Higgs mass, width and CP @ CMS

Higgs Hunting
Sept 11th 2023

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On behalf of the
CMS collaboration

CMS
Compact Muon Solenoid

JOHNS HOPKINS
UNIVERSITY

Higgs properties

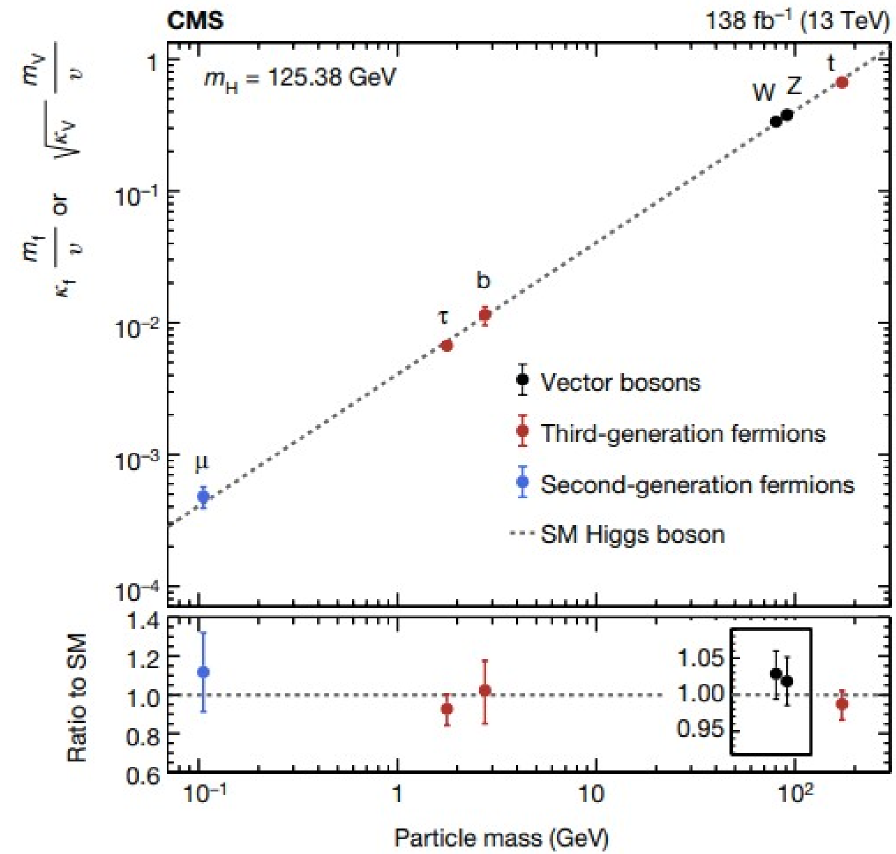
10+1 years since Higgs discovery @LHC

> Characterize and measure in high precision the boson properties

> Mass

> Width

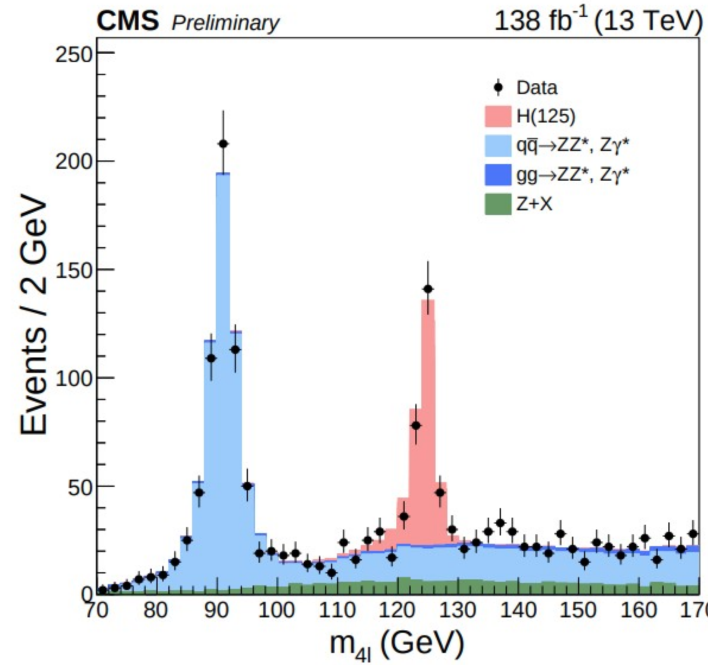
> CP structure of couplings

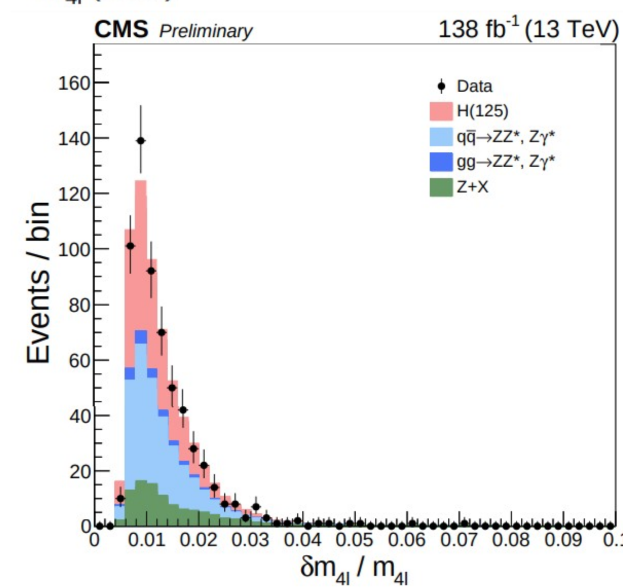


Mass

NEW!

- Full Run 2 H→4l
- 105 < mH < 140GeV
- Measurement improvements
  - Lepton VTXS constrain and BS compatibility
  - Categorize events based on δm4l/m4l
  - Improve estimates on lepton uncertainties using on-shell Z
  - Improved detector calibration

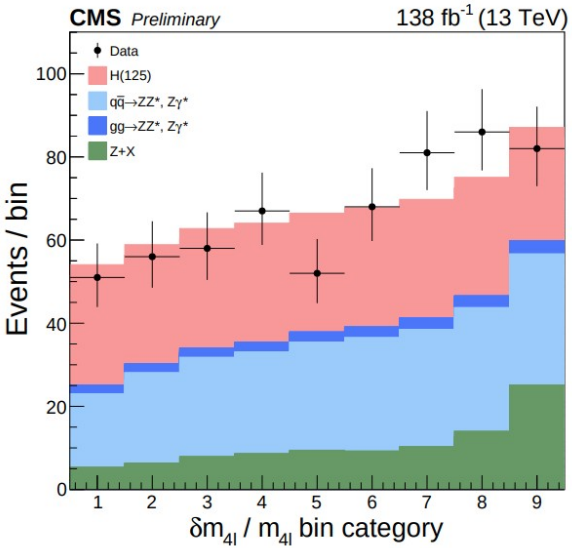


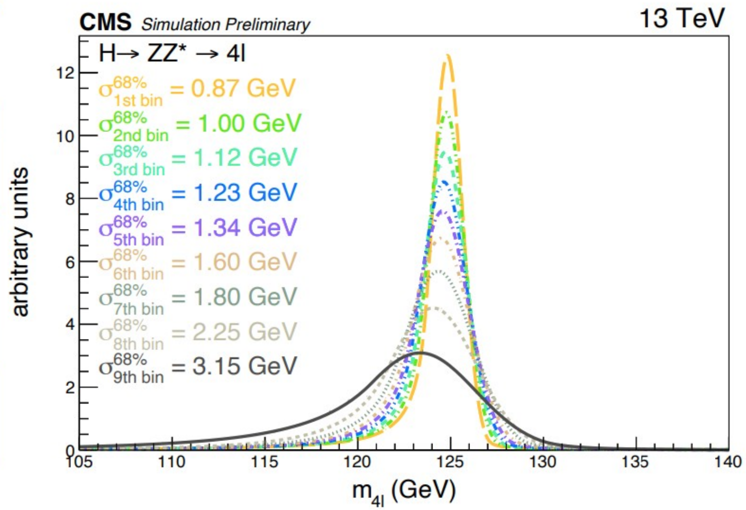


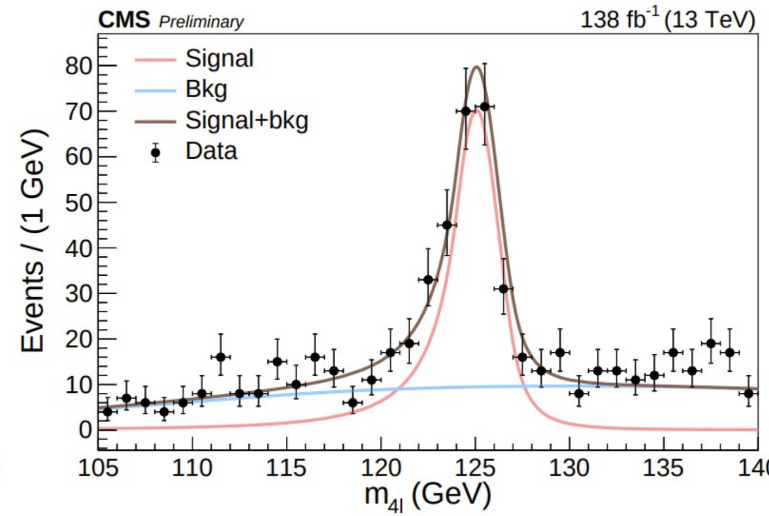
HIG-21-019 (link)

