

Study of the CP property of the Higgs boson to electroweak boson coupling in the VBF $H \rightarrow \gamma\gamma$ channel with the ATLAS detector

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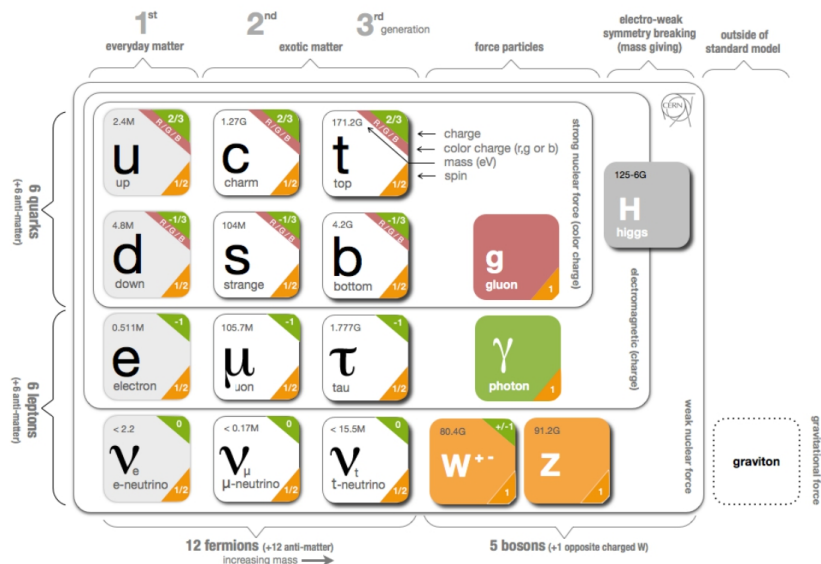


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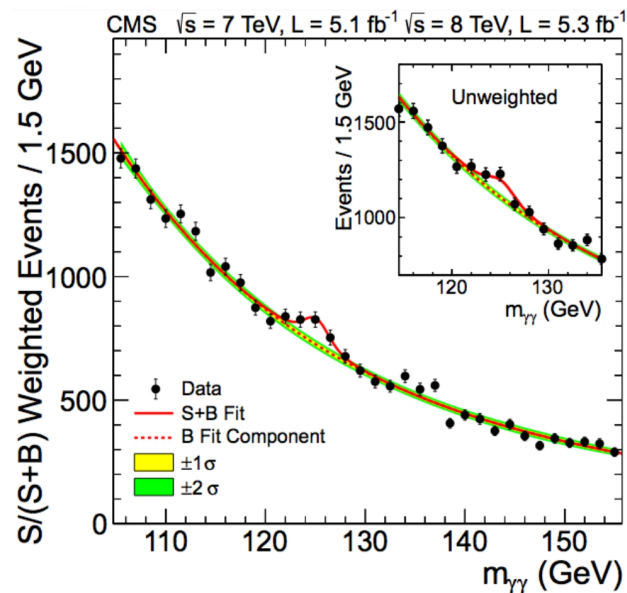
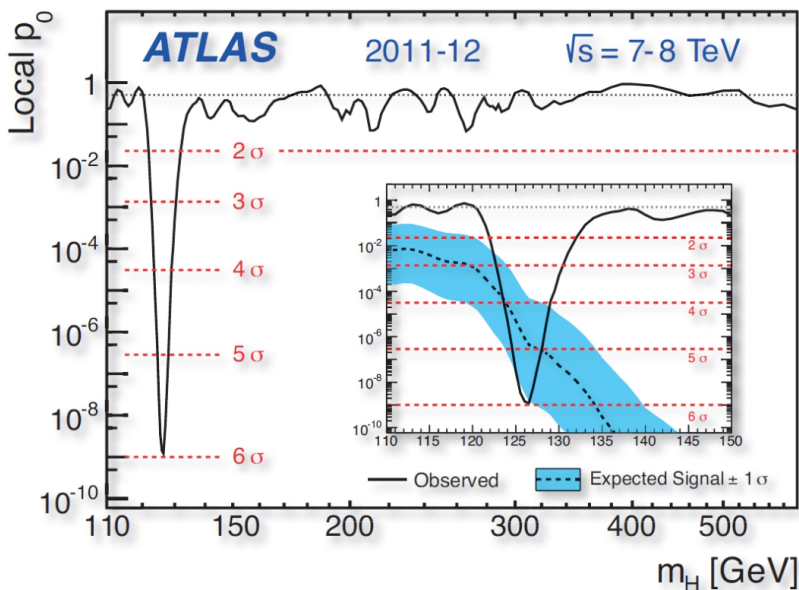




