CP violations in Higgs interactions: experimental summary

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Introduction

- The SM Higgs has J^{PC}=0++
- Small deviation from a pure CP-even interaction of the H with any of the SM particles would be a direct indication of BSM physics
- With Run 2 data, the CP properties of several Higgs couplings have been studied experimentally using production and/or decay information
- This talk summarizes recent CP studies of the Hgg, HVV, Htt, and H$\tau\tau$ couplings by the ATLAS and CMS collaborations

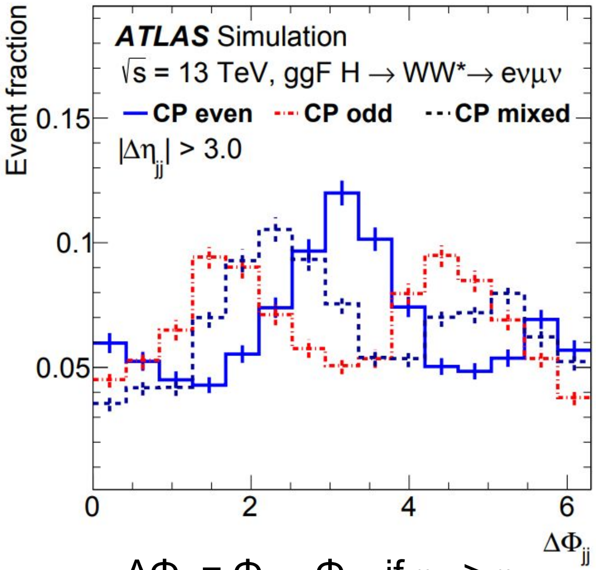
ATLAS HVV via H→WW→eνμν (overview)

arXiv:2109.13808

- Probe CP mixing in effective Hgg interaction using ggF+2-jet events
- Assume HVV - SM like
- Parameterization in terms of CP mixing angle α and κ
  - CP-even: $\kappa_{gg} = 1$, $\cos(\alpha) = 1$
  - CP-old: $\kappa_{gg} = 1$, $\cos(\alpha) = 0$

$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

- Signed-$\Delta\Phi_{jj}$ sensitive to CP



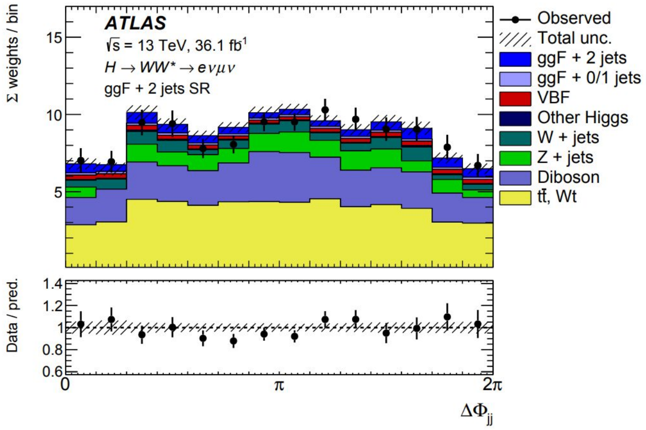
$\Delta\Phi_{jj} = \Phi_{j1} - \Phi_{j2}$, if $\eta_{j1} > \eta_{j2}$
$\Delta\Phi_{jj} = \Phi_{j2} - \Phi_{j1}$, otherwise

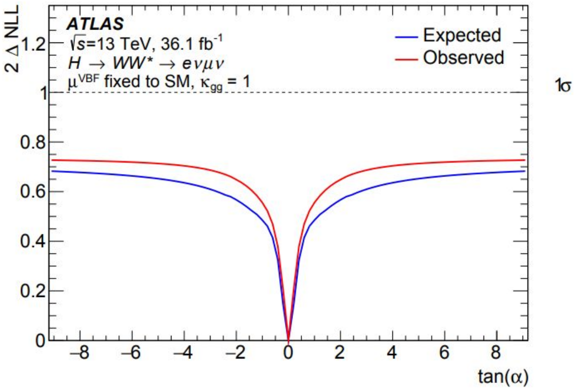
j1 and j2 are leading and subleading jet in pT

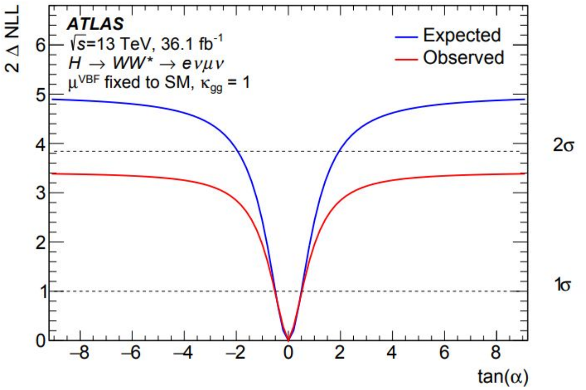
ATLAS HVV via H→WW→eνμν (result)

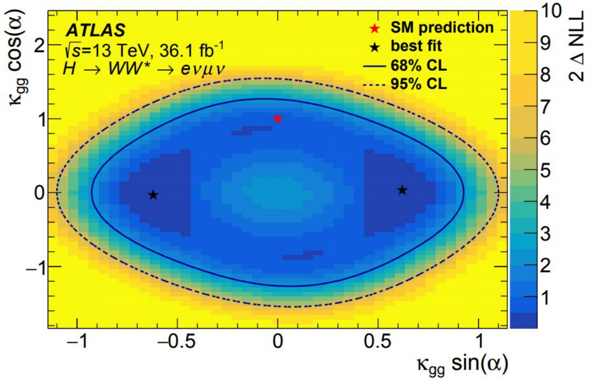
arXiv:2109.13808

- Signal regions: 3 BDT × 4$|\Delta\eta_{jj}|$ regions
- 2 likelihood fits on $\Delta\Phi_{jj}$
    - Shape only (float BSM)
    - Shape + rate constrained to BSM scenario









CMS HVV via H→ZZ→4l (setup)

PhysRevD.104.052004

Generic HVV (V=W,Z,g,γ) scattering amplitude:

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

	SM-like CP even	Anomalous CP-even	CP-odd
V = W/Z	a1	a2, κ1, $κ2^{Zγ}$	a3
V = g	a2		a3

Two approaches to deal with HZZ/HWW coupling:

