EPS HEP

22/08/2023

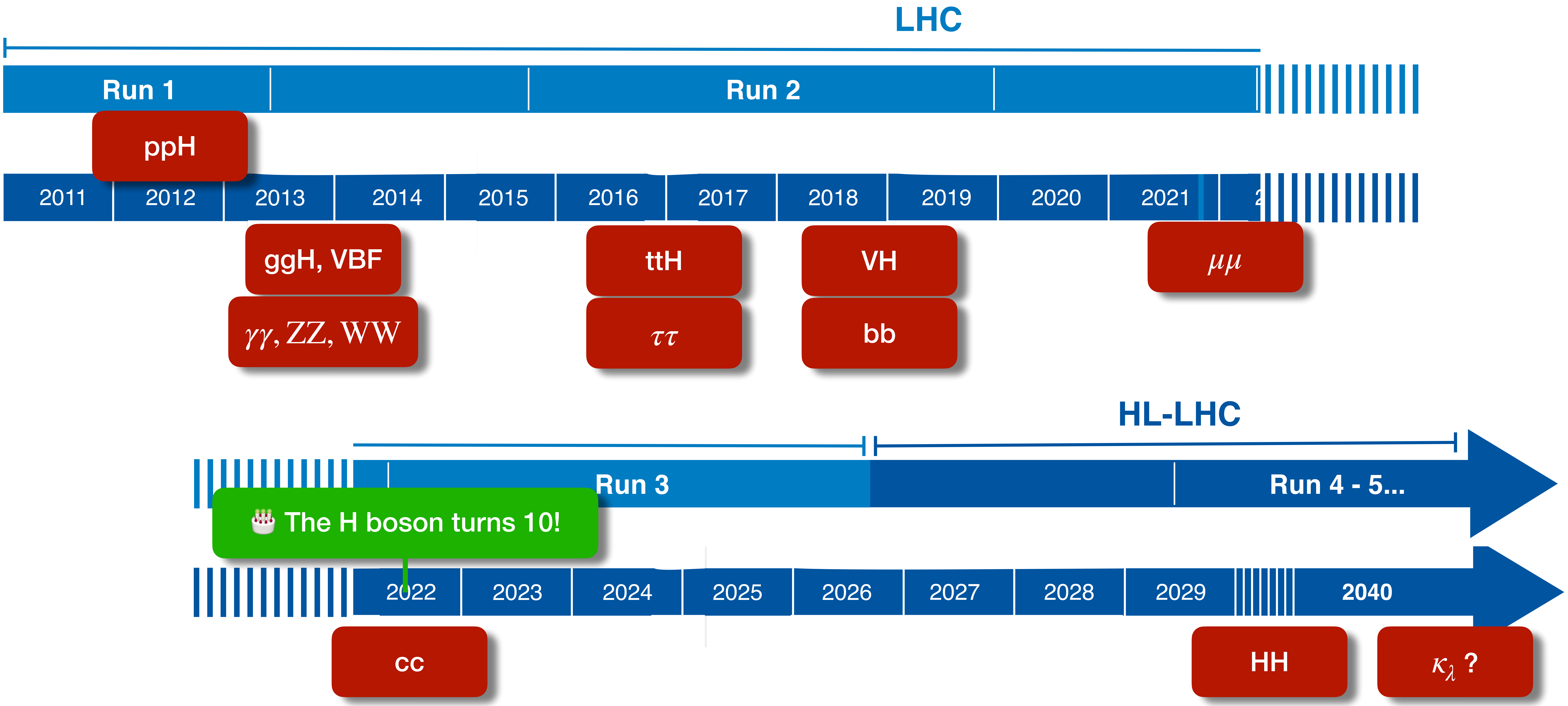
Higgs boson anomalous couplings and EFT at CMS

Matteo Bonanomi

(University of Hamburg)

On behalf of the CMS Collaboration

We have come a long way



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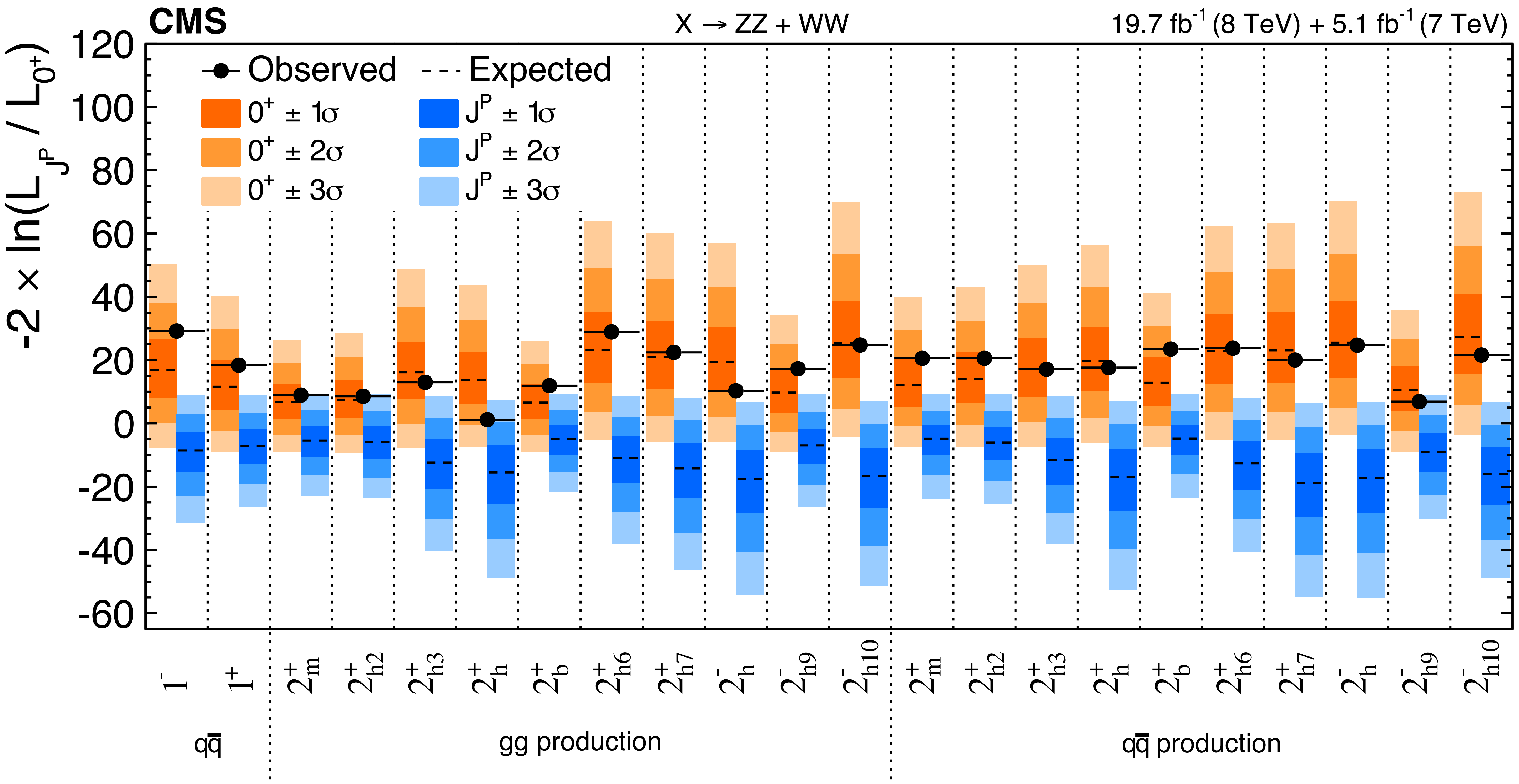
We have characterised the H boson by measuring its mass, width, and CP numbers:

- **Unique scalar particle in the SM**
- **J^{PC} = 0^{++} at 99.9% CL** , in agreement with SM prediction of a CP-even H boson
- **Pure CP-odd ttH ($H\tau\tau$) coupling excluded at 3.9 (3.4) SDs**



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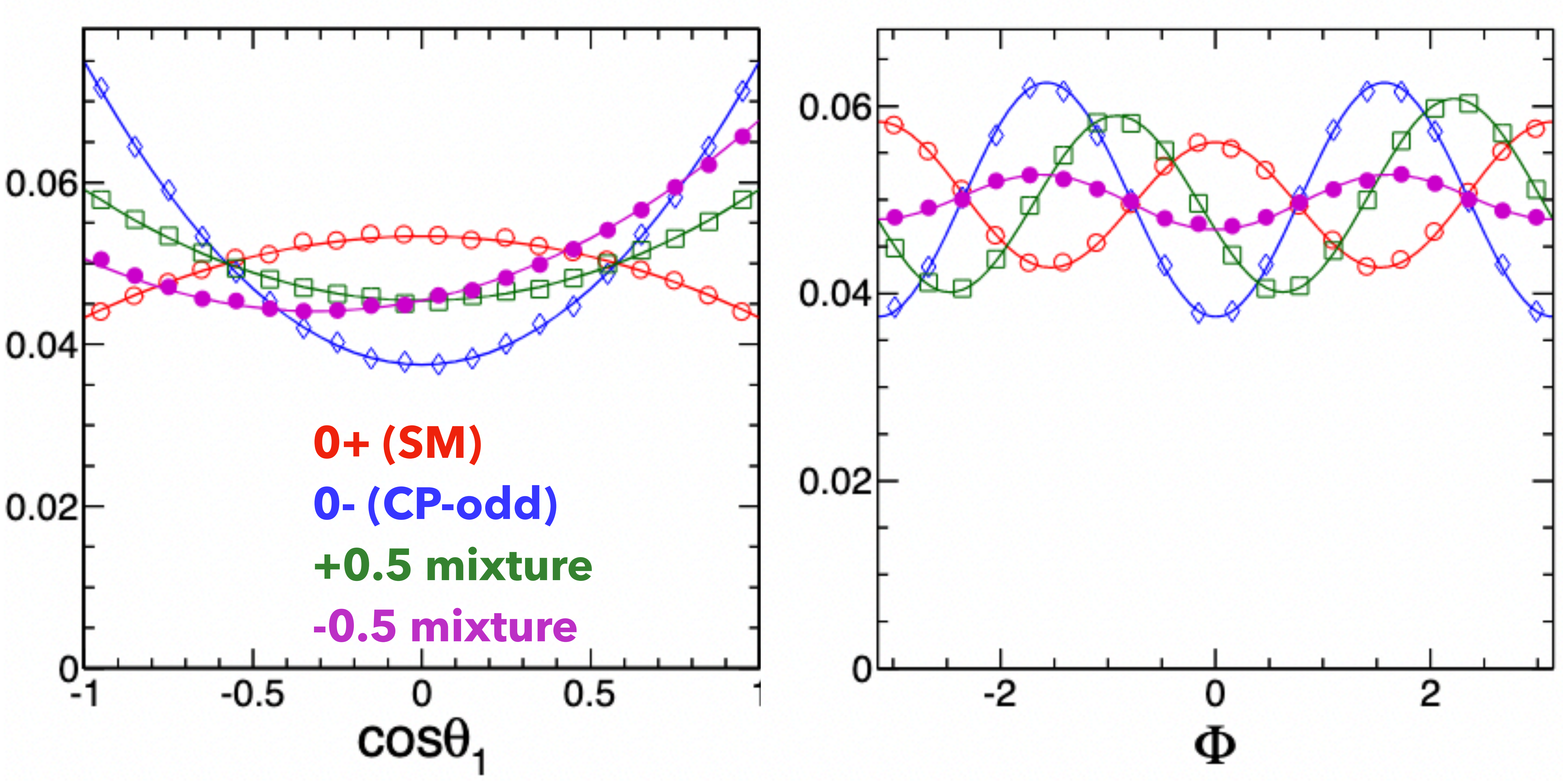

Phys. Rev. D 89, 035007

... but room for small HVV couplings or BSM effects that can lead to CP-odd interactions

The open questions:

Are there HVV anomalous couplings?

Small CP-even and/or CP-odd anomalous couplings are allowed by the current precision

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Different spin-parity assignments could modify allowed types of interactions, manifesting in the kinematics of particles produced in association with Higgs and/or decay products of the Higgs

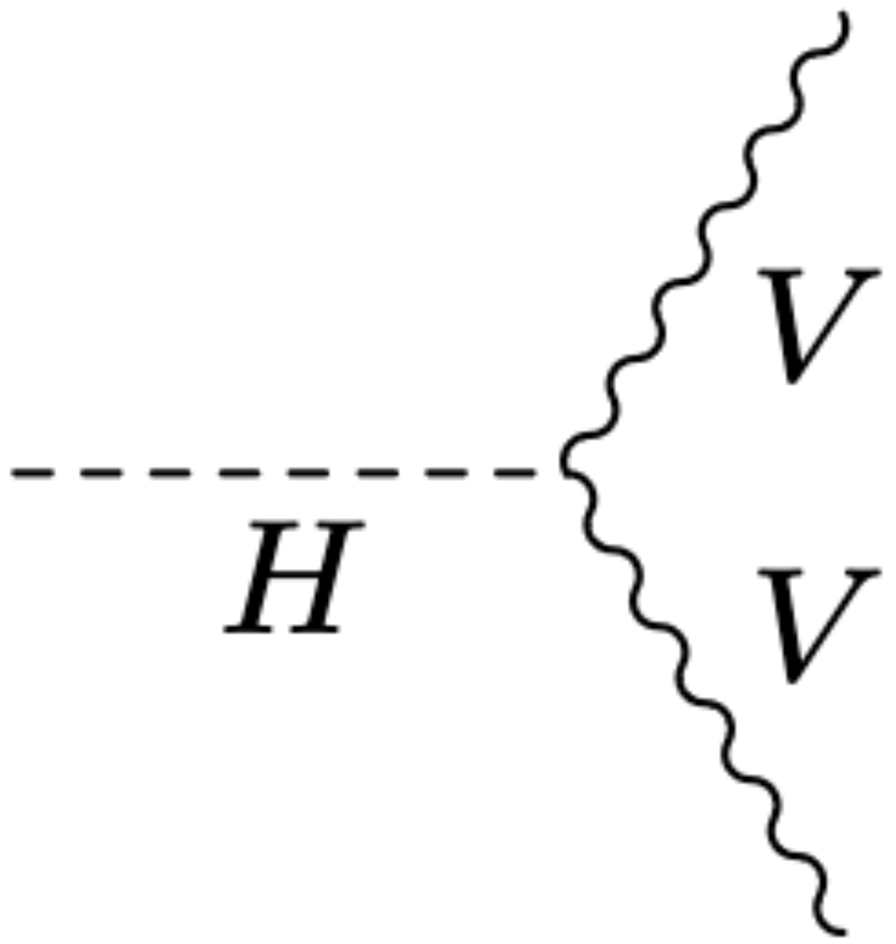
Anomalous Coupling formalism

Scattering amplitude for H couplings with vector bosons:

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

For VV=ZZ, WW, Zγ:

(Both in production and decay)



4 couplings (SM + Anomalous):

- a_1 **(CP): SM**
- a_2 **(CP)**
- a_3 **($\not{\text{CP}}$)**
- a_{Λ_1} **(CP)**
- $a_{\Lambda_1^{Z\gamma}}$ **(CP)**

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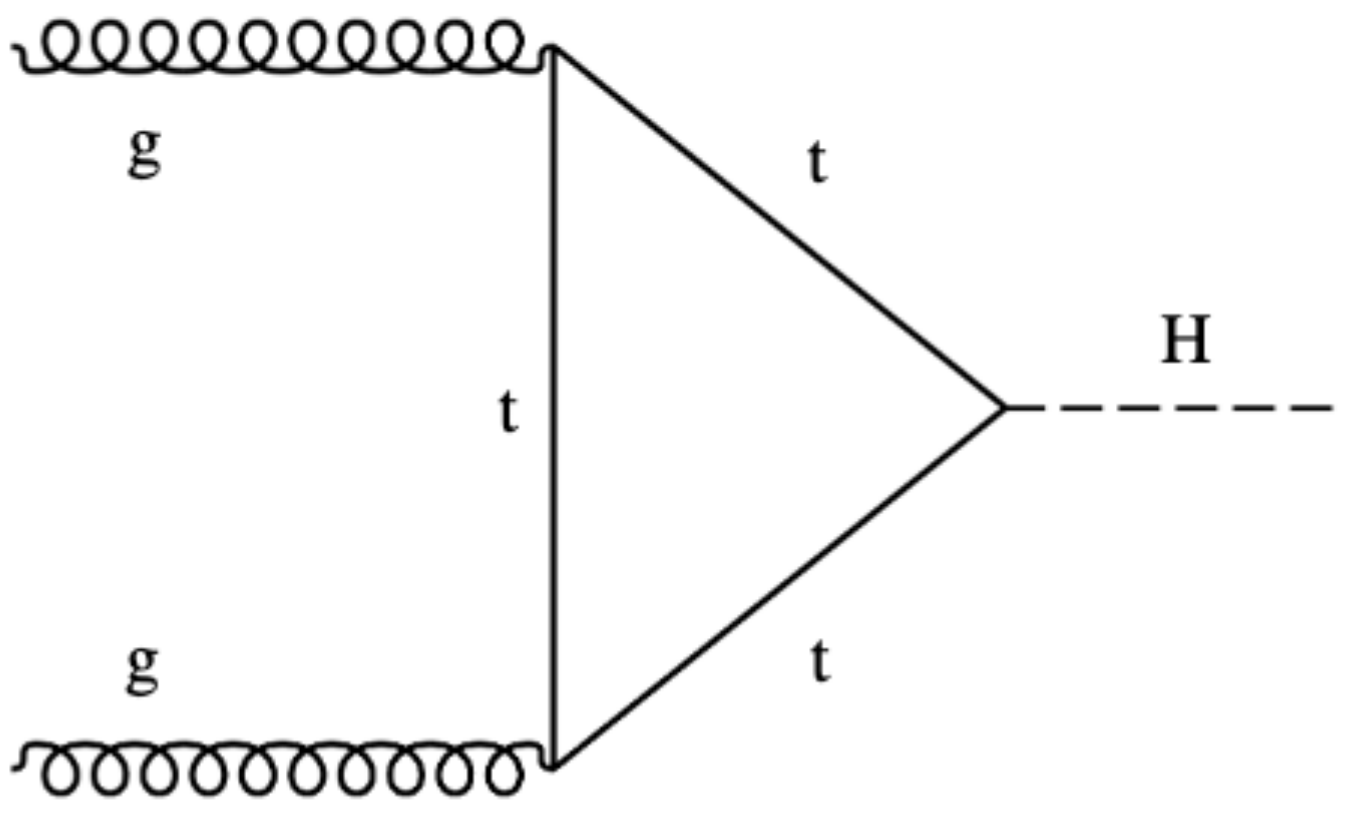
For VV=$\gamma\gamma, gg$:



2 couplings (SM + Anomalous):

- a_2 **(CP): SM**
- a_3 **(~~CP~~)**

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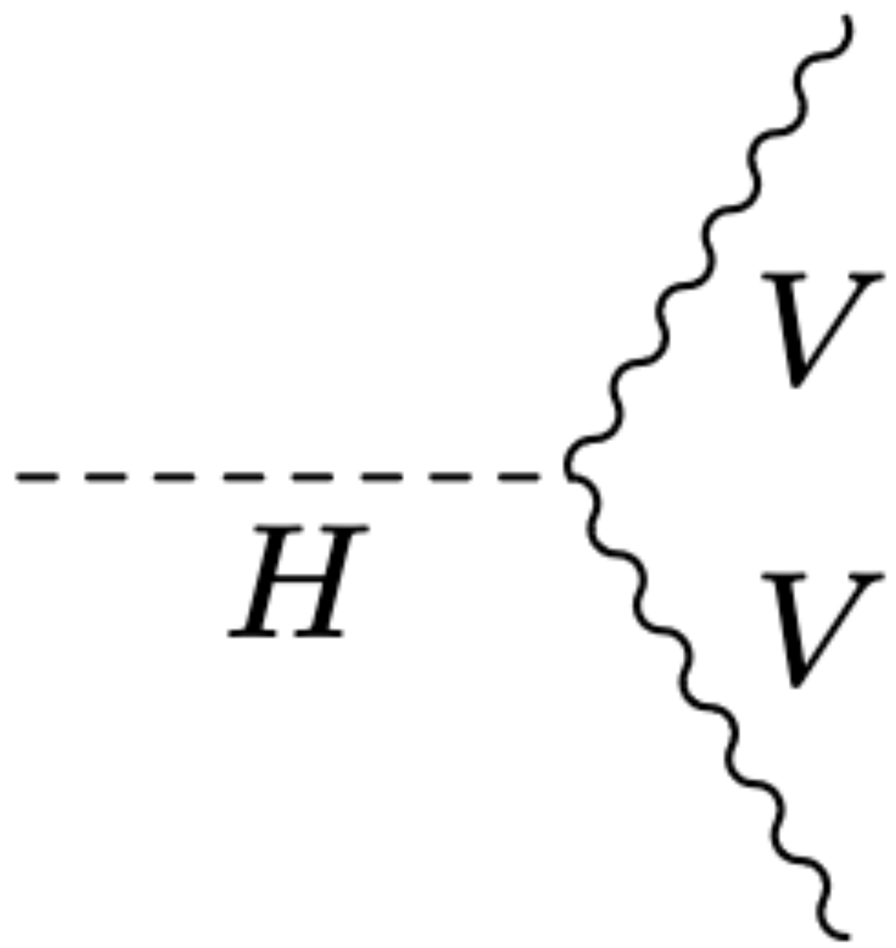

