Probes of CP-violating Higgs couplings and their impact on baryogenesis

Marco Menen (Leibniz University Hanover / PTB Braunschweig)

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Based on: Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein [2202.11753]

And: Bahl, Fuchs, Hannig, MM (in preparation)
Outline & Motivation

The road so far:

➢ CP structure of the discovered Higgs boson still subject of investigation
➢ Most stringent constraints on CP violation for the HVV couplings ATLAS ‘21, ATLAS ‘22
➢ CP Yukawa couplings comparably unconstrained ($\alpha \lesssim 45^\circ$ @95% C. L.) CMS ‘21

Importance of CP violation:

➢ BSM CP violation needed to explain observed baryon asymmetry of the universe
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Probing the CP structure of Higgs couplings:

- Genuine CP-odd observables
- Total rate information
- Kinematic distributions
- Electric dipole moments
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Probing the CP structure of Higgs couplings: Part I

➢ Genuine CP-odd observables
➢ Total rate information
➢ Kinematic distributions
➢ Electric dipole moments

High-energy physics

Low-energy physics
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Importance of CP violation:

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Probing the CP structure of Higgs couplings:

Part II

➢ Genuine CP-odd observables
➢ Total rate information
➢ Kinematic distributions
➢ Electric dipole moments

High-energy physics
Low-energy physics
Free parameters:

- “Higgs characterisation model”: Higgs $H$ assumed to be mixed CP state
- Yukawa coupling: $\mathcal{L}_{\text{Yuk}} = - \sum_f \frac{g_f}{\sqrt{2}} \bar{\psi}_f (c_f + i \gamma_5 \tilde{c}_f) \psi_f \phi$
- SM obtained for $c_f = 1, \tilde{c}_f = 0$
- Effective couplings for $Hgg$ and $H\gamma\gamma$ possible (Part II)

Effects on signal rates:

- Higgs decay into fermions: $\mu_{Hff} = \frac{\Gamma(\phi \to f\bar{f})}{\Gamma_{SM}(H_{SM} \to f\bar{f})} \sim c_f^2 + \tilde{c}_f^2$
- Higgs-top coupling mainly constrained by $\mu_{ggH}$ and $\mu_{H\gamma\gamma}$ (Part II)

Artoisenet et al. ’13
Bahl et al. ’20
Higgs rate measurements:

- HiggsSignals2 used for analysing rate measurements vs BSM models [Bechtle et al. ‘20]
- Data: Combined Run 1 measurement, 31 measurements from Run 2
- Additionally: Latest $H \rightarrow c\bar{c}$ and $H \rightarrow \mu\bar{\mu}$ measurements [CMS ‘20, ATLAS ‘22]

Note: Code has been updated to HiggsTools [Bahl et al. ‘22]
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CP-odd measurements:

- Dedicated CP-analysis in $H \rightarrow \tau\bar{\tau}$ by CMS & ATLAS [CMS ’21, ATLAS ’22]
- Angular distribution of $\tau$ decay products as CP-odd observable

Kinematic distributions:

- Can be used to propose new observables (Part II)
Testing BSM theories with EDMs

- BSM theories with additional CP violation predict large EDMs
- EDM measurements set complementary constraints

Review: Pospelov, Ritz ‘05
See also: Brod et al. ‘22
Electron Electric Dipole Moment (eEDM)

Testing BSM theories with EDMs

- BSM theories with additional CP violation predict large EDMs
- EDM measurements set complementary constraints

Impact of the eEDM:

- EDM with the lowest theoretical uncertainty
- Upper limit: $|d_e| < 1.1 \times 10^{-29} \text{ e cm (90\% CL)}$
- Leading contribution from 2-loop Barr-Zee diagrams:

$$\left| \frac{d_e}{d_e^{\text{ACME}}} \right| = c_e (870.0 \tilde{c}_t + 3.9 \tilde{c}_b + 3.4 \tilde{c}_\tau + \cdots ) + \tilde{c}_e (610.1 c_t + 3.1 c_b + 2.8 c_\tau + \cdots - 1082.6 c_V )$$

