Quantifying CP-Violation.

in the Complex Two Higgs Doublet Model

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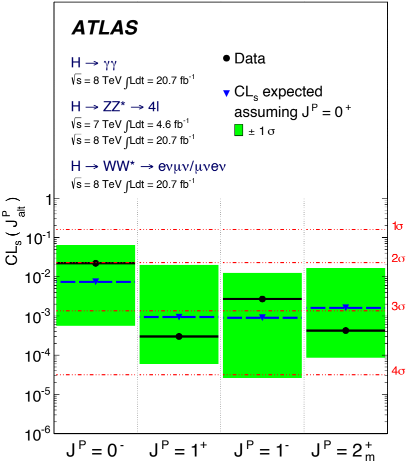
The Higgs Boson

- Spin and parity of the Higgs boson have been probed shortly after its discovery.
- The C and CP nature have only been established assuming that h_{125} is a CP eigenstate.



[1307.1432, ATLAS]

Quantifying CP-Violation – Experiment

Differential Distributions

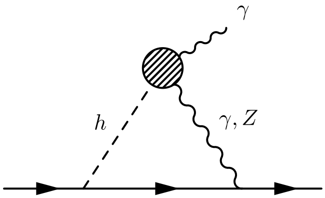
- Current limits on CP violating couplings to gauge bosons.
  [1707.00541, CMS]
  - These are ~ 0 in simple CP-violating BSM models.

$$h_{125} = R_{\mathrm{H}} H + R_{\mathrm{A}} A \quad \Rightarrow \quad c(h_{125} VV) = R_{\mathrm{H}} c(h_{\mathrm{SM}} VV) + \mathrm{NLO}$$

- This could be adressed by using the $H \to \tau\bar{\tau}$ channel.
  [1510.03850, Berge et.al.]

$$c(h_{125}\tau\bar{\tau}) = a(R_H) + i\gamma^5 b(R_A)$$

Electric Dipole Moments



- Electric Dipole Moments (EDMs) of fermions are CP-violating quantities.
- Good limits on the electron EDM [1310.7534, ACME]

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

and reliable theoretical prediction [1311.4704, Abe et.al].

Coexisting Decay Modes

If a second Higgs boson was discovered, the simultaneous observation of certain decays could establish CP-violation using only inclusive measurements. [1506.06755, Fontes et.al.]

$$\text{i.e.} \quad H_1 \to ZZ \quad \& \quad H_2 \to ZZ \quad \& \quad H_2 \to H_1 Z$$

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$$\text{i.e.}\quad h_{125} \to ZZ \quad \& \quad H_2 \to ZZ \quad \& \quad H_2 \to h_{125} Z$$

Quantifications of CP-Violation

Experiment

- direct limits from differential distributions
  - current: $h_{125} \to ZZ^* \to 4l$
  - future: $h_{125} \to \tau\tau$
- fermionic EDMs
- decays of a second Higgs boson

Quantifying CP-Violation – Theory

The Complex 2HDM

The C2HDM is a minimal model with a CP-violating Higgs sector.
Two parameters can be complex:

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

but only one of them is independent

$$\text{Im}(m_{12}^2) = \text{Im}(\lambda_5)v_1v_2\,.$$

$\Rightarrow$ $\text{Im}(\lambda_5)$ or $\arg(\lambda_5)$ as a measure of CP-violation

Pseudoscalar Admixture

In the C2HDM the two neutral CP-even doublet states $\rho_{1,2}$ mix with the non-Goldstone pseudoscalar A as

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 = A \end{pmatrix} .$$

Construct quantifications of CP-violation out of R
(and $\tan\beta = v_2/v_1$)?

Jarlskogg-like Invariants – Gauge Sector

The simplest variable is [Mendez, Pomoral, 1991]

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

which quantifies CP-violation in the Higgs-gauge-sector.

Jarlskogg-like Invariants – Fermion Sector

The top Yukawa coupling is:

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

which is CP-violating if $R_{i2}R_{i3} \neq 0$.

Jarlskogg-like Invariants in the C2HDM

This gives us 3 invariants normalized $\in [0,1]$:

$$\xi_V = 27 \prod_i c(H_i VV)^2 \,,$$
$$\gamma_t = 1024 \prod_i (R_{i2} R_{i3})^2 \,,$$
$$\gamma_b = 1024 \prod_i (R_{i1} R_{i3})^2 \,.$$

These quantify CP-violation in the gauge, u-type and d-type/lepton sector, respectively (for a type II Yukawa).

