Impact of new experimental data on the C2HDM

Duarte Fontes

Institute for Theoretical Physics (ITP) Karlsruhe Institute of Technology (KIT)

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T. Biekötter, M. Mühlleitner, J. C. Romão, R. Santos and J. P. Silva

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- Why the C2HDM?

  1) We know that there must be physics beyond the Standard Model (SM)

  2) There is no fundamental reason for having only one scalar doublet

  3) If particles are added to the SM, strongly suppressed FCNC needs to be justified

In particular, the SM does not have enough CP violation

  - The Complex 2 Higgs Doublet Model (C2HDM) addresses all of this in a simple and consistent way, allowing a rich pheno.

[DF et al, 1711.09419]

- Yet, the pheno. of the C2HDM was thoroughly analyzed in 2017. Why a new analysis now?
  - Because of **new data**:

	2017	**2023**
h_{125}	LHC, 7/8 TeV	LHC, 13 TeV
Extra scalars	HiggsBounds 4.3.1	HiggsTools 1.1.3
EDM	8.7 x 10^{-29} e.cm	4.1 x 10^{-30} e.cm

  - What is the impact of the new data? In particular:
  - In 2017, the C2HDM had a fascinating scenario: h_{125} coupling in a { CP-even way to tops; CP-odd way to b or τ }

Is this scenario still possible now?

- The C2HDM is built by adding Φ_2 to the SM potential, imposing softly broken $\mathbb{Z}_2$ symmetry:

[Ginzburg, Krawczyk, Osland, 0211371]

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

with all parameters real except m_{12}^2 and λ_5 , whose phases in general lead to a CP-violating V

(Note: imposing CP conservation in V leads to an inconsistent model!)

[DF et al, 2103.05002]
[Lima, Logan, 2409.10603]

- The Higgs doublets are:

$$
\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix} \qquad v = \sqrt{v_1^2+v_2^2} = 246\text{GeV}
$$

- The angle β (such that $\tan\beta \equiv \frac{v_2}{v_1}$) diagonalizes the charged Higgses

- As for the neutrals:

$$
\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix} \quad \rho_3 = -\sin(\beta)\eta_1 + \cos(\beta)\eta_2
$$

with $m_1 < m_2 < m_3$, with one of the three fields being h_{125} ,

and
$$
R = \begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -(c_1s_2s_3+s_1c_3) & c_1c_3 - s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3+s_1s_3 & -(c_1s_3+s_1s_2c_3) & c_2c_3 \end{pmatrix}, \quad s_i = \sin\alpha_i, \quad c_i = \cos\alpha_i \; (i=1,2,3)
$$

- The Yukawa term: $\mathcal{L}_Y = -\sum_{i=1}^{3} \frac{m_f}{v} \bar{\psi}_f \left[c^e(h_i f f) + i c^o(h_i f f) \gamma_5 \right] \psi_f h_i$
  - $c^e(h_i f f)$ → **CP-even** like
  - $c^o(h_i f f)$ → **CP-odd** like
  - The $\mathbb{Z}_2$ symmetry is extended to the fermions to avoid FCNC at tree-level. There are four possible $\mathbb{Z}_2$ assignments, hence **four types of models**:
    - Denoting by Φ_u, Φ_d, and Φ_ℓ the doublet Φ_i (i= 1,2) that couples to up-type quarks, down-type quarks and charged leptons:

      - Type-I: $\Phi_u = \Phi_d = \Phi_\ell \equiv \Phi_2$;
      - Type-II: $\Phi_u \equiv \Phi_2 \neq \Phi_d = \Phi_\ell \equiv \Phi_1$;
      - Lepton-Specific (LS): $\Phi_u = \Phi_d \equiv \Phi_2 \neq \Phi_\ell \equiv \Phi_1$;
      - Flipped $\Phi_u = \Phi_\ell \equiv \Phi_2 \neq \Phi_d \equiv \Phi_1$.