Brod et al. ‘13, Altmannshofer et al. ‘15, Panico et al. ‘18, Altmannshofer et al. ‘20

Review: Pospelov, Ritz ‘05  See also: Brod et al. ‘22

ACME ‘18
Update (2022): JILA ‘22
Electroweak baryogenesis (EWBG)

Process of baryogenesis:

➢ Expanding bubbles of broken symmetry start to form
➢ CP violation at bubble wall leads to baryon asymmetry in the broken phase

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- Expanding bubbles of broken symmetry start to form
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Current status:

- Competing approaches: perturbative (VIA) and semi-classical
- Large theoretical uncertainties and differences between them
- Choose most optimistic benchmark for upper limit of BAU:

\[
\frac{Y_B^{\text{VIA}}}{Y_B^{\text{obs}}} = 28\bar{c}_t - 11\bar{c}_\tau - 0.2\bar{c}_b - 0.1\bar{c}_\mu - \ldots
\]

Reviews: Krauss et al. ‘99, Cline ‘06, Morrissey et al. ‘12, Bödeker et al. ‘20

Riotto ‘98, Kainulainen et al. ‘02

Cline, Laurent ‘21, Postma et al. ‘22

Fuchs et al. ‘20, Shapira ‘21
 Collider bounds dominated by $H \rightarrow \tau \tau$

**CP-analysis**

$\tau$-Yukawa coupling in earlier works: de Vries et al. ’17, Fuchs et al. ’20, Shapira ’21, Alonso-Gonzalez et al. ’21
Collider bounds dominated by $H \to \tau\tau$

CP-analysis

$\frac{d_e}{d_e^{\text{ACME}}} \propto |\tilde{c}_\tau|$

$\tau$-Yukawa coupling in earlier works: de Vries et al. ‘17, Fuchs et al. ‘20, Shapira ‘21, Alonso-Gonzalez et al. ‘21
τ-Yukawa CP structure: LHC, eEDM, BAU

From: MM et al. ‘22

Collider bounds dominated by $H \to \tau\tau$

CP-analysis

\[
d_{e}/d_{e}^{\text{ACME}} \propto |\tilde{c}_\tau|
\]

\[
Y_{B}^{\text{VIA}} / Y_{B}^{\text{obs}} \propto \tilde{c}_\tau
\]

\[
\tau\text{-Yukawa coupling in earlier works: de Vries et al. ‘17, Fuchs et al. ‘20, Shapira ‘21, Alonso-Gonzalez et al. ‘21}
\]

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Collider bounds dominated by $H \rightarrow \tau \tau$

CP-analysis

\[ d_e / d_e^{ACME} \propto |\tilde{c}_\tau| \]

\[ Y_B^{VIA} / Y_B^{obs} \propto \tilde{c}_\tau \]

New eEDM limit: Option for $\tau$ as sole BAU source borderline

From: MM et al. ’22

LHC 90% CL
eEDM 90% CL
$Y_B^{VIA} / Y_B^{obs}$

$Y_B^{VIA} / Y_B^{obs} \equiv R_Y \leq 3.2$ as optimistic, upper limit

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t-Yukawa CP structure: LHC, eEDM, BAU

From: MM et al. ’22

\[ R_Y \leq 3\% \]

Only small amounts of \( Y_B \) realizable

eEDM is limiting factor for CP-odd Yukawa
t-Yukawa CP structure: LHC, eEDM, BAU

eEDM is limiting factor for CP-odd Yukawa

Only small amounts of $Y_B$ realizable

Free $e$-Yukawa coupling: Bounds from eEDM completely vanish

$c_t \in [0.86, 1.04]$

$c_e \in [0.8, 1.2]$

$c_e \in [0, 2]$
**CP observables from boosted classifiers**

**General strategy:**

- Exploit full kinematic information by using boosted classifiers
- Identify observables with most sensitivity to CP violation
- Goals: Experimental analysis with found observable / extend STXS binning