The Higgs boson



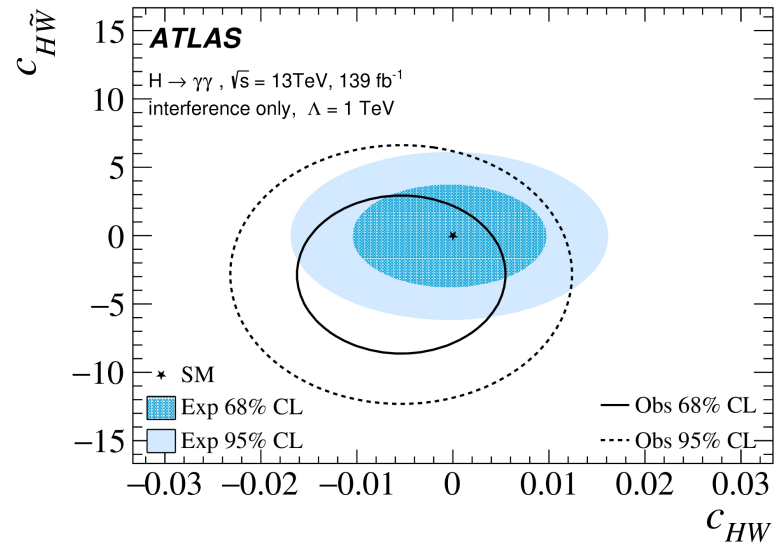
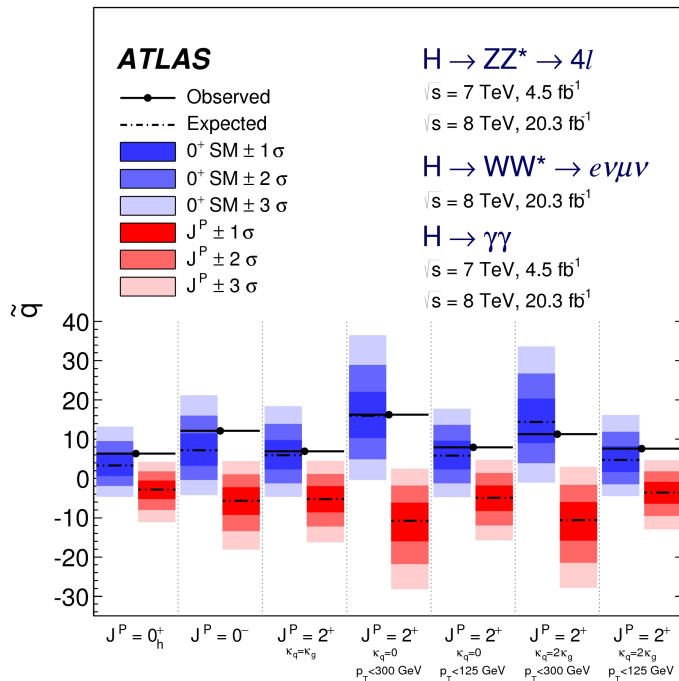
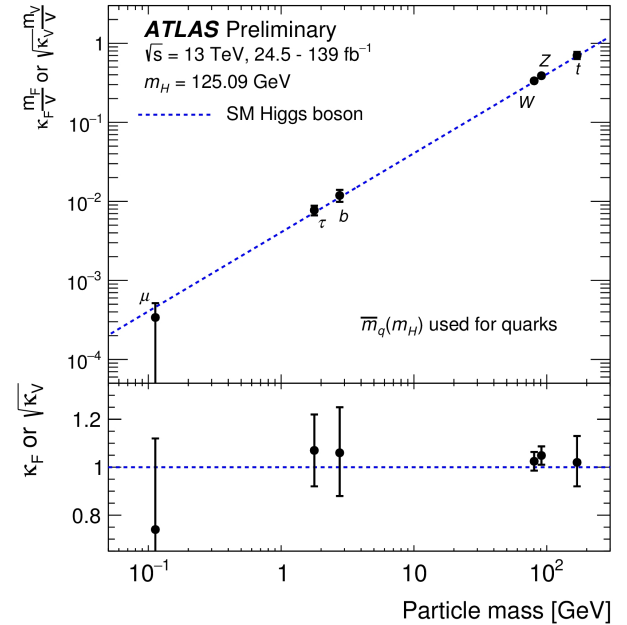
- The SM is a successful model of the particle physics
- The Higgs boson play the unique role in the SM of giving mass to other particles via EW SSB
- Was discovered by ATLAS and CMS in 2012 within bosonic channel





Higgs boson properties

- The properties of the Higgs boson has been precisely measured with LHC run-I/II data since the discovery 10yrs ago
- Great agreement between SM prediction with measurements
- Still room for new physics/new interactions
 - One of the potential is CP-odd components



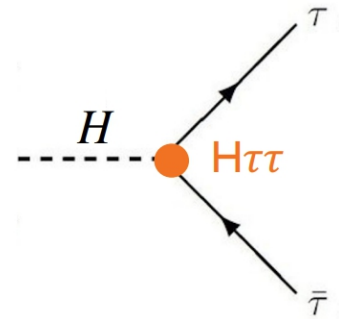
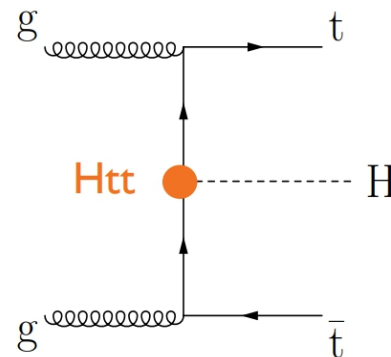
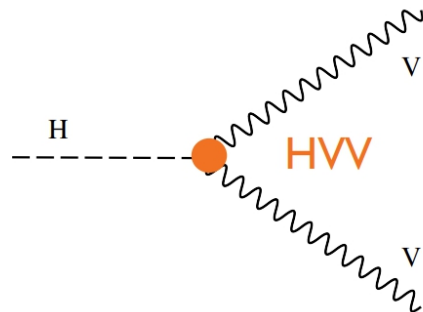
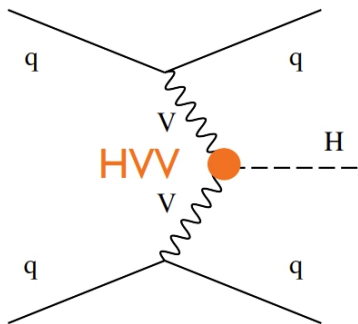


CP property of the Higgs boson

- Determining the CP structure is important in the High Energy Physics
- Key component for Sakharov condition to explain matter-antimatter asymmetry
 - ✓ *Baryon number violation*
 - ✓ *C and CP violation*
 - ✓ *Interactions out of thermal equilibrium*
- Need to find new source of CPV beside the CP phase in CKM which is not enough for matter-antimatter asymmetry

The Higgs boson could be a good portal

- In the SM, the Higgs boson is CP-even
- No strong constraint to exclude CP-odd contribution
 - ✓ Those new CP-odd component could be *new scalars* or *new interactions*





Explore the CP structure via VBF

■ Motivation

- ✓ Study the CP structure of interactions between the Higgs boson and EWK gauge bosons

■ Explored two EFT bases

✓ HISZ basis

- After EWSB, EFT Lagrangian can be written as

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{H\gamma\gamma} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{H\gamma Z} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}_{\mu\nu}^+ W^{-\mu\nu}$$

- Dimensionless parameters introduced: d and \tilde{d} , with assuming $d = \tilde{d}$

$$\tilde{g}_{H\gamma\gamma} = \tilde{g}_{HZZ} = \frac{1}{2} \tilde{g}_{HWW} = \frac{g}{2m_W} \tilde{d} \quad \text{and} \quad \tilde{g}_{H\gamma Z} = 0.$$

