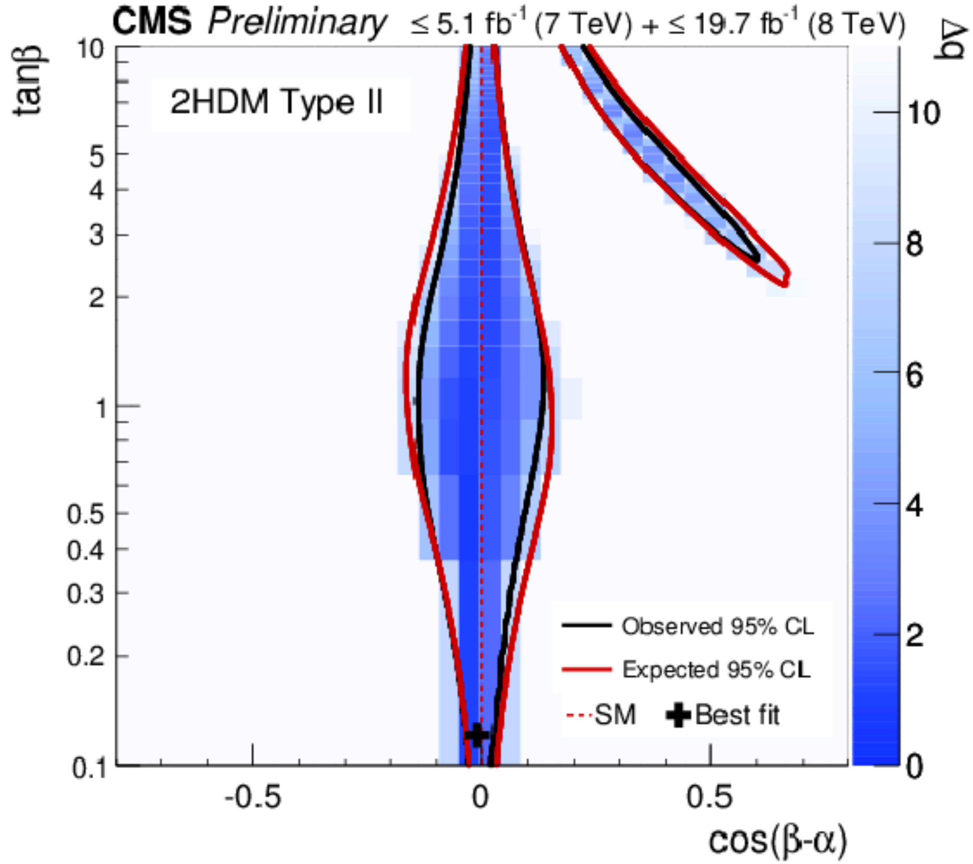
The actual sign of each κ_i depends on the chosen range for the angles.

The 2HDM (CP-conserving and no tree-level FCNC)



