Higgs boson mass, width, CP and anomalous couplings measurements at CMS

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On behalf of CMS Collaboration
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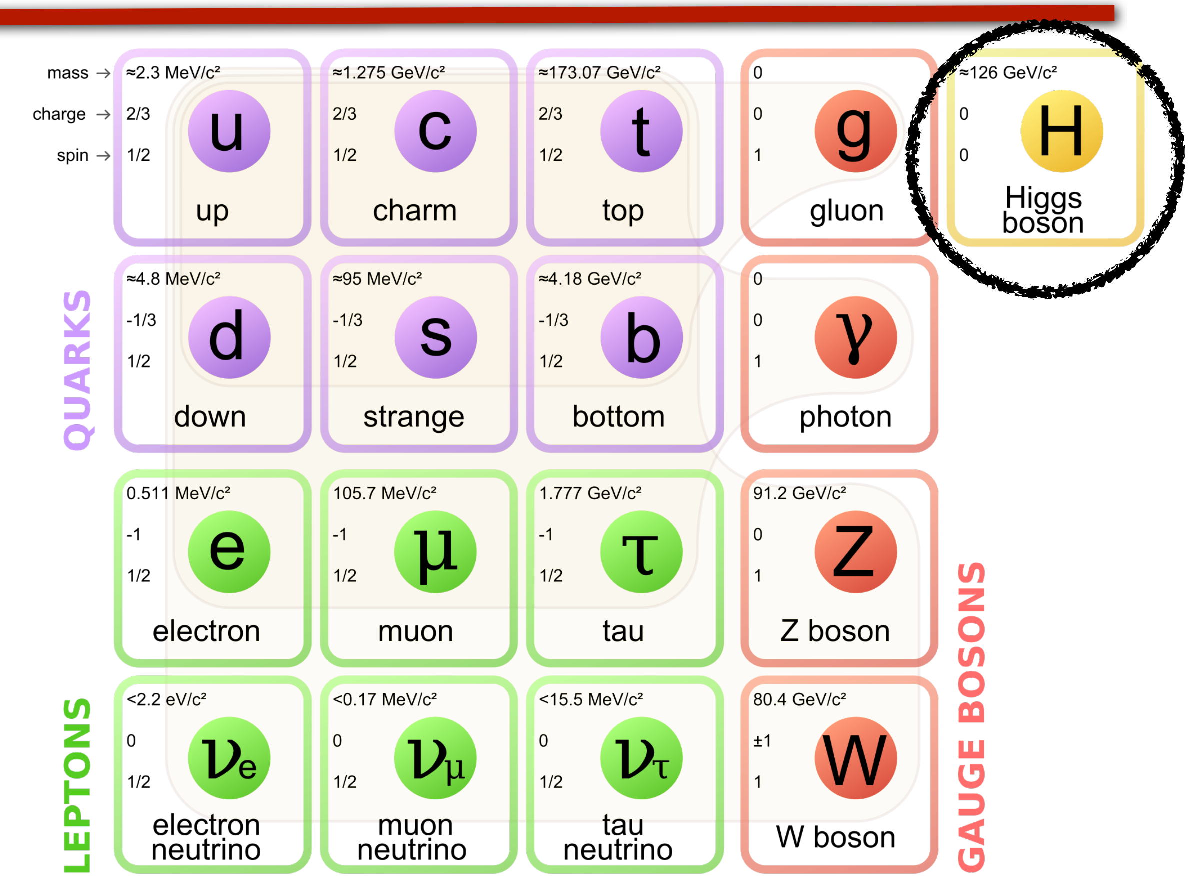
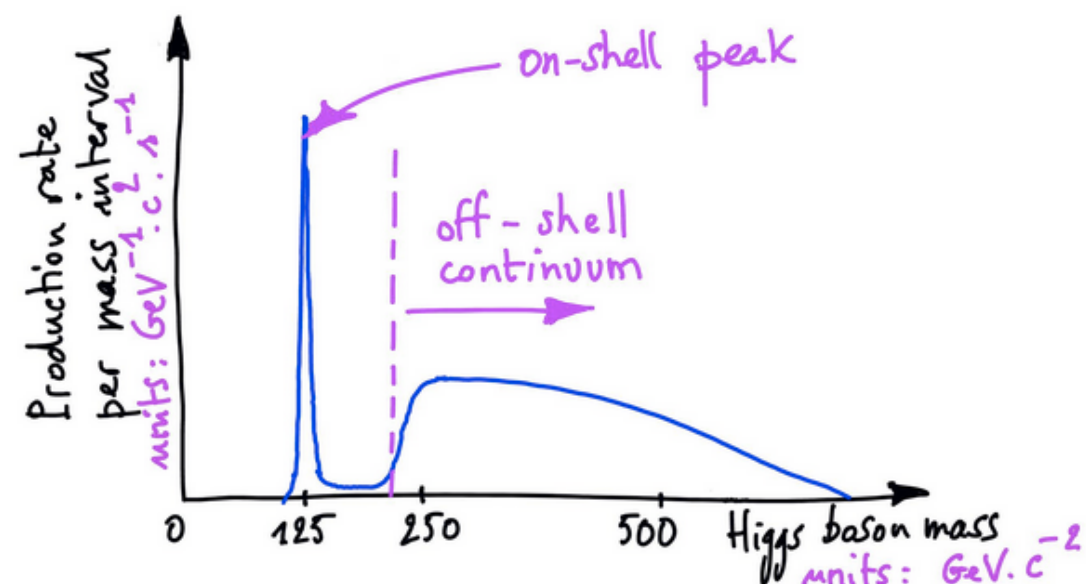
Outline

- Introduction
- Higgs properties measurements
  - Mass
  - Width
  - CP structure
  - Anomalous couplings
- Summary

Higgs is so peculiar

- The only scalar in fundamental particles
- Responsible for EWSB and explain the origin of mass
- Its mass is at EW scale O(100GeV)
- Its special mass lineshape



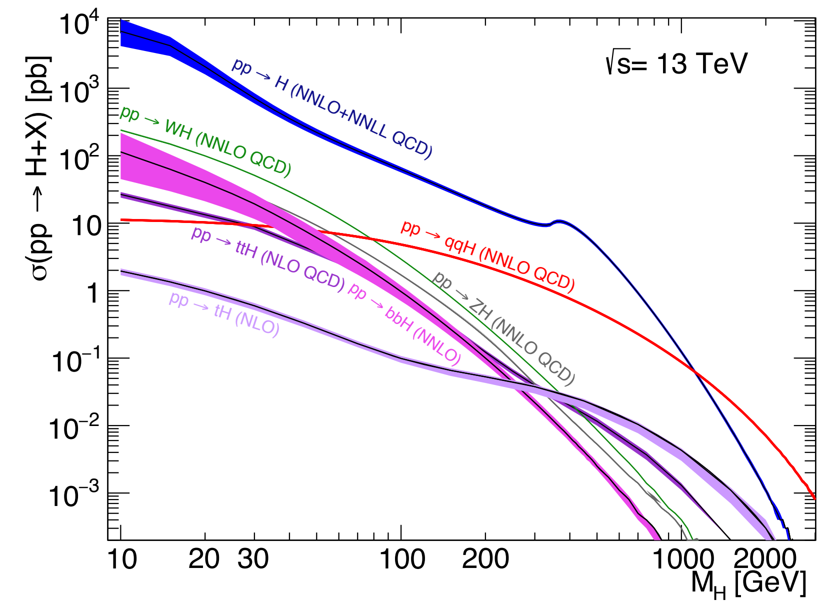


Physics Briefing

Important to measure its properties.

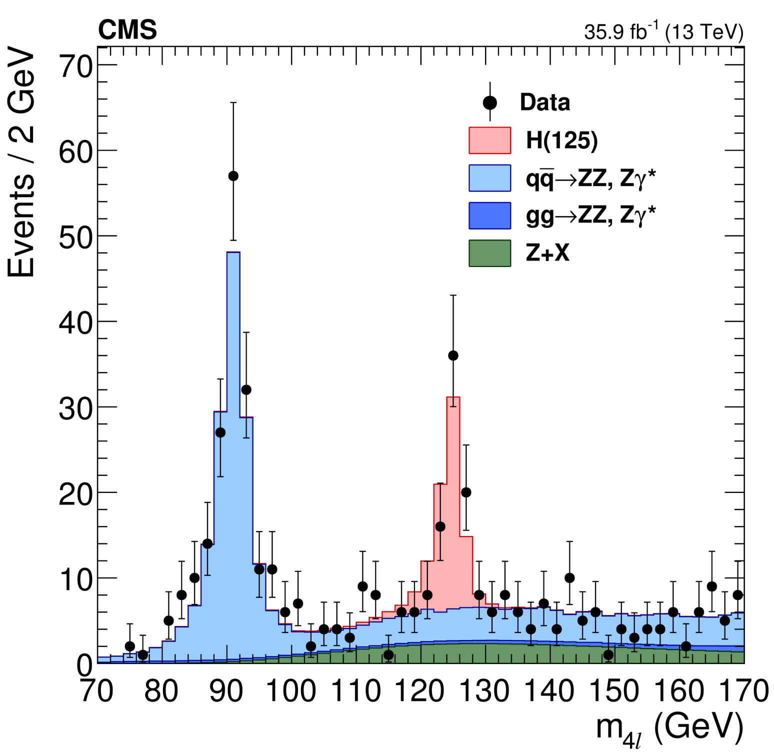
Higgs Boson Mass

- **A free parameter in Standard Model**
- **Important ingredient in SM predictions (e.g Higgs production/decay)**

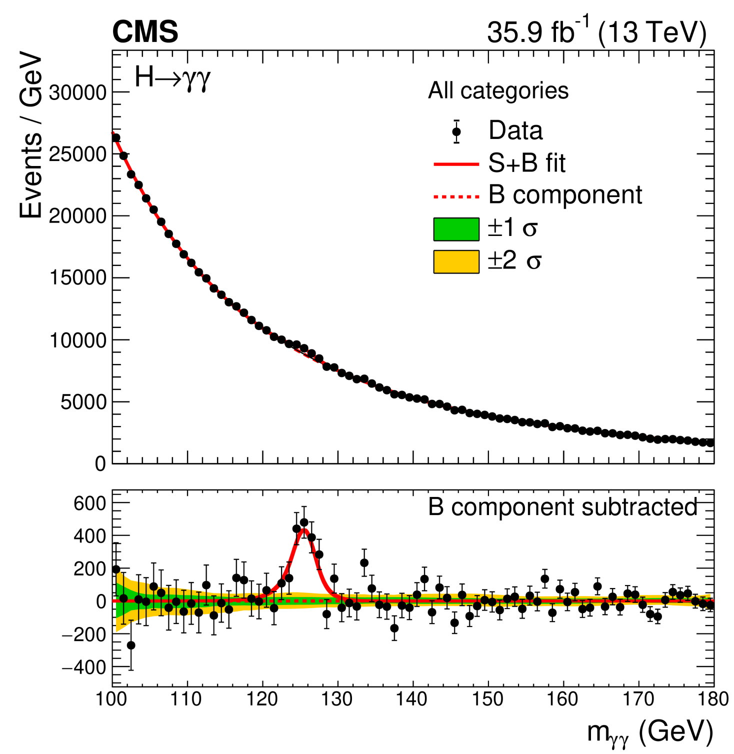


- **Best measured with clean channels: *4l*, *γγ***
- **Most precise measurement from CMS:**
  ***4l+γγ* Run 1 + 2016: 125.38±0.14(0.11) GeV**