1. $a^{WW} = a^{ZZ}$ 2. SU(2) X U(1) - SMEFT

CMS HVV via H→ZZ→4l (setup)

PhysRevD.104.052004

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	SM-like CP even	Anomalous CP-even	CP-odd
V = W/Z	a1	a2, κ1, $κ2^{Zγ}$	a3
V = g	a2		a3

Parametrize using fractions (V = W/Z)

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \, \mathrm{sgn}\left(\frac{a_i}{a_1}\right)$$

CMS HVV via H→ZZ→4l (setup)

PhysRevD.104.052004

Generic HVV (V=W,Z,g,γ) scattering amplitude:

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

	SM-like CP even	Anomalous CP-even	CP-odd
V = W/Z	a1	a2, κ1, κ2$^{Z\gamma}$	a3
V = g	a2		a3

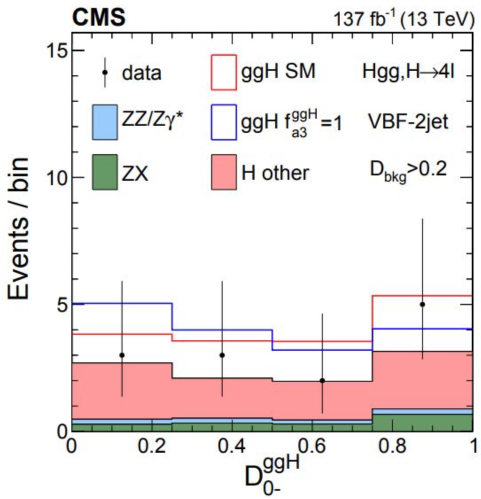
Parametrize using fractions (V = g)

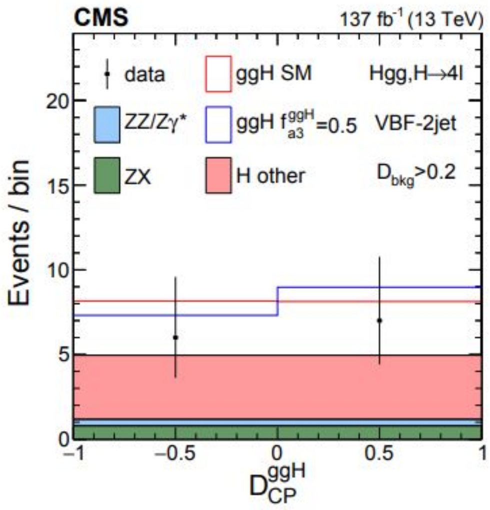
$$f_{a3}^{\mathrm{ggH}} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \, \mathrm{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

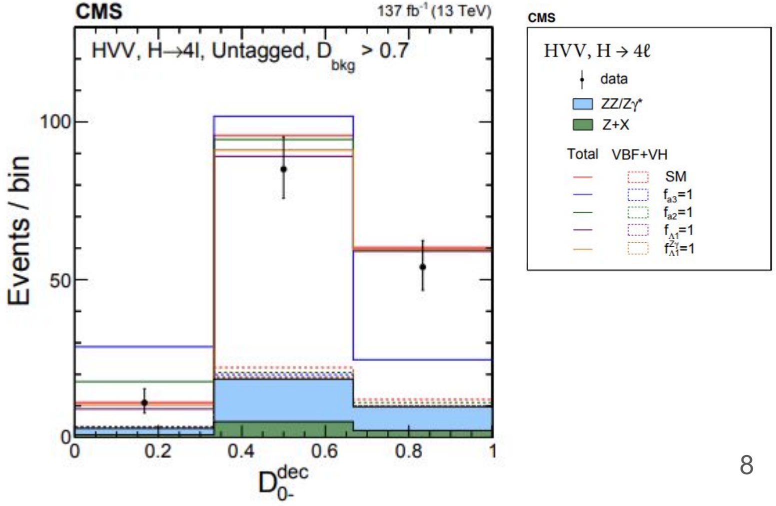
PhysRevD.104.052004

CMS HVV via H→ZZ→4l (analysis strategy)

- Consider all major Higgs production modes (ggF, VBF, VH, ttH, tH)
- Event categorization based on MELA variables to exploit production and decay information
- Perform multi-dimensional fit to extract parameters sensitive to CP







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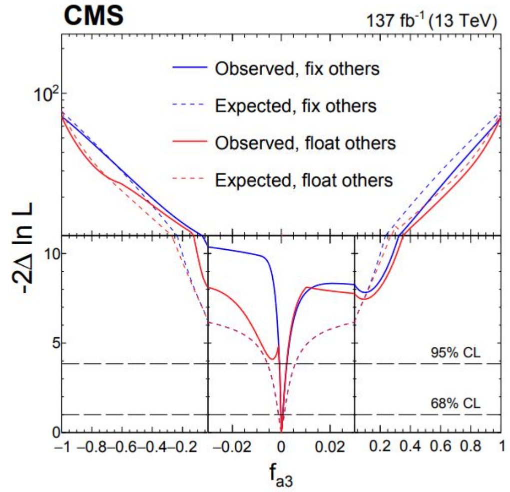
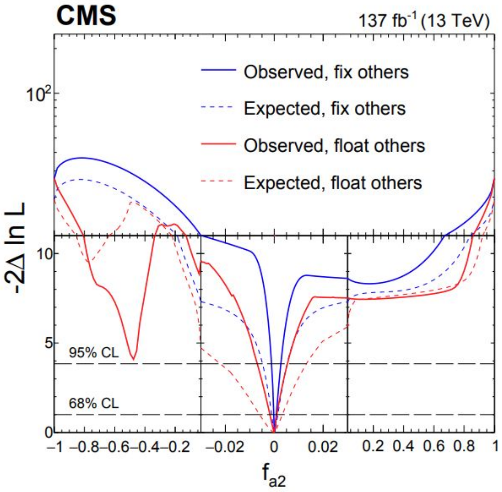
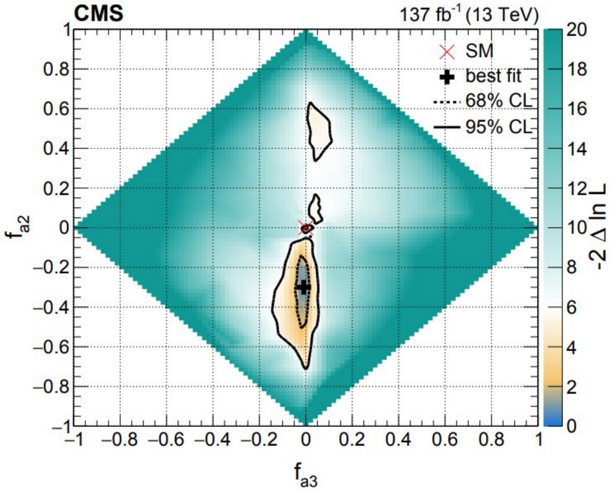
CMS HVV via H→ZZ→4l (selective results)