    - The structure $c^e(h_i f f) + i c^o(h_i f f)\gamma_5$ in terms of the R matrix reads:

	u-type	d-type	leptons
Type I	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$
Type II	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - i t_\beta R_{i3}\gamma_5$	$\frac{R_{i1}}{c_\beta} - i t_\beta R_{i3}\gamma_5$
Lepton-Specific	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - i t_\beta R_{i3}\gamma_5$
Flipped	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - i t_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$

- The CP nature of h_{125}
  - h_{125} can have a mixed CP nature. So, we define: $c^e_f \equiv c^e(h_{125}ff)$, $c^o_f \equiv c^o(h_{125}ff)$

    CP-even like **CP-odd** like
  - Simplest case of CP mixture: $c^e_f c^o_f \neq 0$
    - Note: $\alpha_{h\tau\tau} = \tan^{-1} |c^o_\tau|/|c^e_\tau|$ will be particularly relevant
  - More interesting if h_{125} couples as CP-even to f and CP-odd to g : $\begin{cases} c^e_f c^o_f = 0 = c^e_g c^o_g \\ c^e_f c^o_g \neq 0 \end{cases}$
  - Since h_{125} couples as CP-even to the top, then we are looking for pure CP-odd like couplings to bottoms and/or taus: $c^o_b \simeq 1$ and/or $c^o_\tau \simeq 1$
  - With 2017 data, this was possible in some cases: [DF et al, 1711.09419]

Type	I	II	LS	Flipped
$h_1 = h_{125}$	$\times$	$\times$	$\checkmark$	$\checkmark$
$h_2 = h_{125}$	$\times$	$\checkmark$	$\checkmark$	$\times$
$h_3 = h_{125}$	$\times$	$\times$	$\checkmark$	$\times$

  - What happens with **2023 data**? We need to perform new scans

[for refs., cf. Biekötter et al, 2403.02425]

- Ranges:

One of the h_i is h_{125}. For the others, 30 GeV $\leq m_{H_i} < 1$ TeV.
$$\begin{cases} 580 \text{ GeV} \leq m_{H^\pm} < 1 \text{ TeV}, \text{ in T2 and Flipped} \\ 80 \text{ GeV} \leq m_{H^\pm} < 1 \text{ TeV}, \text{ in T1 and LS} \end{cases}$$

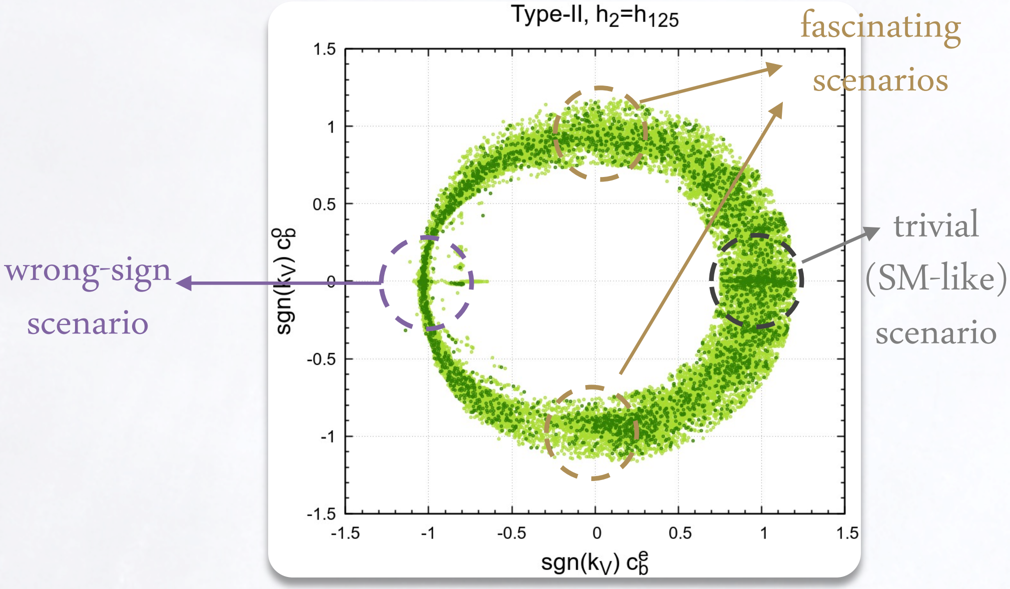
$0.8 \leq \tan\beta \leq 35$ $\quad -\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2}$ $\quad 0 \text{ GeV}^2 \leq \text{Re}(m_{12}^2) < 500000 \text{ GeV}^2$