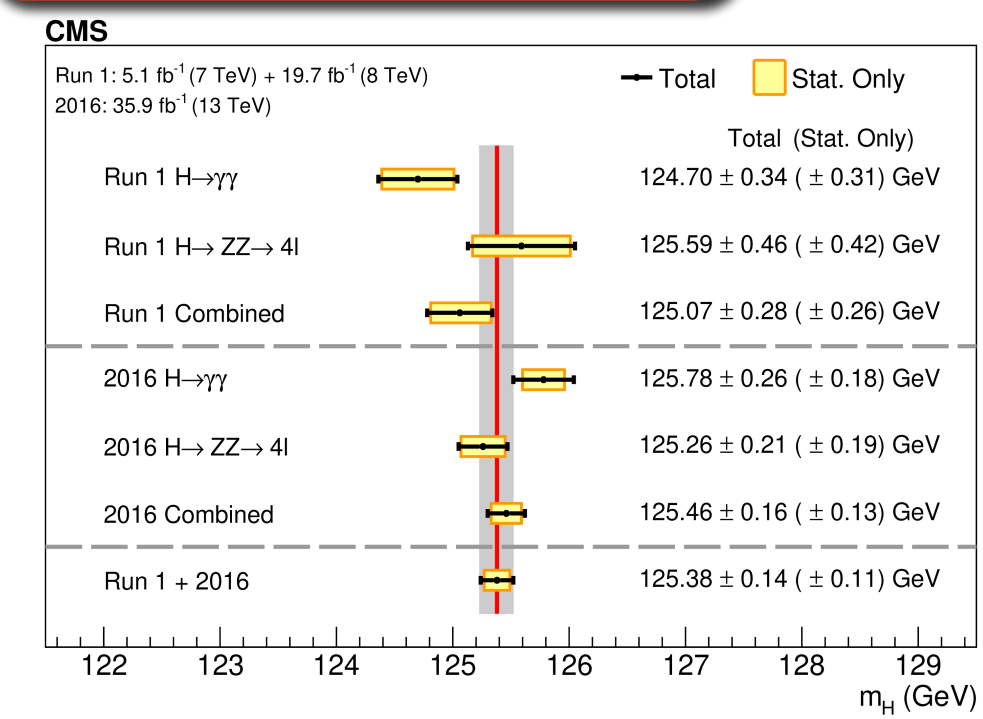
PLB 205(2020)135425



4l : 125.26±0.20(stat)± 0.08(syst)GeV



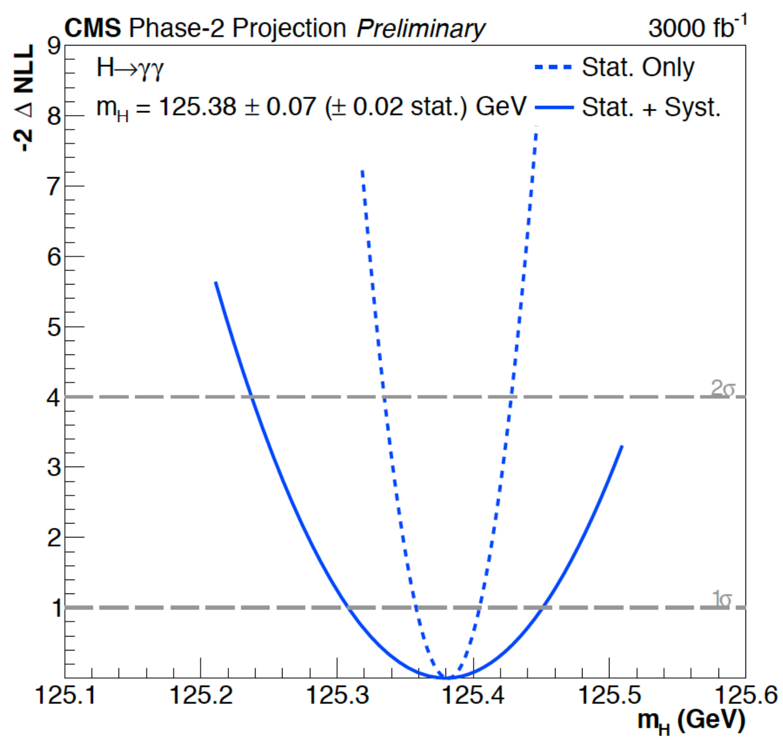
γγ : 125.78±0.18(stat)± 0.18(syst)GeV



Prospect for Higgs Mass Measurement in HL-LHC

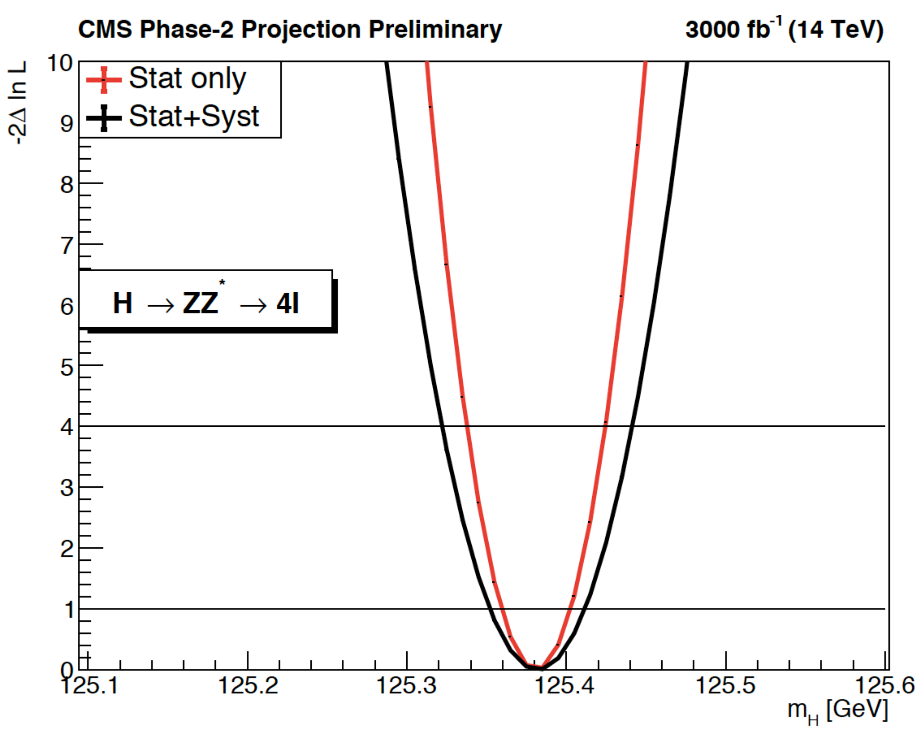
- **Projection based on Run 2 data analysis accounting some changes:**
  - much higher pileup
  - significantly more granular energy corrections of ECAL due to enhanced statistics
  - better resolution for μ and higher acceptance for μ/e due to new tracker

CMS-PAS-FTR-21-008



$\gamma\gamma$: 125.38±0.07(0.02) GeV

CMS-PAS-FTR-21-007



4l : 125.38±0.03(0.022) GeV

Higgs Boson Width

- **Predicted width in SM Γ_H:** **4.07MeV**

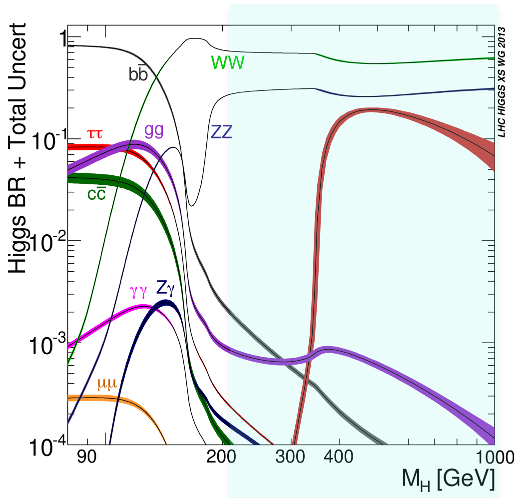
- **Direct measurements :** measuring Higgs lifetime or on-shell width. mass resolution limited by detector resolution 1-2GeV.

$$\sim 3\times10^{-3}\ \text{eV} < \Gamma_H < 0.5 - 3\ \text{GeV}$$

- **Higgs production rate:** $$d\sigma \propto \frac{g^2_{prod}g^2_{dec}}{(q^2_H - m^2_H)^2 + m^2_H\Gamma^2_H}dq^2_H$$

$$\Rightarrow \sigma^{on-shell} \propto \frac{g^2_{prod}g^2_{dec}}{\Gamma_H} \propto \boxed{\mu_{on-shell}}$$

$$\Rightarrow \sigma^{off-shell} \propto \int \frac{g^2_{prod}g^2_{dec}}{(q^2_H - m^2_H)^2}dq^2_H \propto \mu_{off-shell} \propto \boxed{\mu_{on-shell} \times \Gamma_H/\Gamma_{SM}}$$

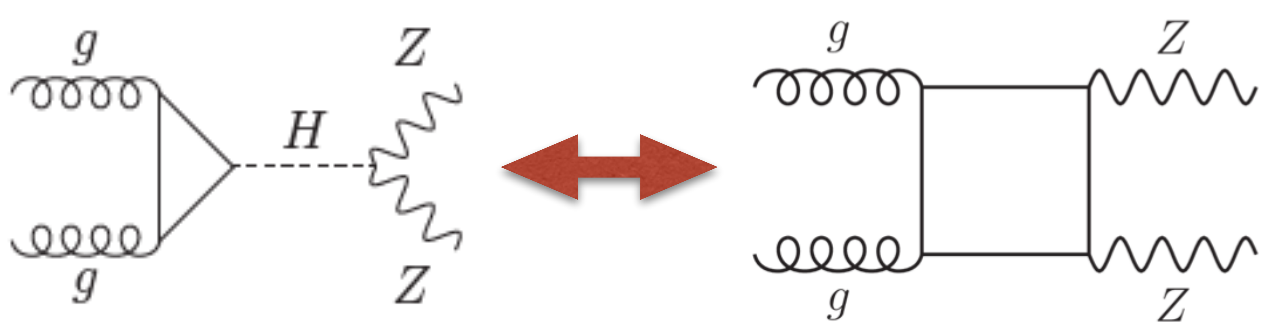


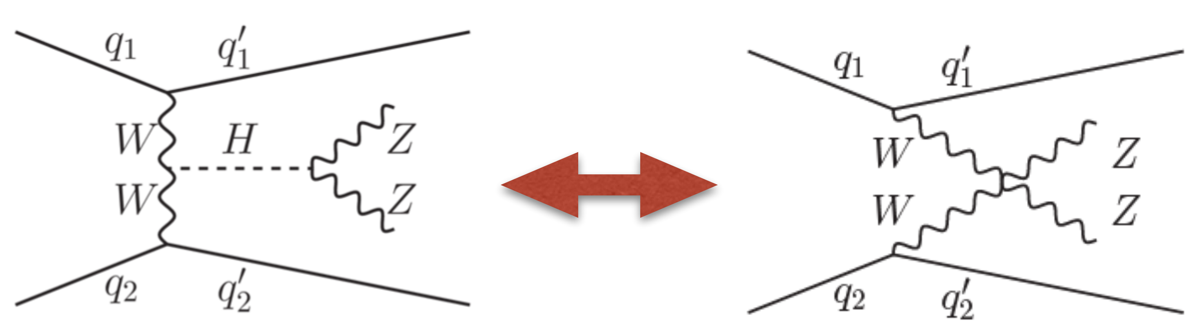
- **Indirect measurement:** measuring the signal strengths in on-shell and off-shell separately, and take their ratio: ZZ is the ideal channel

