Higgs Properties from CMS and ATLAS

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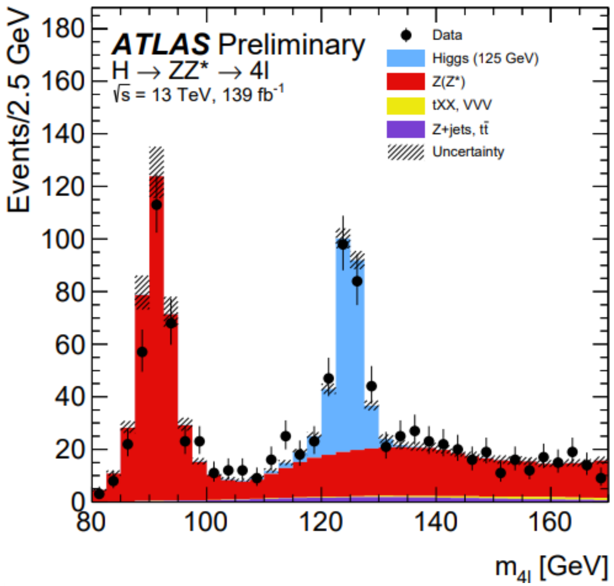
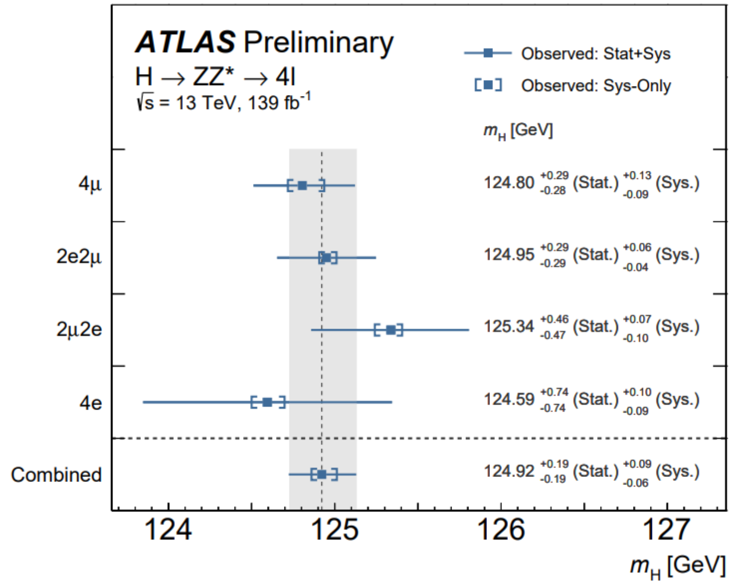
LHCP 17 May 2022

Johns Hopkins University

Higgs Mass Measurements

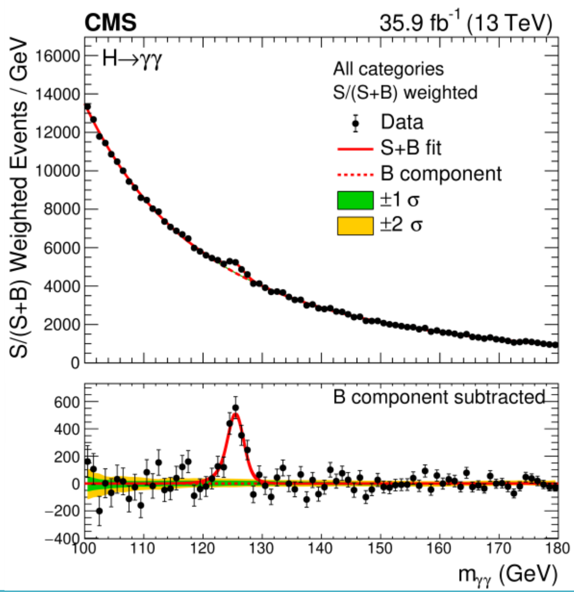


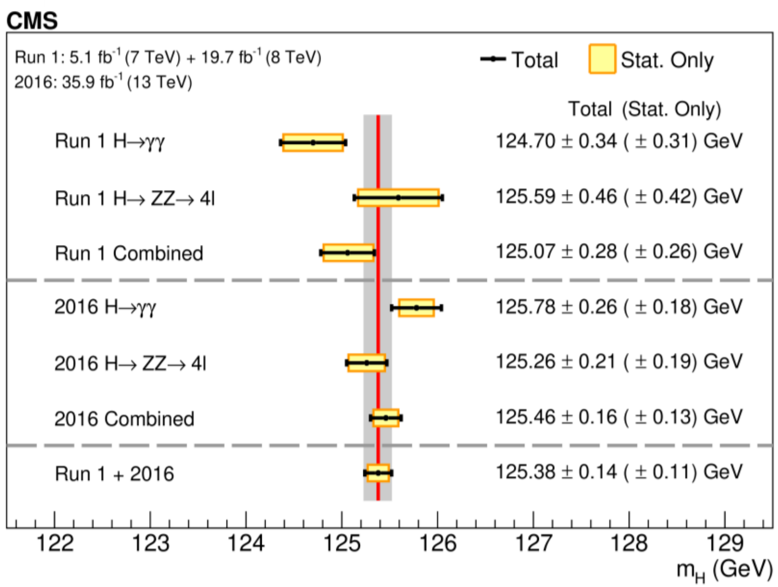


Most precise measurement from ATLAS:

$$M_H = 124.92^{+0.19(0.09)}_{-0.19(0.06)} GeV$$

ATLAS-CONF-2020-005





Most precise measurement from CMS:

$$M_H = 125.38 \pm 0.14(0.11)$$

Combination of measurements from γγ,4l decay channels

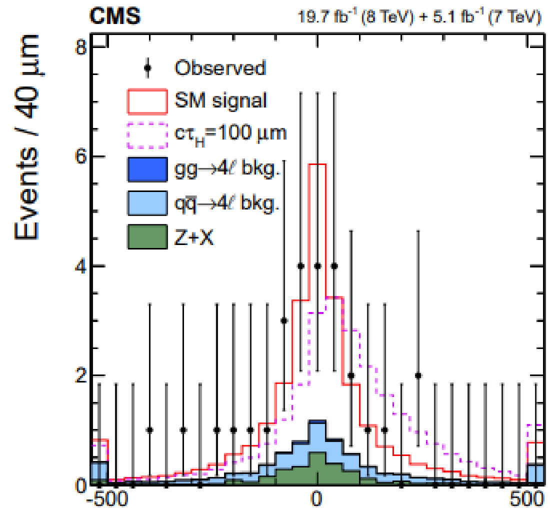
Phys. Lett B 805:135425

Γ_H Measurements

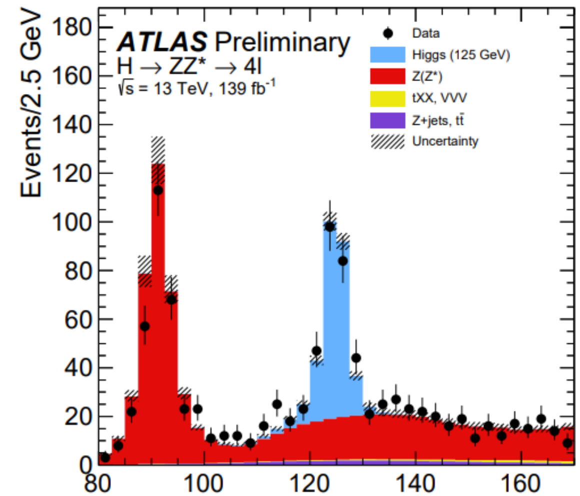
Early measurements set limits on Γ_H by measuring the **Higgs lifetime** or the width of the **on-shell peak:**