Mass

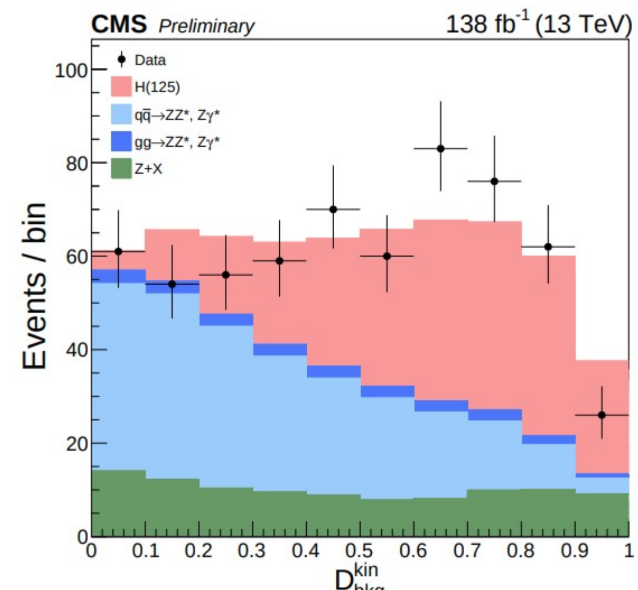
HIG-21-019 (link)







- 9 resolution-based categories
- Construct m4l line-shape DSCB + Landau
- 9 x 2D fit (m4l , $\mathcal{D}_{\text{bkg}}^{\text{kin}}$)

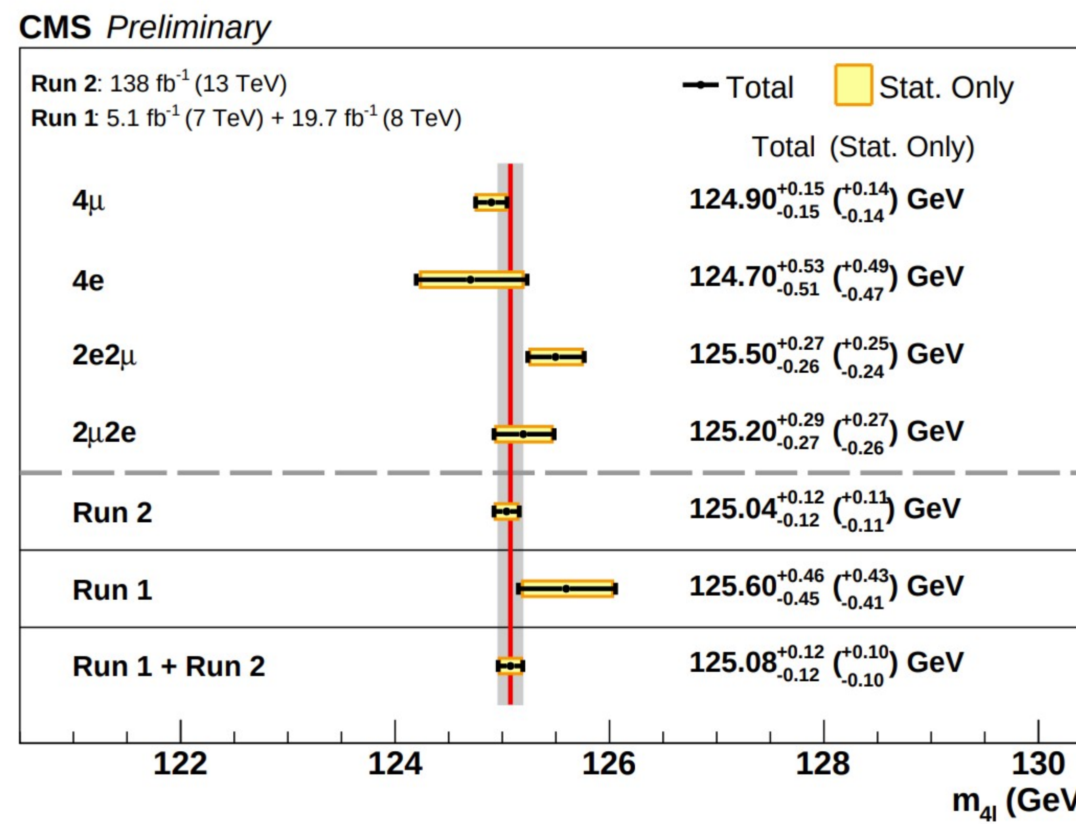


Mass

HIG-21-019 (link)

NEW!

- Combine results with Run 1
- Result statistically limited
- Most precise single channel measurement to date!



$m_H = 125.08 \pm 0.10_{stat} \pm 0.05_{syst}$ (GeV)

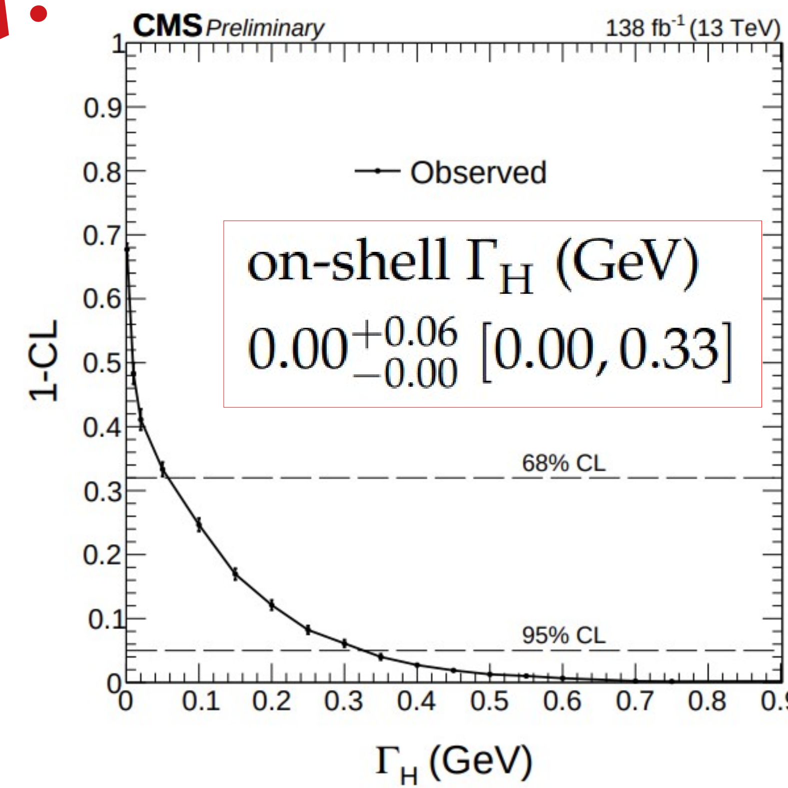
Higgs Width – on-shell measurement

HIG-21-019 (link)

NEW!

- SM: given $m_H \rightarrow \Gamma_H$ can be calculated
- Measure Higgs width
  - Test of Higgs → SM particles
  - A test/complimentary for H→invisible particles
- Techniques:
  - **Using the onshell region (mass pole shape)**
  - Using signal strength in on-shell and off-shell production

$$\Gamma_H^{SM} = 4.1 \text{ MeV}$$



> Convolute (DSCB + Laundau) x Breit-Wigner

> Fit m4l line shape
> measurement **limited by detector resolution**

Higgs Width – off-shell method

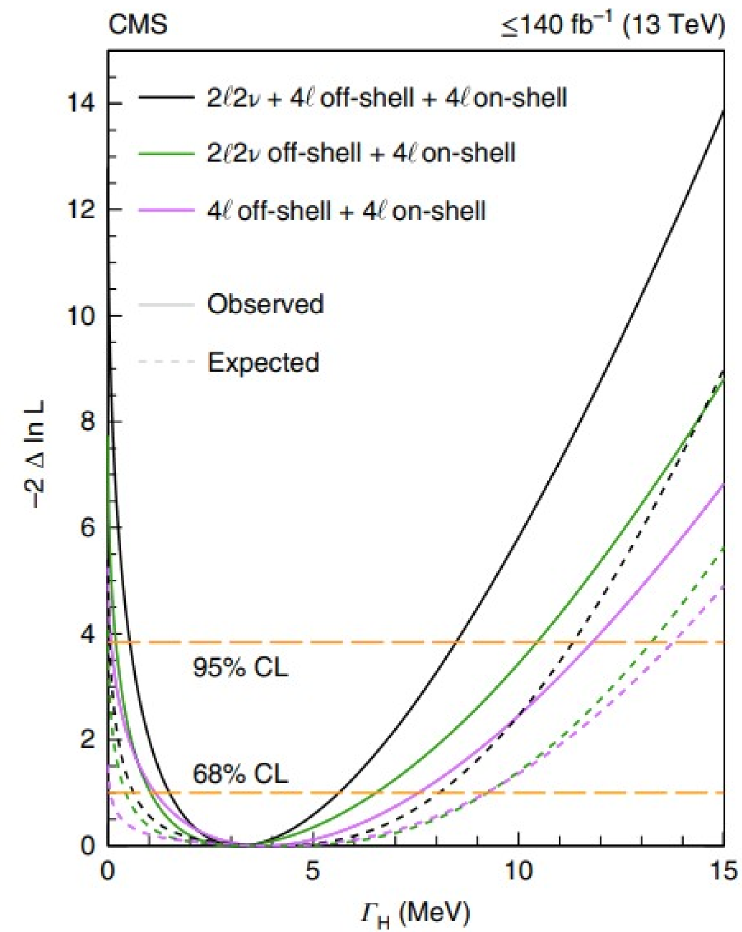
HIG-21-019 (link)