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}.$$

✓ Warsaw basis

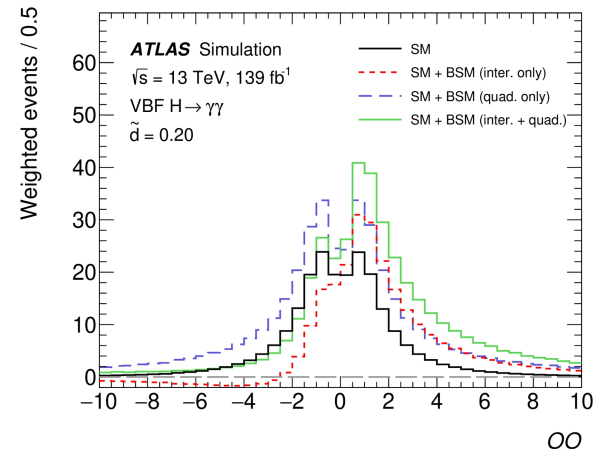
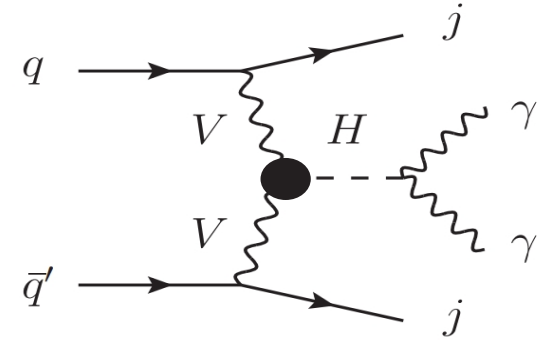
$$\mathcal{L}_{\text{SMEFT}}^{\text{CP-odd}} \supset \frac{C_{H\tilde{W}}}{\Lambda^2} H^\dagger H W_{\mu\nu}^I W^{\mu\nu I} + \frac{C_{H\tilde{B}}}{\Lambda^2} H^\dagger H B_{\mu\nu}^A B^{\mu\nu} + \frac{C_{H\tilde{B}}}{\Lambda^2} H^\dagger \sigma^I H W_{\mu\nu}^I B^{\mu\nu}$$

- VBF production is dominated by HWW vertex, analysis mainly explores $C_{H\tilde{W}}$

■ CP sensitive variable

✓ Optimal Observable

$$OO = \frac{2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

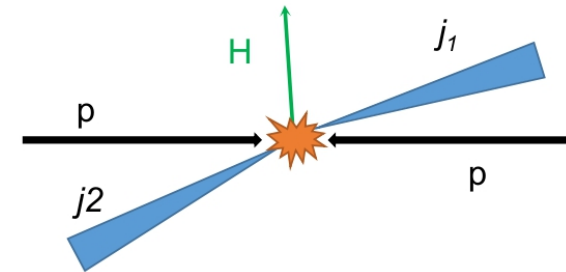




Analysis strategy

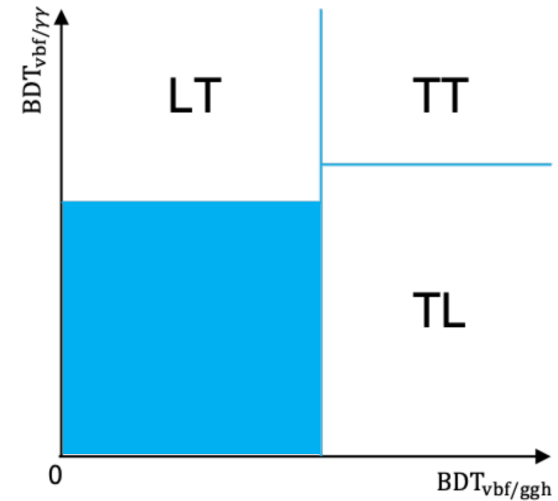
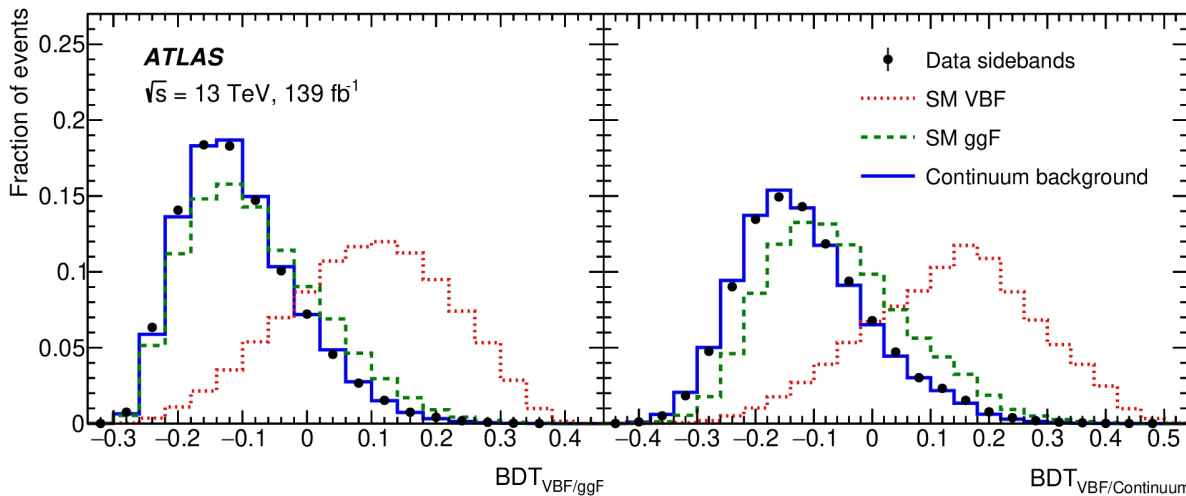
Object definitions follow ATLAS $H \rightarrow \gamma\gamma$ common definitions [arXiv:2202.00487](https://arxiv.org/abs/2202.00487)

- Perform two independent BDT trainings:
 - VBF/ggF , $VBF/Continuum\ background$ separation
 - Define 3 *signal regions* based on BDT outputs
 - VBF purity increases by a factor of 10 with $BDT_{vbf/ggF}$ cut



Training variables

$$m_{jj}, \Delta\eta_{jj}, p_{T}^{\gamma\gamma}, p_T^{Hjj}, \Delta\phi(\gamma\gamma, jj), \Delta R_{\gamma j}^{\min}, \eta^{Z_{epp}}$$