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

Off-shell Higgs in ZZ channel

- **Difficulties for probing off-shell Higgs:**
  - low production rate: ~10% of total xs
  - large destructive interference with continuum background





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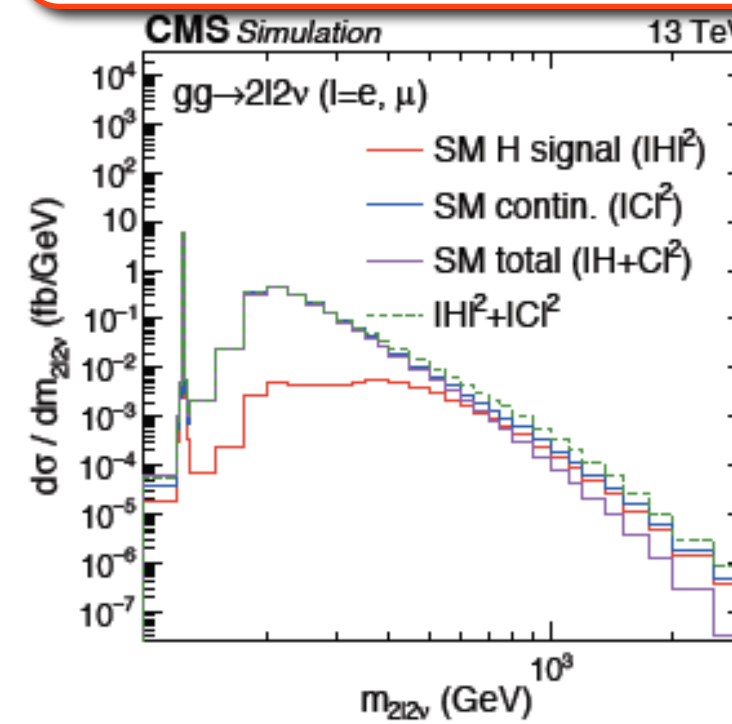
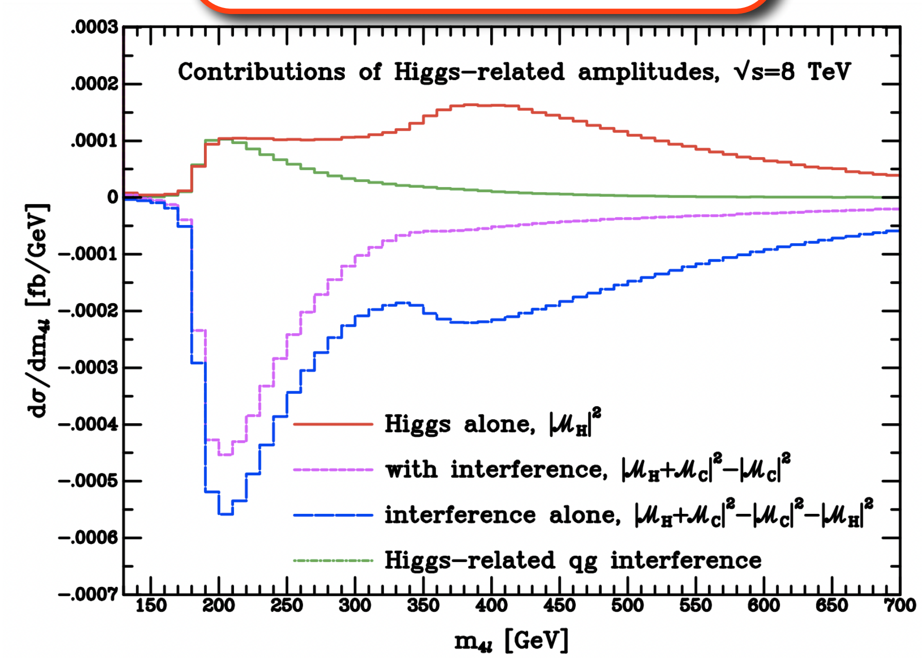
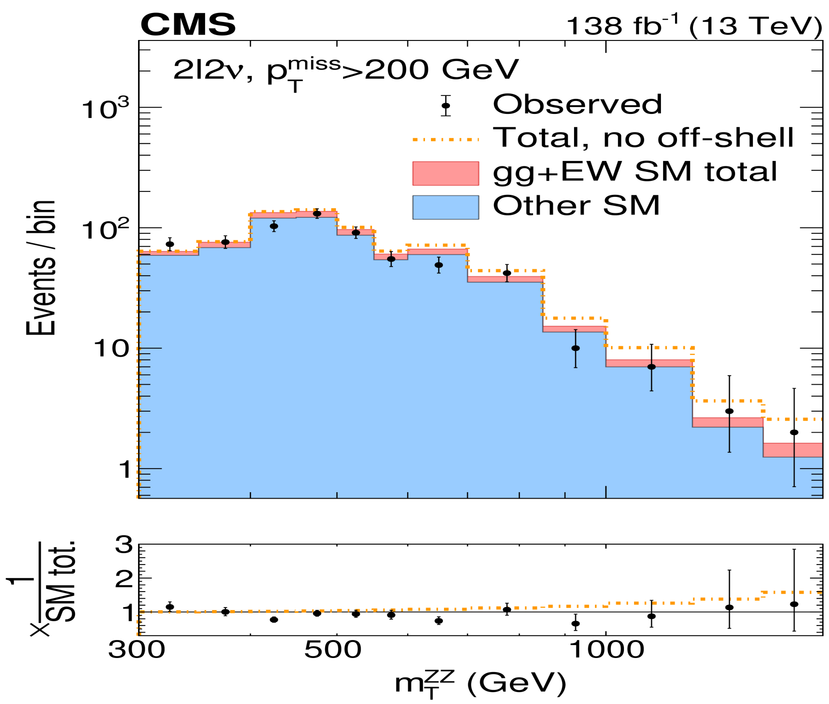


JHEP04(2014)060



Evidence for off-shell Higgs and Measured Width



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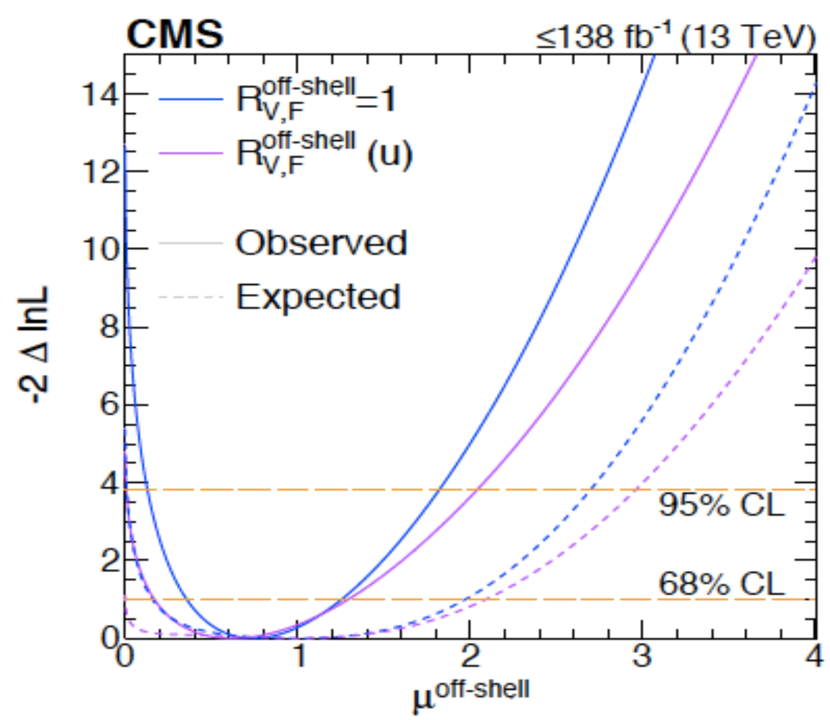
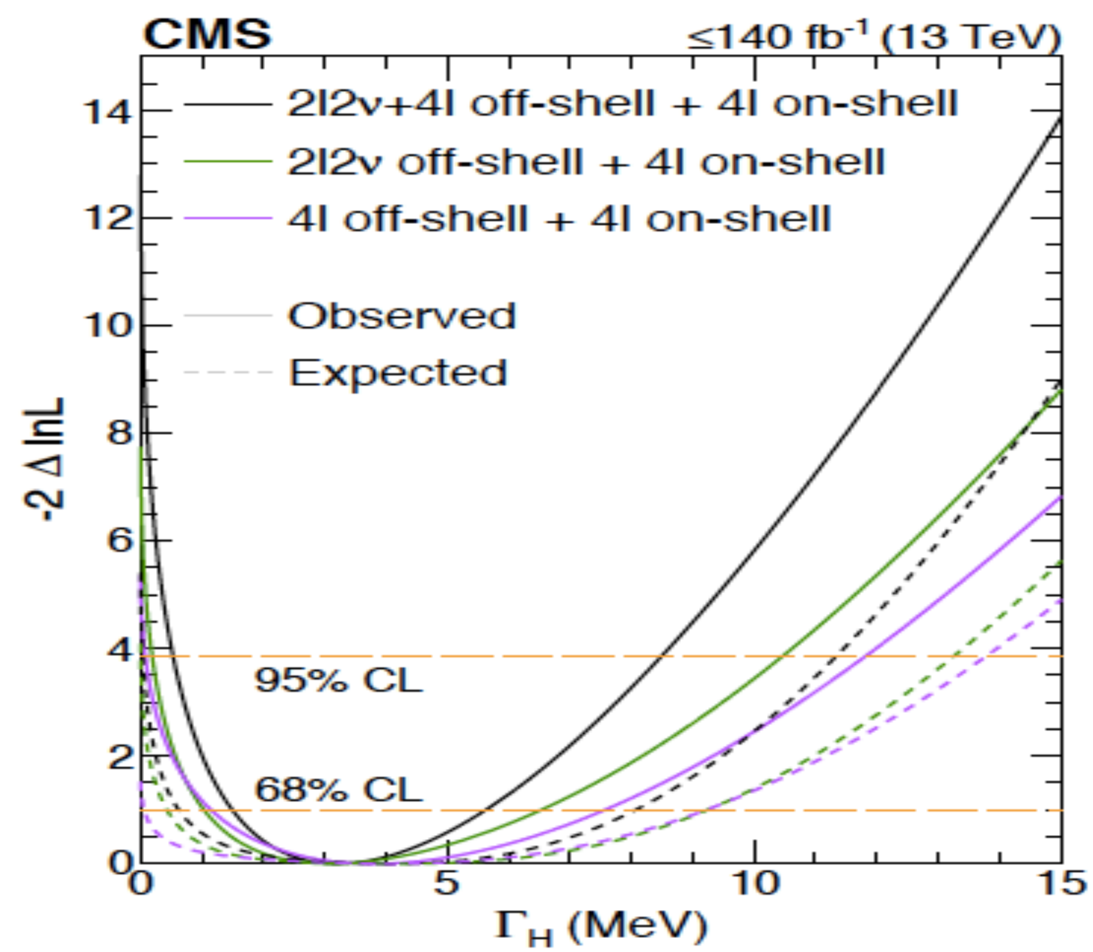
4l on-shell: 140fb^{-1}