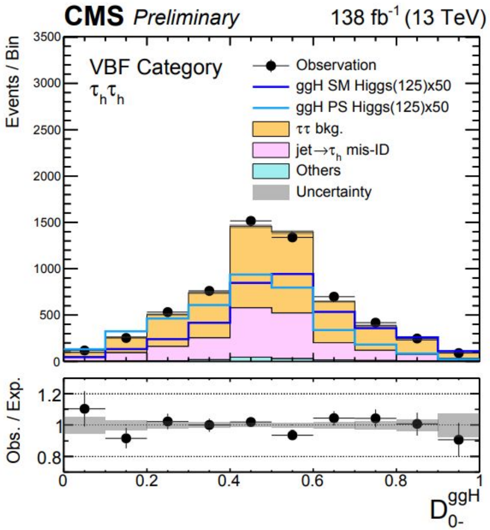


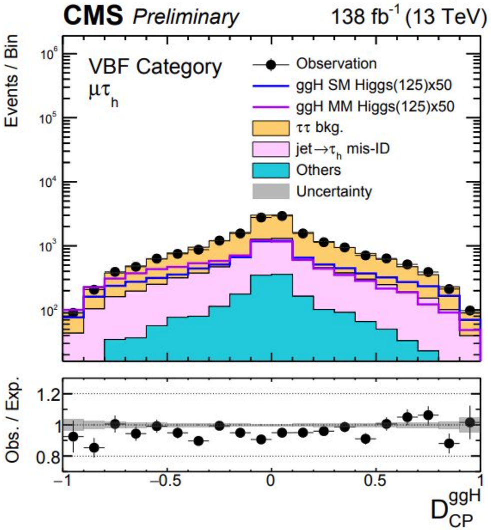
- (Right) 1D scans of f_{ai} parameters using approach 1 ($a^{WW} = a^{ZZ}$)
- (Left) 2D scan of f_{a2} and f_{a3} parameters using approach 2 (SMEFT)
- Minima consistent with the SM
- Corresponding EFT coefficients are also measured (more in paper)

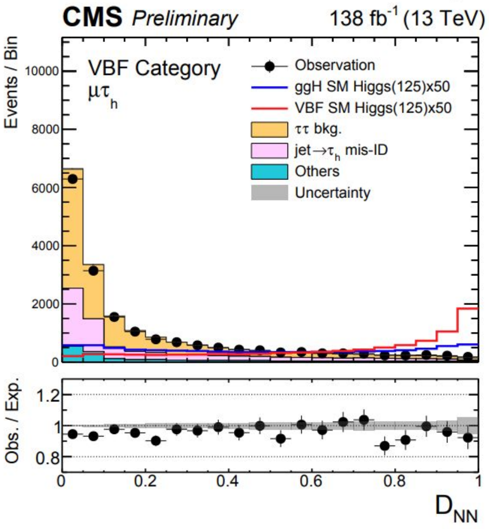
CMS HVV via $H\to\tau\tau$ (overview)

CMS-PAS-HIG-20-007

- Use 4 $\tau\tau$ decay channels: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$
- Explore ggH, VBF and VH production information
- 3 analysis categories: 0-jet, boosted, VBF (most sensitive to CP)
- MELA variables + neural network is used for VBF category

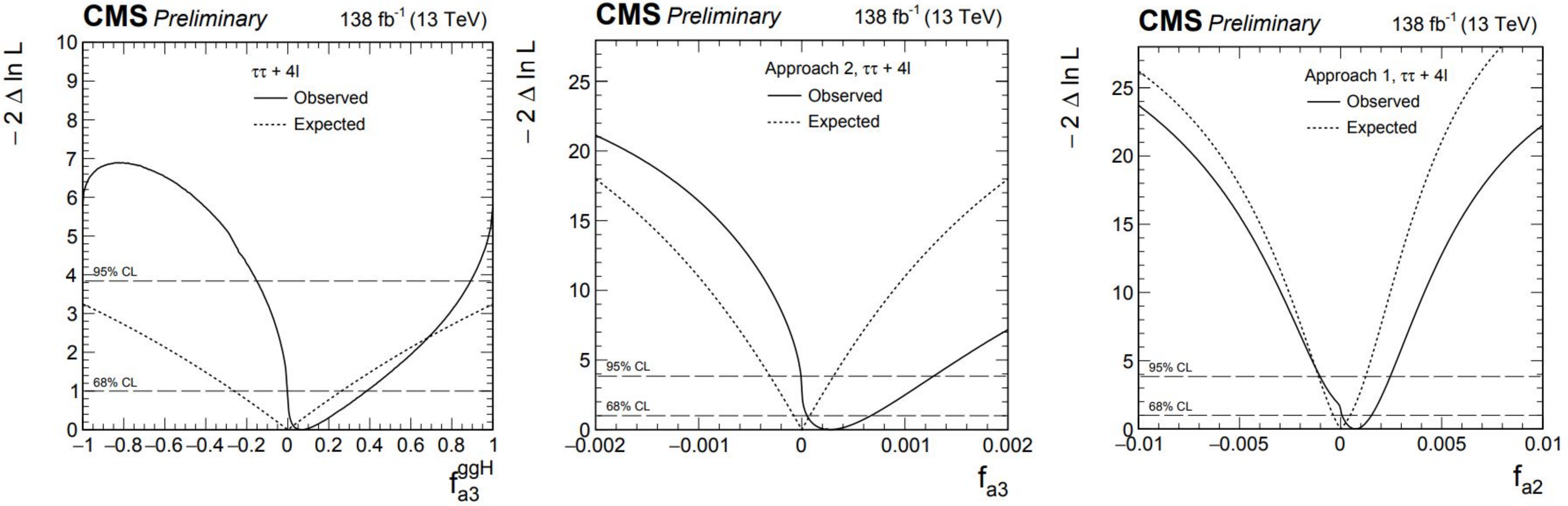






CMS-PAS-HIG-20-007

CMS HVV via H→ττ + H → ZZ (selective results)