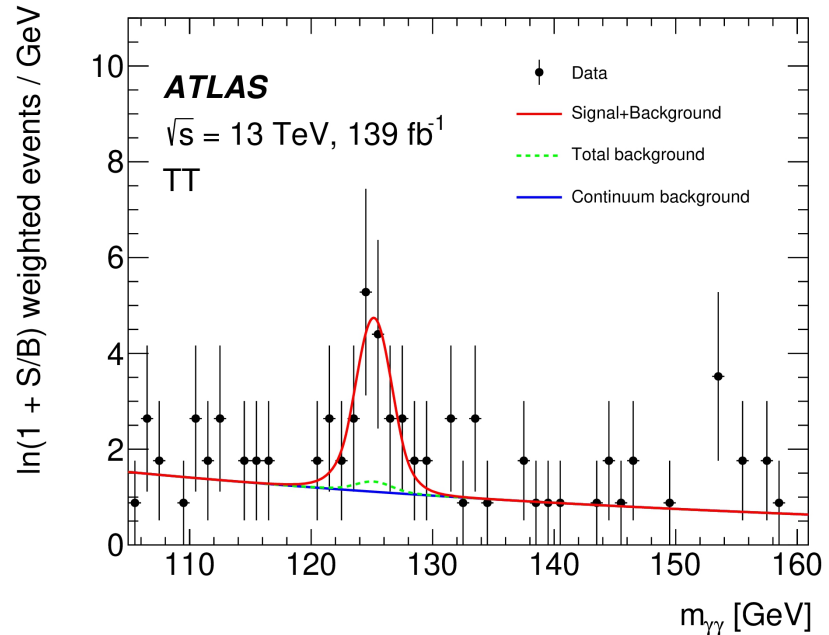
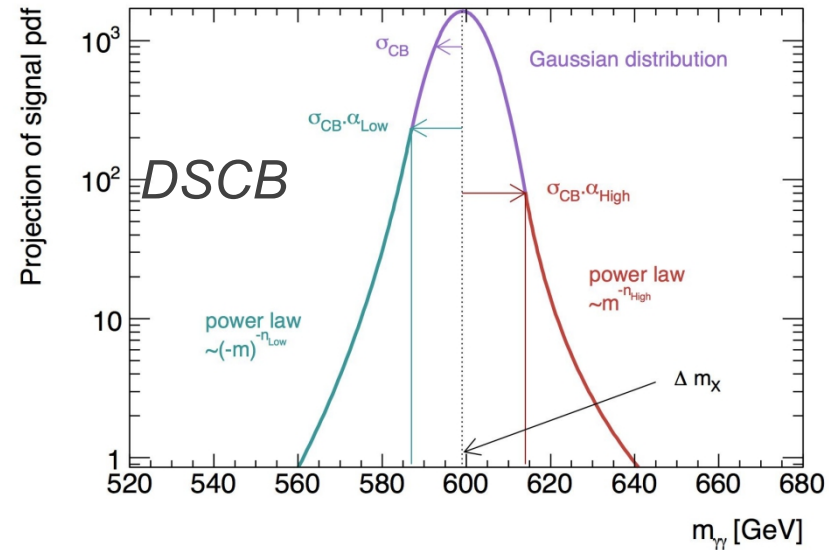


Signal and Background Modeling

- Both **signal** and **background** are modeled with analytic functions
- Signal is modeled with double-sided Crystal Ball function (DSCB)

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{Low} \geq t \geq \alpha_{High} \\ \frac{e^{-0.5\alpha_{Low}^2}}{\left[\frac{\alpha_{Low}}{n_{Low}} \left(\frac{n_{Low}}{\alpha_{Low}} - \alpha_{Low} - t \right) \right]^{n_{Low}}} & \text{if } t < -t = \Delta m_X / \sigma_{CB}, \Delta m_X = m_X - \mu_{CB} \\ \frac{e^{-0.5\alpha_{High}^2}}{\left[\frac{\alpha_{High}}{n_{High}} \left(\frac{n_{High}}{\alpha_{High}} - \alpha_{High} + t \right) \right]^{n_{High}}} & \text{if } t > \alpha_{High}, \end{cases}$$