- Measure Higgs width:
  - test of Higgs on-shell vs off-shell production
  - test of Higgs → SM particles
  - A test/complimentary for H→invisible particles
- Techniques:
  - Using the onshell region (mass pole shape)
  - **Using signal strength in on-shell and off-shell production**

$\Gamma_H^{SM} = 4.1$ MeV

$$\frac{\sigma^{\text{off-shell}}_{vv\to H\to 4\ell}}{\sigma^{\text{on-shell}}_{vv\to H\to 4\ell}} \propto \Gamma_H$$

Nat. Phys. 18, 1329–1334 (2022)



Higgs width – off-shell method

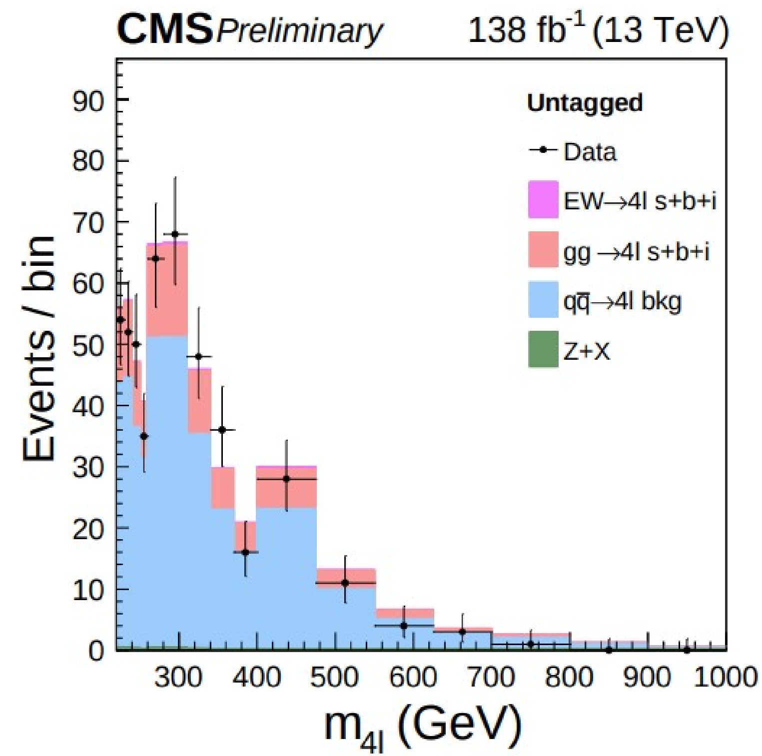
HIG-21-019 (link)

NEW!

- Analyze Full Run2 H→4l
- Select events in H→ ZZ→4l with m4l > 220GeV
- 3 exclusive categories:
  - VBF-tagged
  - VH-tagged
  - Untagged

Allows measuring μV,μF off-shell

- Perform template fit and likelihood
- Negative S B interference



on-shell:

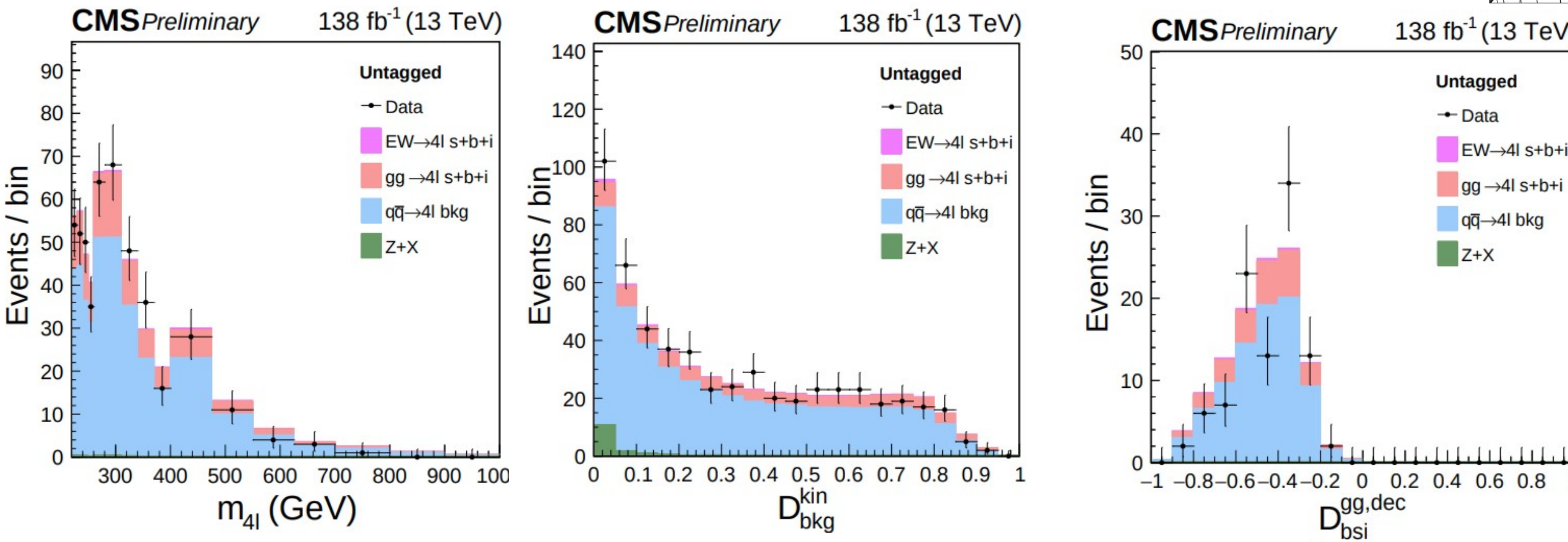
$$\mathcal{P}_{jk}(\vec{x};\vec{\xi}_{jk},\vec{\zeta}) = \mu_j \mathcal{P}^{\text{sig}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \mathcal{P}^{\text{bkg}}_{jk}(\vec{x};\vec{\xi}_{jk})$$

off-shell:

$$\mathcal{P}_{jk}(\vec{x};\vec{\xi}_{jk},\vec{\zeta}) = \frac{\mu_j \Gamma_{\text{H}}}{\Gamma_0} \mathcal{P}^{\text{sig}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \sqrt{\frac{\mu_j \Gamma_{\text{H}}}{\Gamma_0}} \mathcal{P}^{\text{int}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \mu_j \mathcal{P}^{\text{cross}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \mathcal{P}^{\text{bkg}}_{jk}(\vec{x};\vec{\xi}_{jk})$$

Higgs width – off-shell method

HIG-21-019
(link)