- Stringent constraints on CP odd and other anomalous couplings
- H →ττ contributes most significantly for small f_{ai} and f_{a3}^{ggH}

Phys.Rev.Lett.125.061802

ATLAS Htt via ttH/tH, H→γγ (overview)

- CP mixing in the Htt Yukawa coupling can be probed directly in ttH/tH production mode
- The Lagrangian for t-H interaction including CP mixing is

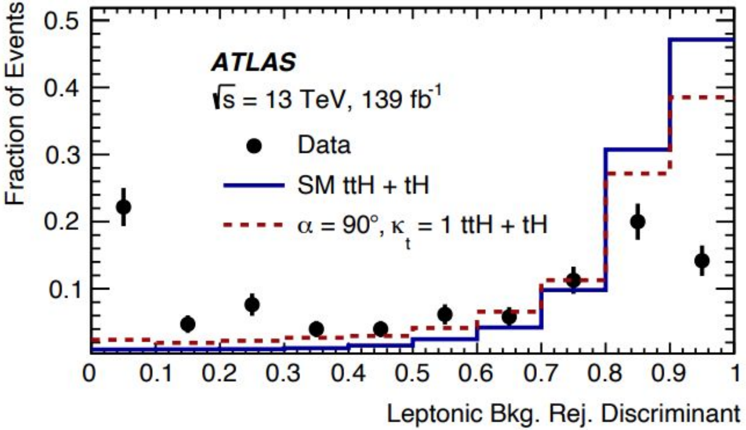
$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

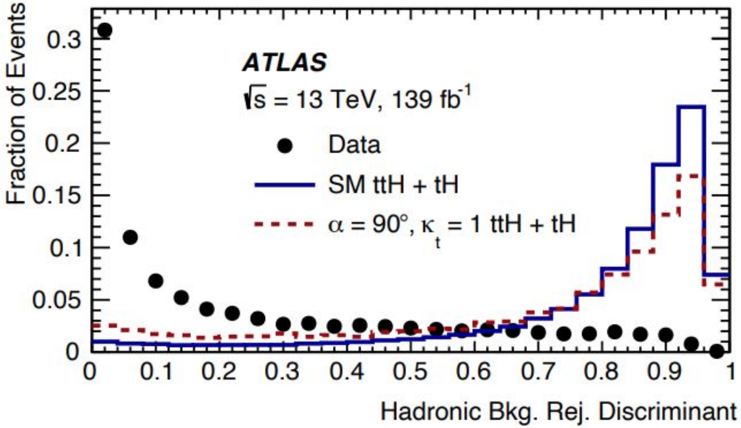
- SM corresponds to $\alpha = 0$, $\kappa_t = 1$, full CP odd is $\alpha = 90°$
- CP-odd component in t-H coupling affects cross sections + kinematics of ttH/tH

Phys.Rev.Lett.125.061802

ATLAS Htt via ttH, H→γγ (strategy)

- Hadronic (≥3 jets, ≥1 b-jet, 0 lep) and leptonic (≥1 b-jet, ≥1 lep) category
- Two BDTs in each category:
  - Background BDT: reject SM background
    - Input features: 4-vec. of γ, j, l and MET
    - Weak dependence on CP mixing angle





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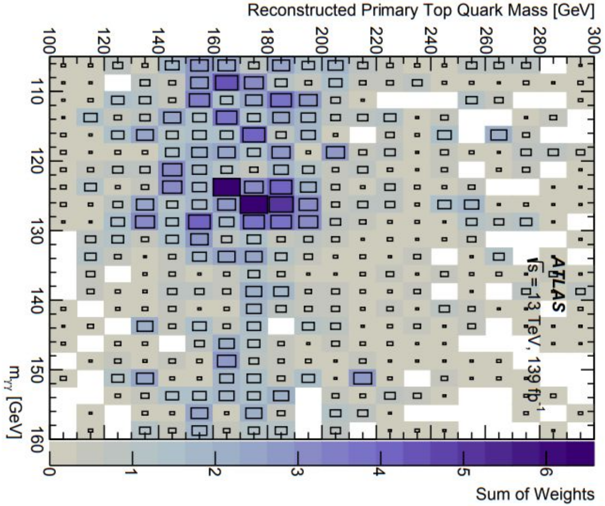
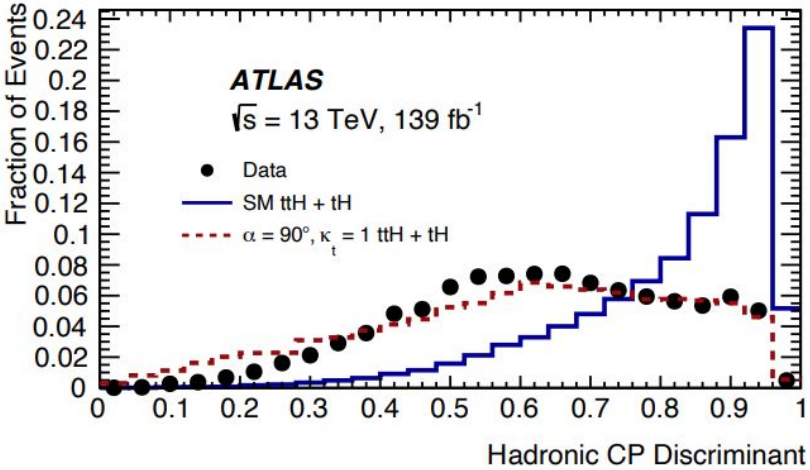
ATLAS Htt via ttH, H→γγ (strategy)

- CP BDT: separate CP even and CP odd ttH/tH, using
    - pT/η of diphoton, HT, njets, nbjets, 1st and 2d min ΔR(γ, j)
    - pT/η/φ/top reco. BDT score of 1st and 2nd reco. top, Δη(t1, t2), Δφ (t1, t2), mtt, mt1H