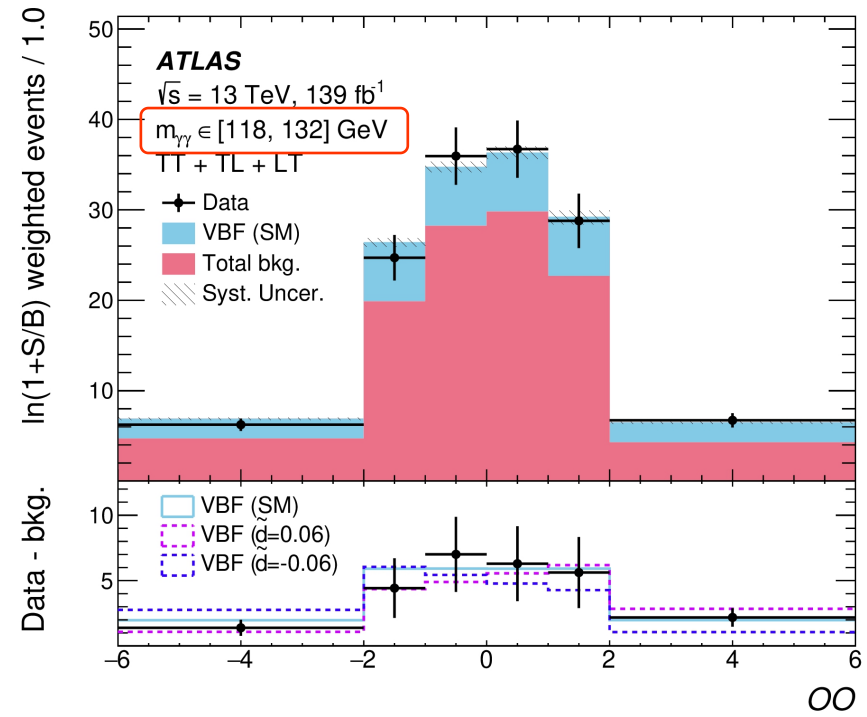
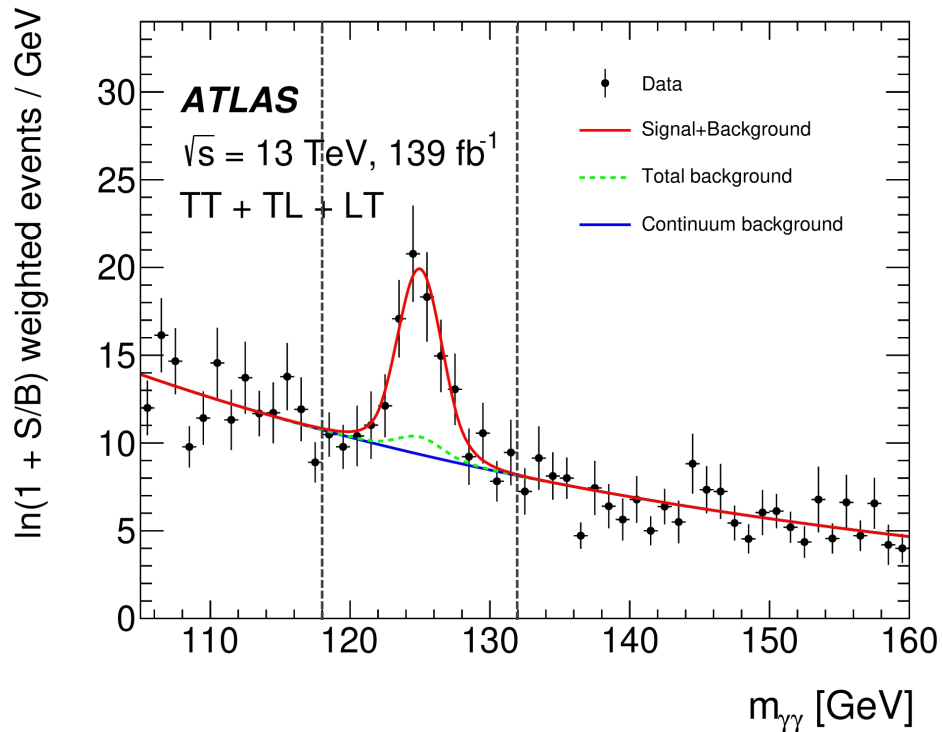
- The background is modeled with analytic function chosen from **power-law/Bernstein polynomial/ExpPoly** functions based on **spurious signal** test results
 - Spurious signal test is done with background-only distributions based on MC templates from $\gamma\gamma$, $\gamma+j$, jj components
 - ✓ Templates are build with **Gaussian process regression** with the Gibbs kernel to reduce statistical uncertainties.

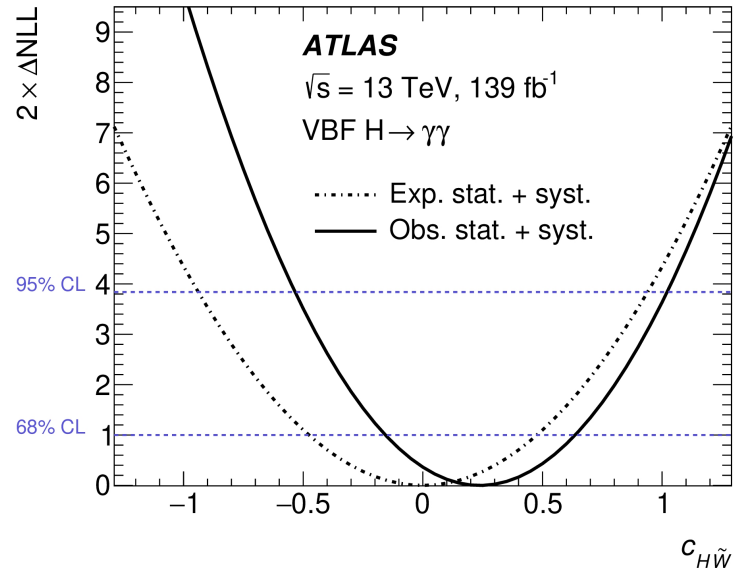
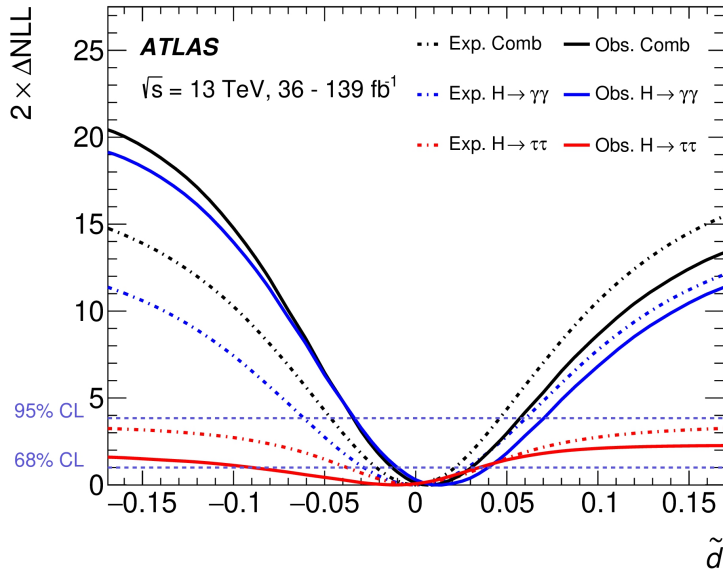




Statistical analysis

- Perform *signal+background* fit on $m_{\gamma\gamma}$ distributions in 6 OO bins in all 3 categories to extract VBF signal
 - OO bins are defined as $[-\infty, -2, -1, 0, 1, 2, \infty]$
 - Test different \tilde{d} or $c_{H\tilde{W}}$ values
 - Majority of sensitivity from high OO bins



