

Searches for CP violation in the Higgs sector with CMS



Andrea Cardini^{*}

on behalf of the CMS collaboration * Deutsches Elektronen-Synchrotron (DESY)





CP violation



- Matter-antimatter had an asymmetry of ~10⁻⁹ at the stage of baryogenesis leading to the richness of matter in the known Universe
- Sakharov conditions to explain the baryon asymmetry in the Universe (BAU):
 - > Baryon number violation
 - C and CP violation
 - > Deviation from thermal equilibrium
- No predicted CP-violating interactions in the Higgs sector of the Standard Model
 - > CP-odd Higgs couplings to fermions or vector bosons could hint to physics beyond the SM
 - > Search for Higgs boson anomalous couplings



Designdoppel GbR - Anna Penkner and Renate Pommerening



CP violation in the Higgs sector

sseudo experiments



- Higgs boson predicted to have spin-parity $0^+ \rightarrow$ direct coupling to Z and W bosons
- CP violation in the Higgs sector:
 - > HVV couplings (V= Z,W bosons)
 - studied in 4 lepton final state / VBF production
 Phys. Rev. D 104 (2021) 052004 arXiv:2205.05120

Pure CP odd excluded already with Run 1 data \rightarrow search for anomalous couplings

- > Yukawa coupling of Higgs to fermions
 - gg → H +jets: effective Higgs-gluon coupling via top quark loop
 Phys. Rev. D 104 (2021) 052004
 - $gg \rightarrow ttH$: direct Yukawa coupling of Higgs to top quarks
 - arXiv:2208.02686
 - $H \rightarrow \tau \tau$ decays: exploit spin correlation between tau leptons and their decay products
 - <u>JHEP 06 (2022) 012</u>

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Phys. Rev. D 89 (2014), 092007





- Investigating CP violation in HVV with an EFT approach
 - Amplitude for Higgs coupling to two spin 1 particles (VV= WW, ZZ, Zγ, γγ, gg etc.) with operators up to dimension 6



- Effect on cross-section parametrized as the fractional contribution of the anomalous coupling to the total cross-section
- Theoretical approach includes also Hyy and Hgg with tree level coupling being set to 0





- Higgs direct and effective couplings to vector bosons studied both in production and decay
- Decay:
 - > Target process: $H \rightarrow VV \rightarrow 4$ leptons
 - > Uses kinematics of leptons in the final state
- Production:
 - > Target process: Vector Boson Fusion (VBF)
 - Higgs CP nature affects kinematics of jets from the initial state
 - > Studied in Higgs decays to ττ, 4 leptons and γγ





CP violation in $H \rightarrow 4$ leptons





> Analysis with full Run 2 also targets interference terms of anomalous couplings with other hypothesis using MVA classifiers

First process used to investigate CP violation in the Higgs sector

$$\mathcal{D}_{\mathrm{int}}\left(\mathbf{\Omega}
ight) = rac{\mathcal{P}_{\mathrm{int}}\left(\mathbf{\Omega}
ight)}{2\sqrt{\mathcal{P}_{\mathrm{sig}}\left(\mathbf{\Omega}
ight) \ \mathcal{P}_{\mathrm{alt}}\left(\mathbf{\Omega}
ight)}}$$

g CMS 250 data 200 $ZZ/Z\gamma^*$ Events / 2 GeV Z+X 150 100 50 100 120 m₄ℓ(GeV)

Phys. Rev. D 104 (2021) 052004







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Combination with off-shell H \rightarrow 2l2v/4 lepton



- Off-shell Higgs production can provide additional sensitivity to anomalous couplings
 - > CP-odd anomalous coupling constrained between [-4.6,11] × 10⁻⁴ at 95% CL





VBF production with $H \rightarrow \tau\tau$ decays



- Higgs decays to tau leptons can be used as a probe both for CP violation in Higgs decays and in combination with H → 4l for the search of CP violation in production
 - > When studying Higgs CP in production the $H \rightarrow \tau\tau$ vertex is kept SM-like
 - The azimuthal angle between jets coming from the initial state offers sensitivity to the Higgs CP quantum number



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• Higgs Yukawa interaction can be parametrized as follows:

>
$$\mathscr{L}_{Y,f} = -\frac{m_f}{v} \bar{\psi}_f (\kappa_f + i\gamma^5 \tilde{\kappa}_f) H \psi_f$$

- > Higgs direct coupling to top quarks investigated in ttH and tH production
 - CP-odd anomalous coupling affects top quark(s) kinematics
 - Investigated with MVA techniques
- > Higgs coupling to τ leptons investigated in decays via τ spin correlation
 - CP mixing encoded in $\alpha^{H\tau\tau}$:
 - $\kappa_{\tau} = \sqrt{\mu^{\tau\tau}} \cos\left(\alpha^{H\tau\tau}\right)$
 - $\bar{\kappa}_{\tau} = \sqrt{\mu^{\tau\tau}} \sin \left(\alpha^{H\tau\tau} \right)$
 - Mixing angle can be accessed via the angle between τ decay planes



 $^{\rm M}$



CP violation in Higgs-top couplings





- Top quark loop has leading contribution to ggH effective coupling

 → simultaneous fit of CP-odd contribution ggH and ttH
 production
 - Combination performed under hypothesis that ggH loop is dominated by top quark

- Higgs couplings are proportional to the mass \rightarrow enhanced coupling with the top quark \rightarrow target ttH and tH production
- Htt coupling CP structure was probed in the H \rightarrow WW, $\tau\tau$ (multilepton) $\gamma\gamma$ and ZZ decays





CP violation in $H \rightarrow \tau \tau$ decays





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CP-even/odd couplings









- Higgs boson couplings have been investigated looking for CP-odd contributions which would be signs of new physics
 CMS Supplementary
- Exclusion limits for pure CP-odd Higgs couplings:
 - > HVV couplings: $|f_{a3}| < O(10^{-3})$ at 95% CL in combination with off-shell production
 - > Htt: $|f_{CP}^{Htt}| < 0.55$ at 68% CL
 - Hττ: tan (α^{Hττ}) < 0.36 at 68% CL</p>
- All analyses exclude pure CP-odd hypothesis and agree with SM prediction
- Promising future for CP violation studies at Run3, HL-LHC, and in combination with ATLAS





Thanks for the attention.



Andrea Cardini¹

on behalf of the CMS collaboration ¹⁾ Deutsches Elektronen-Synchrotron (DESY)





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