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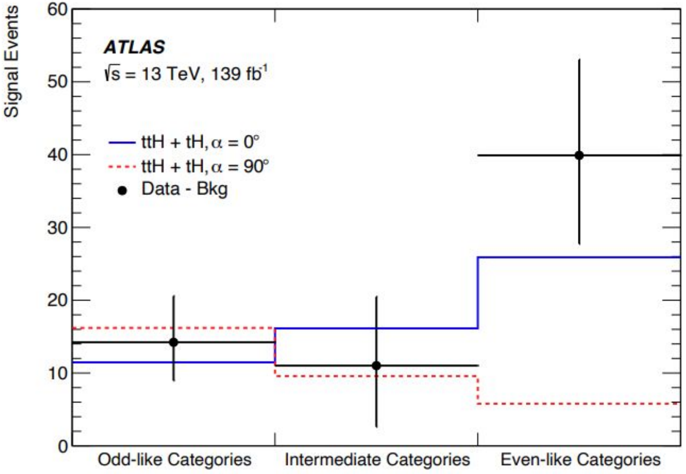
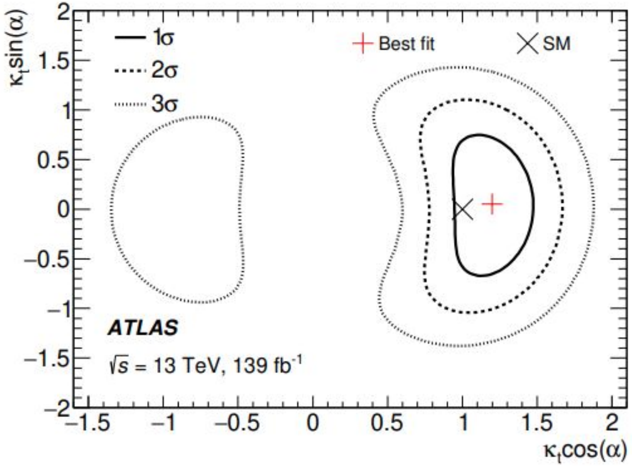
ATLAS Htt via ttH, H→γγ (result)

- Define signal regions (SRs) based on 2 BDT scores
- Parametrize signal yields in SRs based on mixing angle α and Htt strength κ_t
- Fit the mγγ spectrum in all categories simultaneously to extract signal





|α| > 43° excluded @95% CL

Pure CP odd excluded at 3.9σ

Phys.Rev.Lett.125.061801

CMS Htt via ttH, H→γγ (overview)

- Parametrization of CP structure of the Htt amplitude:

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_\mathrm{t}}{v}\overline{\psi}_\mathrm{t}\left(\kappa_\mathrm{t} + \mathrm{i}\tilde{\kappa}_\mathrm{t}\gamma_5\right)\psi_\mathrm{t}$$

- κ_t and $\tilde{\kappa}_t$ are the CP-even and CP-odd Yukawa couplings
- Measure the CP structure with

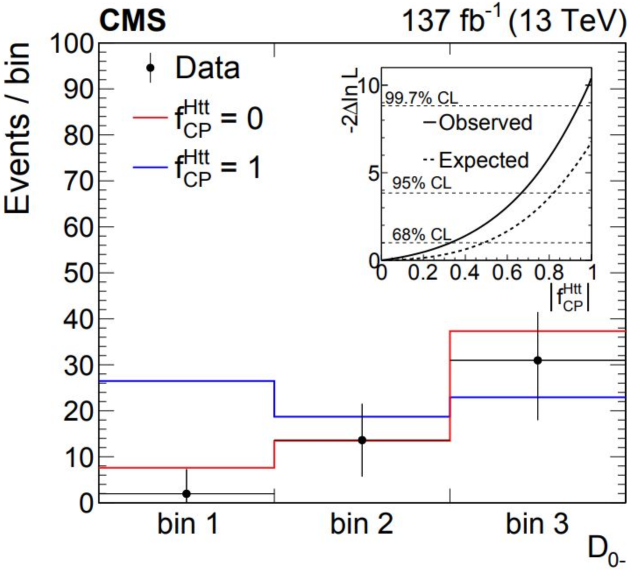
$$f_\mathrm{CP}^\mathrm{Htt} = \frac{|\tilde{\kappa}_\mathrm{t}|^2}{|\kappa_\mathrm{t}|^2 + |\tilde{\kappa}_\mathrm{t}|^2}\,\mathrm{sign}(\tilde{\kappa}_\mathrm{t}/\kappa_\mathrm{t})$$

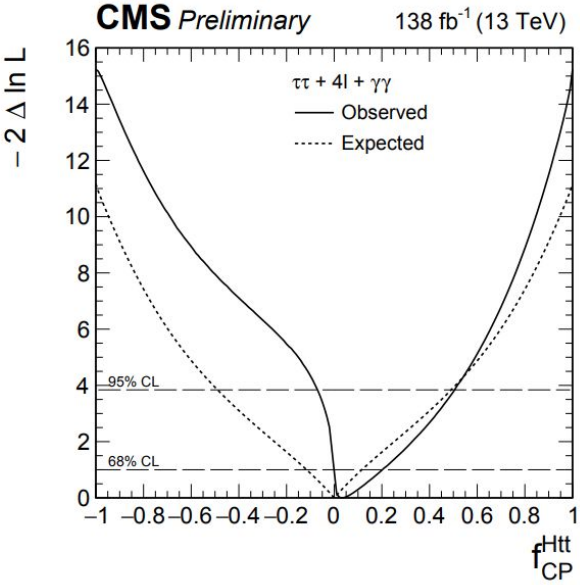
- Overall analysis strategy:
  - Two analysis categories: Leptonic and Hadronic
  - Two BDTs for each category: BDT-bkg to reject SM bkg, and a CP BDT to separate CP-even from CP-odd

Phys.Rev.Lett.125.061801

CMS-PAS-HIG-20-007

CMS Htt via H→$\tau\tau$ + H→ZZ + H→γγ(result)





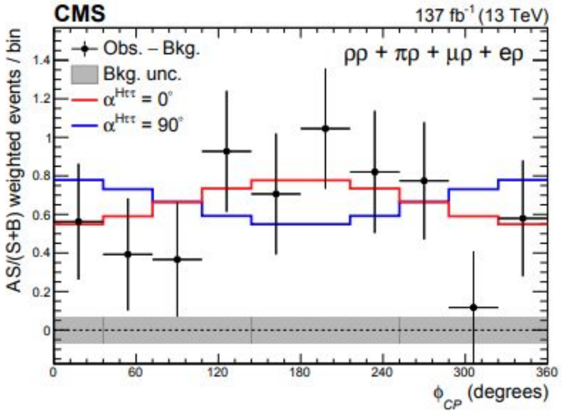
- ttH, H→γγ only
- CP-odd is excluded at 3.2 σ
- $|f^{Htt}_{CP}| < 0.67$ at 95%