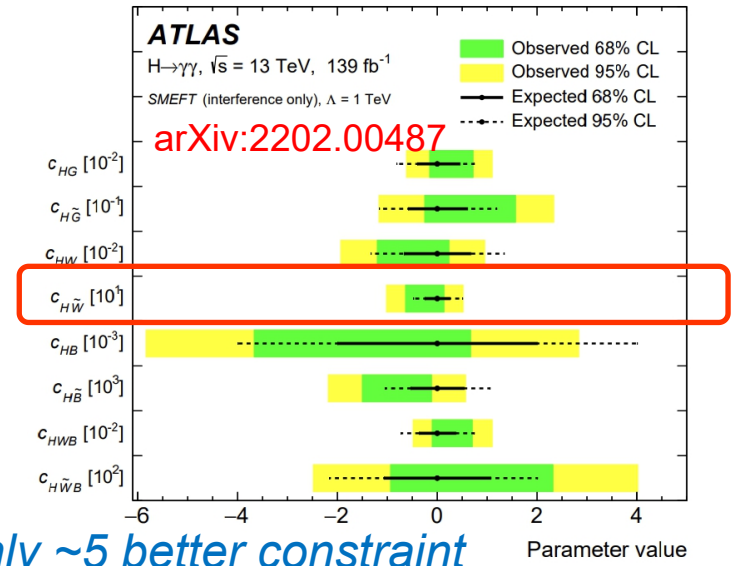
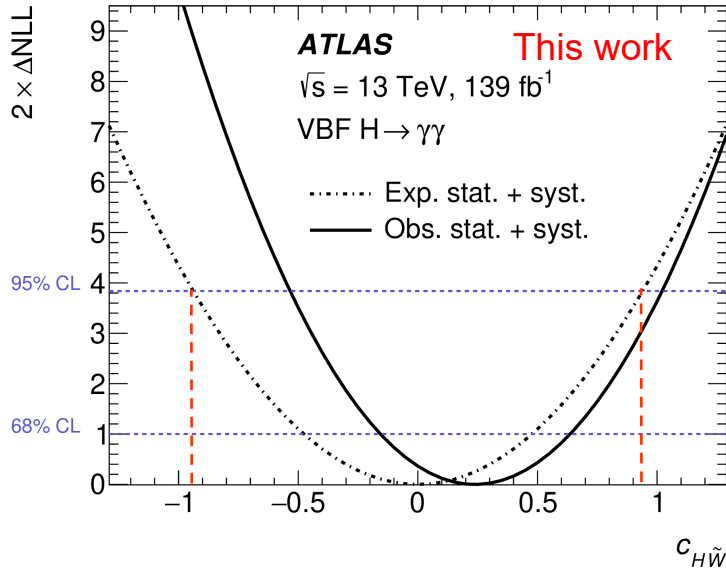


	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
\tilde{d} (inter. only)	$[-0.027, 0.027]$	$[-0.055, 0.055]$	$[-0.011, 0.036]$	$[-0.032, 0.059]$
\tilde{d} (inter.+quad.)	$[-0.028, 0.028]$	$[-0.061, 0.060]$	$[-0.010, 0.040]$	$[-0.034, 0.071]$
d from $H \rightarrow \tau\tau$	$[-0.038, 0.036]$	—	$[-0.090, 0.035]$	—
Combined \tilde{d}	$[-0.022, 0.021]$	$[-0.046, 0.045]$	$[-0.012, 0.030]$	$[-0.034, 0.057]$
$c_{H\tilde{W}}$ (inter. only)	$[-0.48, 0.48]$	$[-0.94, 0.94]$	$[-0.16, 0.64]$	$[-0.53, 1.02]$
$c_{H\tilde{W}}$ (inter.+quad.)	$[-0.48, 0.48]$	$[-0.95, 0.95]$	$[-0.15, 0.67]$	$[-0.55, 1.07]$

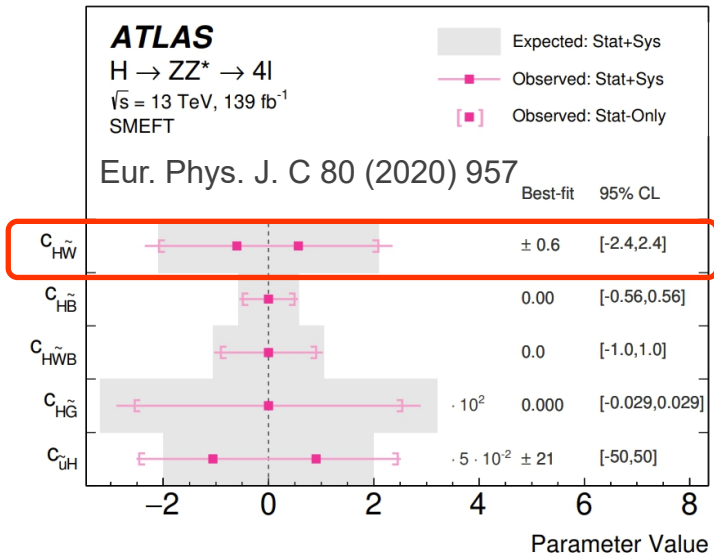
- No sign of CP violation is observed.
- Current most stringent constraints on CP-violation effect in HVV coupling
- Result for \tilde{d} is further combined with $H \rightarrow \tau\tau$ analysis.



Compared to other channels



Roughly ~5 better constraint



Roughly ~2 better constraint

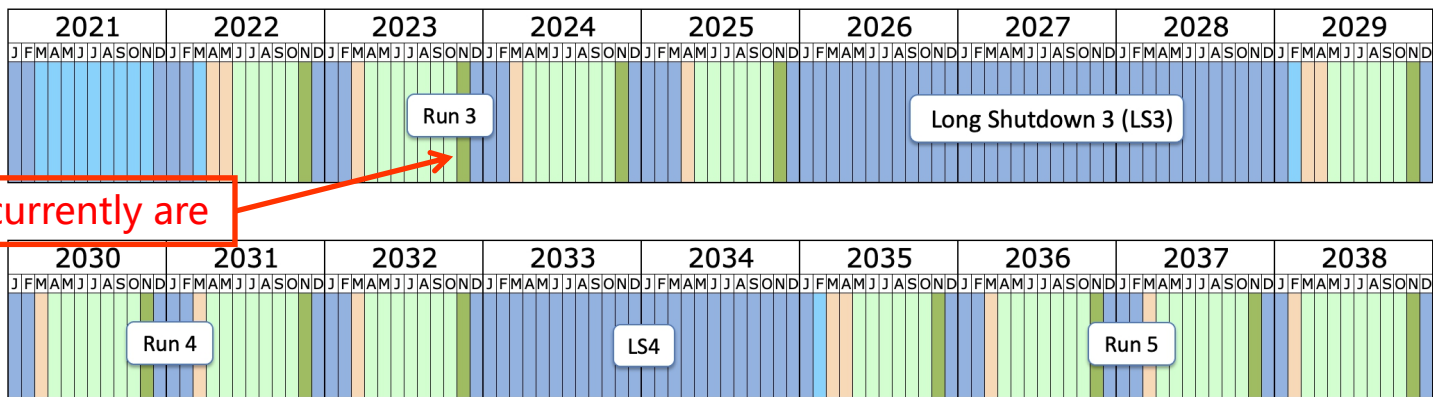
Channels	Coupling	Observed	Expected
Phys. Rev. D 104, 052004 (2021)	$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
	c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
CMS	c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
	c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
VBF & VH & $H \rightarrow 4l$	c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
	$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
	$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
	$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