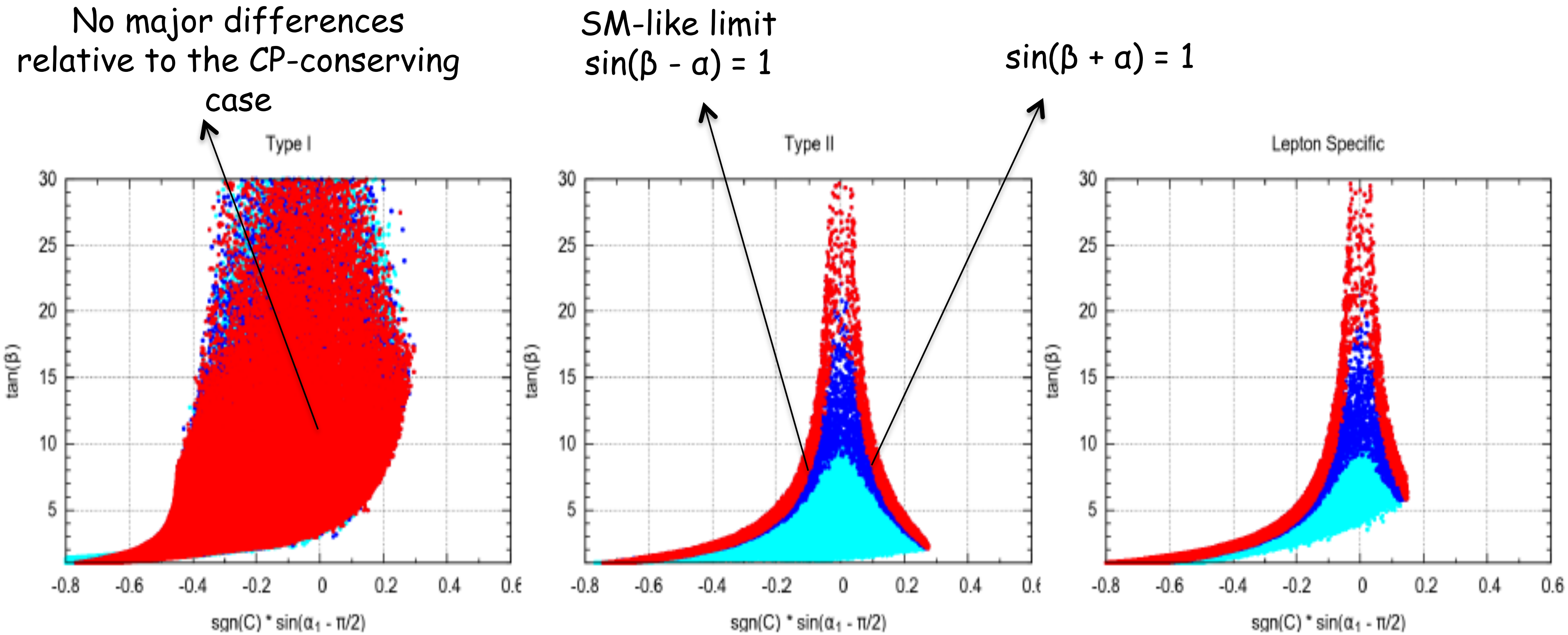
(a) Type I

ATLAS 1509.00672



CMS-PAS-HIG-16-007

Results after run 1



tanβ as a function of $\sin(\alpha_1 - \pi/2)$ for Type I, Type II and LS. Full range (cyan), $s_2 < 0.1$ (blue) and $s_2 < 0.05$ (red).

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.

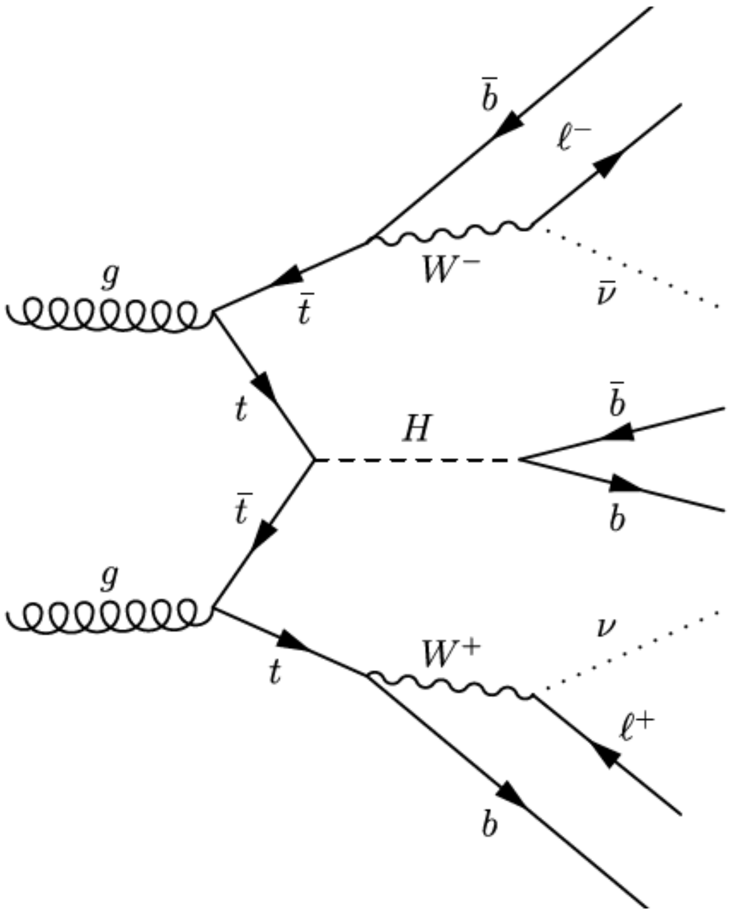
- If $\Phi_t \neq \Phi_\tau$ type I and F (Y) are excluded.