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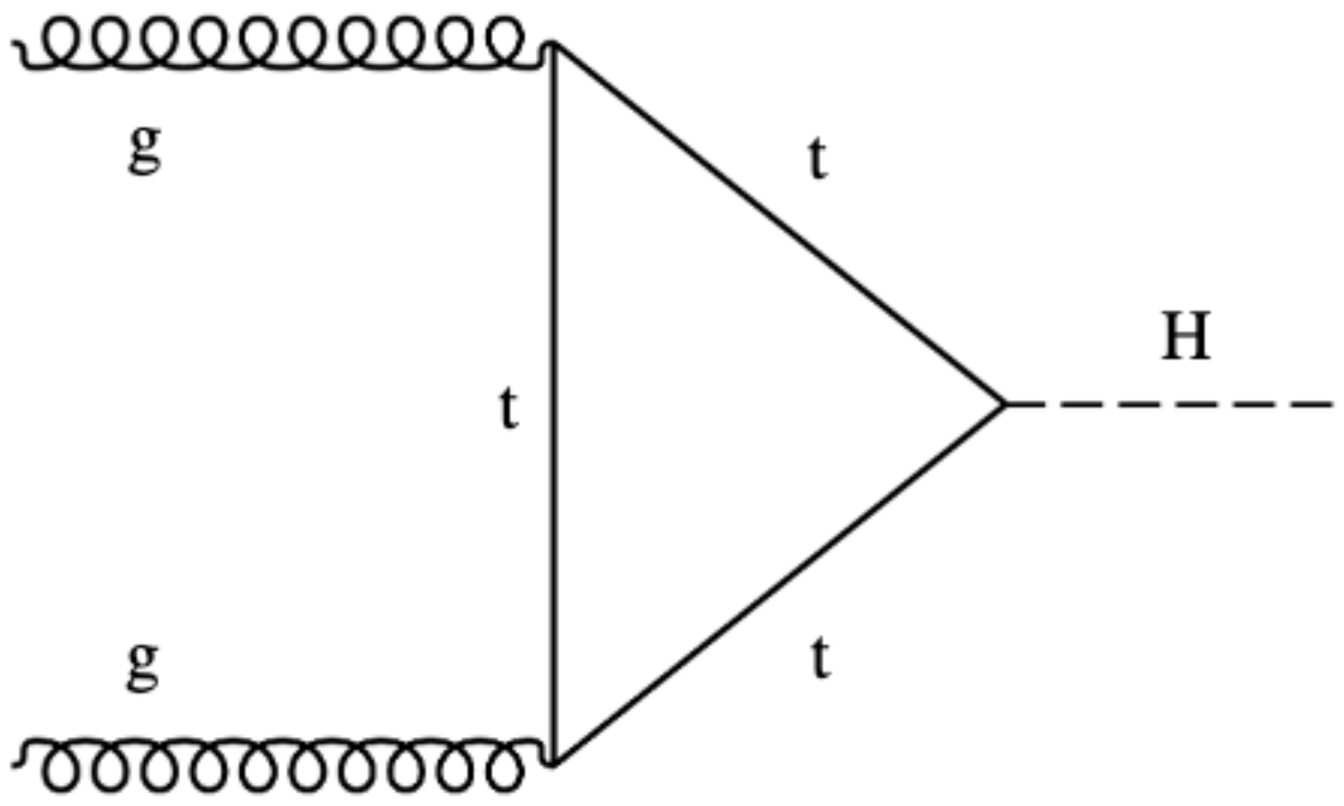

- a_2 **(CP): SM**
- a_3 **(~~CP~~)**

$$f_{a_i} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3...} |a_j|^2 \sigma_j} \mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

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

Anomalous Coupling formalism

Scattering amplitude for H couplings with fermions:

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

CP-even terms

- ttH strong sensitivity to $\kappa_t, \tilde{\kappa}_t$ constraints
- In SM $\kappa_t = 1$, other terms are 0
- **Exclusion of pure CP-odd H boson at 3.7 SD**

CP-odd terms

- **Possible CP-odd terms arising from BSM effects**
- **ggH could probe the CP-structure via ggH+2jets events**

$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

$$|f_{CP}^{Hff}| = \left(1 + 2.38\left[\frac{1}{|f_{a_3}^{ggH}|}\right]\right)^{-1} = \sin^2\alpha^{Hff}$$

From AC to EFT

The sensitivity to Higgs AC can be translated into sensitivity to higher- dimensional operators in EFT

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k c_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)}\mathcal{O}_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

SU(2)xU(1) symmetry

HVV amplitude parametrized in EFT Higgs basis with 15 coefficients

$$\delta c_z = \frac{1}{2} g_1^{ZZ} - 1\,, \qquad c_{zz} = -\frac{2s_w^2 c_w^2}{e^2} g_2^{ZZ}\,, \qquad c_{z\Box} = \frac{M_Z^2 s_w^2}{e^2}\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}\,, \qquad \tilde{c}_{zz} = -\frac{2s_w^2 c_w^2}{e^2} g_4^{ZZ}\,,$$

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$$c_{z\gamma} = -\frac{2s_w c_w}{e^2} g_2^{Z\gamma}\,, \qquad \tilde{c}_{z\gamma} = -\frac{2s_w c_w}{e^2} g_4^{Z\gamma}\,, \qquad c_{\gamma\Box} = \frac{s_w c_w}{e^2}\frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2}\kappa_2^{Z\gamma}\,,$$

$$c_{\gamma\gamma} = -\frac{2}{e^2} g_2^{\gamma\gamma}\,, \qquad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2} g_4^{\gamma\gamma}\,, \qquad c_{gg} = -\frac{2}{g_s^2} g_2^{gg}\,, \qquad \tilde{c}_{gg} = -\frac{2}{g_s^2} g_4^{gg}\,.$$

Assuming here that $\kappa_1^{ZZ} = \kappa_2^{ZZ}, \kappa_1^{WW} = \kappa_2^{WW}$, and $a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = \kappa_1^{gg} = \kappa_2^{gg} = \kappa_1^{Z\gamma} = \kappa_3^{VV} = 0$

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Assuming full SU(2)xU(1) symmetry we're left with 4 HVV independent couplings…