$\sim 3 \times 10^{-3} eV < \Gamma_H < \sim 1 - 3\ GeV$

$$\boldsymbol{\Gamma_{H,SM} = 4.07\ MeV}$$



Phys Rev D 92:072010



ATLAS-CONF-2020-005

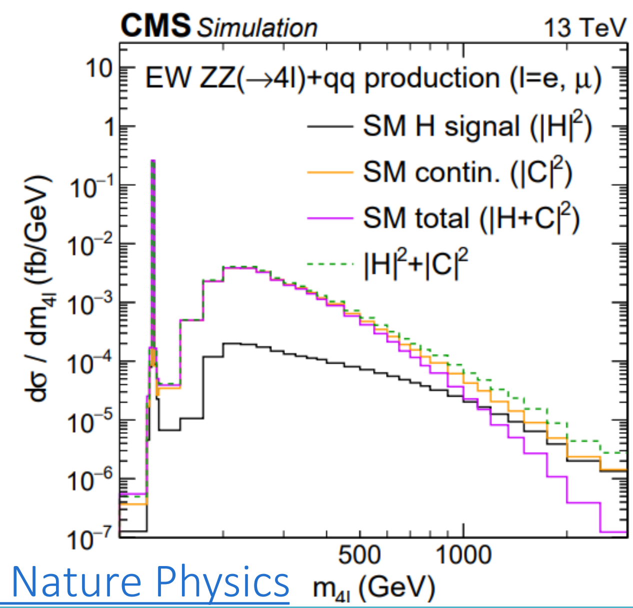
Need to include off-shell information to increase precision

Assuming on-shell and off-shell couplings are equal

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \Gamma_H / \Gamma_H^{SM}$$

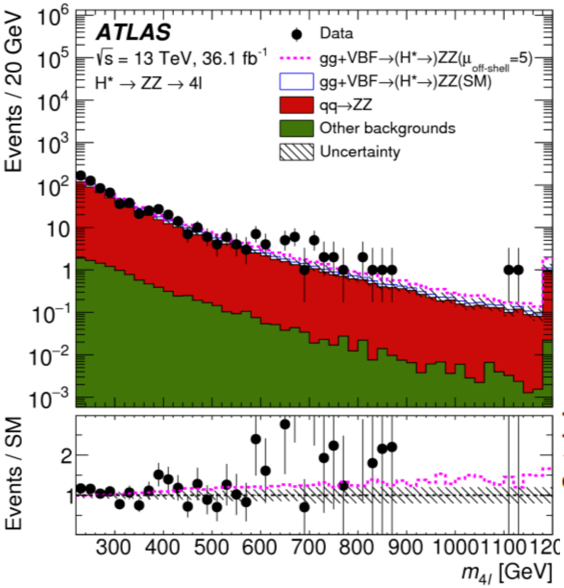
This is measured for different production modes (ggH VBF ATLAS), (ttH,VH,VBF,ggH CMS) including **4l** and **2l2ν** final states

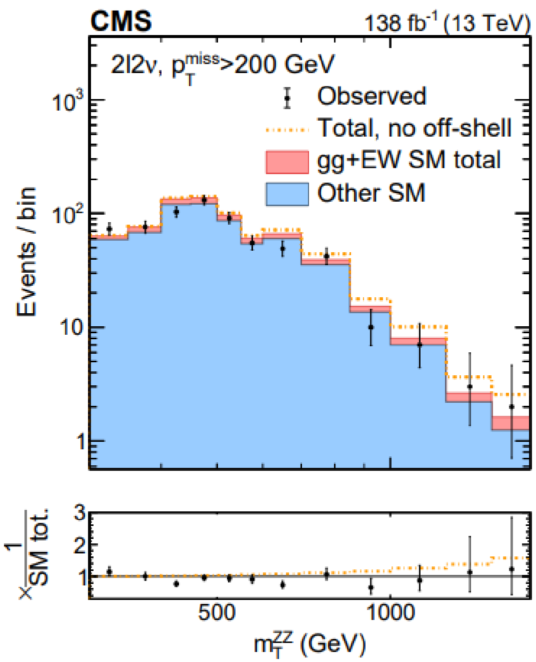
Note: Can only be done in H→WW,ZZ→4l channel