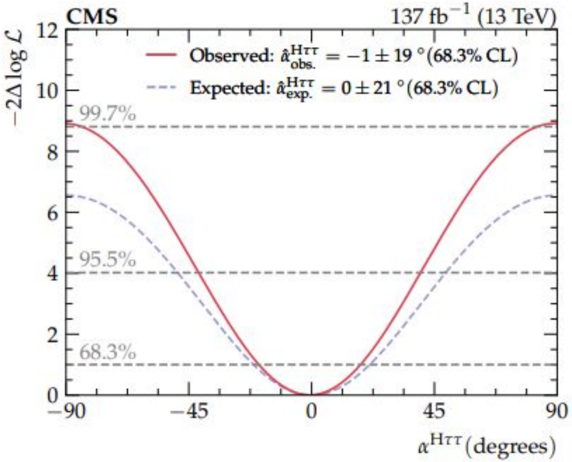
- Assuming the ggH loop is dominated by the top quark
- Measure f^{Htt}_{CP} combining ggH, ttH, and tH

arXiv:2110.04836

CMS Hττ via H→ττ

- First measurement of the effective mixing angle $\alpha^{H\tau\tau}$ between CP-even and CP-odd coupling
- CP-even: $|\alpha\tau\tau| = 0$, CP-odd: $|\alpha| = 90$, CP-mix: $0 < |\alpha\tau\tau| < 90$
- Reconstruct the angle φ_{CP} between the τ decay planes for the various τ decay modes
- CP-odd is excluded at 3.0σ





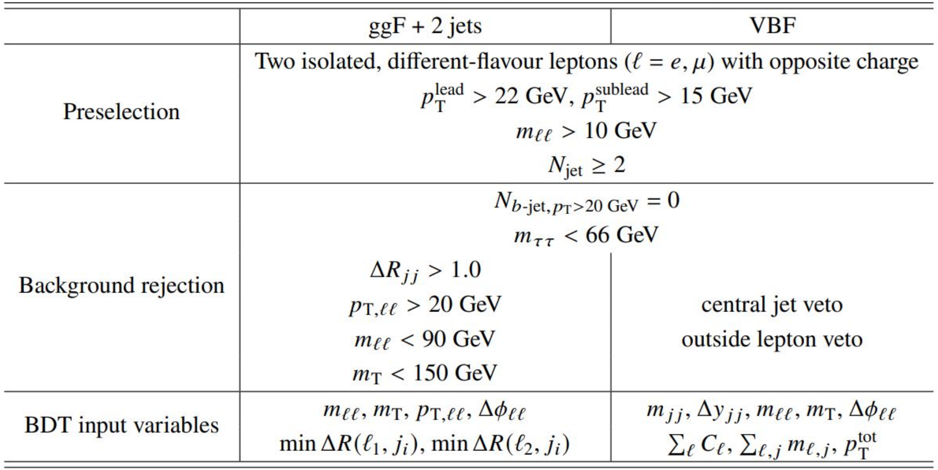
Summary

- Presented the latest measurements of Higgs CP properties by the ATLAS and CMS Collaborations
- All measurements are consistent with the SM
- First studies of Higgs-fermion couplings using Run 2 data
- Stringent limits set of CP-properties of Higgs couplings:
    - HVV, Hgg, Htt, and H$\tau\tau$
- More experimental results are in the pipelines, stay tuned!

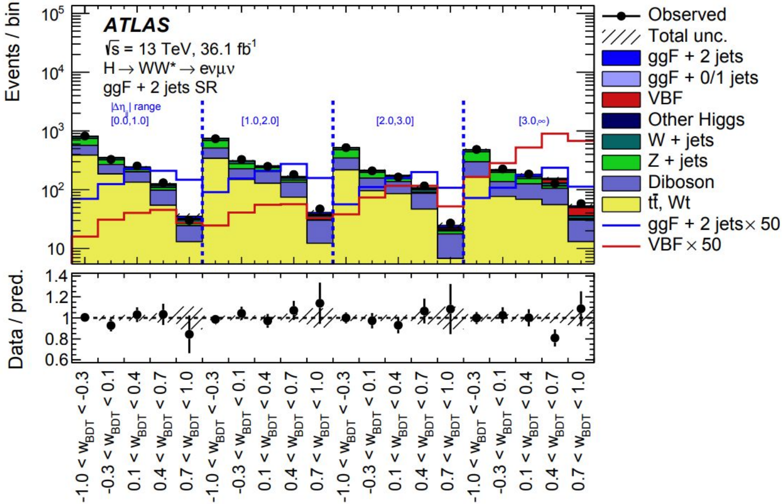
Backup

ATLAS HVV via H→WW→eνμν

Table 3: Event selection criteria used to define the signal regions for the ggF + 2 jets and VBF event categories.



	ggF + 2 jets	VBF
Preselection	Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge $p_{\mathrm{T}}^{\mathrm{lead}} > 22$ GeV, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15$ GeV $m_{\ell\ell} > 10$ GeV $N_{\mathrm{jet}} \geq 2$	
Background rejection	$N_{b\text{-jet}, p_{\mathrm{T}}>20\ \mathrm{GeV}} = 0$ $m_{\tau\tau} < 66$ GeV	
	$\Delta R_{jj} > 1.0$ $p_{\mathrm{T},\ell\ell} > 20$ GeV $m_{\ell\ell} < 90$ GeV $m_{\mathrm{T}} < 150$ GeV	central jet veto outside lepton veto
BDT input variables	$m_{\ell\ell}$, m_{T}, $p_{\mathrm{T},\ell\ell}$, $\Delta\phi_{\ell\ell}$ $\min \Delta R(\ell_1, j_i)$, $\min \Delta R(\ell_2, j_i)$	m_{jj}, Δy_{jj}, $m_{\ell\ell}$, m_{T}, $\Delta\phi_{\ell\ell}$ $\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell,j}$, $p_{\mathrm{T}}^{\mathrm{tot}}$