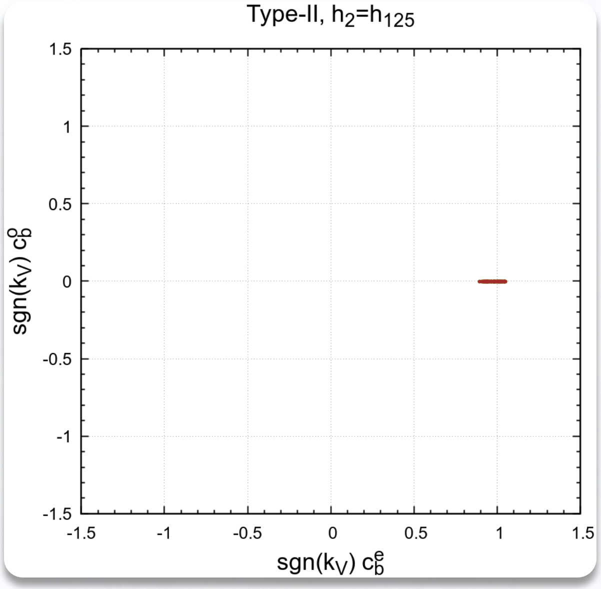
- Theoretical constraints:
  - Boundedness from below
  - Perturbative unitarity
  - Minimum globality
  - S, T, U

- Experimental constraints:
  - Concerning h_{125} : either LHC 7/8 TeV or LHC 13 TeV
  - Concerning extra scalars: either HB 4.3.1 or HT 1.1.3
  - Concerning eEDM: either 8.7 x 10^{-29} e.cm, 1.1 x 10^{-29} e.cm or 4.1 x 10^{-30} e.cm
  - Contraints from $\alpha_{h\tau\tau} = \tan^{-1}|c_\tau^o|/|c_\tau^e|$: either on or off

- Extra notes:
  - I will plot $\text{sgn}(k_V)c_f^o$ vs. $\text{sgn}(k_V)c_f^e$, as the signs of c_f^e and c_f^o have no absolute meaning
  - For each type, I will discuss the relevant $h_i = h_{125}$ cases

- Type II — the only viable option here was $h_2 = h_{125}$





Contraints for h_{125}: LHC, 7/8 TeV

Contraints for extra scalars: HiggsBounds 4.3.1

● EDM: 8.7 x 10^{-29} e.cm ● EDM: 1.1 x 10^{-29} e.cm

Contraints from $\alpha_{h\tau\tau}$: off

Contraints for h_{125}: LHC, 13 TeV

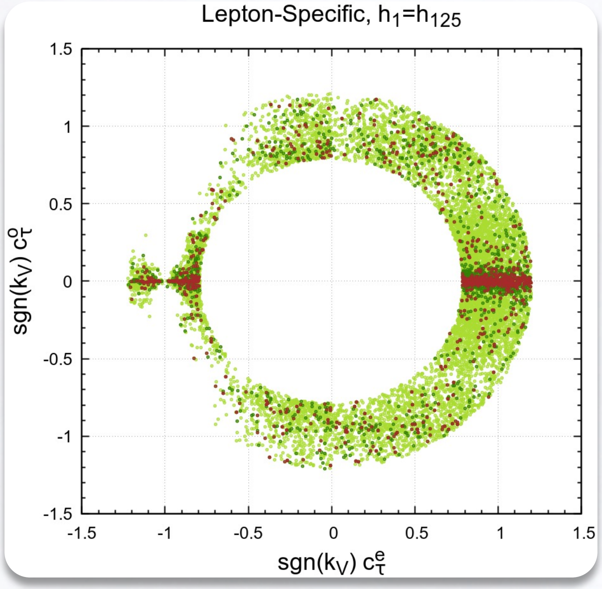
Contraints for extra scalars: HigssTools 1.1.3