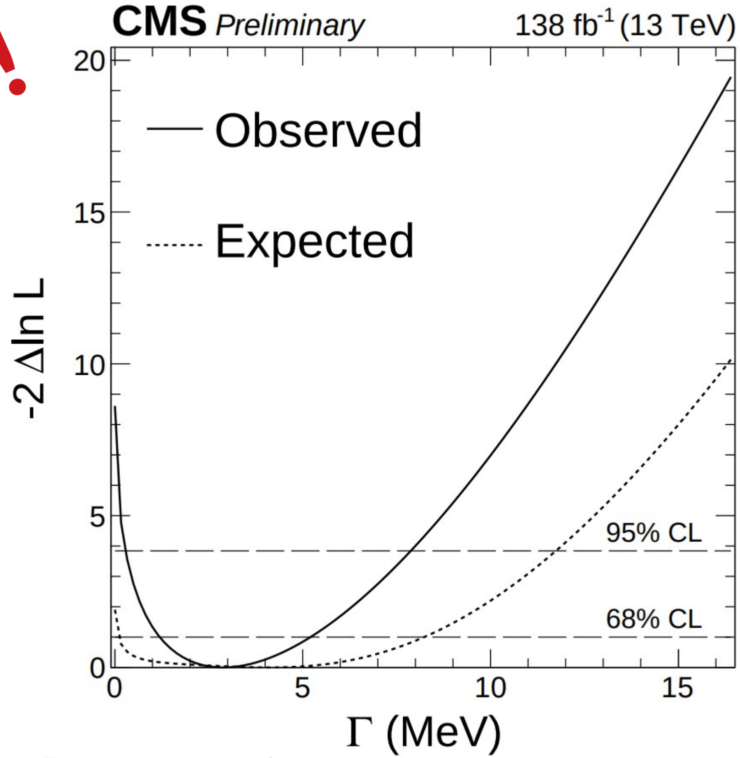
- **Observables:**

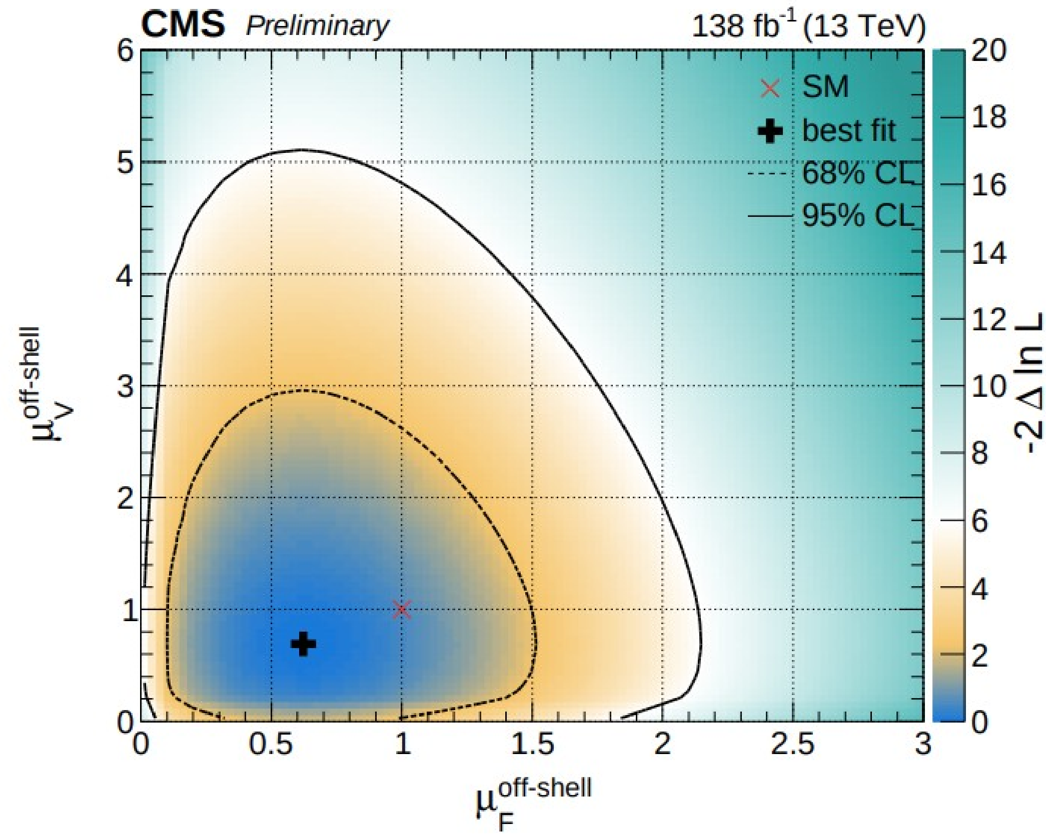
  M4L + 2 discriminants:
- Measurement is statistically limited
- Main uncertainties related to dominant backgrounds
  - k-factor uncertainties

Higgs width – off-shell method

HIG-21-019 (link)

NEW!





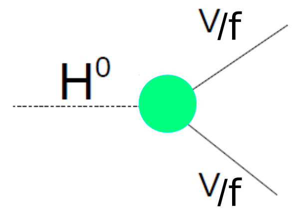
Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.64^{+0.50}_{-0.37}$ [0.06, 1.69]	$1.00^{+0.99}_{-0.97}$ [0.00, 2.80]
$\mu_F^{\text{off-shell}}$	$0.62^{+0.57}_{-0.41}$ [0.03, 1.81]	$1.00^{+1.05}_{-1.00}$ [0.00, 2.93]
$\mu_V^{\text{off-shell}}$	$0.69^{+1.32}_{-0.63}$ [0.00, 3.91]	$1.00^{+3.34}_{-1.00}$ [0.00, 7.65]

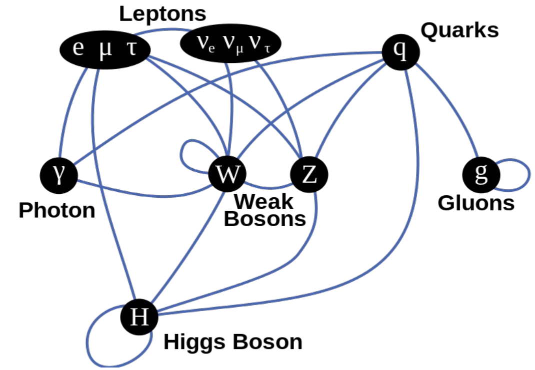
Full Run2 H→4l

$$\Gamma_H \text{ (MeV)} = 2.9^{+2.3}_{-1.7} \ [0.3, 7.9]$$

CP - AC measurements

- **Study Higgs Couplings:**
  - Uncover CPV in Higgs sector
  - Uncover BSM phenomena





- **Dedicated measurements**
  - Targeted analysis
  - Dedicated sensitive observables to specific couplings
  - Gen + Full Detector simulation of AC effects

    (Interference effects, acceptance effects+)

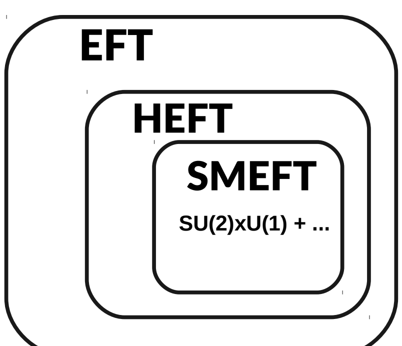
- **Utilize EFT**

Interference effects important and valuable

P α $|A^{tot}|^2$

$|A^{tot}|^2 = | A^{prod} \times A^{decay} |^2$

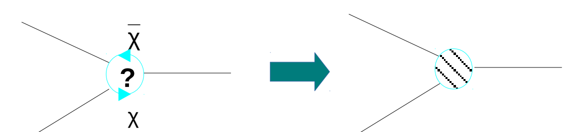
$= |(A_1+A_2+A_3)\mathbf{x}(B_1+B_2+B_3)|^2$



$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Mass eigenstate basis + symmetries → **Higgs basis**

Weak eigenstate basis : **Warsaw basis**



EFT – basis

Mass eigenstate → Higgs basis

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^*$$

$$+ \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$$A(\mathrm{Hff}) = -\frac{m_\mathrm{f}}{v} \bar{\psi}_\mathrm{f} \left(\kappa_\mathrm{f} + \mathrm{i}\tilde{\kappa}_\mathrm{f}\gamma_5\right) \psi_\mathrm{f}$$

V = W,Z,g,γ

f = leptons + quarks

Approach 1

$$g_1^{WW} = g_1^{ZZ}$$
$$g_2^{WW} = c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}$$
$$g_4^{WW} = c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}$$
$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2},$$
$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) = 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}$$

- Natural choice for Higgs couplings
- Less operators

Weak eigenstate: Warsaw basis

- More general - used in EW TOP and Higgs sector
- SMEFT build in (SU(2)x U(1))
- Has many more dim 6 operators

Approach 2: SMEFT

SU(2)xU(1) + custodial sym.
set c_w^2 to SM value

custodial sym.
set $c_w^2 = 1$

$$g_1^{WW} = g_1^{ZZ}$$
$$g_2^{WW} = c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}$$
$$g_4^{WW} = c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}$$
$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2},$$
$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) = 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}$$

Rotations between basis feasible and demonstrated in measurements !

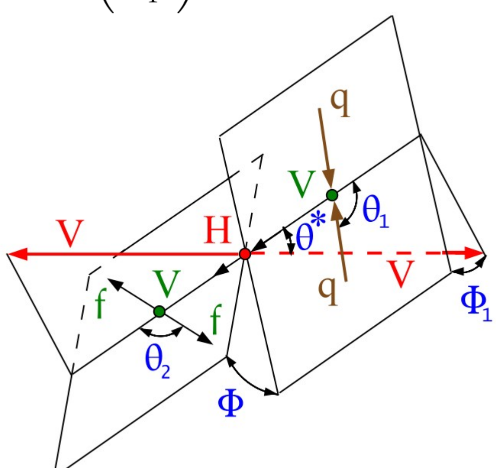
HVV: H→4l

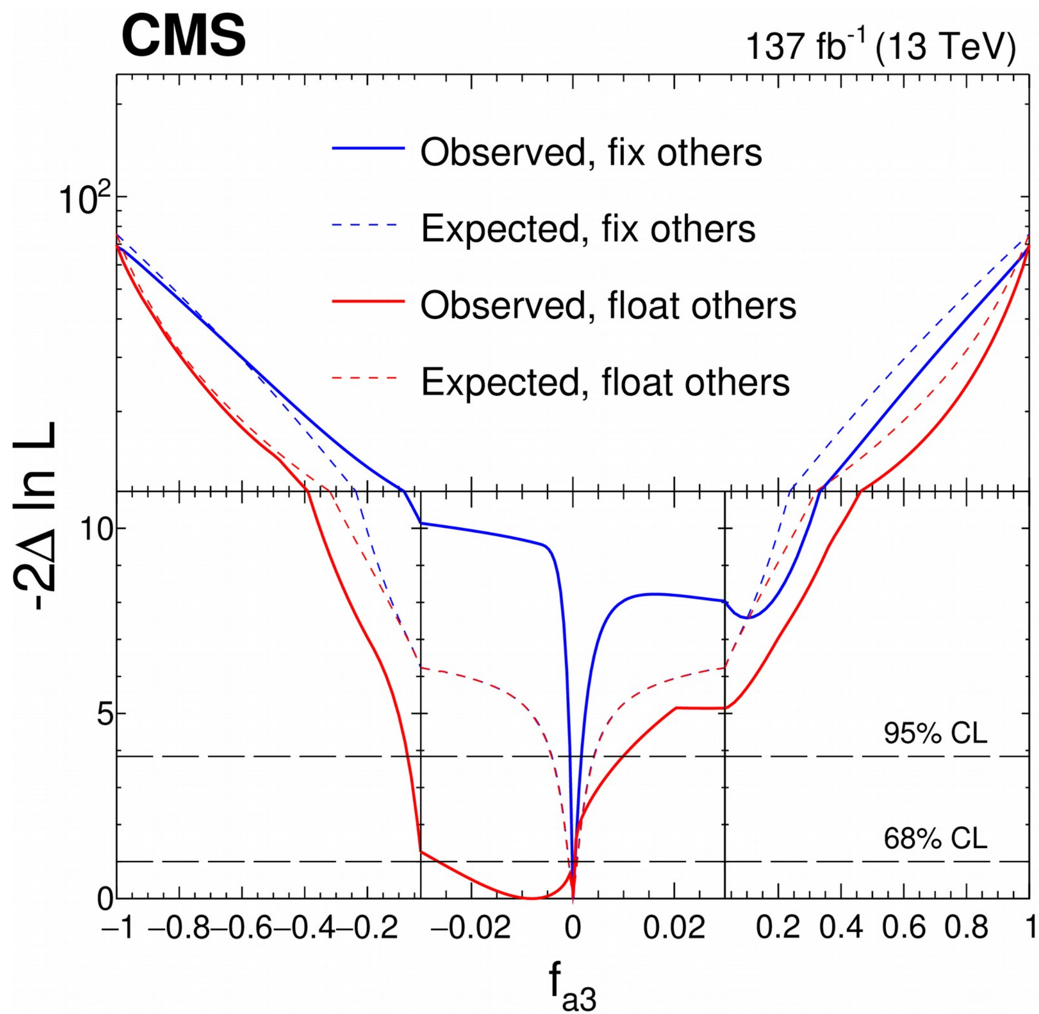
PhysRevD.104.052004

- 2e2μ, 4e, 4μ
- 105< m4l < 140 GeV + 6 categories targeting prod. modes.
- Approach 1 with 4 independent A.C. + SM
- Simultaneous scan of all AC considered
- Non-zero minima
- **SM consistent**