Assuming here that $\kappa_1^{ZZ} = \kappa_2^{ZZ}, \kappa_1^{WW} = \kappa_2^{WW}$, and $a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = \kappa_1^{gg} = \kappa_2^{gg} = \kappa_1^{Z\gamma} = \kappa_3^{VV} = 0$

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… and two Hgg couplings

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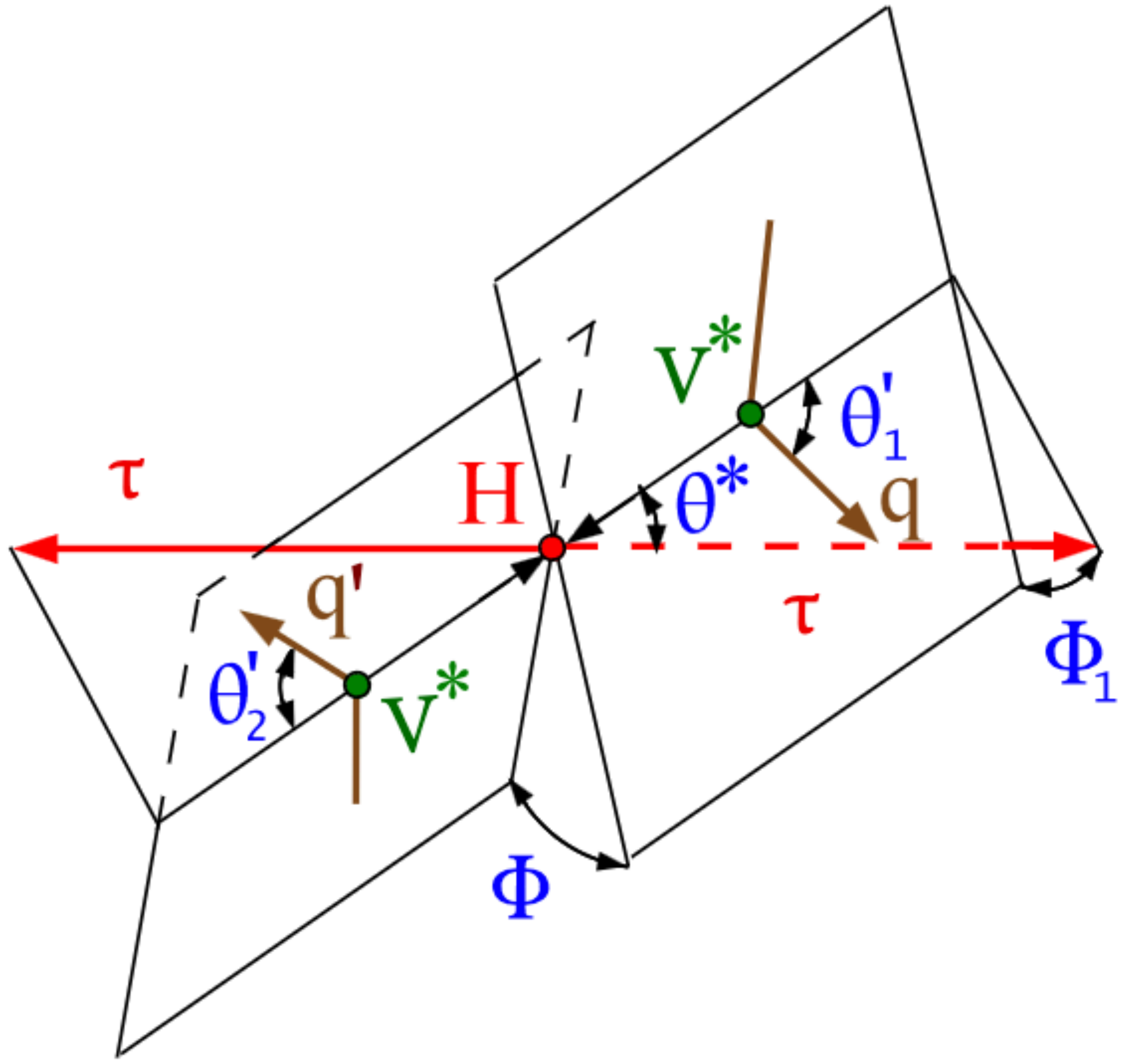
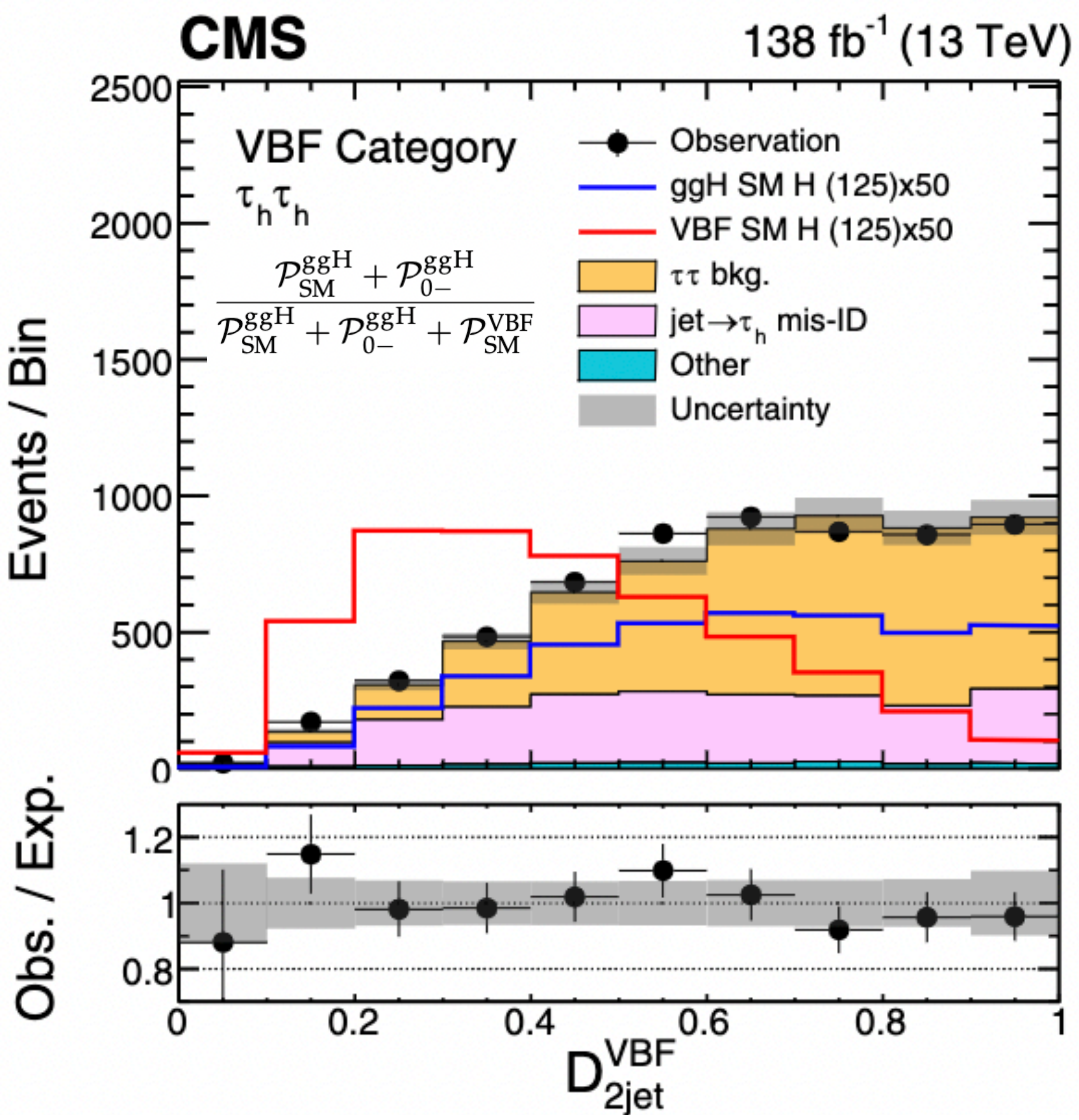
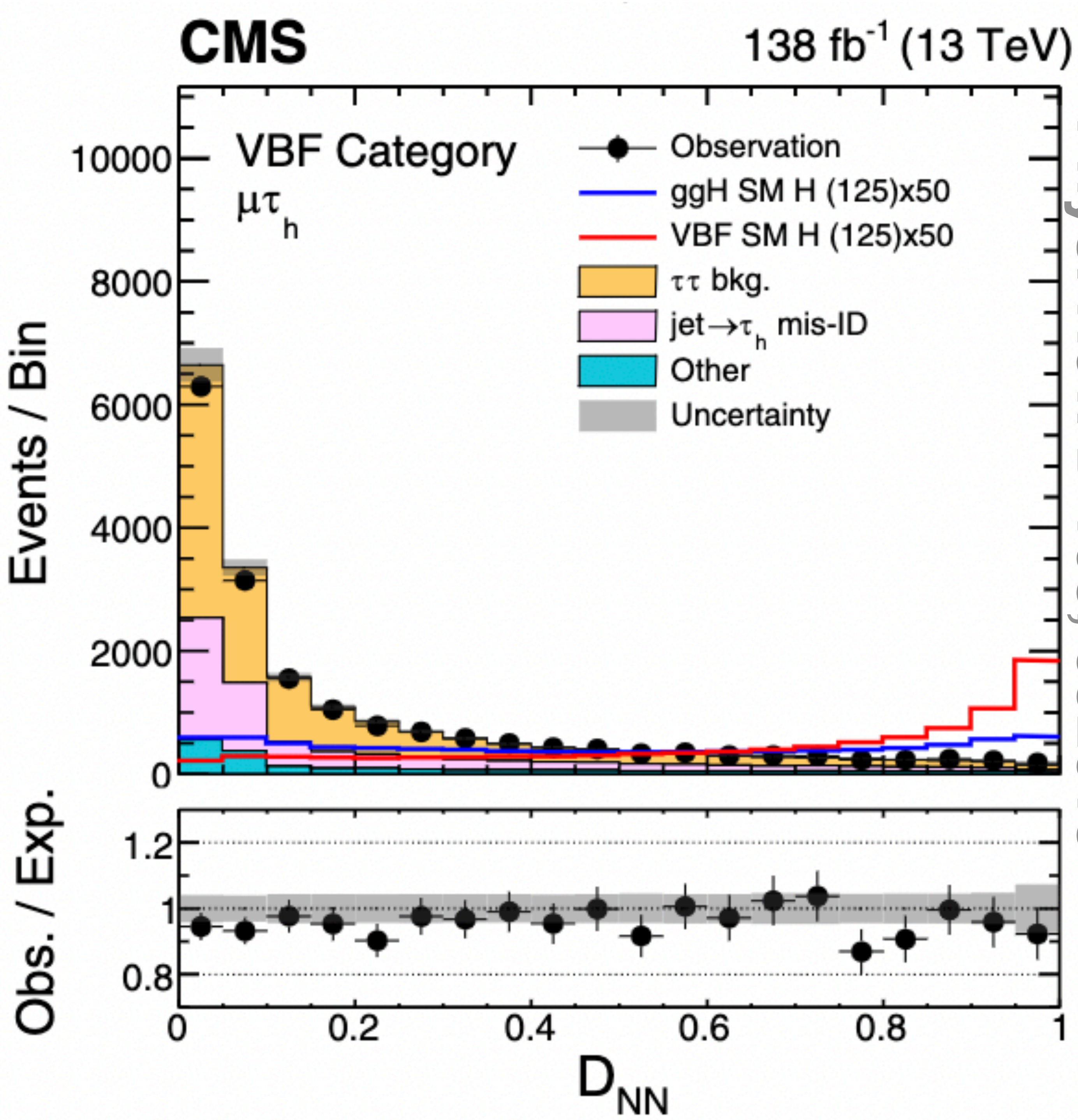
How do we measure AC?