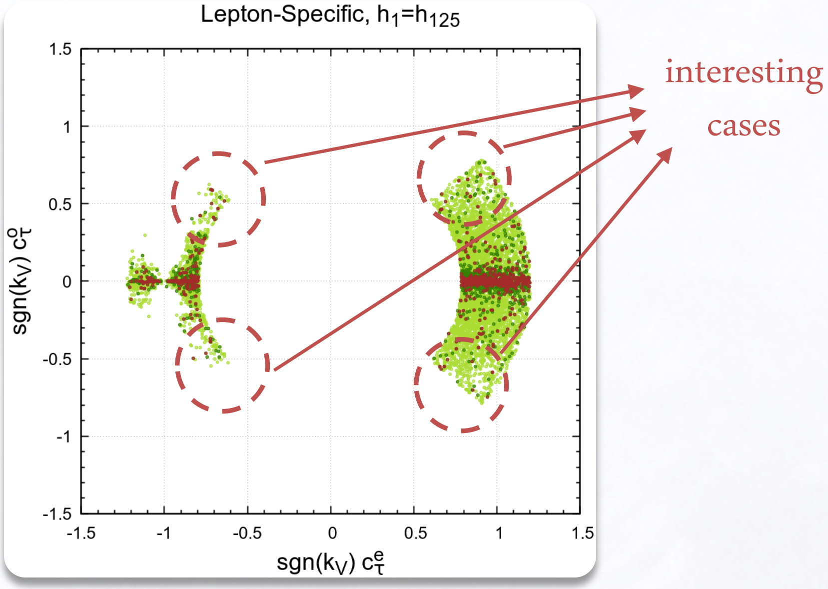
EDM: 4.1 x 10^{-30} e.cm

Contraints from $\alpha_{h\tau\tau}$: on

- The current data excludes any non-trivial scenario
- This is due to a combination of EDM and extra scalars

- Lepton-Specific, with $h_1 = h_{125}$





Contraints for h_{125}: LHC, 13 TeV

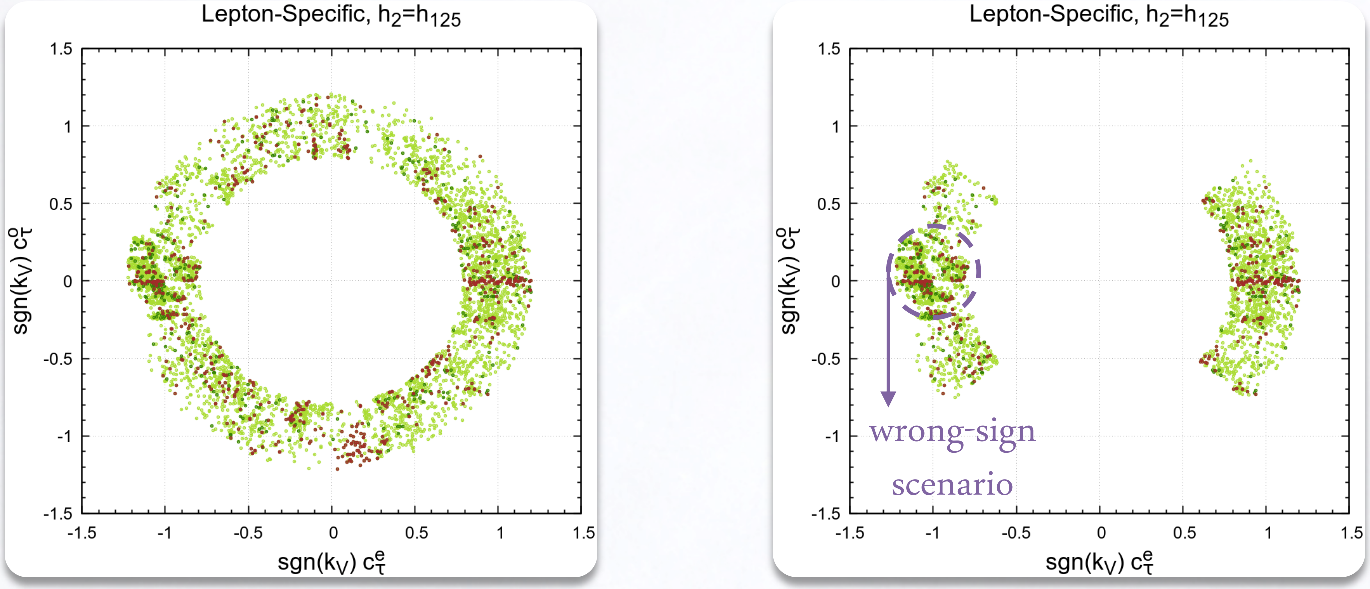
Contraints for extra scalars: HiggsTools 1.1.3