4l off-shell: 78fb^{-1}

*2l2**ν*** off-shell: 138fb^{-1}





- **off-shell Higgs evidence: 3.6σ**
- **Observed** $\Gamma_H = 3.2^{+2.4}_{-1.7}\text{MeV}$

Higgs CP Structure

- **Higgs is CP even scalar in SM: $J^{PC} = 0^{++}$**
- **Alternative spin/parity hypothesis excluded by > 99.9% CL at Run 1 with bosonic channels**
- **Strong theoretical motivation to search for CP-violating effects in couplings of Higgs and fermions**

CP-odd contribution for Higgs and bosons couplings largely suppressed

	Probing process	Scale of CP-odd contribution
Fermion	Htt, $H\tau\tau$	O(1): tree level
Gauge boson	Hzz, Hww, $Hz\gamma$, $H\gamma\gamma$, Hgg	$O(1/\Lambda^2)$

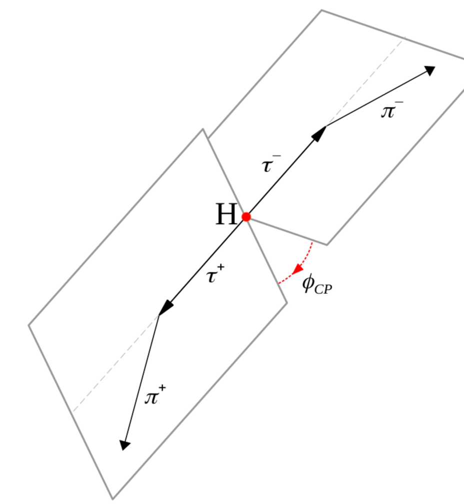
Λ is the scale of BSM physics in effective field theory

Probe CP violation in $H\tau\tau$

- **Lagrangian for τ Yukawa coupling parameterized with**

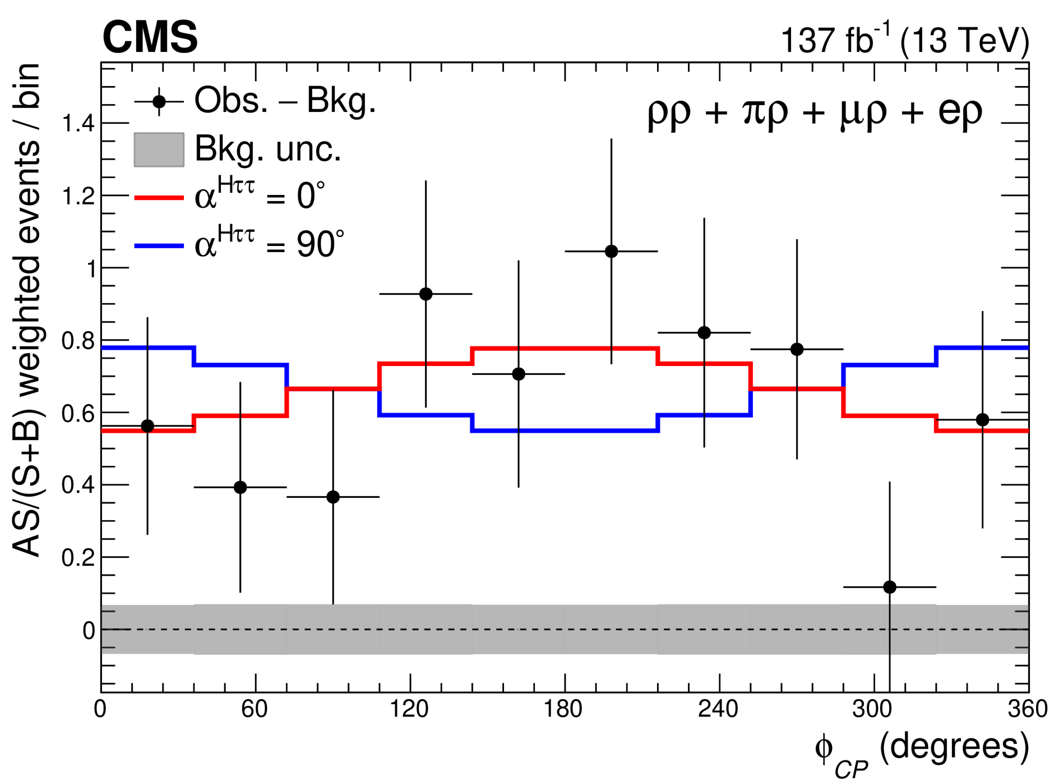
CP even **CP odd**

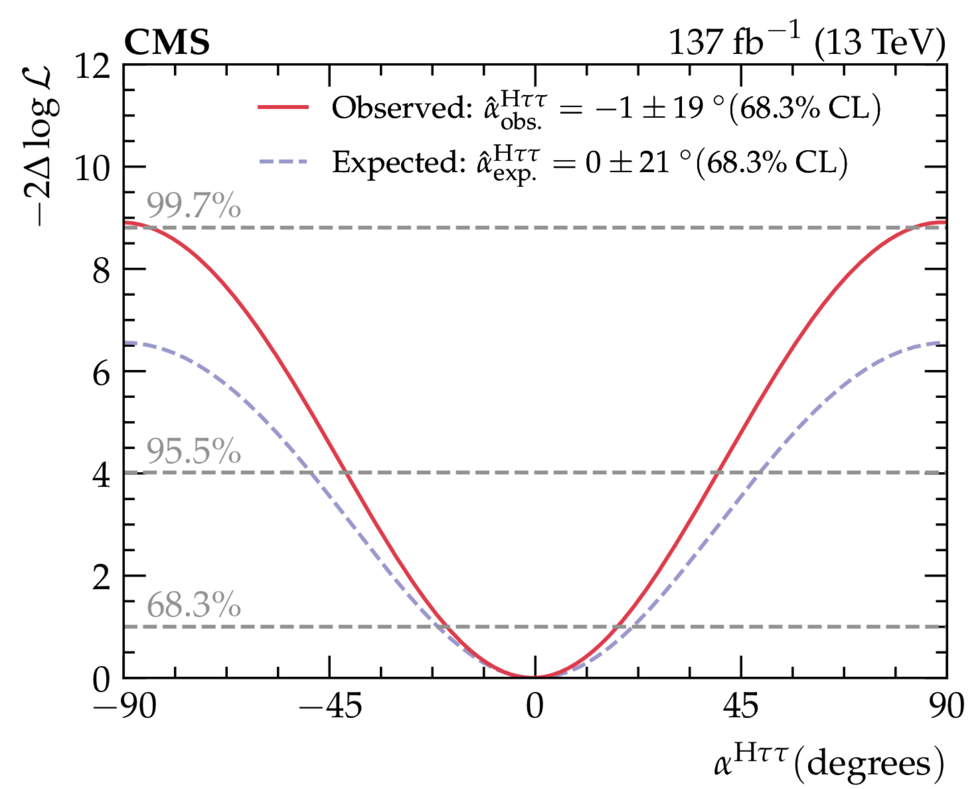
$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau) \qquad \tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



- **Use observable Φ_{CP} to probe the effective mixing angle $\alpha^{H\tau\tau}$**

JHEP 06(2022)012





observed: -1±19°
expected: 0±21°

Probe CP violation in ttH+tH

- **Similarly, Lagrangian for top Yukawa coupling parameterized with**

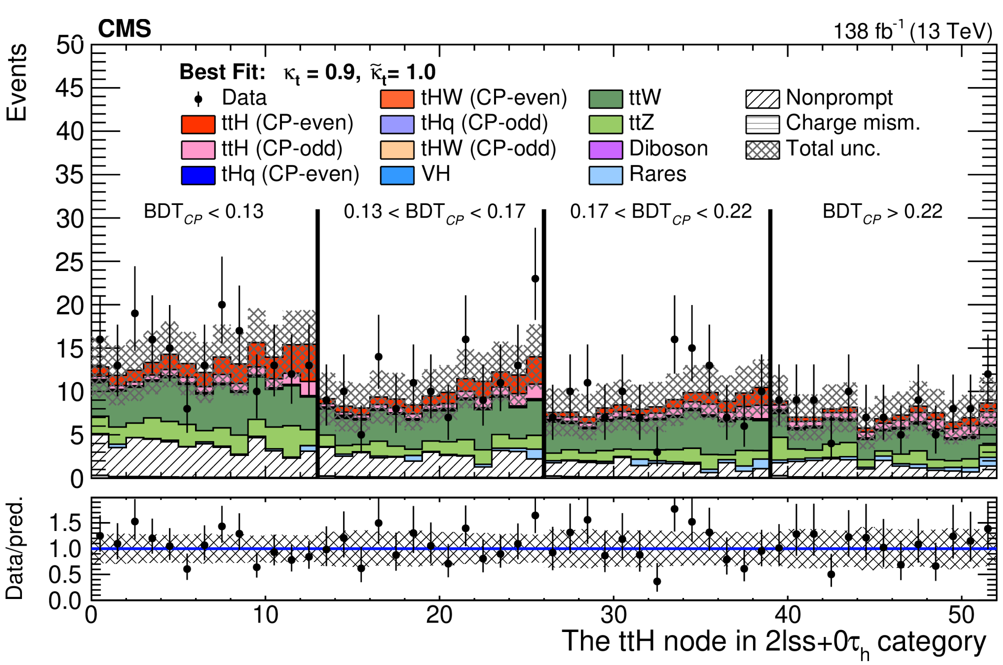
CP even (→ κ_t) **CP odd** (→ $\tilde{\kappa}_t$)