Quantifications of CP-Violation

Experimental

- direct limits from differential distributions
  - current: $H \to ZZ^* \to 4l$
  - future: $H \to \tau\tau$
- fermionic EDMs: d_e
- decays of a second Higgs boson: $H_\downarrow \to ZZ$, $H_\downarrow \to Zh_{125}$

Theory

- phases of the Lagrangian: $\arg \lambda_5$, $\mathrm{Im}(\lambda_5)$
- Jarlskogg-like invariants: ξ_V, γ_t, γ_b

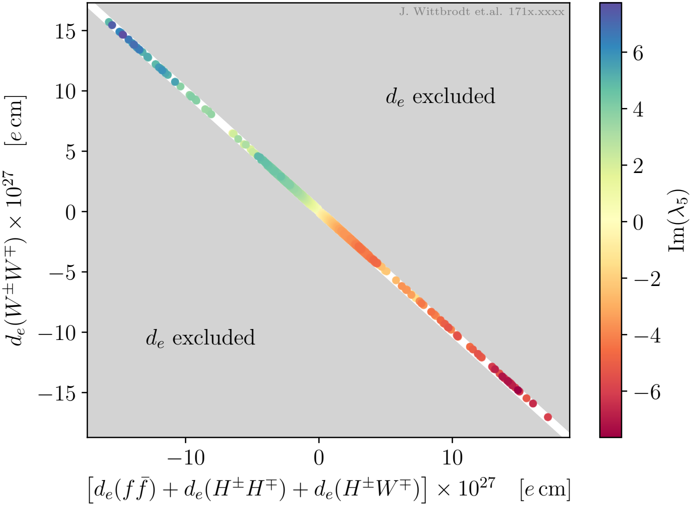
Phenomenology of CP-Violation

Parameter Scan in the C2HDM

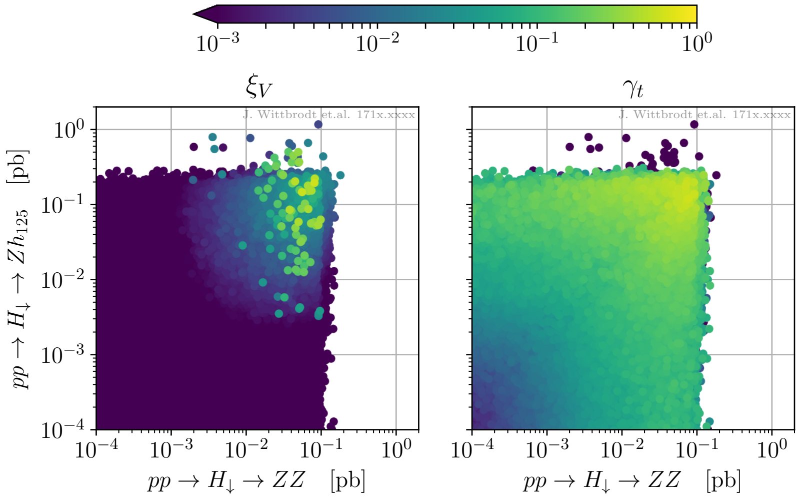
Search for allowed C2HDM parameter points using ScannerS
[1703.07750, Mühlleitner, JW et.al.]

- bounded and absolutely stable tree-level vacuum
- perturbative unitarity
- electroweak precision constraints (STU)
- B physics constraints
- Higgs search exclusion bounds (HiggsBounds)
- Higgs boson signal strengths
- electron EDM

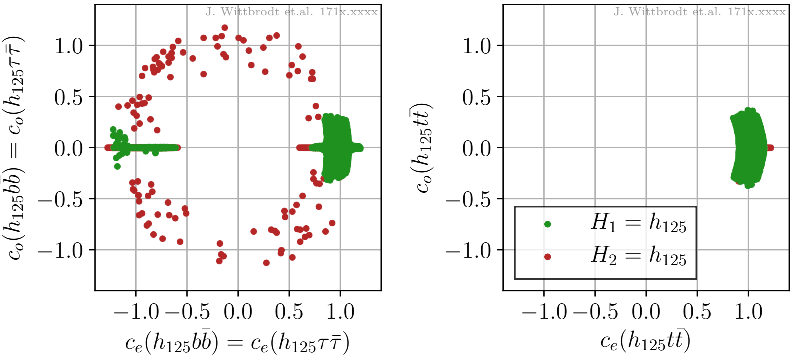
Constraints from EDMs – Type II



Coexisting Decay Modes – Type II



Large Pseudoscalar Yukawas – Type II



$$c(h_{125}f\bar{f}) = c_e(h_{125}f\bar{f}) + i\gamma^5 c_o(h_{125}f\bar{f})$$

Conclusion

- 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 h_{125} might be observable at LHC.

Outlook

- CP-violation in Type II Yukawa sectors is more strongly constrained than in the other types. [171x.xxxx, Fontes, JW et.al.]
- The C2HDM can provide an $\mathcal{O}(\pi/2)$ CP-phase for EW-Baryogenesis. [171x.xxxx, Basler, JW et.al.]

Thanks for your attention.

C2HDM Yukawa couplings

	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	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
lepton-specific	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
flipped	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$