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

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



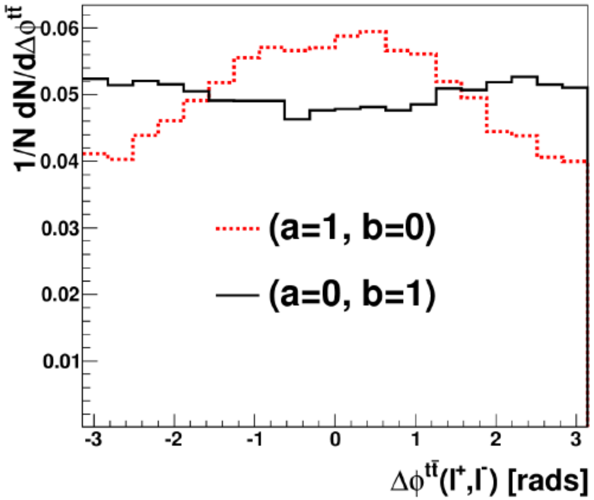
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

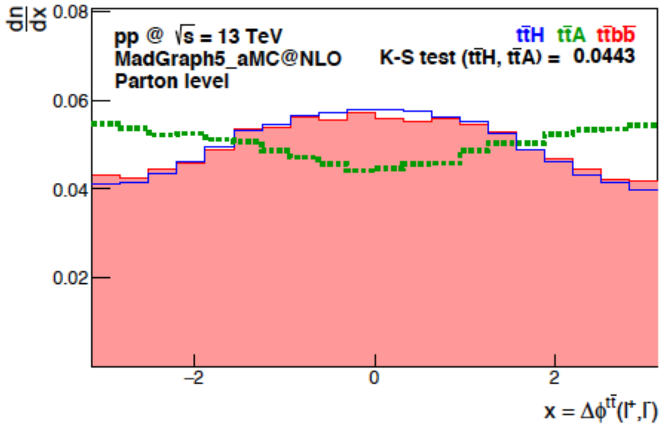
Signal: tt fully leptonic and H -> bb

Background: most relevant is the irreducible tt background

Review of tth

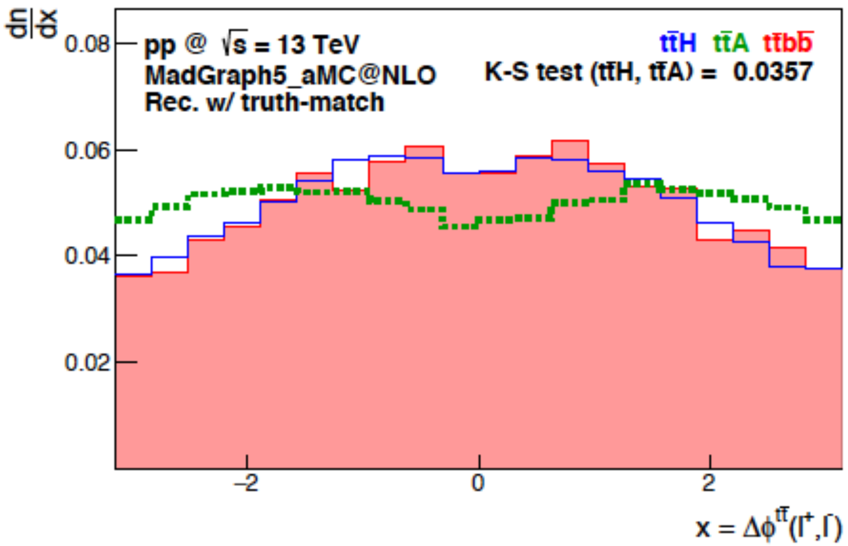
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