EDM: 8.7 x 10^{-29} e.cm   EDM: 1.1 x 10^{-29} e.cm   EDM: 4.1 x 10^{-30} e.cm

Contraints from $\alpha_{h\tau\tau}$: off   Contraints from $\alpha_{h\tau\tau}$: on

- The current data on the h_{125}, EDM and extra scalars still allows the fascinating scenario
- Yet, contraints from $\alpha_{h\tau\tau}$ prevent it
- Still, the interesting case $c_\tau^o \simeq c_\tau^e$ is still possible

- Lepton-Specific, with $h_2 = h_{125}$



Contraints for h_{125}: LHC, 13 TeV

Contraints for extra scalars: HiggsTools 1.1.3

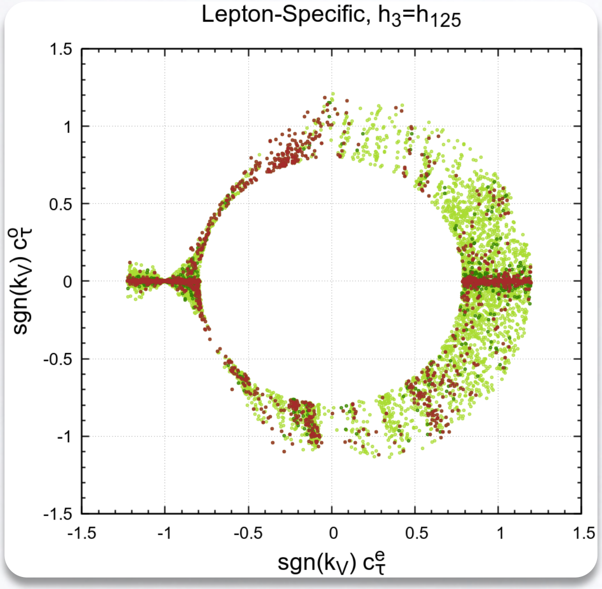
● EDM: 8.7 x 10^{-29} e.cm ● EDM: 1.1 x 10^{-29} e.cm ● EDM: 4.1 x 10^{-30} e.cm

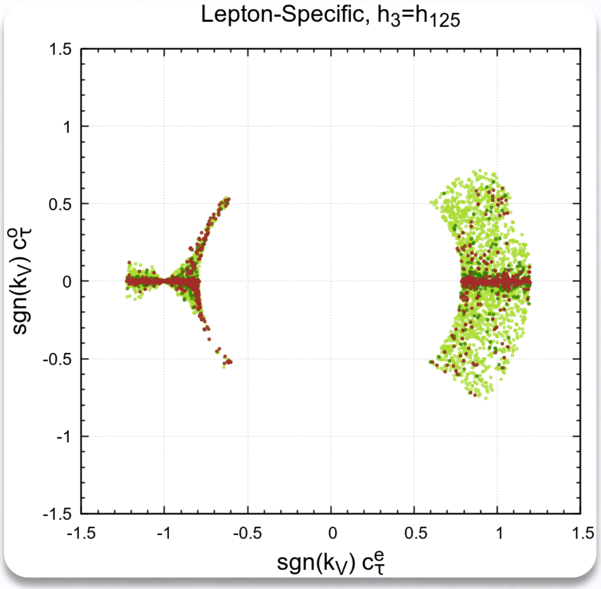
Contraints from $\alpha_{h\tau\tau}$: off

Contraints from $\alpha_{h\tau\tau}$: on

- The conclusions here are similar to those of the previous slide
- Note that, in both cases, the wrong-sign scenario is still allowed