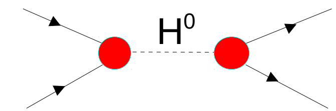
Effective fractional xsec:

$$f_{ai}^{VV} = \frac{|a_i^{VV}|^2 \alpha_{ii}^{(dec)}}{\sum_j |a_j^{VV}|^2 \alpha_{jj}^{(dec)}} \,\mathrm{sign}\left(\frac{a_i^{VV}}{a_1}\right)$$





HVV: H→4l



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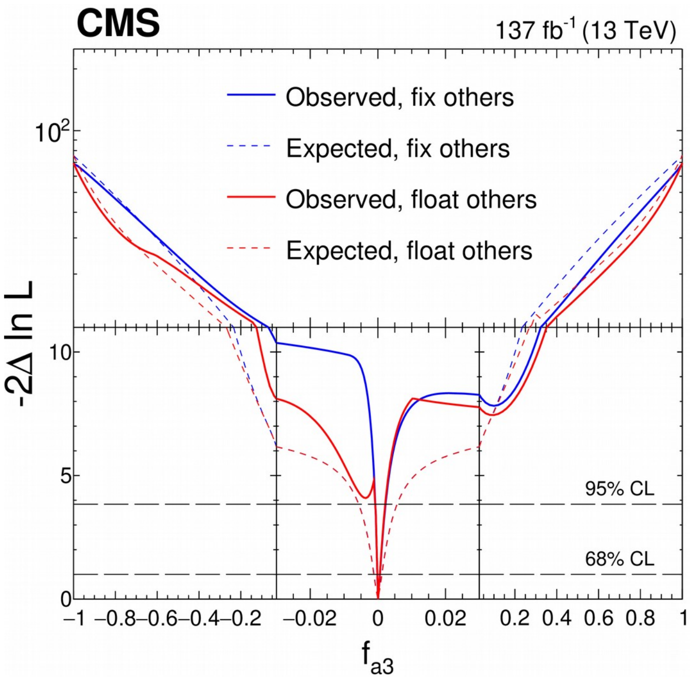
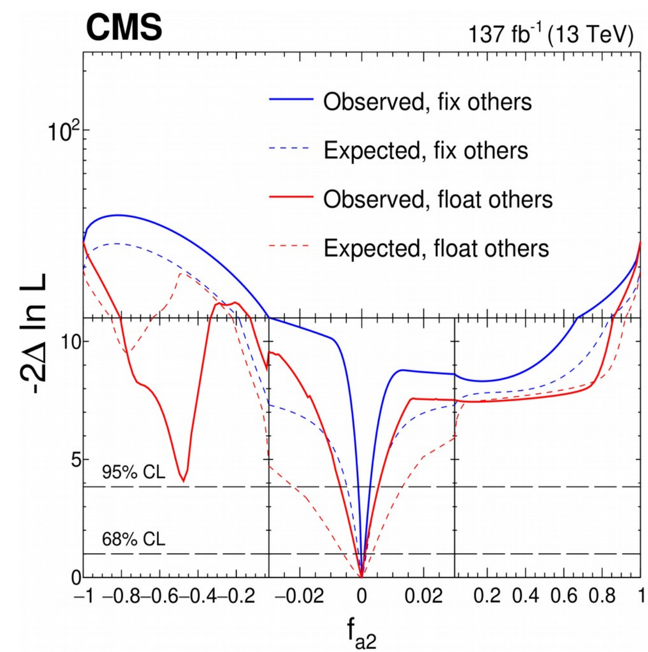
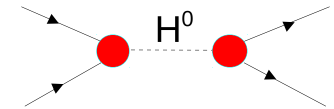


- SU(2)xU(1) sym. (SMEFT) with only 3 independent A.C.
- **Stringent constraints driven by production information**
- **Full Run2**
- **Minima consistent with SM**

Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00004	0.00000
	$f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	$[-0.00007, 0.00044]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.00055, 0.00168]$	$[-0.00412, 0.00412]$
	Approach 1	best fit	-0.00805	0.00000
	float $f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.02656, 0.00034]$	$[-0.00086, 0.00086]$
		95% CL	$[-0.07191, 0.00990]$	$[-0.00423, 0.00422]$
	Approach 2	best fit	0.00005	0.0000
	float $f_{a2}, f_{\Lambda 1}$	68% CL	$[-0.00010, 0.00061]$	$[-0.0012, 0.0012]$
		95% CL	$[-0.00072, 0.00218]$	$[-0.0057, 0.0057]$



HVV: H→ 4l



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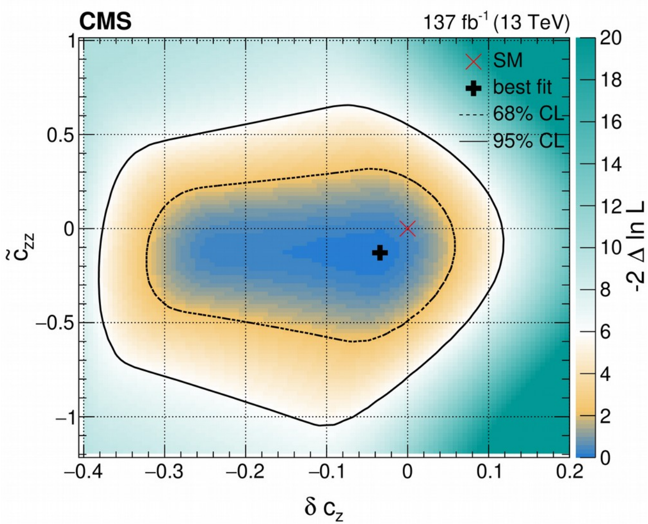
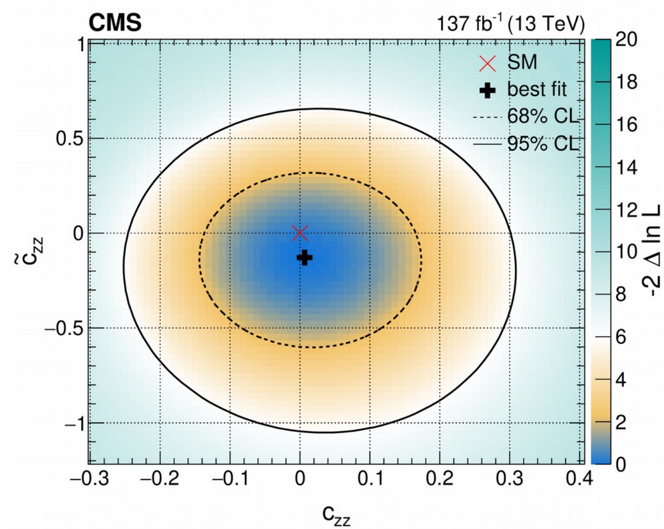


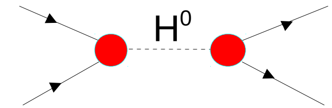


Channels	Coupling	Observed
VBF & VH & $H \to 4\ell$	δc_z	$-0.03^{+0.06}_{-0.25}$
	c_{zz}	$0.01^{+0.11}_{-0.10}$
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$

Translated to Warsaw basis:

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

Off-shell studies in H→4l +2l2ν



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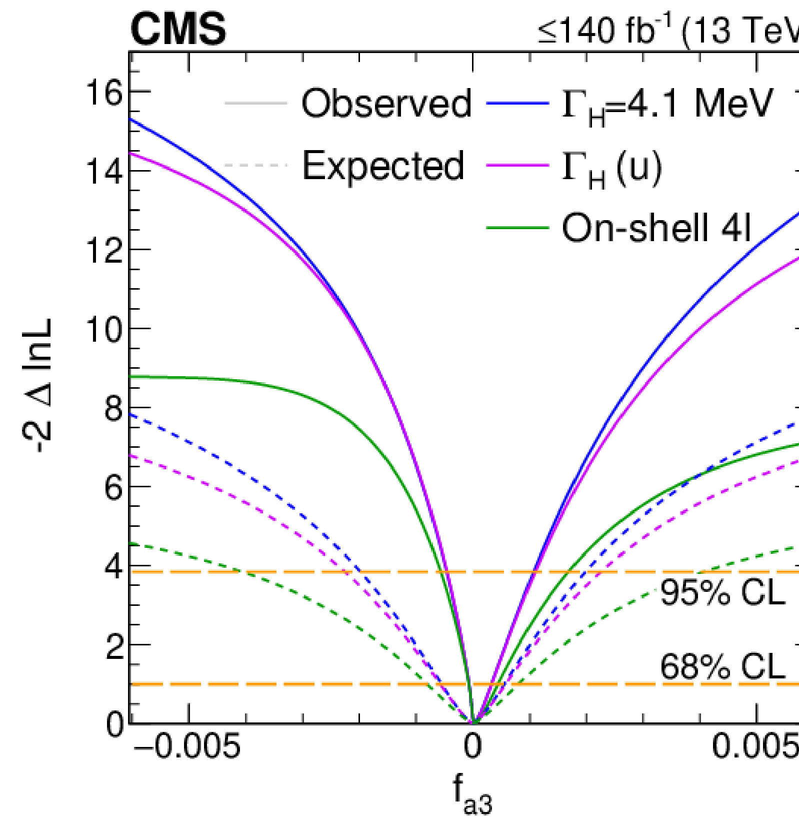
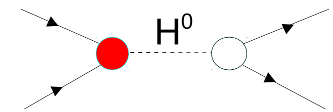
- Use same formalism as on-shell H→4l AC analysis
- M4l > 220 GeV (2e2μ, 4e, 4μ)
- Design categories targeting ggF + EW production of the Higgs
- Use ME based observables + m4l
- Consider 1 AC at a time
- Constrain Higgs width + AC
- Combine with H→ ZZ→ 2l2ν