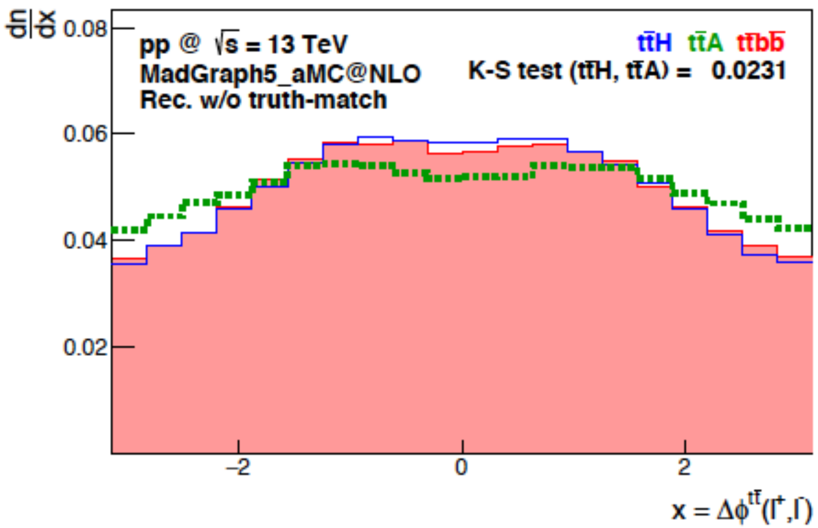


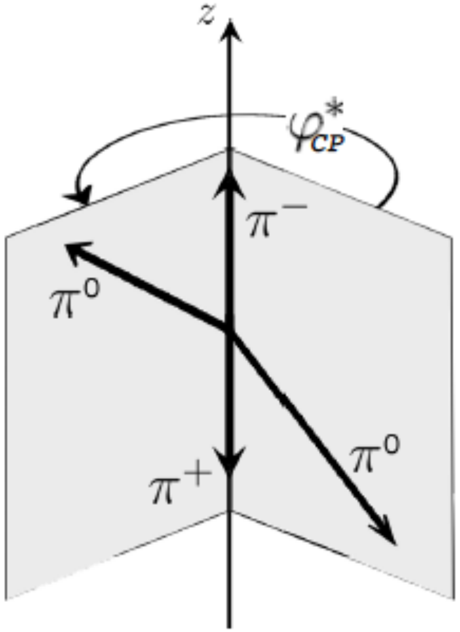


Boudjema, Godbole, Guadagnoli, Mohan 2015

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







BERGE, BERNREUTHER, KIRCHNER, 2015

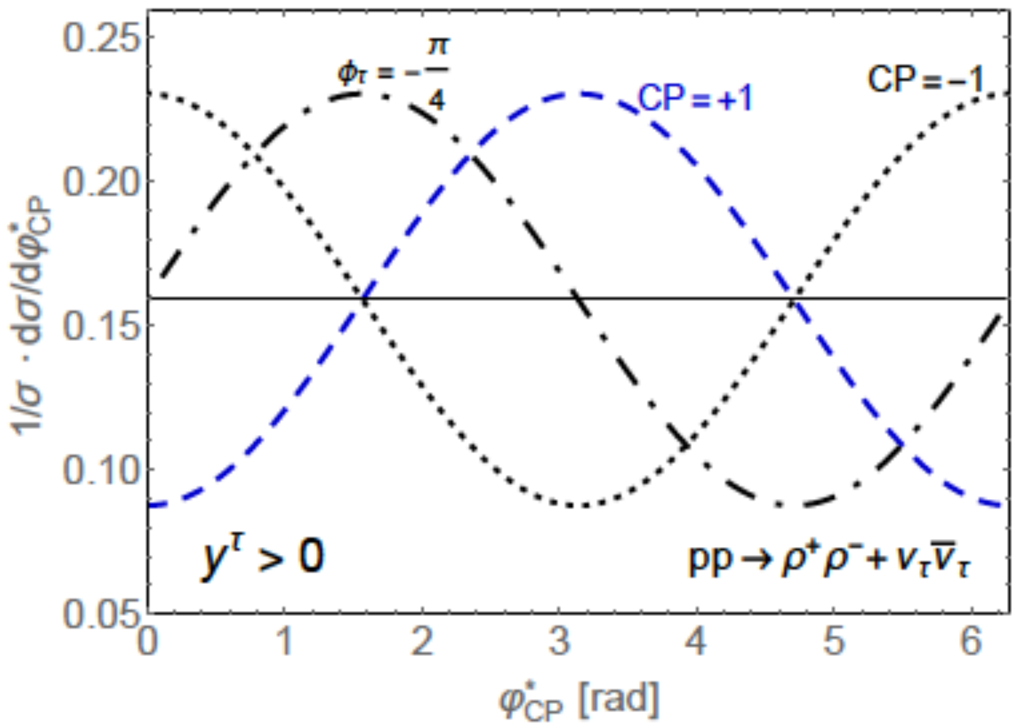


Illustration of φ^*_{CP} in the ρ decay-plane method as defined in (14) for $pp \to h^0 \to \tau^-\tau^+ \to \rho^-\rho^+ + 2\nu$.

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

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.

CP - what have ATLAS and CMS measured so far?