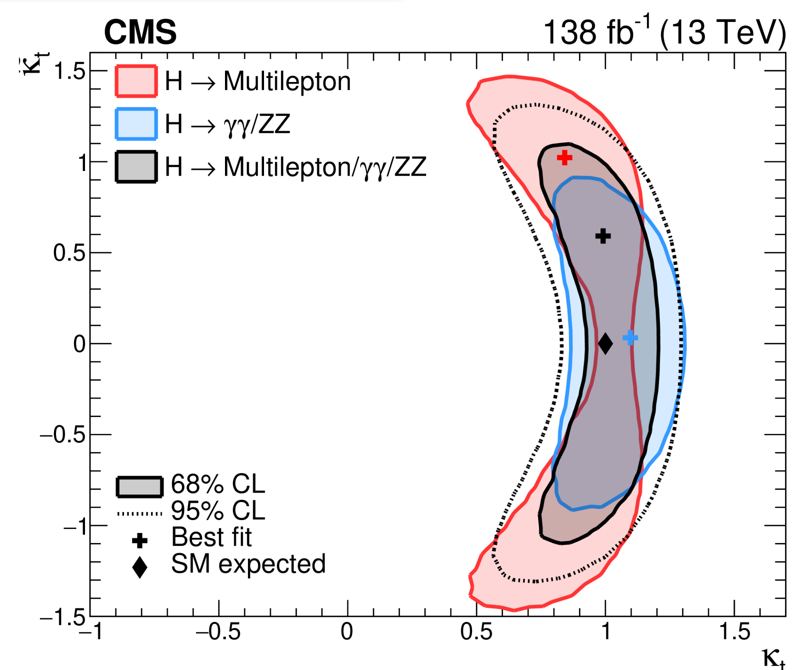
$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H \qquad f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

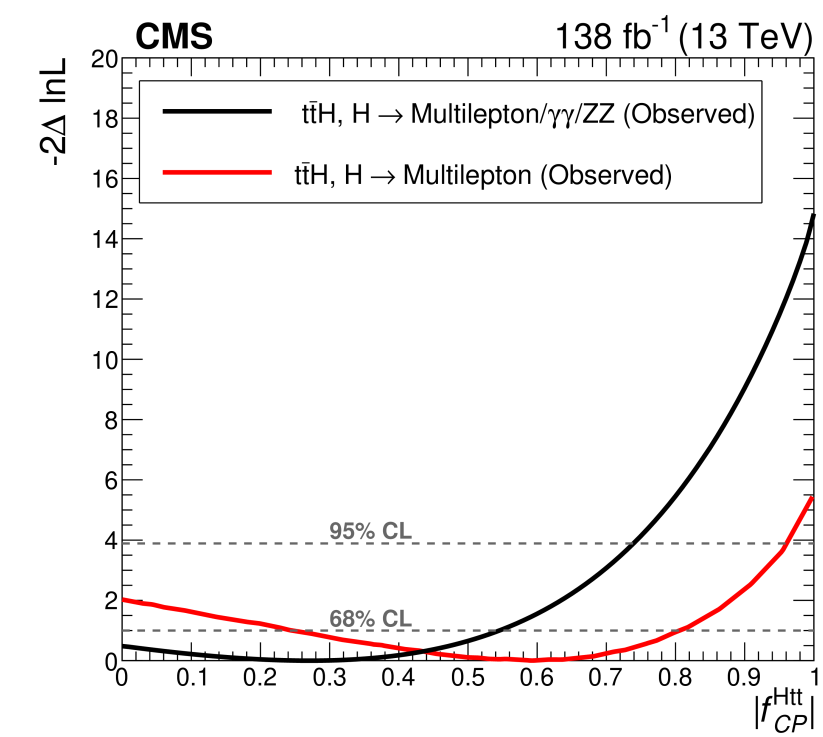
- **ttH+tH (multilepton channel): train BDT to separate CP-even and CP-odd**

$$2\ell SS + 0\tau_h,\ 2\ell SS + 1\tau_h,\ \text{and}\ 3\ell + 0\tau_h.$$

arXiv:2208.02686, accepted by JHEP







$|f_{CP}^{Htt}| = 0.28$ (<0.55 at 1σ)

Pure CP-odd disfavored at 3.2σ

HVV Anomalous Couplings

- **Interaction amplitude of H and VV(ZZ, WW, Zγ, $\gamma\gamma$ and gg) are parameterized as:**

CP odd

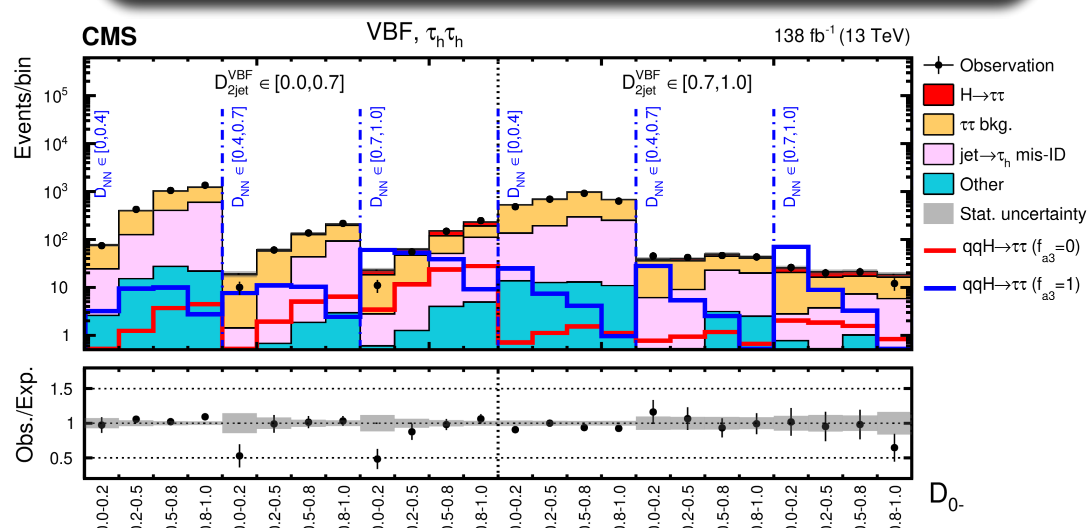
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}}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

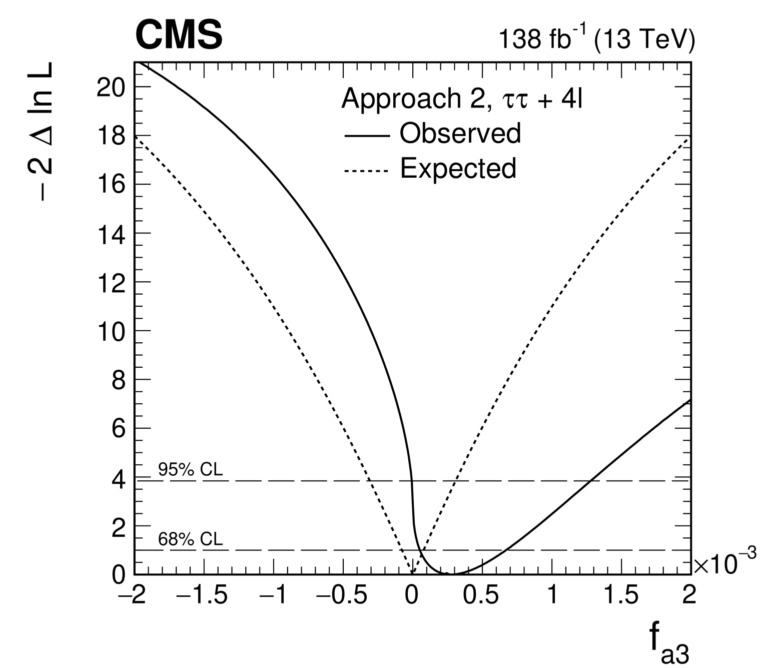
- **Define:** $f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}$ $\quad a_j = a_2, a_3, \frac{1}{\Lambda_1^2}$

- **Measure** $f_{ai}\cos(\Phi_{ai})$ **by assuming** $a_i \geq 0, \cos(\Phi_{ai}) = \pm 1$ **to probe HVV Anomalous couplings, multiple analyses performed with on-shell Higgs events: H→$\tau\tau$, H→4l, H→ $\gamma\gamma$**

arXiv:2205.05120, accepted by PRD

Coupling	Discriminant
a_3^{gg}	$\mathcal{D}_{0-}^{\mathrm{ggH}}$
a_3	$\mathcal{D}_{0-}$
a_2	$\mathcal{D}_{0h+}$
κ_1	$\mathcal{D}_{\Lambda 1}$
$\kappa_2^{Z\gamma}$	$\mathcal{D}_{\Lambda 1}^{Z\gamma}$





Hgg Anomalous Couplings

- **Constrain Hgg anomalous couplings by measuring ggH production**

$$\mu_{\mathrm{ggH}} = 1.1068\kappa_t^2 + 0.0082 - 0.1150\kappa_t + 2.5717\tilde{\kappa}_t^2 + 1.0298(12\pi^2 c_{gg})^2 + 2.3170(8\pi^2\tilde{c}_{gg})^2 + 2.1357(12\pi^2 c_{gg})\kappa_t - 0.1109(12\pi^2 c_{gg}) + 4.8821(8\pi^2\tilde{c}_{gg})\tilde{\kappa}_t.$$

- **Two EFT couplings:**

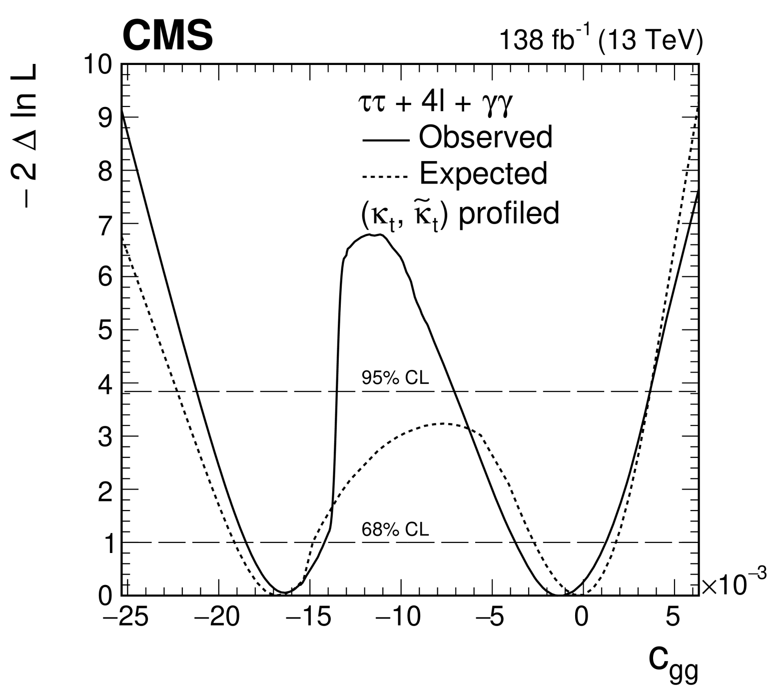
$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg},$$ **CP even**