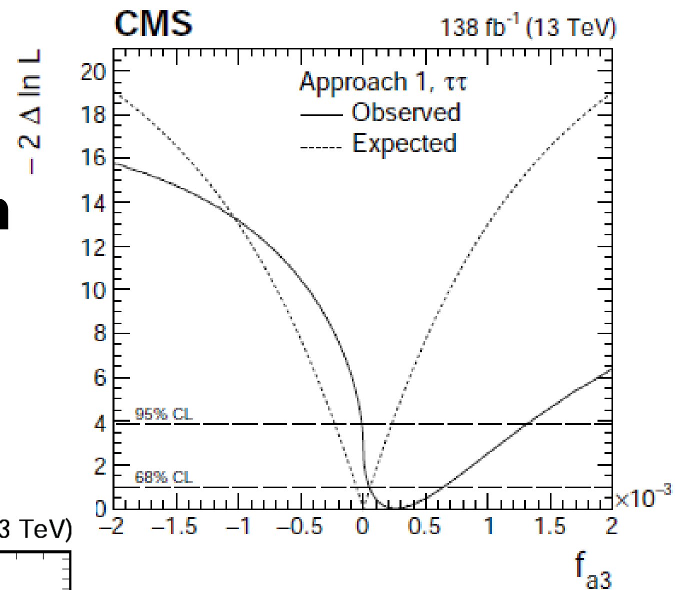


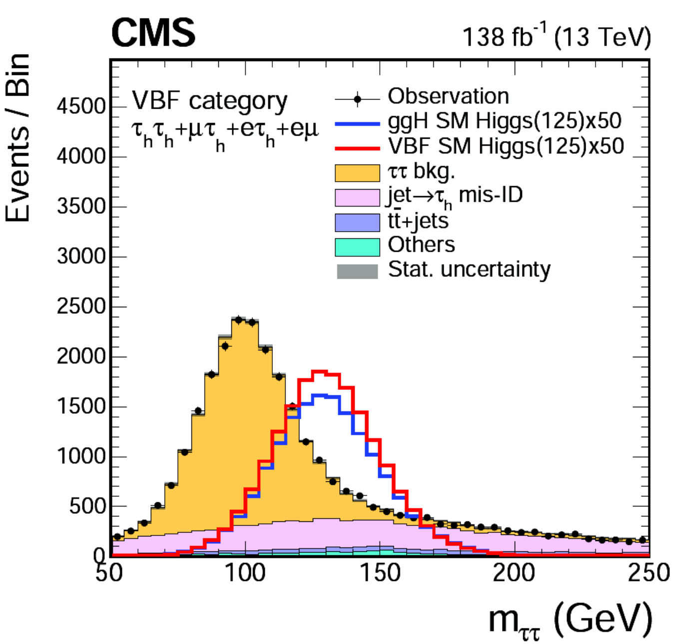
HVV: H→ττ + H→4l



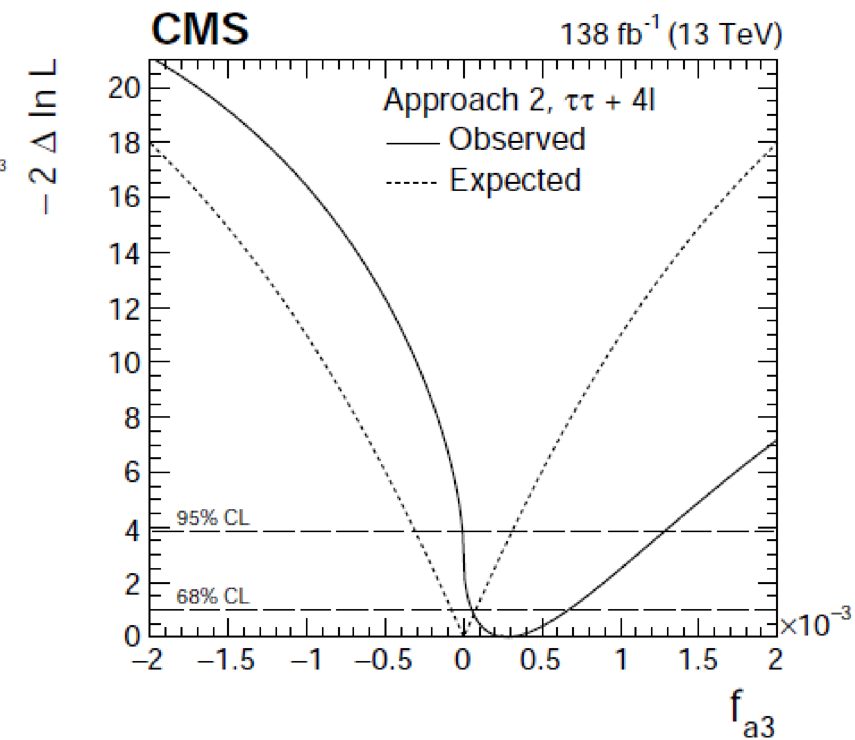
PhysRevD.108.032013

- Single AC scans
- Study production
- Utilize ME discr.

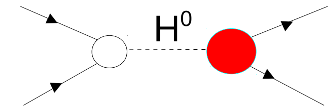




Combine results with H4l



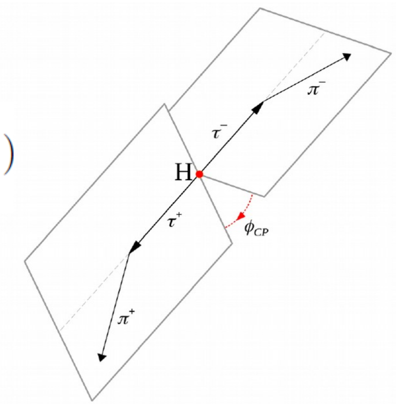
Yukawa ττH : H→ ττ CMS

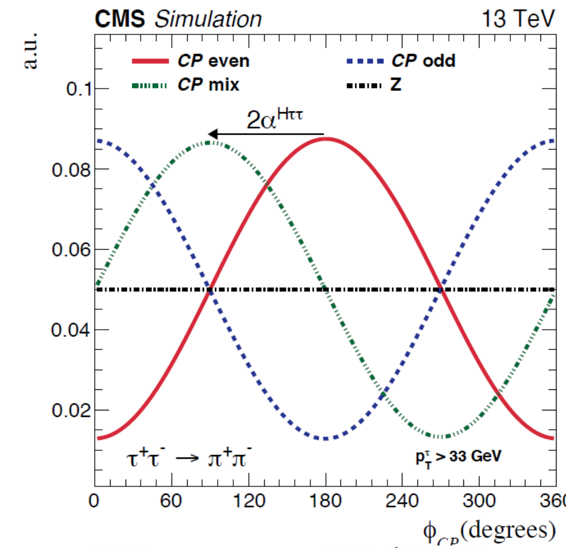


JHEP06(2022)012

$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$





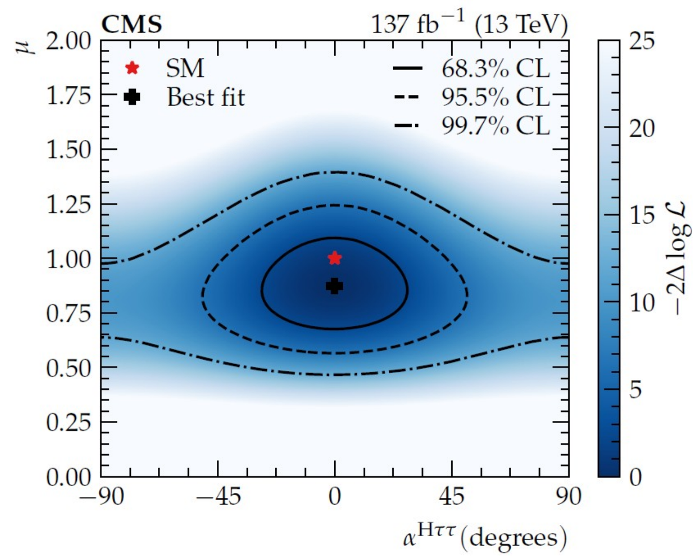
Full Run2 data

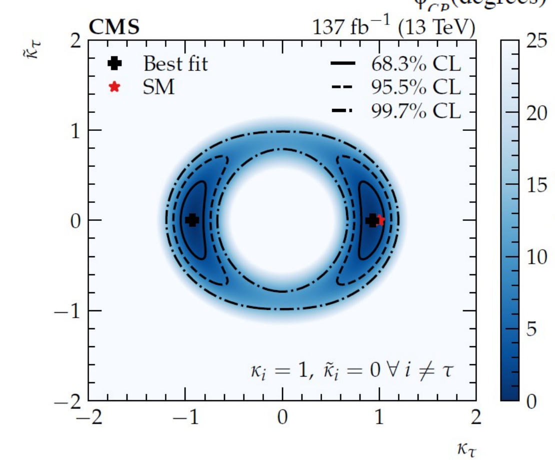
Decay vertex probed

Use decays to ττ pair to measure CP odd/ even mixing in Hττ

Use ~70% of τ BR:

$\tau_h\tau_h$, $\tau_\mu\tau_h$ + $\tau_e\tau_h$

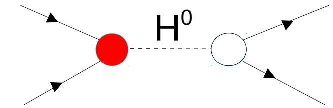


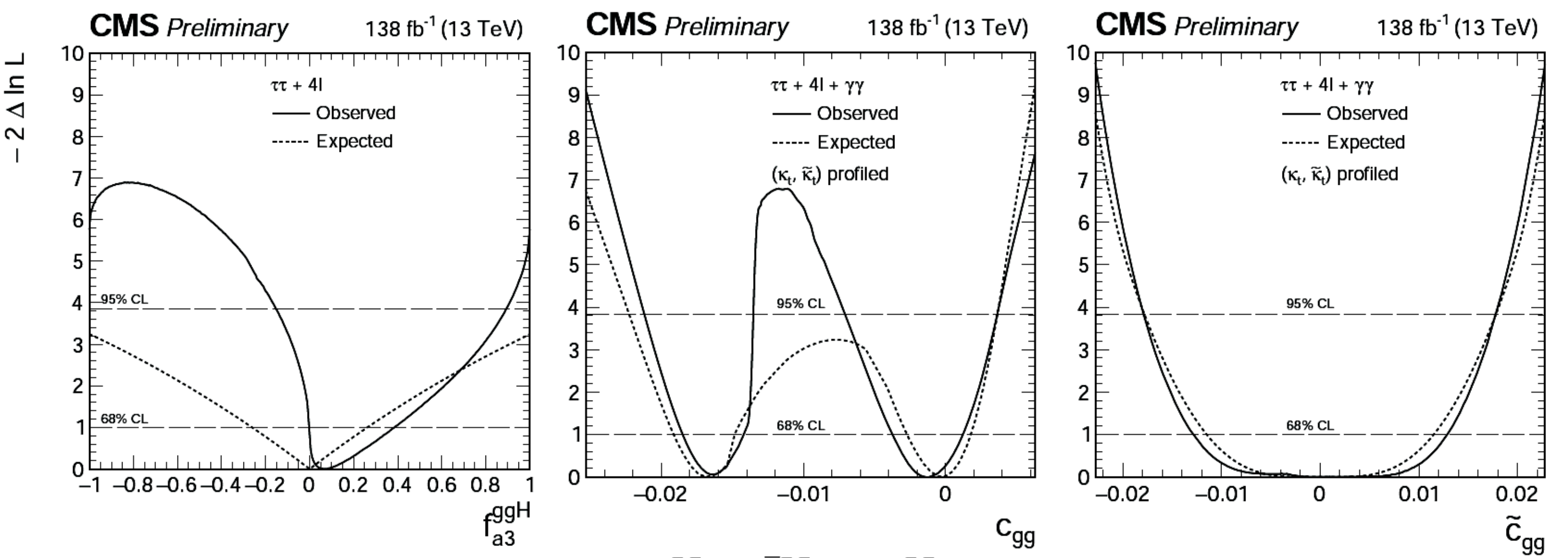


4 reconstruction methods of φ_{CP}

Pure CP odd excluded at 3σ

Hgg : using ggF in 4l,γγ,ττ CMS





PhysRevD.108.032013
PhysRevD.104.052004

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

$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg}$$

$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg}$$

Combination of H→4l, H→ττ, H→γγ

FULL RUN2

Measure CP sensitive fa3^{ggH} and μ_{ggH}

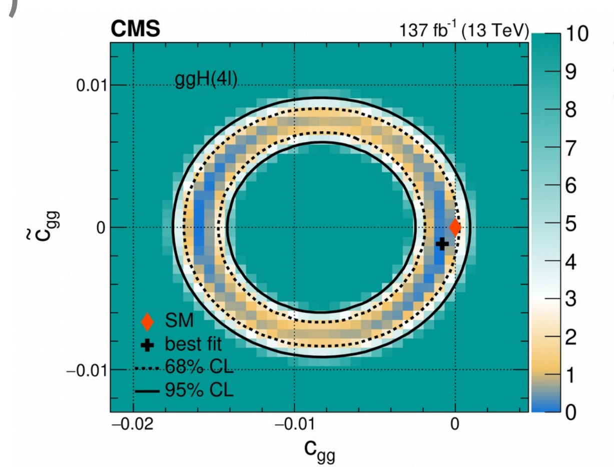
Use events in VBF2J to study ggH category

4 couplings fit simultaneously:

Constrain ktop measured from the tH,ttH process and study cgg

tH & $t\bar{t}$H & ggH (ttH,tH from: H→4l H→γγ)

Parameter	Scenario		68% CL / (10^{-2})
c_{gg}	Profiled	Observed	$-0.11^{+0.20}_{-0.26} \cup [-1.85, -1.42]$
		Expected	$0.00^{+0.18}_{-0.27} \cup [-1.91, -1.48]$
$\tilde{c}_{gg}$	Profiled	Observed	0.00 ± 1.29
		Expected	0.00 ± 1.15
c_{gg}	Fixed	Observed	$-0.08^{+0.07}_{-0.15} \cup [-1.65, -1.54]$
		Expected	$0.00^{+0.06}_{-0.14} \cup [-1.73, -1.50]$
$\tilde{c}_{gg}$	Fixed	Observed	$0.22^{+0.28}_{-0.22} \cup [-0.50, 0.00]$
		Expected	0.00 ± 0.45



Yukawa ttH : ttH(ggH),H→4l/γγ/ττ/WW

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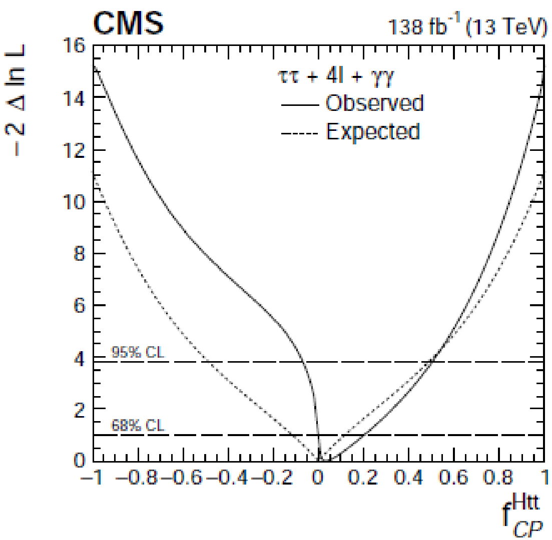
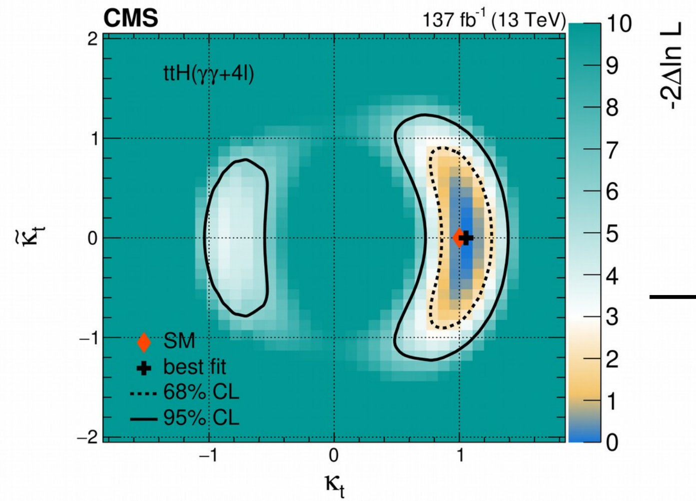
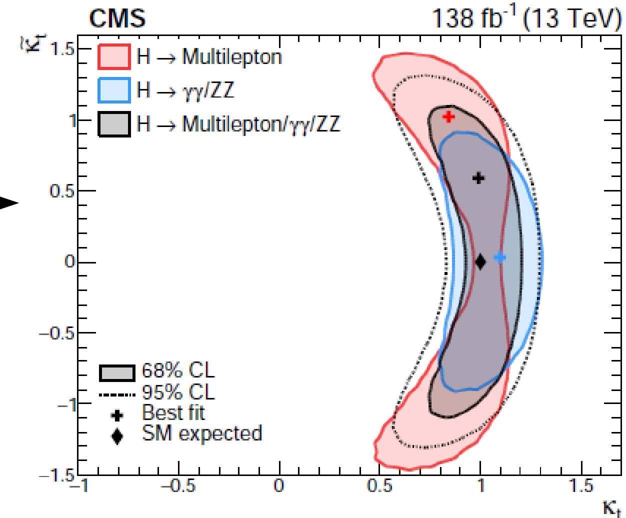
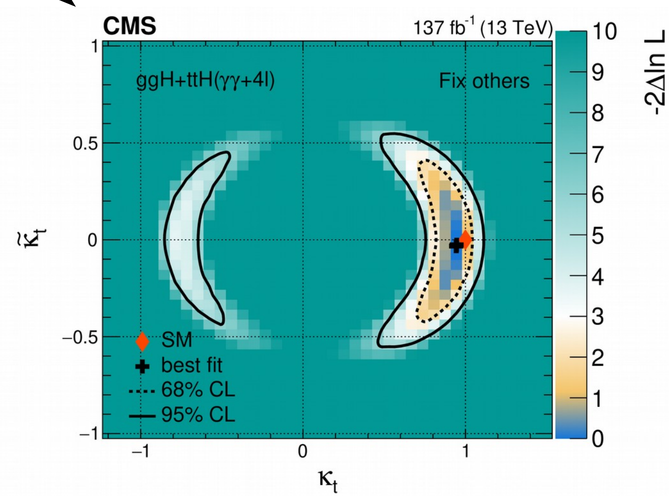