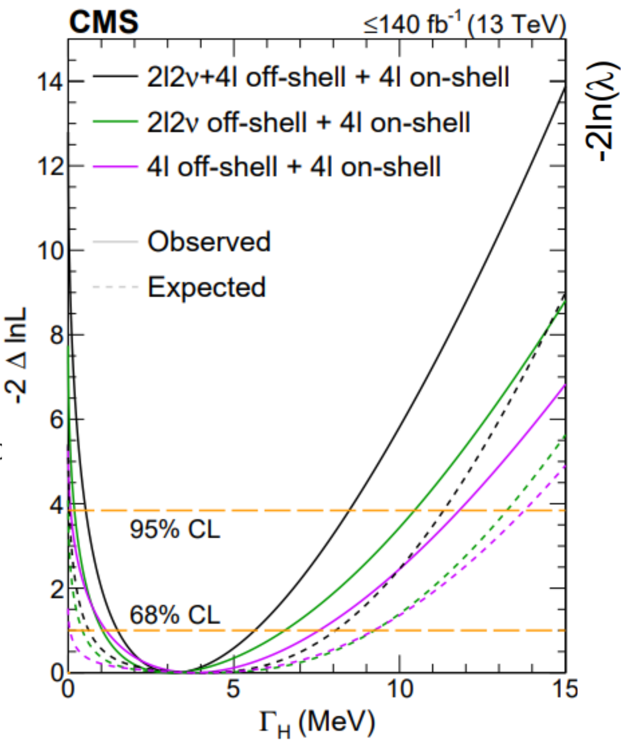


Submitted to Nature Physics

Γ_H Measurements







$140\ fb^{-1}$ on-shell 4l

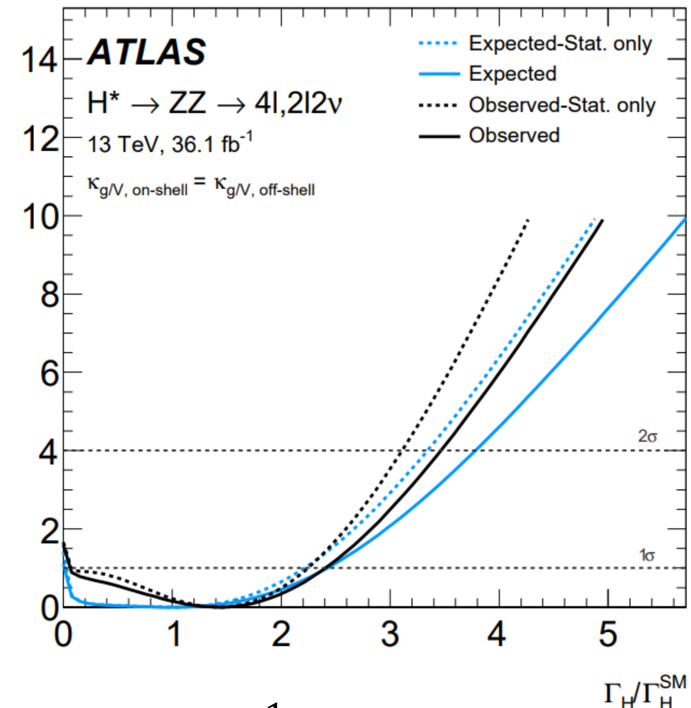
$78\ fb^{-1}$ off-shell 4l

$138\ fb^{-1}$ off-shell 2l2ν

Γ_H=$3.2^{+2.5}_{-1.7}$MeV

3.6 σ evidence for off-shell H production!

[Submitted to Nature Physics]



$36.1\ fb^{-1}$off-shell 4l,2l2ν

$36.1\ fb^{-1}$on-shell 4l

Upper limit on Γ_H of 14.4 MeV

[Phys Lett B. 786.223]

Higgs CP Properties at the LHC

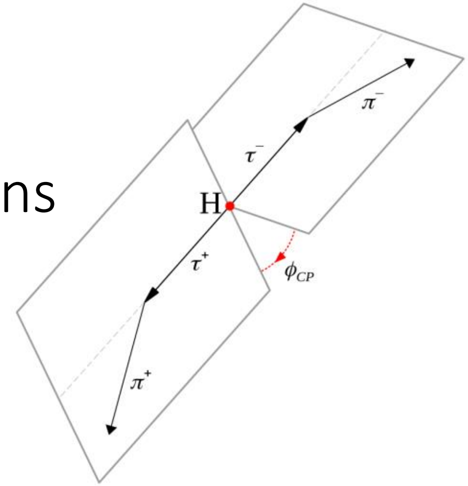
SM Higgs is even under CP inversion

Observing anything other than CP-even interactions of the Higgs indicates BSM physics.

Family	CP structure probed	Scale of CP-odd contributions
Fermion	Htt,Hττ	O(1) (Tree level)
Gluon	Hgg	O(1/v^2) Dim 6
EW Vector Boson	HZZ,HWW,HZγ,Hγγ	O(1/v^2) Dim 6

Summary of CP measurements from Atlas and CMS

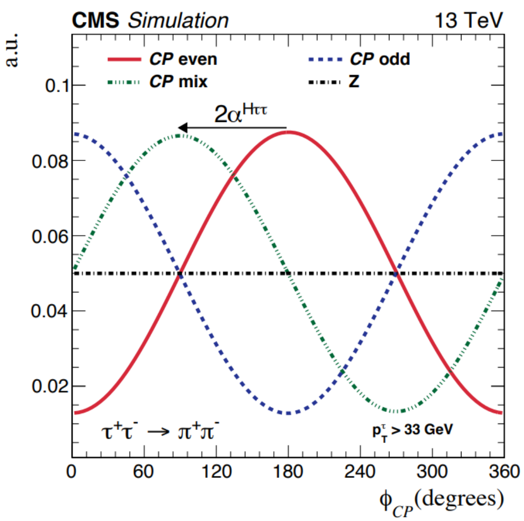
CP structure Higgs Tau Tau

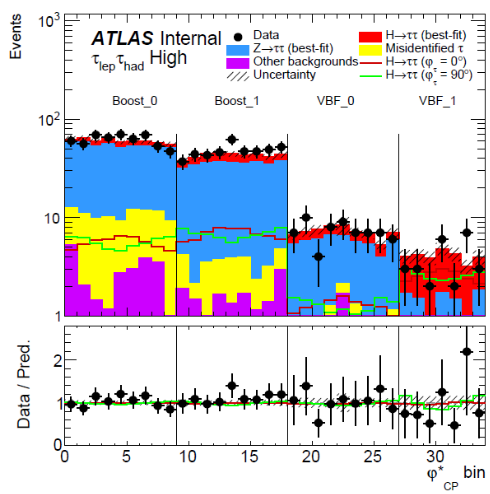


Effective Lagrangian for Yukawa Coupling to tau leptons parameterized by CP-Even and CP-odd components

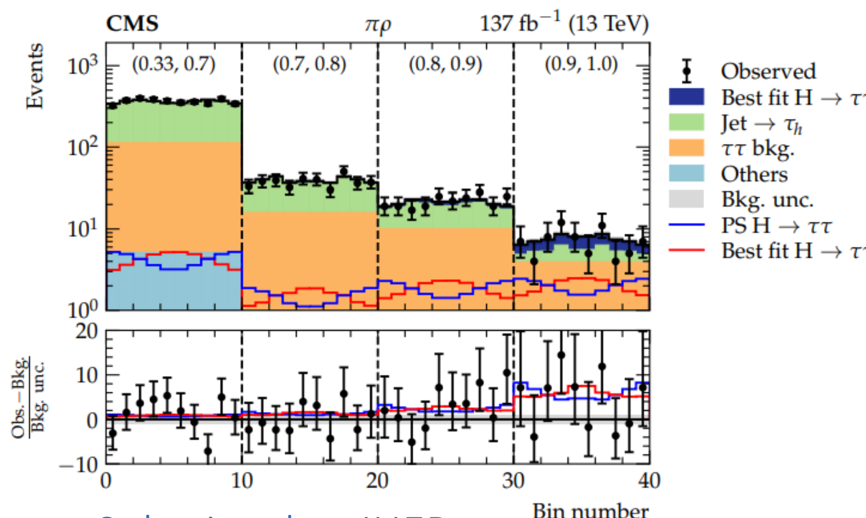
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

ϕ_τ (ATLAS) = $\alpha^{H\tau\tau}$(CMS) = Effective CP mixing angle





[ATLAS-CONF-2022-032]