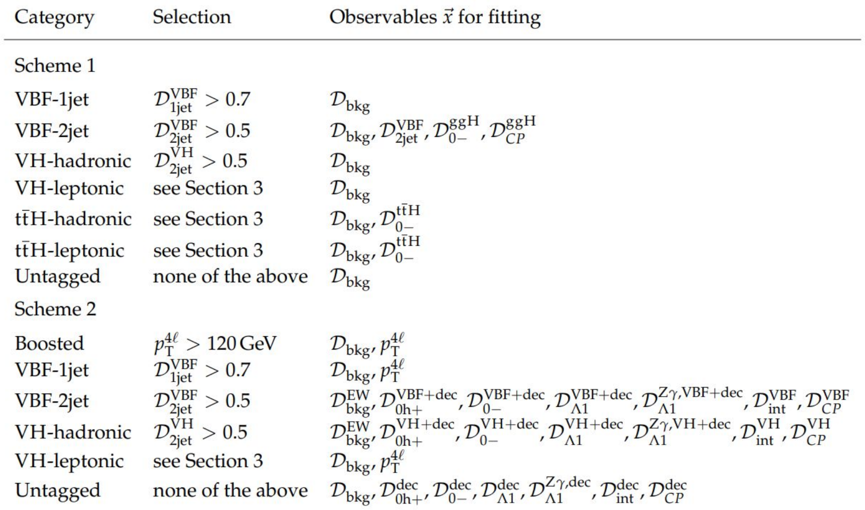
CMS HVV/Hff via H→ZZ→4l

$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})},$$

$$\mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})\ \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}},$$

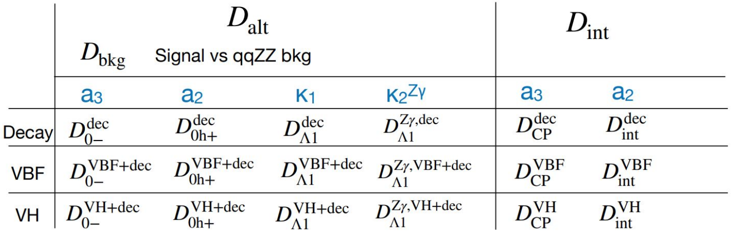
D_{alt}: separate two models, e.g. ggH vs VBF, SM vs BSM

D_{int}: deals with interference between two models



Category	Selection	Observables $\vec{x}$ for fitting
Scheme 1		
VBF-1jet	$\mathcal{D}_{\text{1jet}}^{\text{VBF}} > 0.7$	$\mathcal{D}_{\text{bkg}}$
VBF-2jet	$\mathcal{D}_{\text{2jet}}^{\text{VBF}} > 0.5$	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{\text{2jet}}^{\text{VBF}}, \mathcal{D}_{0-}^{\text{ggH}}, \mathcal{D}_{CP}^{\text{ggH}}$
VH-hadronic	$\mathcal{D}_{\text{2jet}}^{\text{VH}} > 0.5$	$\mathcal{D}_{\text{bkg}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\text{bkg}}$
$\text{t}\bar{\text{t}}$H-hadronic	see Section 3	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{t}\bar{\text{t}}\text{H}}$
$\text{t}\bar{\text{t}}$H-leptonic	see Section 3	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{t}\bar{\text{t}}\text{H}}$
Untagged	none of the above	$\mathcal{D}_{\text{bkg}}$
Scheme 2		
Boosted	$p_{\text{T}}^{4\ell} > 120\,\text{GeV}$	$\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$
VBF-1jet	$\mathcal{D}_{\text{1jet}}^{\text{VBF}} > 0.7$	$\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$
VBF-2jet	$\mathcal{D}_{\text{2jet}}^{\text{VBF}} > 0.5$	$\mathcal{D}_{\text{bkg}}^{\text{EW}}, \mathcal{D}_{0h+}^{\text{VBF+dec}}, \mathcal{D}_{0-}^{\text{VBF+dec}}, \mathcal{D}_{\Lambda1}^{\text{VBF+dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\text{VBF+dec}}, \mathcal{D}_{\text{int}}^{\text{VBF}}, \mathcal{D}_{CP}^{\text{VBF}}$
VH-hadronic	$\mathcal{D}_{\text{2jet}}^{\text{VH}} > 0.5$	$\mathcal{D}_{\text{bkg}}^{\text{EW}}, \mathcal{D}_{0h+}^{\text{VH+dec}}, \mathcal{D}_{0-}^{\text{VH+dec}}, \mathcal{D}_{\Lambda1}^{\text{VH+dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\text{VH+dec}}, \mathcal{D}_{\text{int}}^{\text{VH}}, \mathcal{D}_{CP}^{\text{VH}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$
Untagged	none of the above	$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0h+}^{\text{dec}}, \mathcal{D}_{0-}^{\text{dec}}, \mathcal{D}_{\Lambda1}^{\text{dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\text{dec}}, \mathcal{D}_{\text{int}}^{\text{dec}}, \mathcal{D}_{CP}^{\text{dec}}$

Observables in HVV



	D_{alt}				D_{int}	
	D_{bkg} Signal vs qqZZ bkg					
	a_3	a_2	κ_1	$\kappa_2^{Z\gamma}$	a_3	a_2
Decay	D_{0-}^{dec}	D_{0h+}^{dec}	$D_{\Lambda1}^{\text{dec}}$	$D_{\Lambda1}^{Z\gamma,\text{dec}}$	$D_{\text{CP}}^{\text{dec}}$	$D_{\text{int}}^{\text{dec}}$
VBF	$D_{0-}^{\text{VBF+dec}}$	$D_{0h+}^{\text{VBF+dec}}$	$D_{\Lambda1}^{\text{VBF+dec}}$	$D_{\Lambda1}^{Z\gamma,\text{VBF+dec}}$	$D_{\text{CP}}^{\text{VBF}}$	$D_{\text{int}}^{\text{VBF}}$
VH	$D_{0-}^{\text{VH+dec}}$	$D_{0h+}^{\text{VH+dec}}$	$D_{\Lambda1}^{\text{VH+dec}}$	$D_{\Lambda1}^{Z\gamma,\text{VH+dec}}$	$D_{\text{CP}}^{\text{VH}}$	$D_{\text{int}}^{\text{VH}}$