**Our approach:**

- Free effective Higgs-gluon coupling $c_g, \tilde{c}_g$
- Train on $c_g^2, \tilde{c}_g^2$ and interference events in ggF + 2 jets
- Compare classifiers to traditional CP observable $\Delta \phi_{jj}$

Based on: Bhardwaj et al. ‘21 (CPV in HVV couplings)

Bahl, Fuchs, Hannig, MM (in preparation)

ATLAS ‘21
Can constrain $\tilde{c}_g \in [-0.25, 0.25]$ @ 68% C.L. $\Rightarrow \tilde{c}_t \in [-0.25, 0.25]$

Best existing limit: $\tilde{c}_t \in [-0.4, 0.4]$ (in VBF-like region + ttH)  CMS '21
Conclusions

- LHC can probe CP structures of individual Higgs couplings

- Potential of $\tau$ to be sole and viable EWBG source reduced to marginal coupling range by latest eEDM results

- EDMs put strong constraints on CP-violating couplings, but the constraints can be lifted by cancellations

- Exploitation of full information needed (kinematics, channels, low-energy probes) $\rightarrow$ machine learning as powerful tool

More results: MM et al. ‘22 [2202.11753] + stay tuned for upcoming study
Backup
Motivation

1. Baryon number violation
   - Not observed, but realizable in the SM

2. Charge (C) and charge-parity (CP) violation
   - Observed in the decay of neutral K-mesons in 1964
   - CP violation in the SM is not sufficient to explain BAU

3. Deviation from thermal equilibrium
   - Electroweak symmetry breaking (EWSB) has to be strongly first order, unfulfilled for $m_H = 125$ GeV

$\frac{m_H}{m_H} < 80$ GeV needed
Backup: EWSB Transition

1\textsuperscript{st} Order:
\[ \langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Discontinuous} \]

2\textsuperscript{nd} Order:
\[ \langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Continuous} \]

Talk at CLIC from Jose Miguel No
\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{D} \frac{1}{\Lambda^{D-4}} \left( \sum_{i} C_{i}^{D} \mathbf{O}_{i}^{D} \right) \]

Dim 5: \( O_{\nu\nu}^{5} = (\bar{\phi}^{\dagger}L_{p})^{T} C (\bar{\phi}^{\dagger}L_{r}) \rightarrow \text{Lepton number violation} \)

e.g.

Dim 6: \( O_{e\phi}^{6} = (\phi^{\dagger}\phi)(\bar{L}_{p}e_{r}\phi) \rightarrow \text{Modified Higgs-lepton coupling} \)

\[ \Lambda \geq \nu = 246 \text{ GeV} \]
Backup: Higgs Characterization Model

1306.6464

• Parameterize $ggH$ and $H\gamma\gamma$ interactions in terms of Yukawa modifiers:

$$\mu_{ggH} = 1.11 c_t^2 + 2.56 \tilde{c}_t^2 - 0.12 c_t c_b - 0.20 \tilde{c}_t \tilde{c}_b + 0.01 c_b^2 + 0.01 \tilde{c}_b^2$$

$$\mu_{H\gamma\gamma} = 0.08 c_t^2 + 0.18 \tilde{c}_t^2 + 1.62 c_V^2 - 0.71 c_V c_t + O(\leq 10^{-3})$$

• Analogously for associated production modes ($ggZh$, $ttH$, $tH$, $tWH$)

2007.08542
Backup: $\tau$-Yukawa CP analysis

Dedicated CP analysis by CMS and ATLAS:

$2110.04836$, $2212.05833$

CP mixing angle: $\alpha^{H\tau\tau} = \arctan\left(\frac{\bar{c}_\tau}{c_\tau}\right)$

Angle between $\tau$ decay planes: $\phi_{CP}$

\[
d\Gamma(H \rightarrow \tau^+\tau^-) \sim 1 - \cos(\phi_{CP} - 2\alpha^{H\tau\tau})
\]