68% constraints

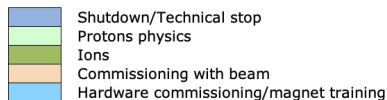
Summary



- The discovery of the Higgs boson in LHC open the new era of particle physics
- Precision measurement show good agreement with the SM predictions
- Study of CP properties would be the key ingredient for new physics searches
- Search for CP-odd component in VBF $H \rightarrow \gamma\gamma$ does not show significant excess with ATLAS run-II data
 - *Only 5% data collected, more results in coming years*



Last updated: January 2022



Keep looking like a child.
Be curious about the unknown.

Backup





The effective $U(1)_Y$ and $SU(2)_{I_W, L}$ invariant Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_{\tilde{B}B}}{\Lambda^2} O_{\tilde{B}B} + \frac{c_{\tilde{W}W}}{\Lambda^2} O_{\tilde{W}W} + \frac{c_{\tilde{B}}}{\Lambda^2} O_{\tilde{B}}$$

three dimension-6 operators

$$O_{\tilde{B}B} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi, \quad O_{\tilde{W}W} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \quad O_{\tilde{B}} = (D_\mu \Phi)^\dagger \hat{B}_{\mu\nu} D_\nu \Phi,$$

$$D_\mu = \partial_\mu + \frac{i}{2} g' B_\mu + i g \frac{\sigma_a}{2} W_\mu^a \sigma_a$$

After **SSB**, unitary gauge effective lagrangian can be written as **mass basis**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{H\gamma\gamma} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{H\gamma Z} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}_{\mu\nu}^+ W^{-\mu\nu}.$$

written into two dimensionless couplings \tilde{d} and \tilde{d}_B

$$\tilde{g}_{H\gamma\gamma} = \frac{g}{2m_W} (\tilde{d} \sin^2 \theta_W + \tilde{d}_B \cos^2 \theta_W), \quad \tilde{g}_{H\gamma Z} = \frac{g}{2m_W} \sin 2\theta_W (\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W} (\tilde{d} \cos^2 \theta_W + \tilde{d}_B \sin^2 \theta_W), \quad \tilde{g}_{HWW} = \frac{g}{m_W} \tilde{d}.$$

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} c_{\tilde{W}W}, \quad \tilde{d}_B = -\frac{m_W^2}{\Lambda^2} \tan^2 \theta_W c_{\tilde{B}B}.$$



Optimal observable

an arbitrary choice $\tilde{d} = \tilde{d}_B$ is adopted

$$\tilde{g}_{H\gamma\gamma} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{H\gamma Z} = 0.$$

Generic tensor structure of HVV

$$T^{\mu\nu}(p_1, p_2) = \sum_{V=W,Z} \frac{2m_V^2}{v} g^{\mu\nu} + \sum_{V=W,Z,\gamma} \frac{2g}{m_V} \tilde{d} \varepsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}.$$

Only one variable to describe CP-odd

Parametrize amplitude as the sum of SM amplitude and CP-odd one

$$\mathcal{M} = \mathcal{M}_{SM} + \tilde{d} \cdot \mathcal{M}_{CP-odd}.$$

The VBF cross section is proportional to the squared matrix element:

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \tilde{d} \cdot 2\text{Re}(\mathcal{M}_{SM}^* \mathcal{M}_{CP-odd}) + \tilde{d}^2 \cdot |\mathcal{M}_{CP-odd}|^2.$$

$$OO = \frac{2\text{Re}(\mathcal{M}_{SM}^* \mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

Optimal
observable



Optimal observable

Code implemented by HLep group based on HAWK (core code written by Fortran)

<https://gitlab.cern.ch/Htt2016.developers/HLeptonsCPRW>

Input variables (truth-level):

- Higgs boson 4-momentum
- 4-momentum of leading and subleading VBF jets
- Bjorken x_1 , x_2

$$x_{1/2}^{\text{reco}} = \frac{M_{\text{Hjj}}}{\sqrt{s}} e^{\pm y_{\text{Hjj}}}$$

Input variables (reco-level):

- Higgs boson 4-momentum from two decay objects
- 4-momentum of leading and subleading VBF jets
- Bjorken x_1 , x_2 from reconstruction

$$x_1^{\text{reco}} = \frac{M_{\text{final}}}{\sqrt{s}} e^{y_{\text{final}}}$$
$$x_2^{\text{reco}} = \frac{M_{\text{final}}}{\sqrt{s}} e^{-y_{\text{final}}},$$

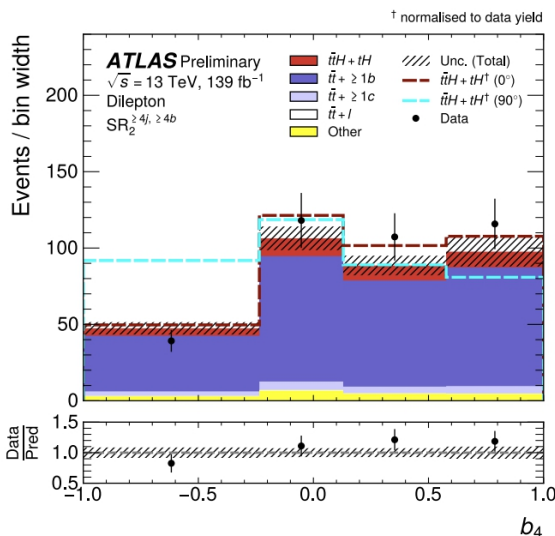
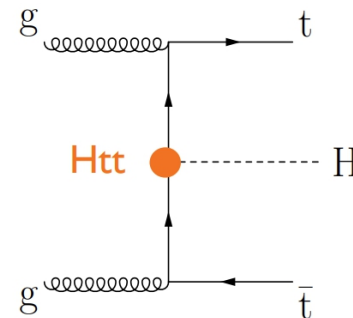