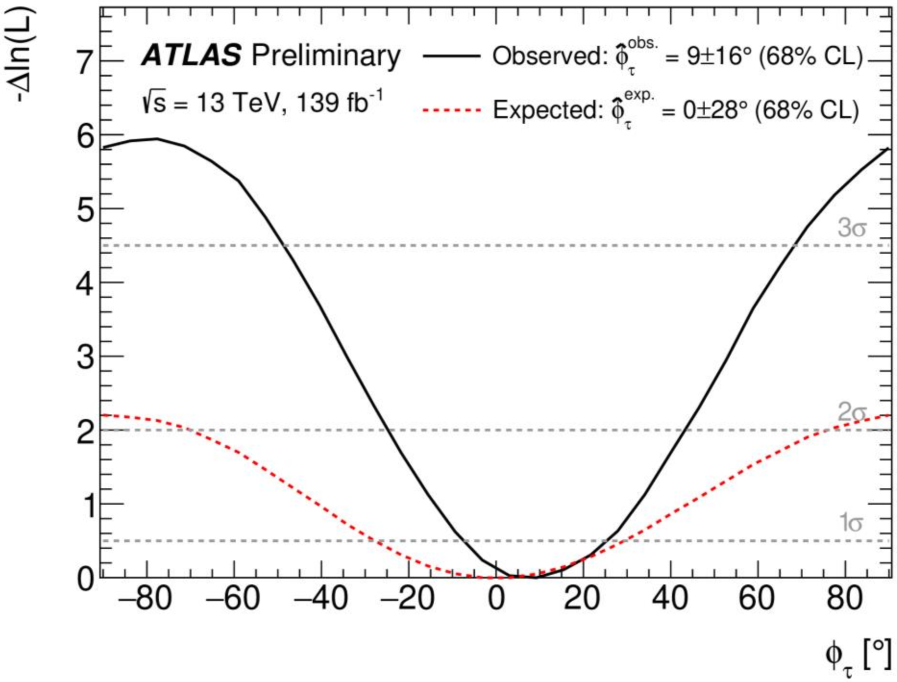


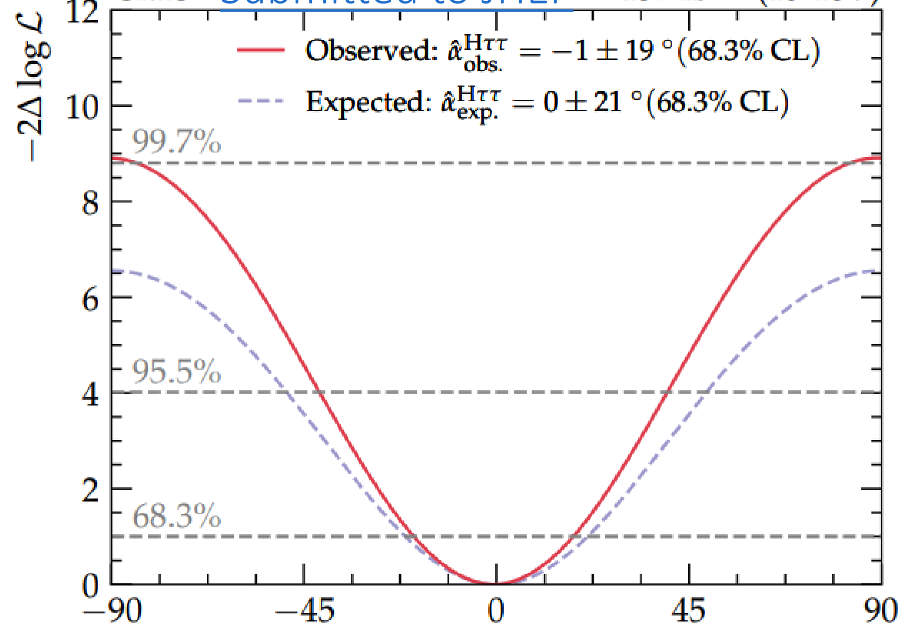
[Submitted to JHEP]

Measure $\phi_{CP}(\phi^*_{CP})$ to directly probe CP structure of Yukawa Coupling

ϕ_{CP} Results

[ATLAS-CONF-2022-032]





Submitted to JHEP

Same term in Lagrangian

$\phi_{CP} = 9 \pm 16^\circ$

Exclude Pure CP-Odd hypothesis at **3.4 σ**

$\phi_{CP} = -1 \pm 19^\circ$

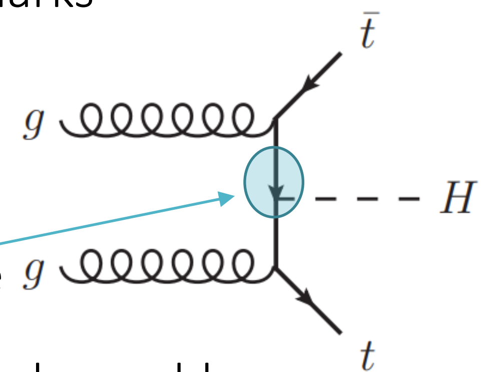
Exclude Pure CP-Odd hypothesis at **3σ**

Results in agreement with SM expectations as well as each other

CP Structure of Higgs Top Yukawa

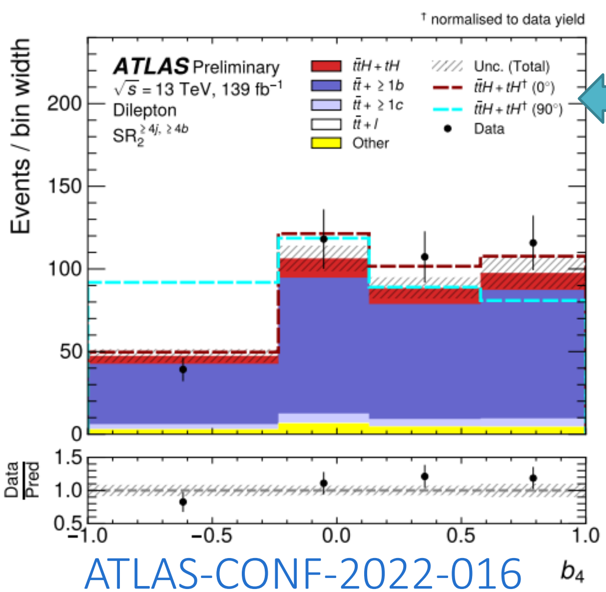
Similarly, effective Lagrangian for Yukawa Coupling to top quarks parameterized by CP-Even and CP-odd components