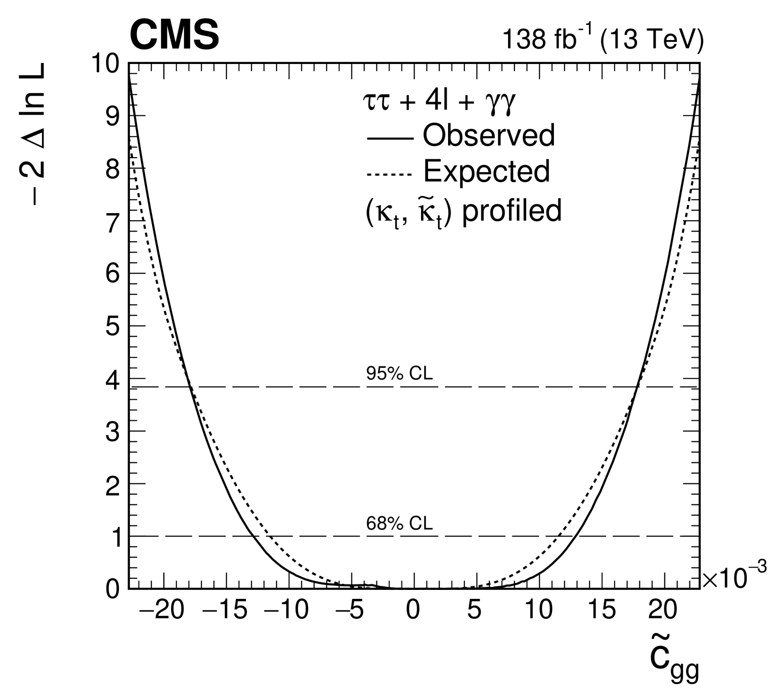
$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg},$$ **CP odd**

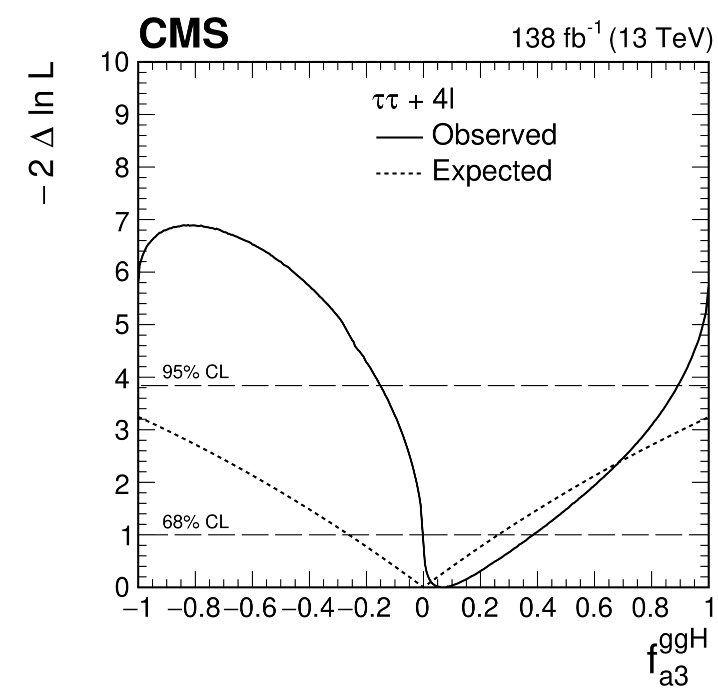
- **Effective fractional XS for Hgg:**

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

arXiv:2205.05120, accepted by PRD







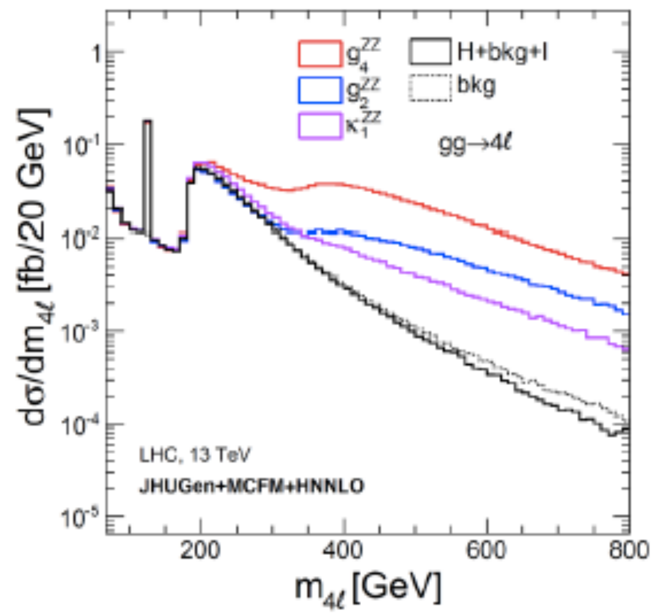
HVV Anomalous Couplings from Off-shell

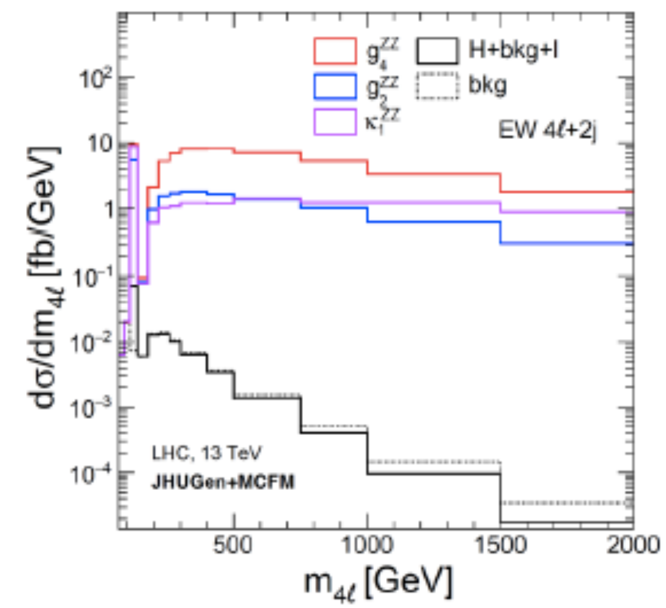
- **HVV anomalous couplings introduce distinct kinematics in off-shell region.**
- **More significant in VBF production mode.**

$\kappa_1 \sim \Lambda_1^{-2}$

$g_2 \sim a_2$

$g_4 \sim a_3$





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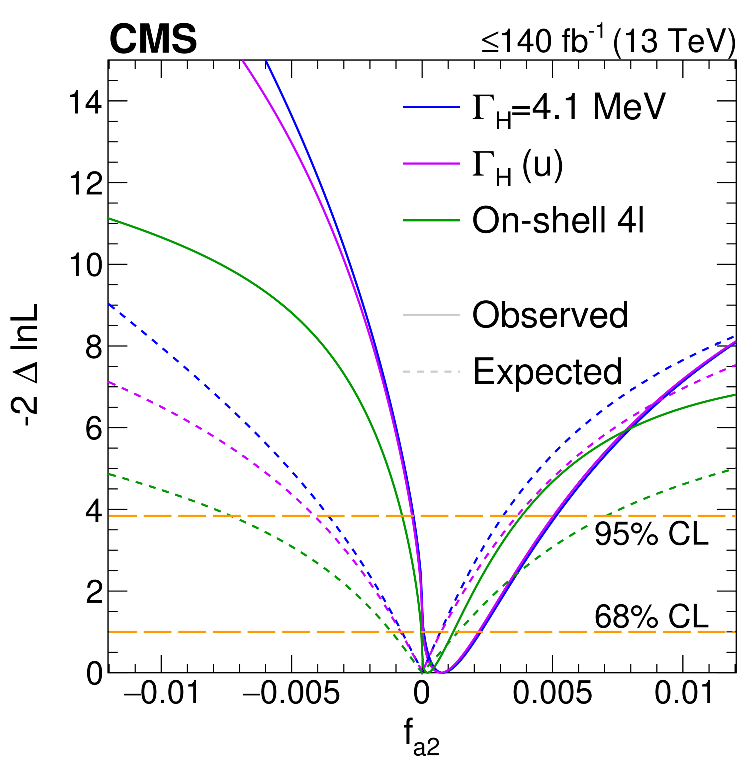

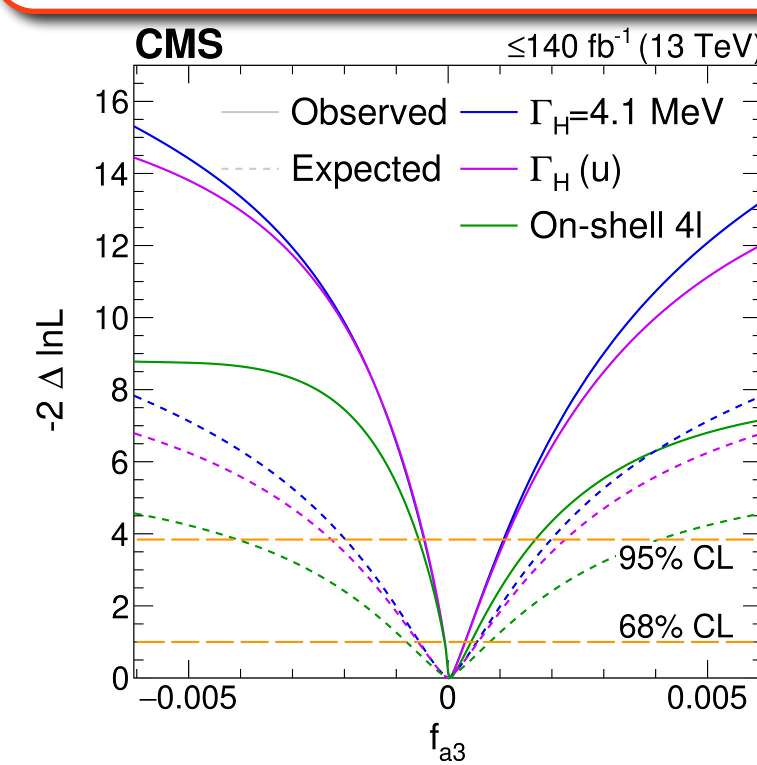

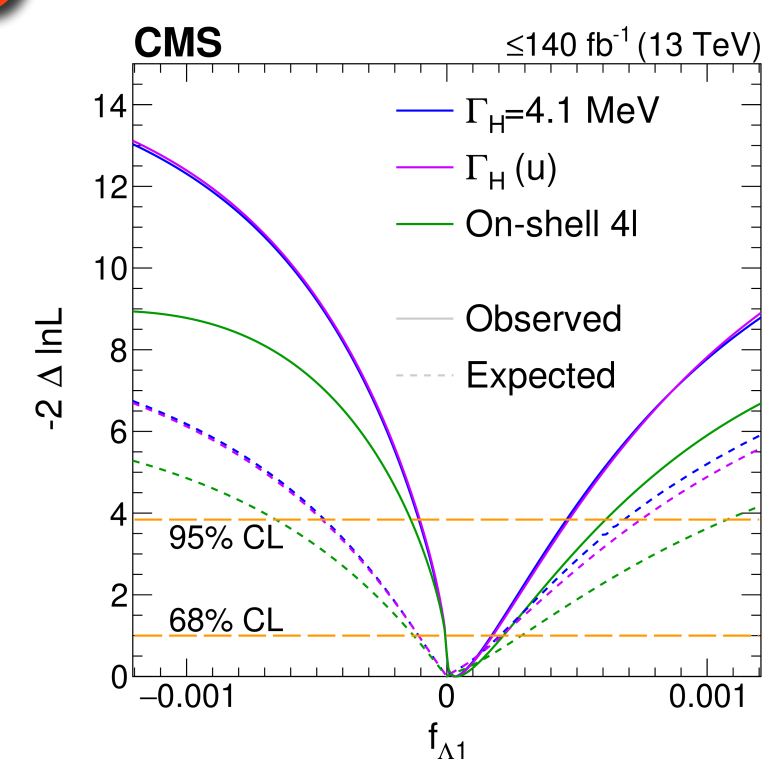

- **off-shell events brings O(10%) ~ O(50%) improvement on limits**

Summary

- **Higgs mass measurement**: 125.38±0.14(0.11) GeV **($\gamma\gamma$ + *4l* Run 1 + 2016)**
- **First evidence of off-shell Higgs production at LHC**: *4l +2l2ν* ⇒ **3.6σ**
- **Higgs width measurement:** $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV
- **CP violating effect probed in fermion sector, pure CP odd coupling excluded > 3σ**
- **Stringent limits on HVV anomalous couplings.**
- **More precise measurement with Run 3 data. Stay tuned!**