Different approaches employed to achieve good AC sensitivity

- **"Optimal observables"** approach: reduce phase space dimensionality by combining observables
- **Matrix element methods** (MEM): build Neymann-Pearson-like discriminants based on parton-level information
- **Machine learning** techniques**:** build NN classifiers to exploit correlations and boost the sensitivity







Phys. Rev. D 108, 032013

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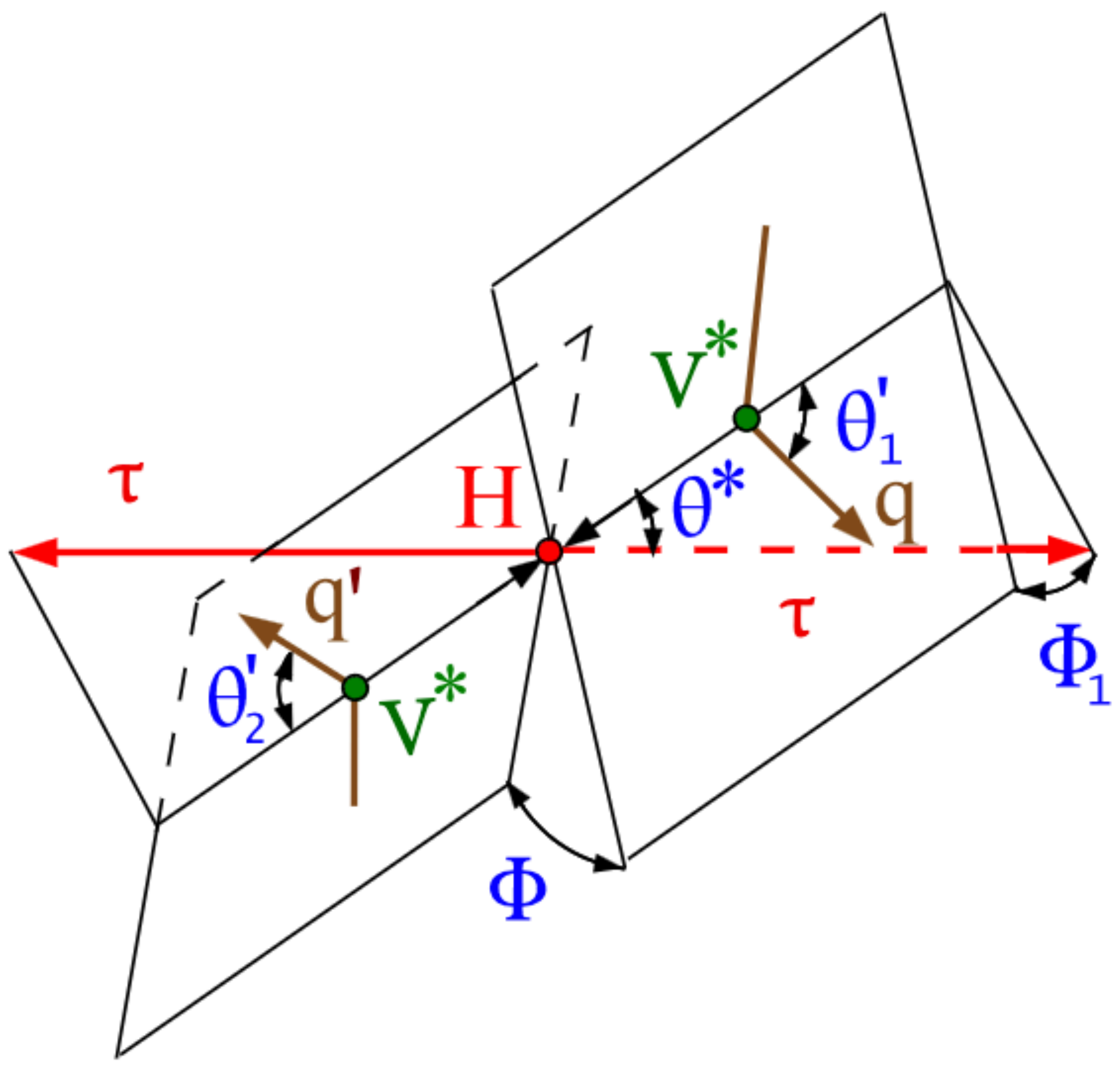