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



Analyze ttH, or tH production to probe CP structure

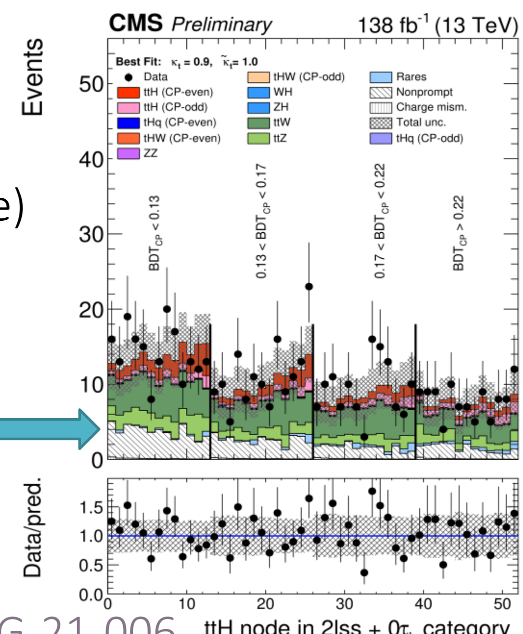
ATLAS and CMS construct BDTs for classification and optimal observables



ATLAS-CONF-2022-016

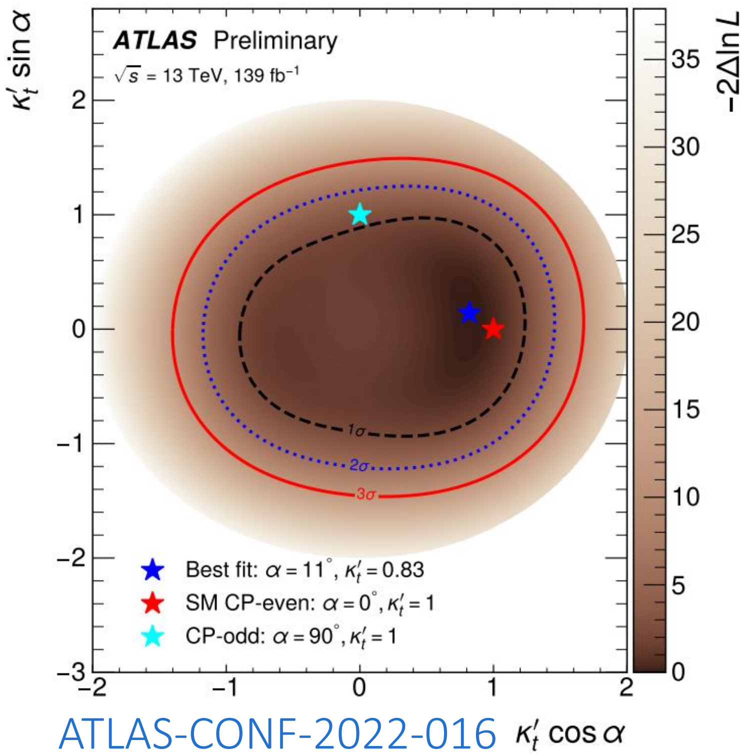
ttH+tH,H→bb
(Most recent decay mode)
Not yet combined with
Atlas H → γγ

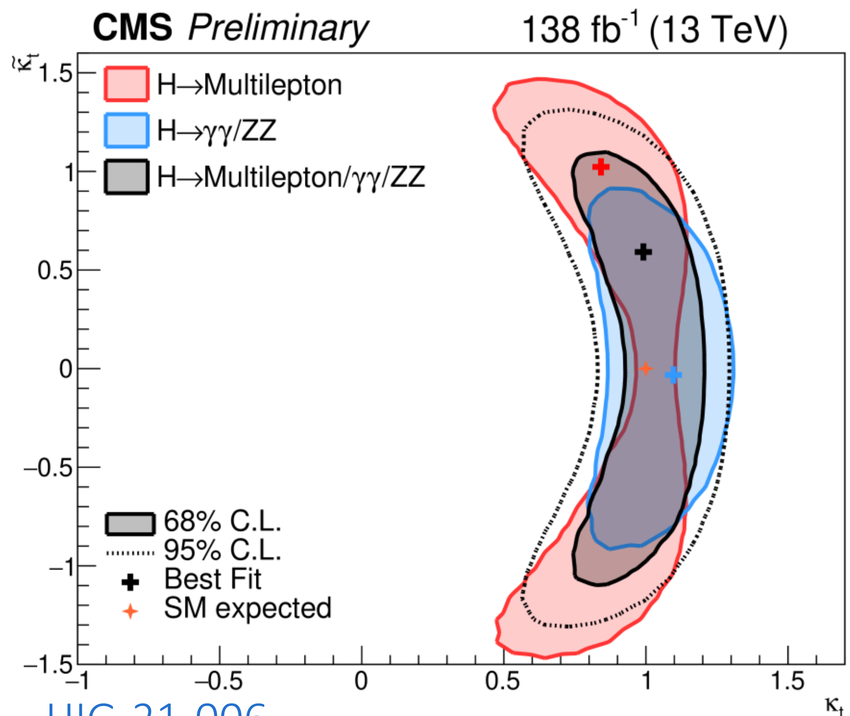
ttH+tH,H→multilepton
(Most recent decay mode)
Combined with H →4l,γγ



HIG-21-006

CP Structure of Higgs Top Yukawa





ATLAS-CONF-2022-016

HIG-21-006

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\overline{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t$$

Coupling strength $\kappa_t' = 0.83^{+0.30}_{-0.46}$

CP-mixing angle $\alpha = 11^{\circ}{}^{+55^\circ}_{-77^\circ}$ ⟸ $f_{CP}^{Htt} = (\sin\alpha)\,|\sin\alpha|$ ⟹ $f_{CP}^{\mathrm{Htt}} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$

Pure CP-odd disfavored at 1.2σ

Consistent with H→γγ

$|f_{CP}^{Htt}| = 0.28$ (< .55 at 1σ)

Pure CP-odd disfavored at 3.2σ

Measurements consistent with SM expectation

CP Structure of HVV couplings

No CP–Odd HVV at tree level allowed under SU(2)xU(1)

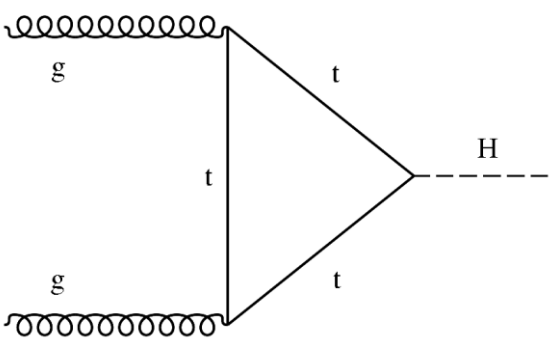
-Dimension 6 operators allow for CP-Odd HVV interactions

EFT provides general coupling framework to probe HVV CP-structure

ATLAS and CMS use different formalism but both place constraints on Dim 6 CP-Odd contributions