CP measurement from others

CP properties of Higgs-top coupling with ttH

Effective Lagrangian for Yukawa coupling to top quarks parameterized by CP-Even and CP-odd components

$$\mathcal{L}_{t\bar{t}H} = -\kappa'_t y_t \phi \bar{\psi}_t (\cos \alpha + i\gamma_5 \sin \alpha) \psi_t$$



$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1| |\vec{p}_2|}$$

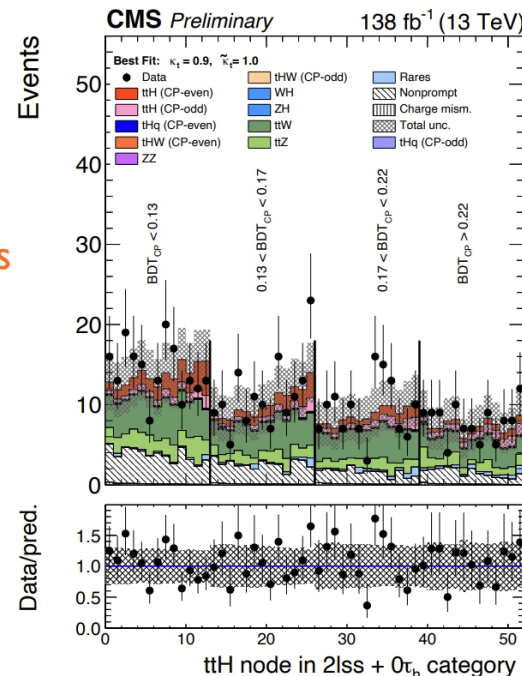
Two recent examples:

$t\bar{t}H+tH$
 $H \rightarrow bb$

$t\bar{t}H+tH$
 $H \rightarrow \text{MultiLeptons}$

Analyses use MVA discriminants and CP-sensitive observables

When possible, multiple decay channels can be combined...



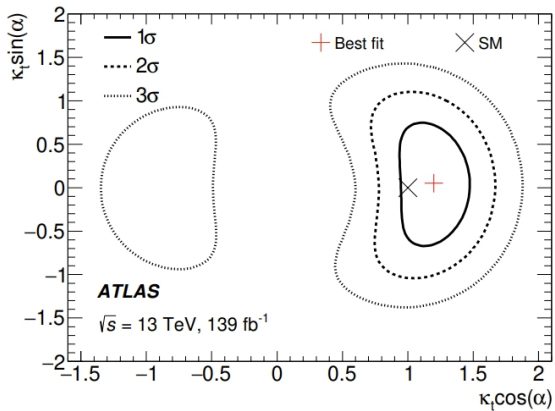


CP measurements from others

CP properties of Higgs-top coupling with ttH

ATLAS ttH H→γγ

[Phys. Rev. Lett. 125 \(2020\) 061802](#)

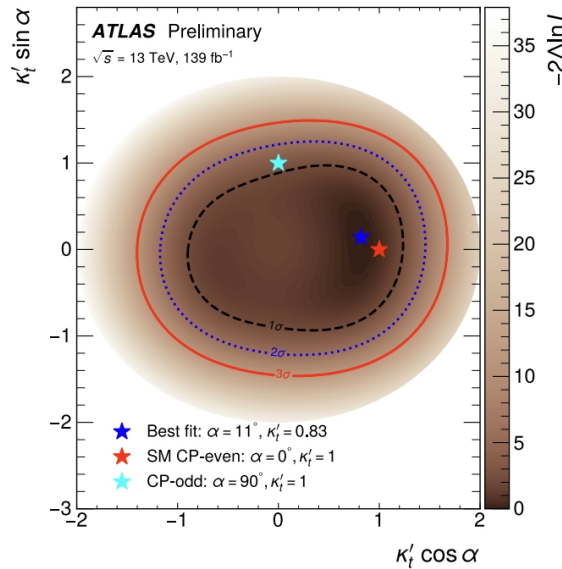


pure CP-odd coupling
excluded at 3.9σ

$|\alpha| > 43$ deg excluded @ 95% CL.

ATLAS ttH H→bb

[ATLAS-CONF-2022-016](#)

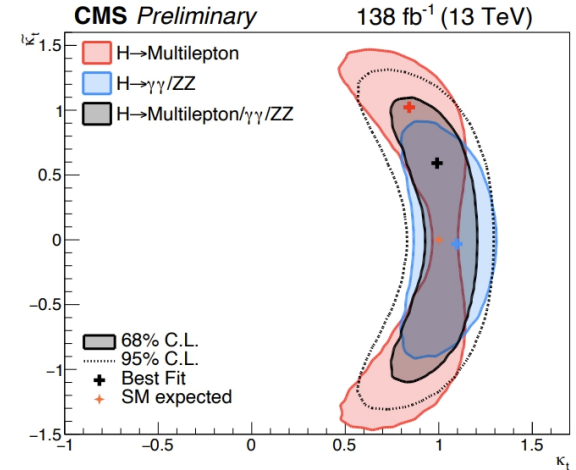


pure CP-odd coupling
disfavoured at 1.2σ

$\alpha = 11^\circ \begin{matrix} +55^\circ \\ -77^\circ \end{matrix}$

CMS ttH H→ML + H→γγ + H→ZZ

[PAS HIG-21-006](#)



pure CP-odd coupling
excluded at 3.7σ

$$\mathcal{A}(Hff) = \frac{m_f}{v} \bar{\psi}_f (\kappa_t + i\tilde{\kappa}_t \gamma_5) \psi_f$$

$$f_{CP}^{Htt} = \frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}$$

$$|f_{Htt}| = (\sin \alpha)^2$$

$|f_{Htt}| = 0.28 (< 0.55 \text{ at } 1\sigma)$