thank you

- backup

2*l*2*ν*+4*l* combined results summary

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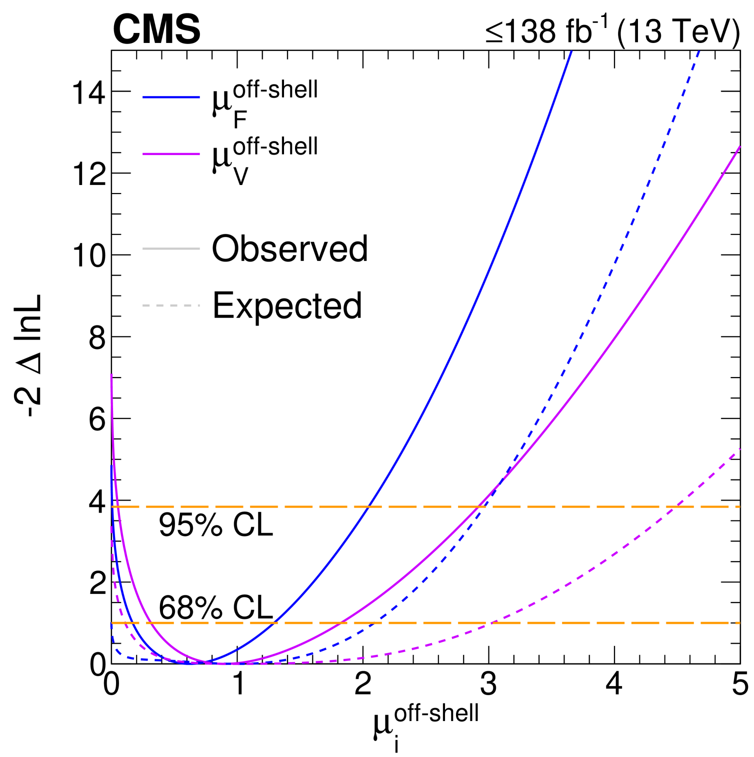
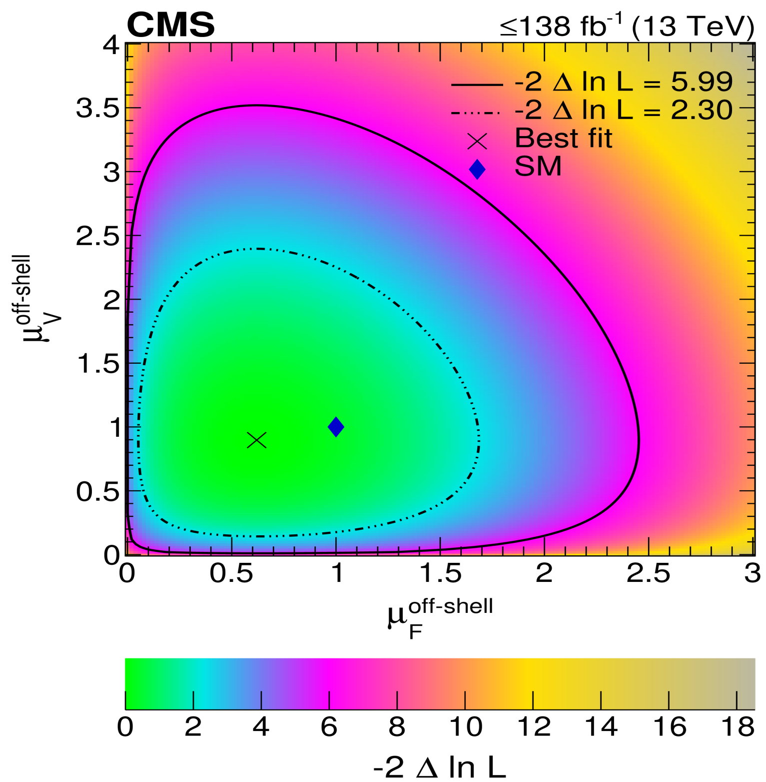
Param.	Cond.	c.v.	Observed 68% | 95% CL	Expected 68% | 95% CL
$\mu_F^{off.}$	$\mu_V^{off.}$ (u)	0.62	$[0.17, 1.3] \mid [0.0060, 2.0]$	$[2 \cdot 10^{-5}, 2.1] \mid < 3.0$
$\mu_V^{off.}$	$\mu_F^{off.}$ (u)	0.90	$[0.31, 1.8] \mid [0.051, 2.9]$	$[0.11, 3.0] \mid < 4.5$
$\mu^{off.}$	$R_{V,F}^{off.} = 1$	0.74	$[0.36, 1.3] \mid [0.13, 1.8]$	$[0.16, 2.0] \mid [0.0086, 2.7]$
	$R_{V,F}^{off.}$ (u)	0.62	$[0.17, 1.3] \mid [0.0061, 2.0]$	$[4 \cdot 10^{-5}, 2.1] \mid [1 \cdot 10^{-5}, 3.0]$
Γ_H	SM-like	3.2	$[1.5, 5.6] \mid [0.53, 8.5]$	$[0.62, 8.1] \mid [0.035, 11.3]$
Γ_H	f_{a2} (u)	3.4	$[1.6, 5.7] \mid [0.60, 8.4]$	$[0.52, 8.0] \mid [0.015, 11.3]$
Γ_H	f_{a3} (u)	2.7	$[1.3, 4.8] \mid [0.47, 7.3]$	$[0.53, 8.0] \mid [0.015, 11.3]$
Γ_H	$f_{\Lambda 1}$ (u)	2.7	$[1.3, 4.8] \mid [0.46, 7.2]$	$[0.55, 8.1] \mid [0.019, 11.3]$

μ_{offshell} and Anomalous Couplings





Parameter	Condition	Best fit	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
Γ_H (MeV)	SM-like	3.2	[1.5, 5.6]	[0.5, 8.5]	[0.6, 8.1]	[0.03, 11.3]
	f_{a2} (u)	3.4	[1.6, 5.7]	[0.6, 8.4]	[0.5, 8.0]	[0.02, 11.3]
	f_{a3} (u)	2.7	[1.3, 4.8]	[0.5, 7.3]	[0.5, 8.0]	[0.02, 11.3]
	$f_{\Lambda 1}$ (u)	2.7	[1.3, 4.8]	[0.5, 7.3]	[0.6, 8.1]	[0.02, 11.3]
$f_{a2}\,(\times 10^5)$	$\Gamma_H = \Gamma_H^{SM}$	79	[6.6, 225]	[−32, 514]	[−78, 70]	[−359, 311]
	Γ_H (u)	72	[2.7, 216]	[−38, 503]	[−82, 73]	[−413, 364]
$f_{a3}\,(\times 10^5)$	$\Gamma_H = \Gamma_H^{SM}$	2.2	[−6.4, 32]	[−46, 107]	[−55, 55]	[−198, 198]
	Γ_H (u)	2.4	[−6.2, 33]	[−46, 110]	[−58, 58]	[−225, 225]
$f_{\Lambda 1}\,(\times 10^5)$	$\Gamma_H = \Gamma_H^{SM}$	2.9	[−0.62, 17]	[−11, 46]	[−11, 20]	[−47, 68]
	Γ_H (u)	3.1	[−0.56, 18]	[−10, 47]	[−11, 21]	[−48, 75]

Nature Phys. 18(2022)1329

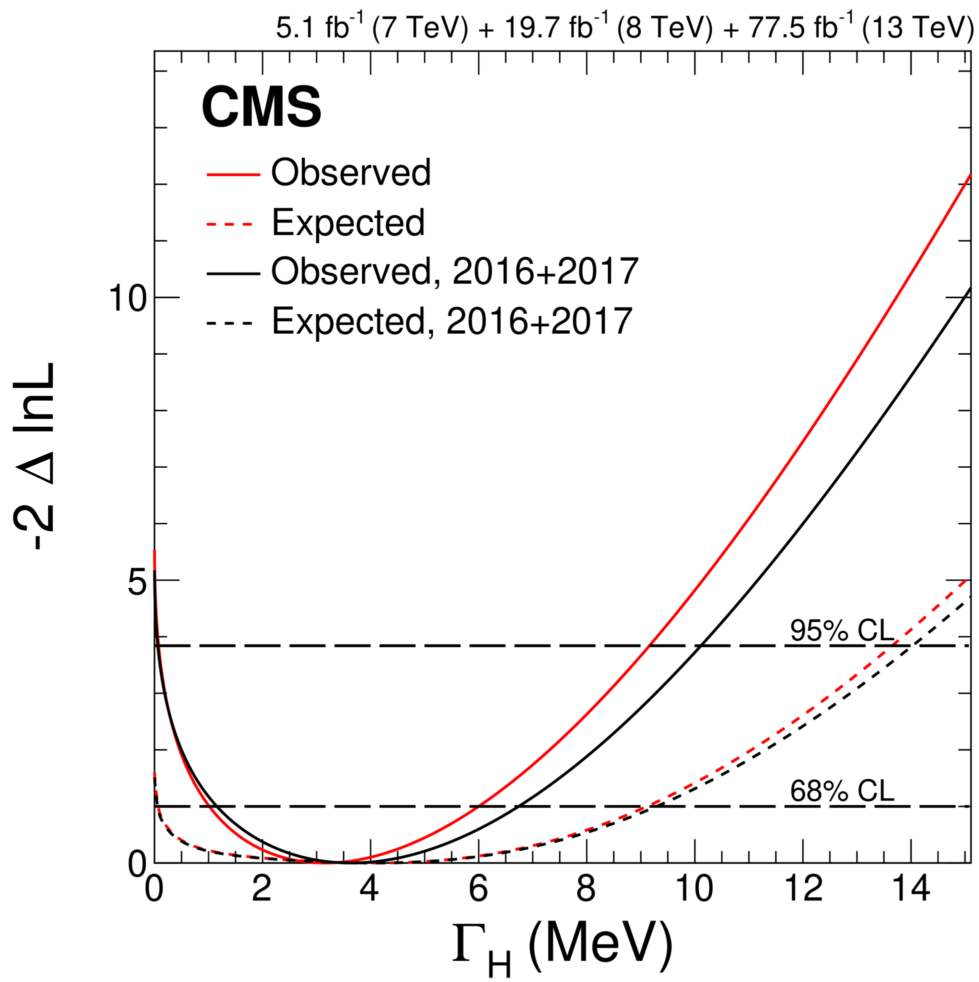
Previous results on width measurement

- **CMS: H→ZZ→4*l***

on-shell: Run 1 + Run 2 (77.5fb^{-1})

off-shell: Run 2 (77.5fb^{-1})