$1410.6362$

→ Direct CP constraints
Backup: $\tau$-Yukawa CP analysis

Determination of CP mixing angle $\alpha_{H\tau\tau}$

- CMS Simulation
- 13 TeV
- $\tau^+\tau^- \rightarrow \pi^+\pi^-$
- $p_T > 33$ GeV

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Backup: EDM contributions

Brod, Stamou ´18
Backup: Baryogenesis

- CP violating interactions at bubble wall lead to chiral asymmetry
- Strong sphaleron process: Washout in quark sector
- Chiral asymmetry diffuses to symmetric phase, more efficient for leptons
- Weak sphaleron process: Baryon number violation from symmetric phase
- Baryon number violation frozen in by bubble wall
Backup: VIA vs. WKB

CP violating source terms vanishes in VIA at first order
Effects at higher orders currently under investigation  Postma et al. ‘22
**τ-Yukawa CP structure: LHC constraints**

Global signal rate fit with HiggsSignals:

\[ c_f^2 + \tilde{c}_f^2 \propto \frac{\Gamma(\phi \to ff)}{\Gamma(H^{SM} \to ff)} \]

+ CMS CP analysis:

\[ \alpha^H_{\tau\tau} = \arctan\left(\frac{\tilde{c}_\tau}{c_\tau}\right) = (-1 \pm 19)^\circ \text{ at } 1\sigma \]

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)

\[ \tau = \arctan(\frac{c_\tau}{\tilde{c}_\tau}) \]

CMS ‘21

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t,b-Yukawa CP structure: LHC constraints

\[ \text{ggH} \propto 1.11c_t^2 + 2.56\tilde{c}_t^2 \rightarrow \text{ellipsoid} \]
\[ H\gamma\gamma \propto 1.62c_V^2 - 0.71c_Vc_t \rightarrow \text{cut-off} \]

Well understood: Bahl, Bechtle, Heinemeyer, Katzy, Klingl, Peters, Saimpert, Stefaniak, Weiglein (2020)

ggH: Small deformation

H \rightarrow bb: Ring
Backup: Additional results

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)
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Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)
t & b complementarity

Fuchs, Losada, Nir, Viernik (2020) found $R_Y \leq 0.12$ for SM-like CP-even parameters

Cancellations possible:
\[
\left| \frac{d_e}{d_e^{\text{ACME}}} \right| \sim 870.0 \tilde{c}_t + 3.9 \tilde{c}_b
\]

$R_Y \leq 42\%$

eEDM no longer limiting factor

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)
\( \tau \ & \ t / \tau \ & \ b \) complementarity

\[ R_Y \leq 6.9 \]

Cancellations can enhance maximally allowed baryon asymmetry

eEDM no longer limiting factor
Constraints of $\mu$-Yukawa coupling

$H \rightarrow \mu\mu$ observed ($3\sigma$): ATLAS Collaboration (2021) & CMS Collaboration (2021)

LHC constraints already way stronger than eEDM
Impact of $e$ in a global fermion phase

Shared phase $c_f \equiv c_t = c_b = c_\tau = \cdots$

$\left| \frac{d_e}{d_e^{\text{ACME}}} \right| \propto c_e (870.0 \bar{c}_t) + \bar{c}_e (610.1 c_t - 1082.6 c_V)$

$R_y \leq 8\%$

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)
Flowchart ggF2j study

Bahl, Fuchs, Hannig, MM (in preparation)

X = ggF2j, VBF

Classifier X-production

$|\mathcal{M}_{\text{even}}|^2$

Classifier $P(|\mathcal{M}_{\text{even}}|^2)$

Limits X-production

Classifier $P(\text{Interf.})$

$|\mathcal{M}_{\text{odd}}|^2$

Interf.
Limits ggF2j study – VBF region

Bahl, Fuchs, Hannig, MM (in preparation)

\[ \Delta \chi^2 \]

\[ \Delta \phi_{jj} \]

\[ \mathcal{L} = 139 \text{ fb}^{-1} \]

VBF region

Work in progress
Variable importance interf. ggF2j study

Bahl, Fuchs, Hannig, MM (in preparation)

Plots made with: Shapley
Variable importance interf. ggF2j study

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