Observables in Hff

D_{alt}

D_{bkg} $D_{\text{2jet}}^{\text{VBF}}$ To separate ggH and VBF events
a_2 and a_3 separation depends on D_{2jet}

D_{0-}^{ttH} D_{0-}^{ggH}

D_{int}

$D_{\text{CP}}^{\text{ggH}}$

CMS HVV via H→ττ

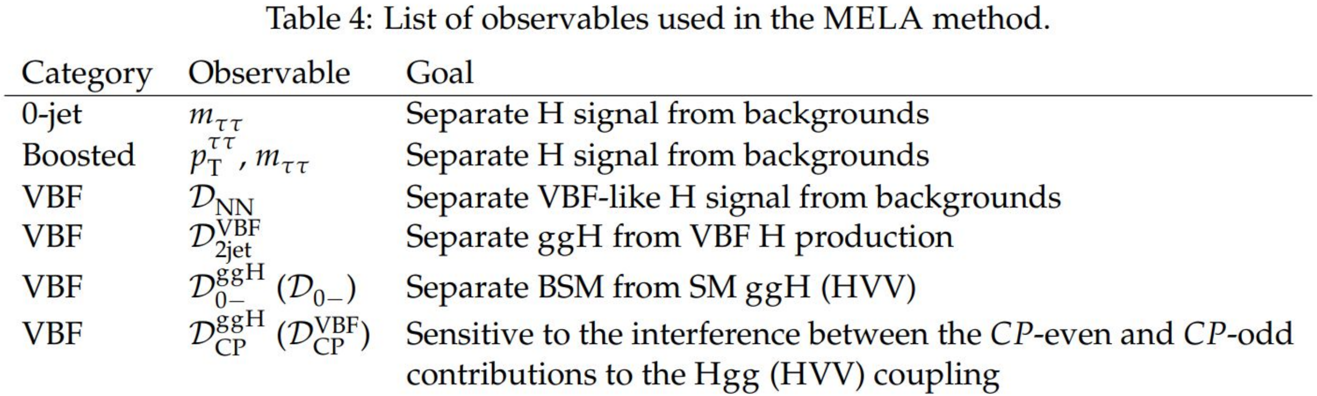


Table 4: List of observables used in the MELA method.

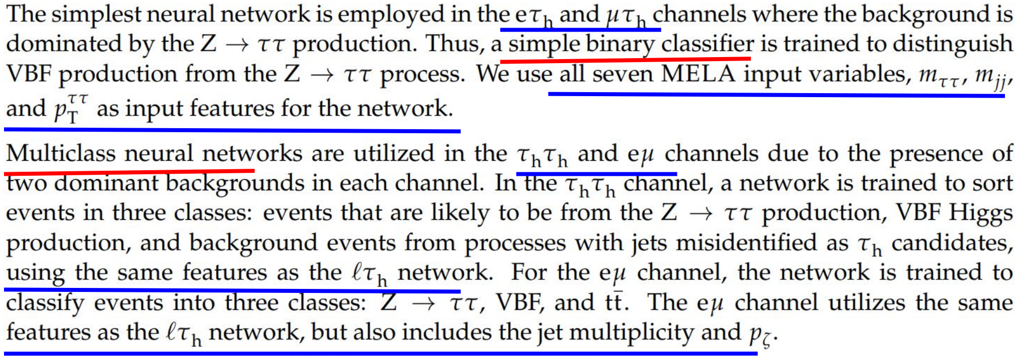
Category	Observable	Goal
0-jet	$m_{\tau\tau}$	Separate H signal from backgrounds
Boosted	$p_{\mathrm{T}}^{\tau\tau}$, $m_{\tau\tau}$	Separate H signal from backgrounds
VBF	$\mathcal{D}_{\mathrm{NN}}$	Separate VBF-like H signal from backgrounds
VBF	$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF}}$	Separate ggH from VBF H production
VBF	$\mathcal{D}_{0-}^{\mathrm{ggH}}$ ($\mathcal{D}_{0-}$)	Separate BSM from SM ggH (HVV)
VBF	$\mathcal{D}_{\mathrm{CP}}^{\mathrm{ggH}}$ ($\mathcal{D}_{\mathrm{CP}}^{\mathrm{VBF}}$)	Sensitive to the interference between the *CP*-even and *CP*-odd contributions to the Hgg (HVV) coupling

$$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF}} = \frac{\mathcal{P}_{\mathrm{SM}}^{\mathrm{ggH}} + \mathcal{P}_{0-}^{\mathrm{ggH}}}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{ggH}} + \mathcal{P}_{0-}^{\mathrm{ggH}} + \mathcal{P}_{\mathrm{SM}}^{\mathrm{VBF}}}$$

$$\mathcal{D}_{0-}^{\mathrm{ggH}} = \frac{\mathcal{P}_{\mathrm{SM}}^{\mathrm{ggH}}}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{ggH}} + \mathcal{P}_{0-}^{\mathrm{ggH}}}$$

$$\mathcal{D}_{\mathrm{CP}}^{\mathrm{ggH}} = \frac{\mathcal{P}_{\mathrm{SM}-0-}^{\mathrm{ggH}}}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{ggH}} + \mathcal{P}_{0-}^{\mathrm{ggH}}}$$

CMS HVV via H→ττ



The simplest neural network is employed in the $e\tau_h$ and $\mu\tau_h$ channels where the background is dominated by the $Z \to \tau\tau$ production. Thus, a simple binary classifier is trained to distinguish VBF production from the $Z \to \tau\tau$ process. We use all seven MELA input variables, $m_{\tau\tau}$, m_{jj}, and $p_T^{\tau\tau}$ as input features for the network.

Multiclass neural networks are utilized in the $\tau_h\tau_h$ and $e\mu$ channels due to the presence of two dominant backgrounds in each channel. In the $\tau_h\tau_h$ channel, a network is trained to sort events in three classes: events that are likely to be from the $Z \to \tau\tau$ production, VBF Higgs production, and background events from processes with jets misidentified as τ_h candidates, using the same features as the $\ell\tau_h$ network. For the $e\mu$ channel, the network is trained to classify events into three classes: $Z \to \tau\tau$, VBF, and $t\bar{t}$. The $e\mu$ channel utilizes the same features as the $\ell\tau_h$ network, but also includes the jet multiplicity and p_ζ.