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

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}_{\mu\nu}^{+} W^{-\mu\nu},$$

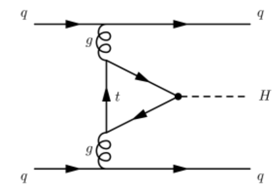


Hgg CP-structure inaccessible in decay

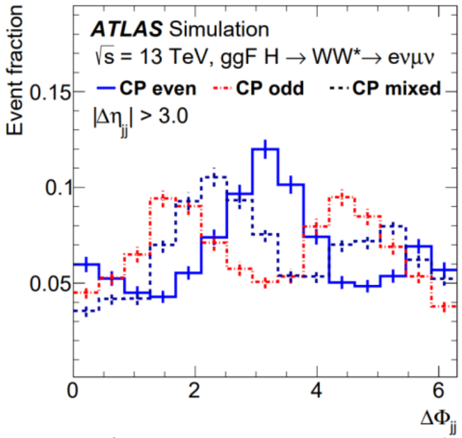
CP-Odd terms in ggH loop approximated at point-like coupling

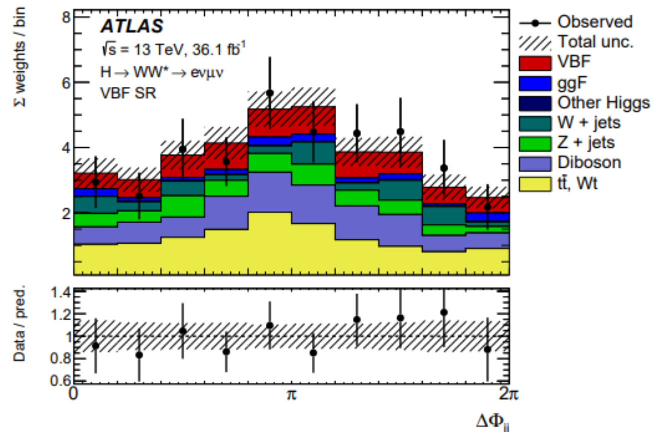
$$\mathcal{L}_0^{\mathrm{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg} \cos(\alpha) G_{\mu\nu}^a G^{a,\mu\nu} + \kappa_{gg} \sin(\alpha) G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}\right) H$$

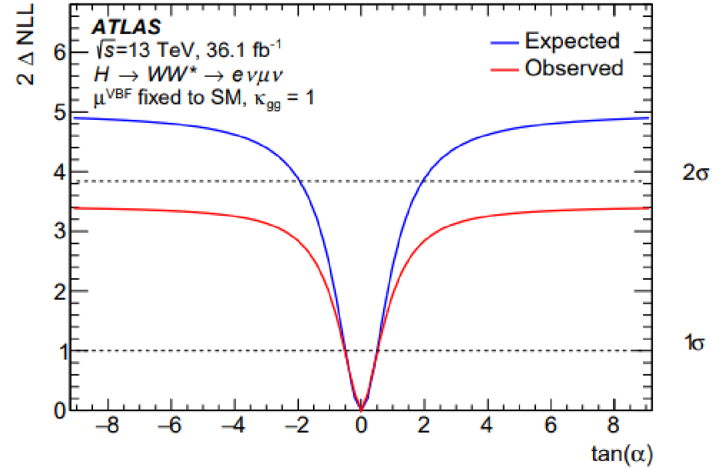
Higgs-gluon coupling CP results



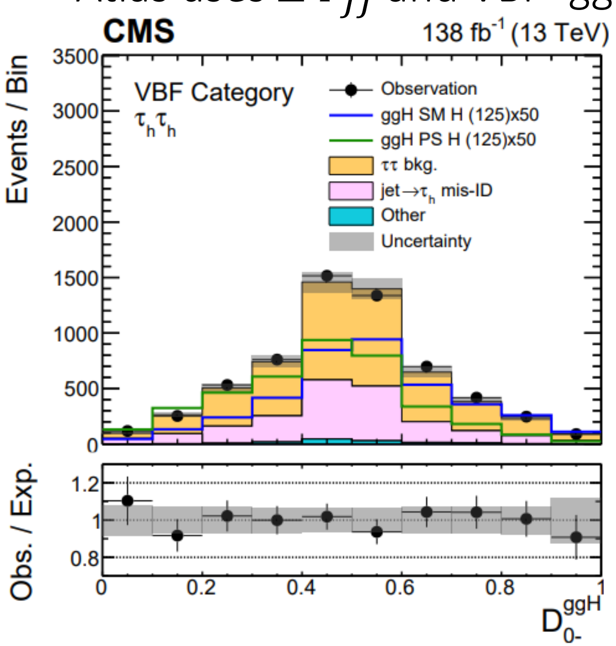
Accepted by EPJC







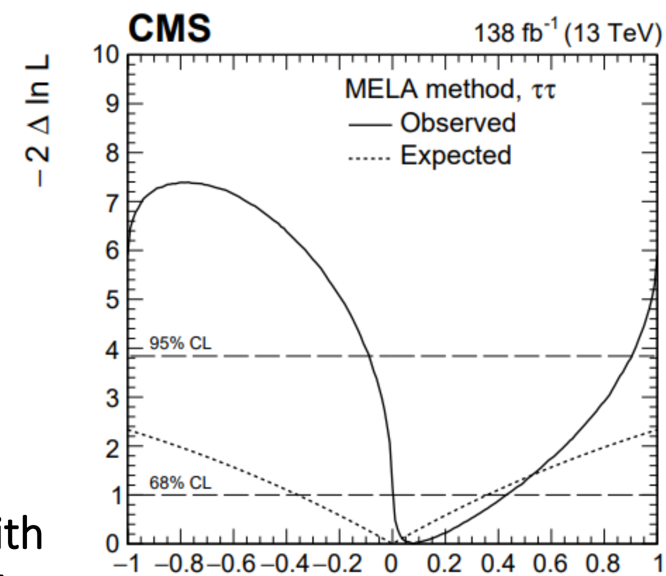
Atlas uses $\Delta\Phi_{jj}$ and VBF+ggH, H→WW