- Lepton-Specific, with $h_3 = h_{125}$





Contraints for h_{125}: LHC, 13 TeV

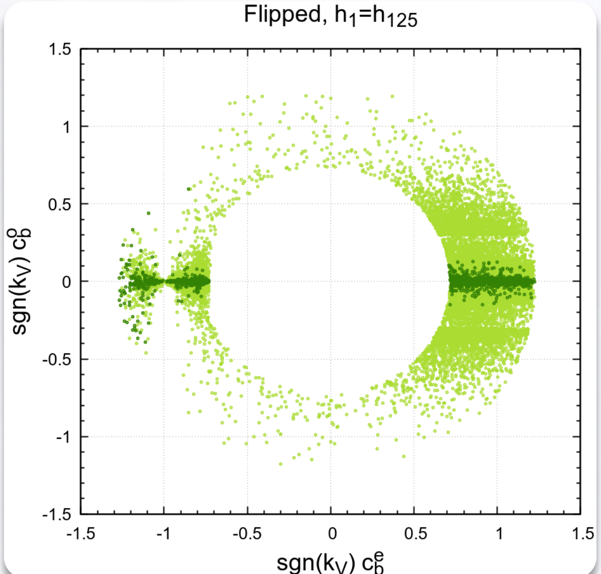
Contraints for extra scalars: HiggsTools 1.1.3

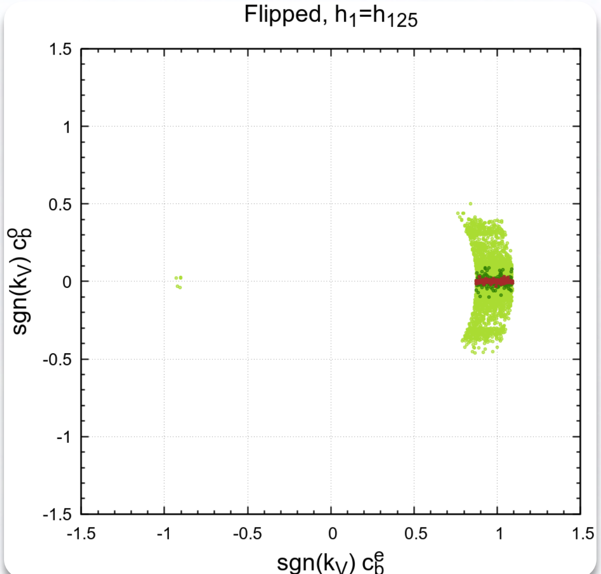
● EDM: 8.7 x 10^{-29} e.cm ● EDM: 1.1 x 10^{-29} e.cm ● EDM: 4.1 x 10^{-30} e.cm

Contraints from $\alpha_{h\tau\tau}$: off | Contraints from $\alpha_{h\tau\tau}$: on

- The conclusions here are similar to those of the previous two slides

- **Flipped** — the only viable option here was $h_1 = h_{125}$





EDM: 8.7 x 10^{-29} e.cm   EDM: 1.1 x 10^{-29} e.cm   EDM: 4.1 x 10^{-30} e.cm

Contraints for h_{125}: LHC, 7/8 TeV	Contraints for h_{125}: LHC, 13 TeV
Contraints for extra scalars: HiggsBounds 4.3.1	Contraints for extra scalars: HigssTools 1.1.3

- In this model, contraints from $\alpha_{h\tau\tau}$ are irrelevant
- Still, any interesting case is excluded, due to contraints from extra scalars
- New data on h_{125} leads to a decrease of the width of the ring

- The C2HDM is one of the simplest BSM models with one new CP-violating parameter
- The 2017 data still allowed for a fascinating scenario: h_{125} coupling in a { CP-even way to tops / CP-odd way to b or τ }
- New data essentially rules out that case. We now have:

Type	I	II	LS	Flipped
$h_1 = h_{125}$	$\times$	$\times$	τ	$\underline{\times}$
$h_2 = h_{125}$	$\times$	$\underline{\times}$	τ	$\times$
$h_3 = h_{125}$	$\times$	$\times$	τ	$\times$

$\times$: already with 2017 data, it was not possible to have large the fascinating scenario

$\underline{\times}$: with 2017 data, it was possible to have the fascinating scenario, but not with 2023 data

τ : the fascinating scenario is excluded, and large c_f^o are constrained by $\alpha_{h\tau\tau}$

- Lepton-specific is the only model where some interesting CP cases persist (as well as the wrong-sign case)
- The possible amount of CP-violation is then limited ultimately by $\alpha_{h\tau\tau}$
- Is the fascinating scenario still possible in other models?