- Effective Lagrangian (ATLAS notation)

ATLAS, 1506.05669

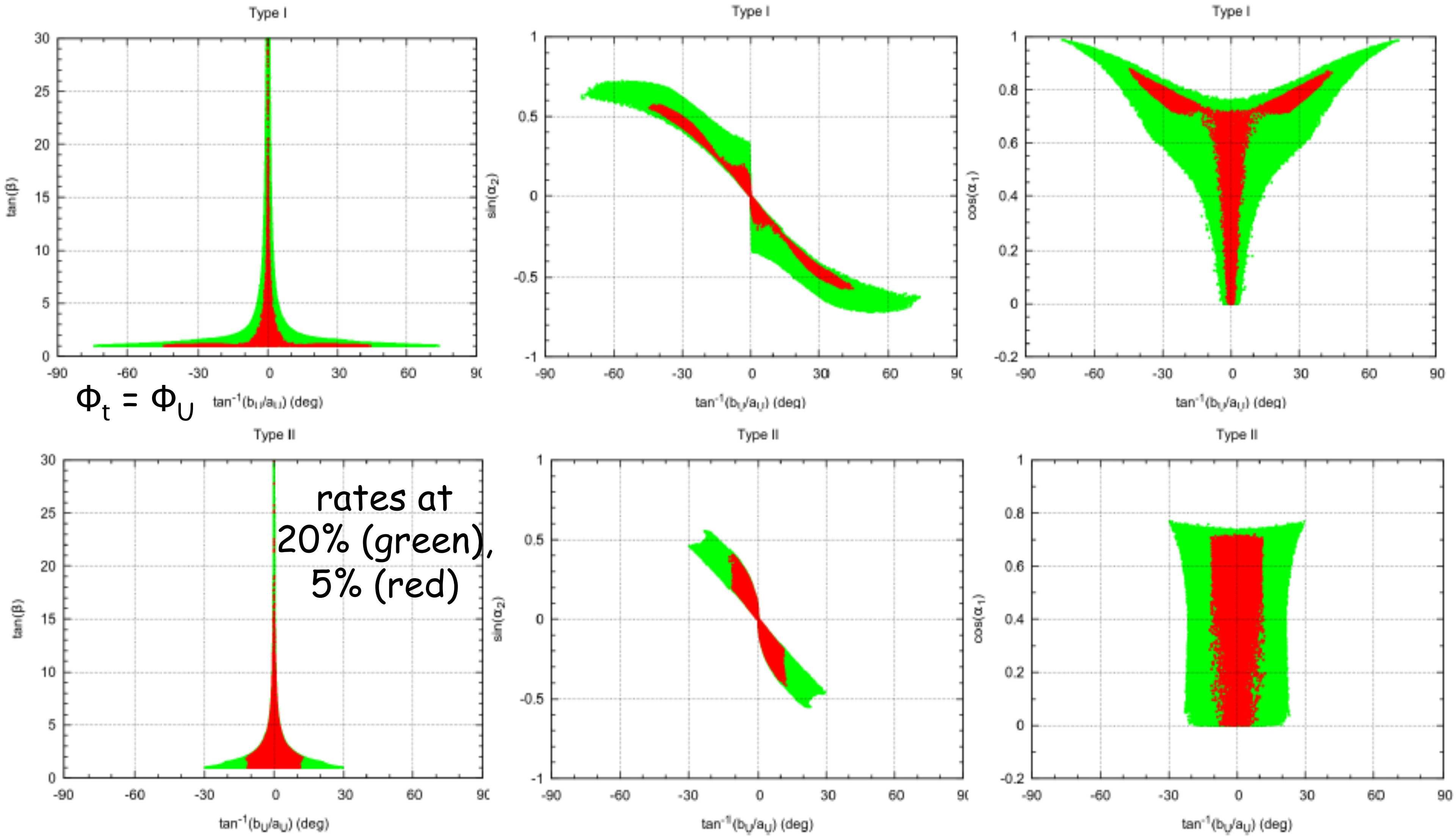
$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]\Big\} X_0$$

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{\rm v}{\Lambda}\kappa_{AVV} \quad \text{and} \quad \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{\rm v}{\Lambda}\kappa_{HVV}$$

Having all extra couplings compatible with zero does not mean CP-conservation!

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

Limits on Φ_t based on the rates only



Competitive for Type I but not for Type II

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 α_2. In fact if c_1=0 the particle seems to be a pure pseudoscalar but…