PRD 99 (2019) 112003



68% [95%]

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.78^{+0.72}_{-0.53}$ [0.02, 2.28]	$1.00^{+1.20}_{-0.99}$ [0.0, 3.2]
$\mu_F^{\text{off-shell}}$	$0.86^{+0.92}_{-0.68}$ [0.0, 2.7]	$1.0^{+1.3}_{-1.0}$ [0.0, 3.5]
$\mu_V^{\text{off-shell}}$	$0.67^{+1.26}_{-0.61}$ [0.0, 3.6]	$1.0^{+3.8}_{-1.0}$ [0.0, 8.4]

HVV anomalous coupling from on-shell

CMS-HIG-19-009

Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1 $f_{a2}=f_{\Lambda1}=f_{\Lambda1}^{Z\gamma}=0$	best fit	0.00004	0.00000
		68% CL	[−0.00007, 0.00044]	[−0.00081, 0.00081]
		95% CL	[−0.00055, 0.00168]	[−0.00412, 0.00412]
	Approach 1 float f_{a2}, $f_{\Lambda1}$, $f_{\Lambda1}^{Z\gamma}$	best fit	−0.00805	0.00000
		68% CL	[−0.02656, 0.00034]	[−0.00086, 0.00086]
		95% CL	[−0.07191, 0.00990]	[−0.00423, 0.00422]
	Approach 2 float f_{a2}, $f_{\Lambda1}$	best fit	0.00005	0.0000
		68% CL	[−0.00010, 0.00061]	[−0.0012, 0.0012]
		95% CL	[−0.00072, 0.00218]	[−0.0057, 0.0057]
f_{a2}	Approach 1 $f_{a3}=f_{\Lambda1}=f_{\Lambda1}^{Z\gamma}=0$	best fit	0.00020	0.0000
		68% CL	[−0.00010, 0.00109]	[−0.0012, 0.0014]
		95% CL	[−0.00078, 0.00368]	[−0.0075, 0.0073]
	Approach 1 float f_{a3}, $f_{\Lambda1}$, $f_{\Lambda1}^{Z\gamma}$	best fit	−0.24679	0.0000
		68% CL	[−0.41087, −0.15149] ∪ [−0.00008, 0.00065]	[−0.0017, 0.0014]
		95% CL	[−0.66842, −0.08754] ∪ [−0.00091, 0.00309]	[−0.0082, 0.0073]
	Approach 2 float f_{a3}, $f_{\Lambda1}$	best fit	−0.00002	0.0000
		68% CL	[−0.00178, 0.00103]	[−0.0060, 0.0033]
		95% CL	[−0.00694, 0.00536]	[−0.0206, 0.0131]
$f_{\Lambda1}$	Approach 1 $f_{a3}=f_{a2}=f_{\Lambda1}^{Z\gamma}=0$	best fit	0.00004	0.00000
		68% CL	[−0.00002, 0.00022]	[−0.00016, 0.00026]
		95% CL	[−0.00014, 0.00060]	[−0.00069, 0.00110]
	Approach 1 float f_{a3}, f_{a2}, $f_{\Lambda1}^{Z\gamma}$	best fit	0.18629	0.00000
		68% CL	[−0.00002, 0.00019] ∪ [0.07631, 0.27515]	[−0.00017, 0.00036]
		95% CL	[−0.00523, 0.35567]	[−0.00076, 0.00134]
	Approach 2 float f_{a3}, f_{a2}	best fit	0.00012	0.0000
		68% CL	[−0.00021, 0.00141]	[−0.0013, 0.0030]
		95% CL	[−0.00184, 0.00443]	[−0.0056, 0.0102]
$f_{\Lambda1}^{Z\gamma}$	Approach 1 $f_{a3}=f_{a2}=f_{\Lambda1}=0$	best fit	−0.00001	0.0000
		68% CL	[−0.00099, 0.00057]	[−0.0026, 0.0020]
		95% CL	[−0.00387, 0.00301]	[−0.0096, 0.0082]
	Approach 1 float f_{a3}, f_{a2}, $f_{\Lambda1}$	best fit	−0.02884	0.0000
		68% CL	[−0.09000, −0.00534] ∪ [−0.00068, 0.00078]	[−0.0027, 0.0026]
		95% CL	[−0.29091, 0.03034]	[−0.0099, 0.0096]

HVV anomalous coupling from 4l on-shell + off-shell

TABLE VI. Summary of allowed 68% C.L. (central values with uncertainties) and 95% C.L. (in square brackets) intervals for the anomalous coupling parameters $f_{ai}\cos(\phi_{ai})$ obtained from the analysis of the combination of Run 1 (only on-shell) and Run 2 (on-shell and off-shell) data sets. Three constraint scenarios are shown: using only on-shell events, using both on-shell and off-shell events with the Γ_H left unconstrained, or with the constraint $\Gamma_H = \Gamma_H^{SM}$.

Parameter	Scenario	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	On-shell	$-0.0001^{+0.0004}_{-0.0015}$ [−0.163, 0.090]	$0.0000^{+0.0019}_{-0.0019}$ [−0.082, 0.082]
	Any Γ_H	$0.0000^{+0.0003}_{-0.0010}$ [−0.0165, 0.0087]	$0.0000^{+0.0015}_{-0.0015}$ [−0.038, 0.038]
	$\Gamma_H = \Gamma_H^{SM}$	$0.0000^{+0.0003}_{-0.0009}$ [−0.0067, 0.0050]	$0.0000^{+0.0014}_{-0.0014}$ [−0.0098, 0.0098]
$f_{a2}\cos(\phi_{a2})$	On-shell	$0.0004^{+0.0026}_{-0.0006}$ [−0.0055, 0.0234]	$0.0000^{+0.0030}_{-0.0023}$ [−0.021, 0.035]
	Any Γ_H	$0.0004^{+0.0026}_{-0.0006}$ [−0.0035, 0.0147]	$0.0000^{+0.0019}_{-0.0017}$ [−0.015, 0.021]
	$\Gamma_H = \Gamma_H^{SM}$	$0.0005^{+0.0025}_{-0.0006}$ [−0.0029, 0.0129]	$0.0000^{+0.0012}_{-0.0016}$ [−0.010, 0.012]
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	On-shell	$0.0002^{+0.0030}_{-0.0009}$ [−0.209, 0.089]	$0.0000^{+0.0012}_{-0.0006}$ [−0.059, 0.032]
	Any Γ_H	$0.0001^{+0.0015}_{-0.0006}$ [−0.090, 0.059]	$0.0000^{+0.0013}_{-0.0007}$ [−0.017, 0.019]
	$\Gamma_H = \Gamma_H^{SM}$	$0.0001^{+0.0015}_{-0.0005}$ [−0.016, 0.068]	$0.0000^{+0.0013}_{-0.0006}$ [−0.015, 0.018]
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}{}^{Z\gamma})$	On-shell	$0.0000^{+0.3554}_{-0.0087}$ [−0.17, 0.61]	$0.0000^{+0.0091}_{-0.0100}$ [−0.098, 0.343]

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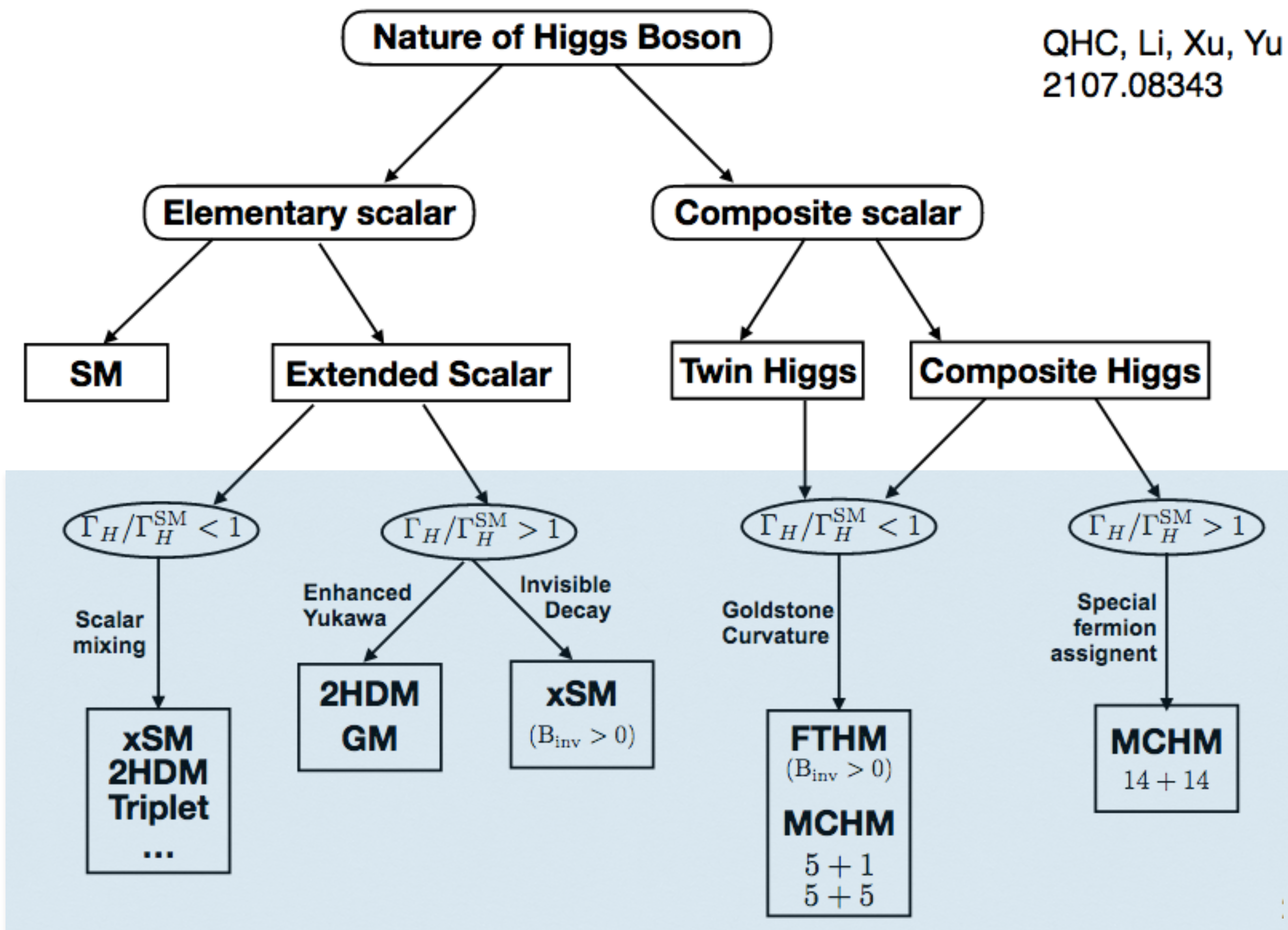
What if Γ_H deviates from SM

4. Higgs boson width



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