CMS uses MELA discriminants in recent result with ggH,VBF, H → ττ

H → ττ result combined with earlier H → 4l

Both results consistent with Standard Model expectations

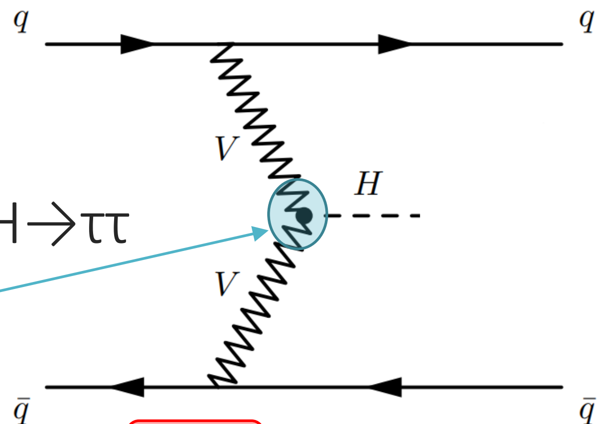


Submitted to Phys Rev D

ATLAS HVV results

Analyze HVV couplings in VBF production and H→ττ

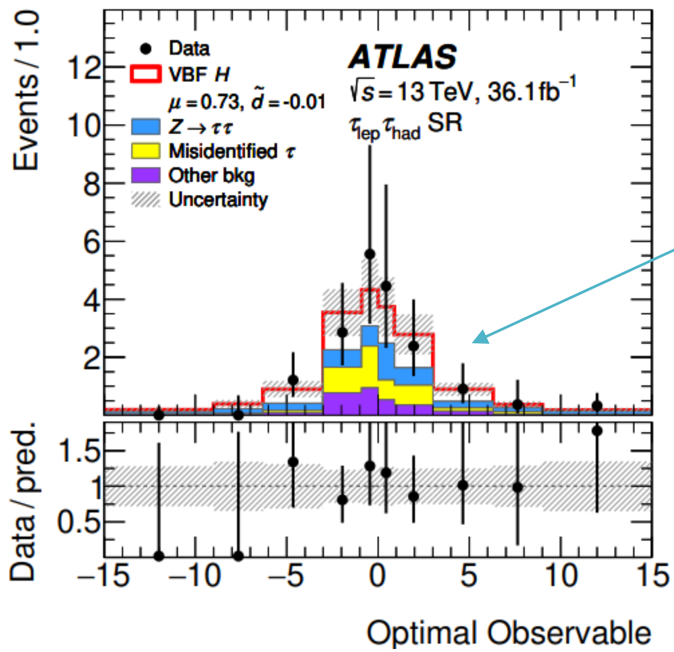
Kinematic information from associated jets correlated with coupling structure at HVV vertex



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

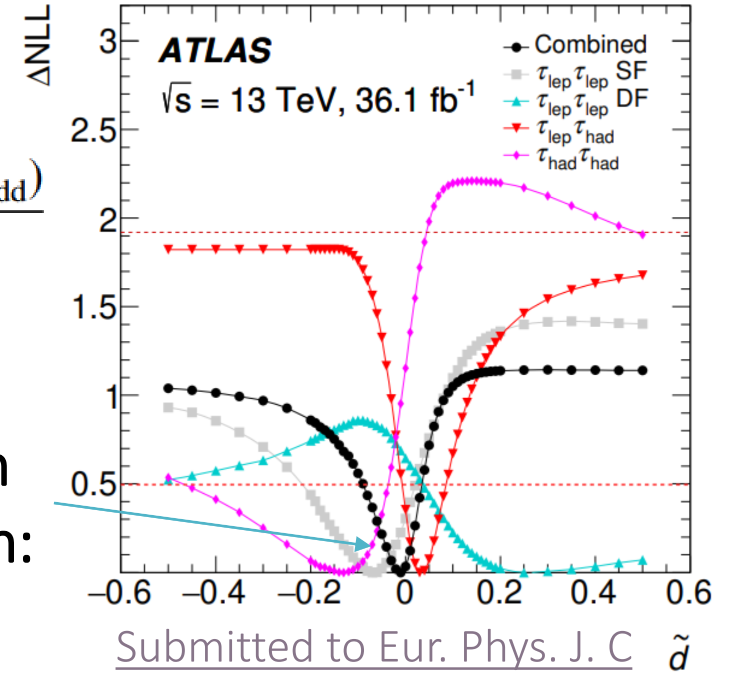
$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \qquad \tilde{g}_{HAZ} = 0$$

Single coupling strength $\tilde{d}$ parameterizes CP-Odd component



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

$\tilde{d}$ constraints consistent with SM expectation: $\tilde{d} = 0$



Submitted to Eur. Phys. J. C

CMS HVV CP Structure

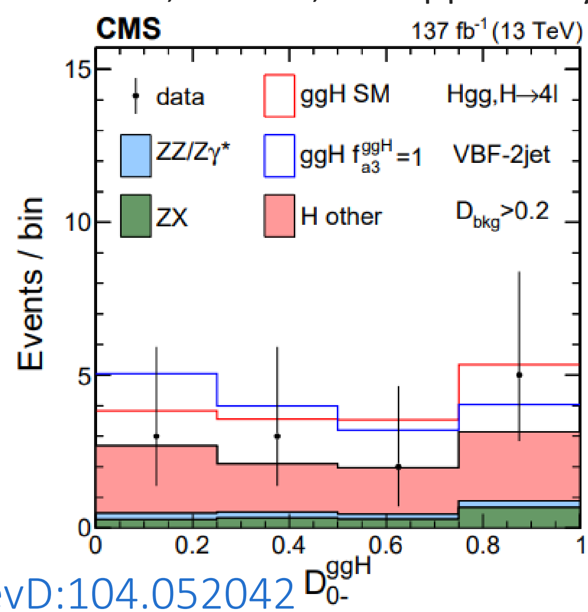
HVV couplings parameterized by tensor structures in scattering amplitude which allow for modelling of any EFT effects

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

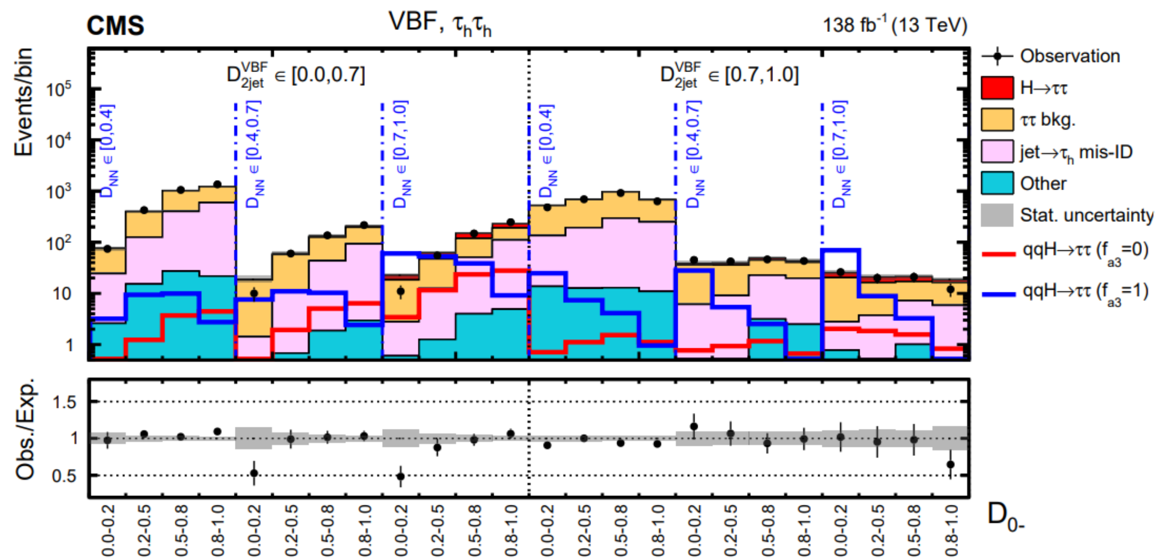
Fractional contribution of CP-Odd HZZ coupling