- **Measure f_{CP}^{Htt} in production**
- **Combine**
  - **H→ 4l**
  - **H→ττ** **+ Also multi- lepton(ττ/WW) +ZZ+γγ**
  - **H→γγ**

- **Combine measurements with uncorrelated μs**
- **Interpret as top couplings**

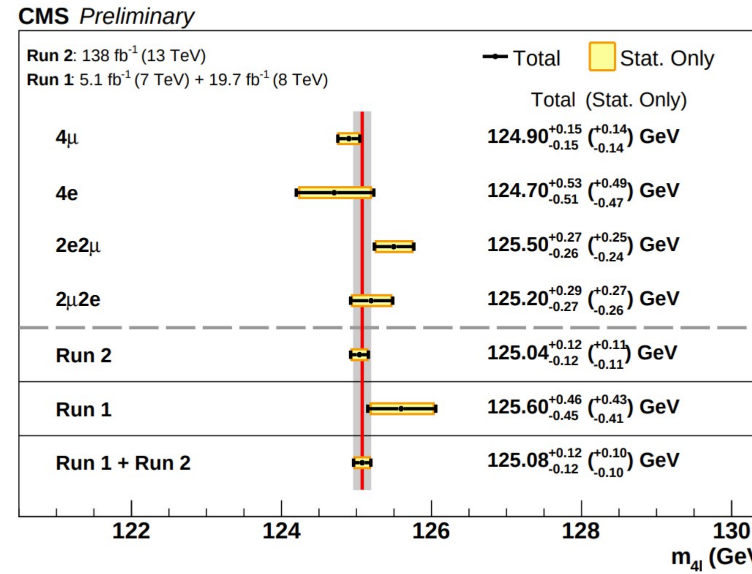
$$A(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\tilde{\kappa}_f\gamma_5\right)\psi_f$$

Summary

- **New Full Run2 Mass + width** results from CMS in H→4l
- H→4l mass measurement most precise in a single channel

mH = 125.08 ±0.12 (GeV)

uncert < 0.1% !



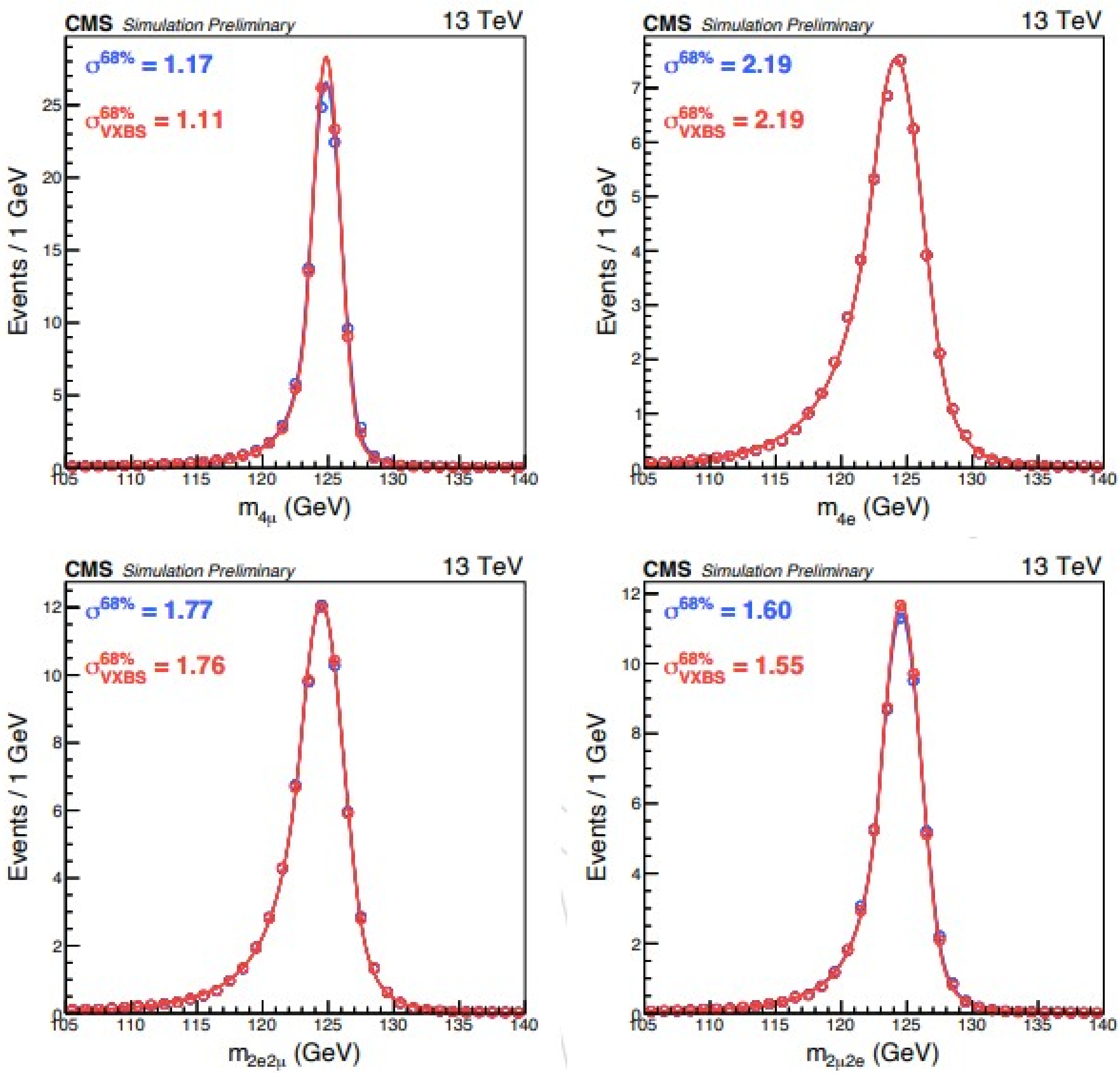
- A.C. measured within EFT framework
- Combinations with multiple final states
- **CPV well constrained**

  > New AC results tomorrow by Angela!

Parameter	Observed
m_H (GeV)	125.08 ± 0.12
on-shell Γ_H (GeV)	$0.00^{+0.06}_{-0.00}$ [0.00, 0.33]
off-shell Γ_H (MeV)	$2.9^{+2.3}_{-1.7}$ [0.3, 7.9]

Additional material

Mass VTX constraint



Effective Lagrangian and couplings (Higgs basis)

(arXiv:2002.09888)

$$\mathcal{L}_{\rm hvv} = \frac{h}{v}\Big[(1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}$$
$$+(1+\delta c_w)\frac{g^2v^2}{2}W_\mu^+W_\mu^- + c_{ww}\frac{g^2}{2}W_{\mu\nu}^+W_{\mu\nu}^- + c_{w\Box}g^2\left(W_\mu^-\partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) + \tilde{c}_{ww}\frac{g^2}{2}W_{\mu\nu}^+\tilde{W}_{\mu\nu}^-$$
$$+c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu}$$
$$+c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu} + \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\Big],$$

$$\mathcal{L}_{hff} = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f\, h$$

Necessary to consider impact of AC in Γ:

$$\sigma(i\to H\to f) \propto \frac{\left(\sum\alpha_{jk}g_jg_k\right)\left(\sum\alpha_{lm}g_lg_m\right)}{\Gamma_{\rm tot}}$$

$$\Gamma_{\rm tot} = \sum_f \Gamma_f = \Gamma_{\rm tot}^{\rm SM}\times\sum_f\left(\frac{\Gamma_f^{\rm SM}}{\Gamma_{\rm tot}^{\rm SM}}\times\frac{\Gamma_f}{\Gamma_f^{\rm SM}}\right) = \Gamma_{\rm tot}^{\rm SM}\times\sum_f\left(\mathcal{B}_f^{\rm SM}\times R_f(\vec{g}_j)\right)$$

$$\delta c_z = \frac{1}{2}g_1^{ZZ} - 1, \quad c_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_2^{ZZ}, \quad c_{z\Box} = \frac{M_Z^2s_w^2}{e^2}\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, \quad \tilde{c}_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_4^{ZZ},$$
$$\delta c_w = \frac{1}{2}g_1^{WW} - 1, \quad c_{ww} = -\frac{2s_w^2}{e^2}g_2^{WW}, \quad c_{w\Box} = \frac{M_W^2s_w^2}{e^2}\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}, \quad \tilde{c}_{ww} = -\frac{2s_w^2}{e^2}g_4^{WW},$$
$$c_{z\gamma} = -\frac{2s_wc_w}{e^2}g_2^{Z\gamma}, \quad \tilde{c}_{z\gamma} = -\frac{2s_wc_w}{e^2}g_4^{Z\gamma}, \quad c_{\gamma\Box} = \frac{s_wc_w}{e^2}\frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2}\kappa_2^{Z\gamma},$$
$$c_{\gamma\gamma} = -\frac{2}{e^2}g_2^{\gamma\gamma}, \quad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2}g_4^{\gamma\gamma}, \quad c_{gg} = -\frac{2}{g_s^2}g_2^{gg}, \quad \tilde{c}_{gg} = -\frac{2}{g_s^2}g_4^{gg}.$$