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_3}{a_1}\right)$$

Multiple analyses constraining HVV couplings with ggH, VBF, VH, ttH, tH production and H→ττ, H→4l, H→γγ decay

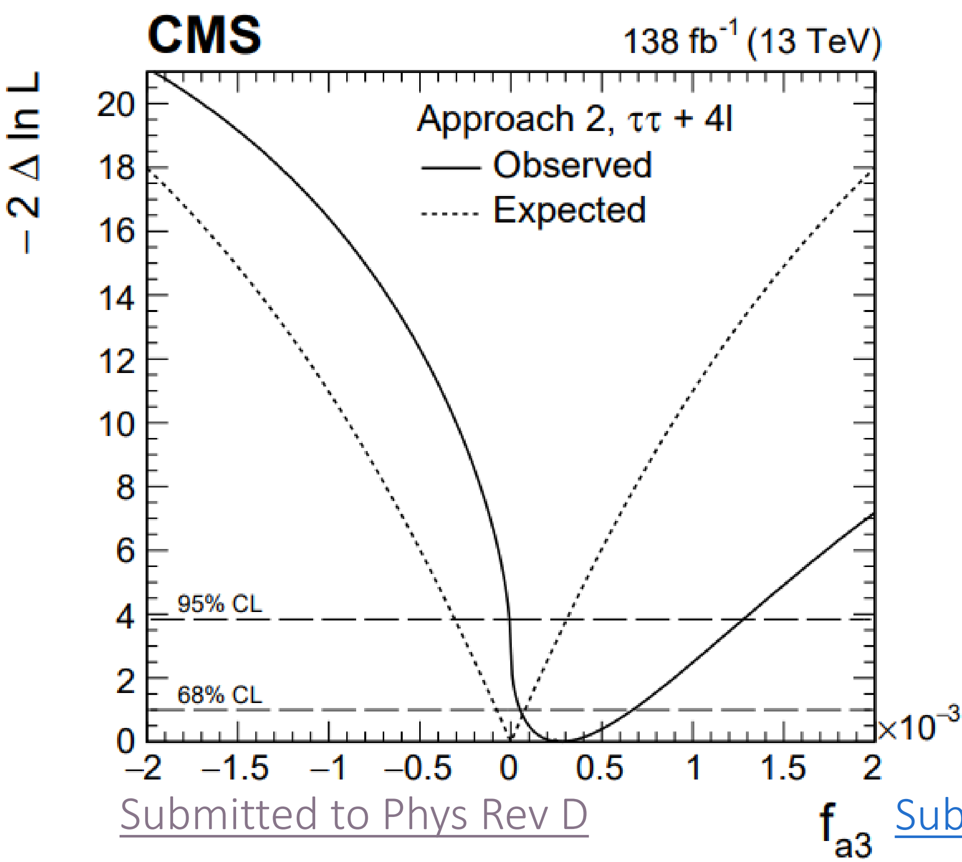


PhysRevD:104.052042



Submitted to Phys Rev D.

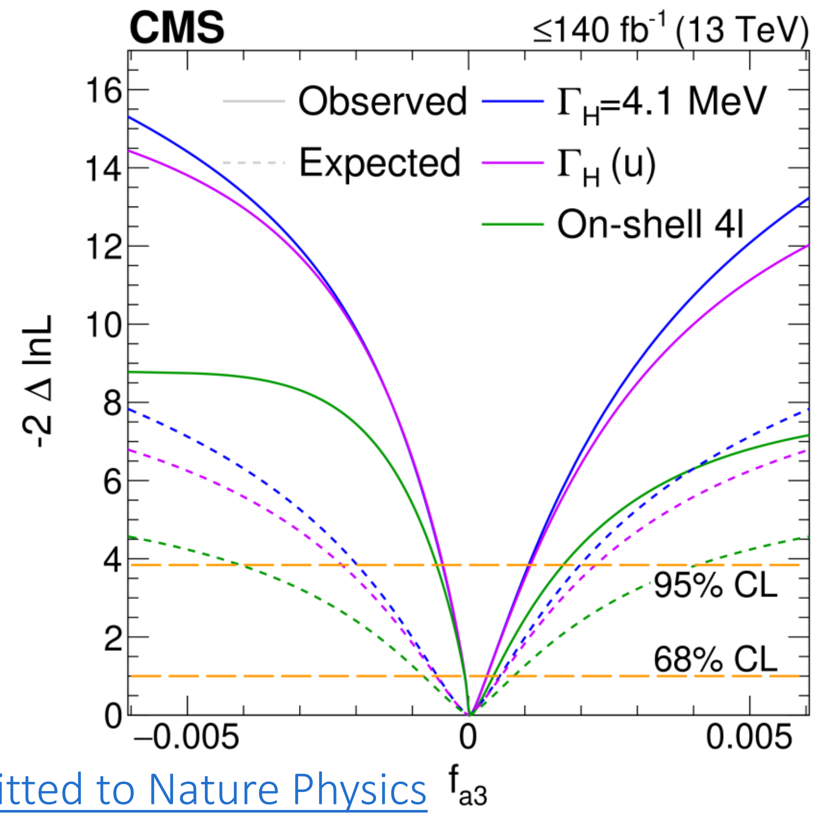
CMS HVV results



[Submitted to Phys Rev D]

Constraints from combined analysis have other anomalous HVV fixed to 0

$f_{a3}=0.20^{+0.26}_{-0.16}\times10^{-3}$



[Submitted to Nature Physics]

Constraints from H→4l + Off-shell events

Additional anomalous couplings floated in fits

$f_{a3}=0.024^{+0.32}_{-0.064}\times10^{-3}$

Measurements consistent with SM expectation

Conclusion

Higgs mass measured to great precision

Expect improvement with full Run 2 dataset

First evidence of Higgs Off Shell Production!

$\boldsymbol{\Gamma_H}=\mathbf{3.2^{+2.5}_{-1.7}}$MeV

In the fermion sector tau and top quark CP-structure is probed

New for Run 2: Pure CP-odd coupling excluded at > 3σ

CP-structure of Higgs gluon couplings probed with jet correlations in the gluon fusion loop

CP-structure of HVV couplings probed through a variety of production and decay modes

Stronger constraints expected with Run 3 data!