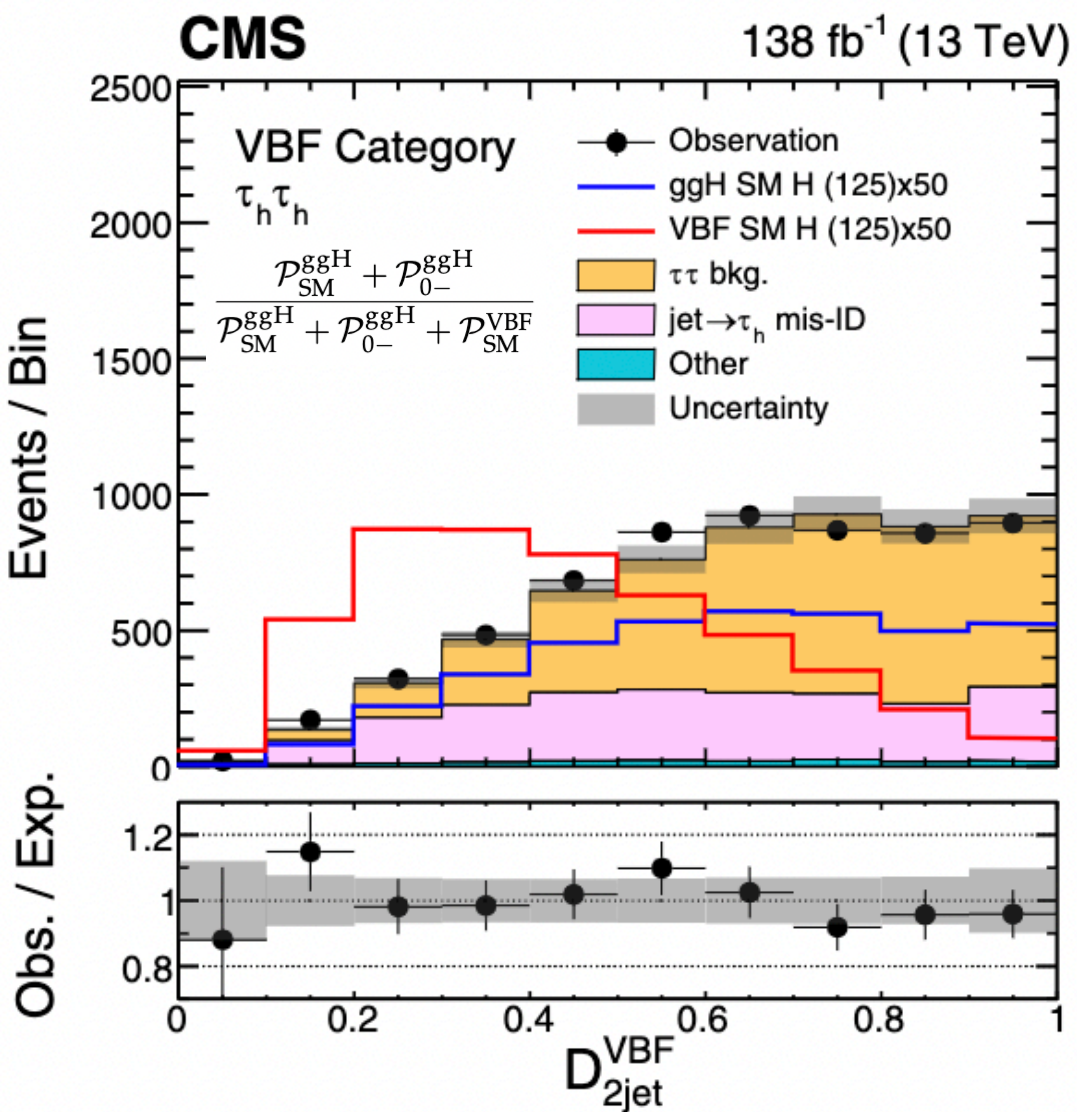

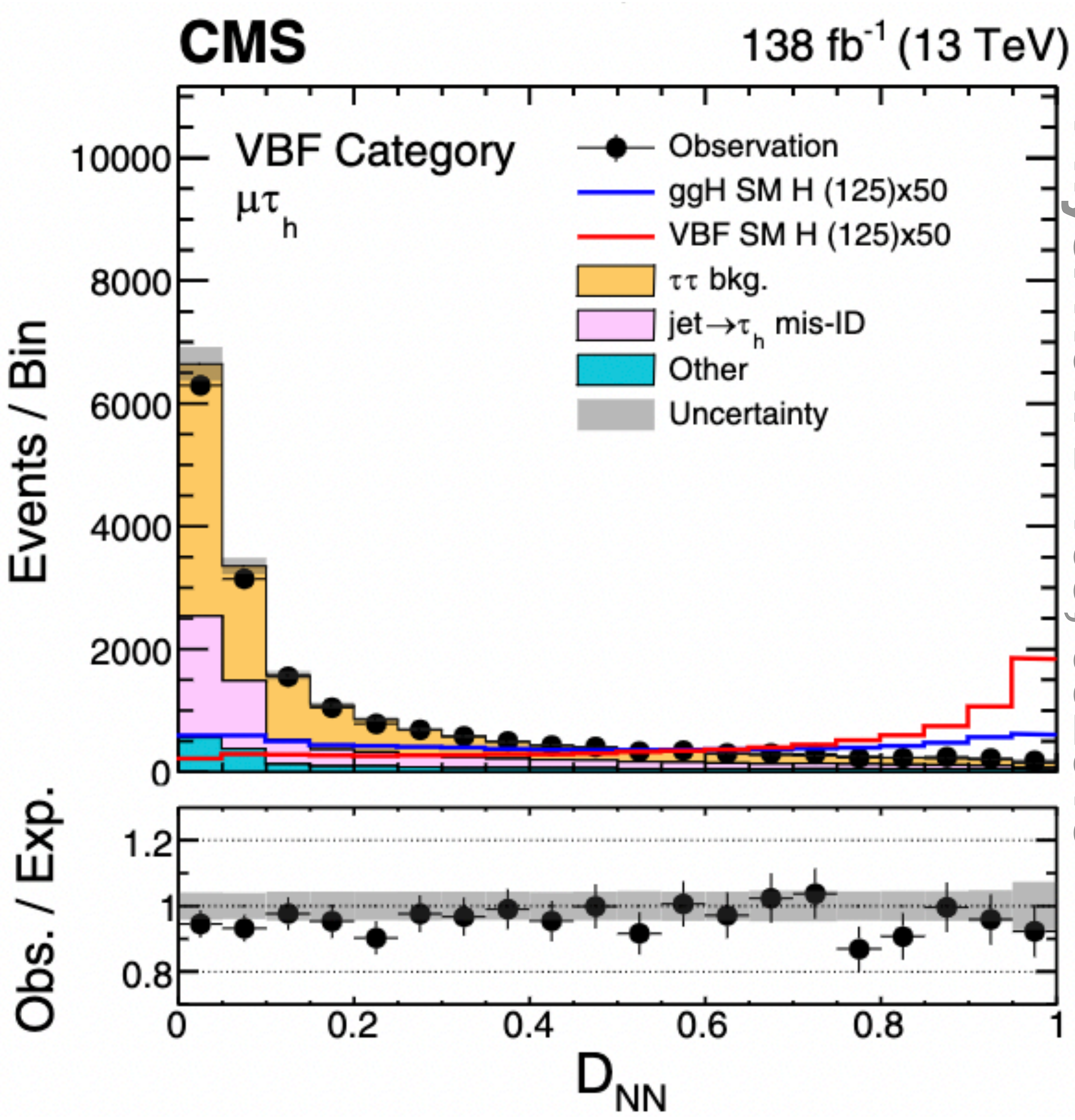

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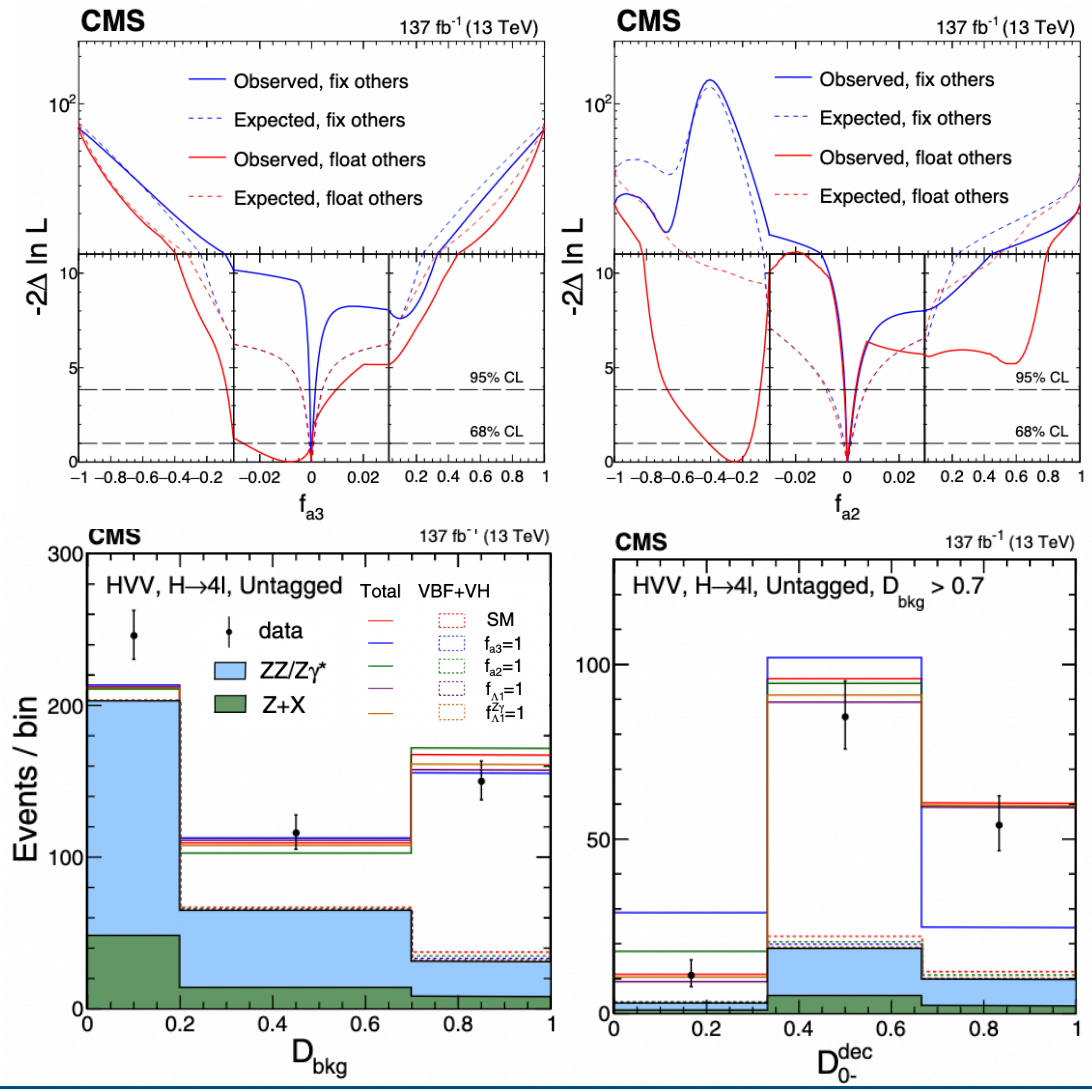
HVV limits in HZZ

Simultaneous measurement of 4 HVV AC

- Assuming $a_i^{WW} = a_i^{ZZ}$
- **Sharp minima:** feature arising from **combination of production and decay**
- **Above** $f_{a_i} = 0.02$ **the H(4l) decay dominates**
- **The results** are still **statistically consistent with the SM**
- **More data needed to possibly unveil new physics** and to disentangle VBF and VH productions



Eur. Phys. J. C 81 (2021) 488

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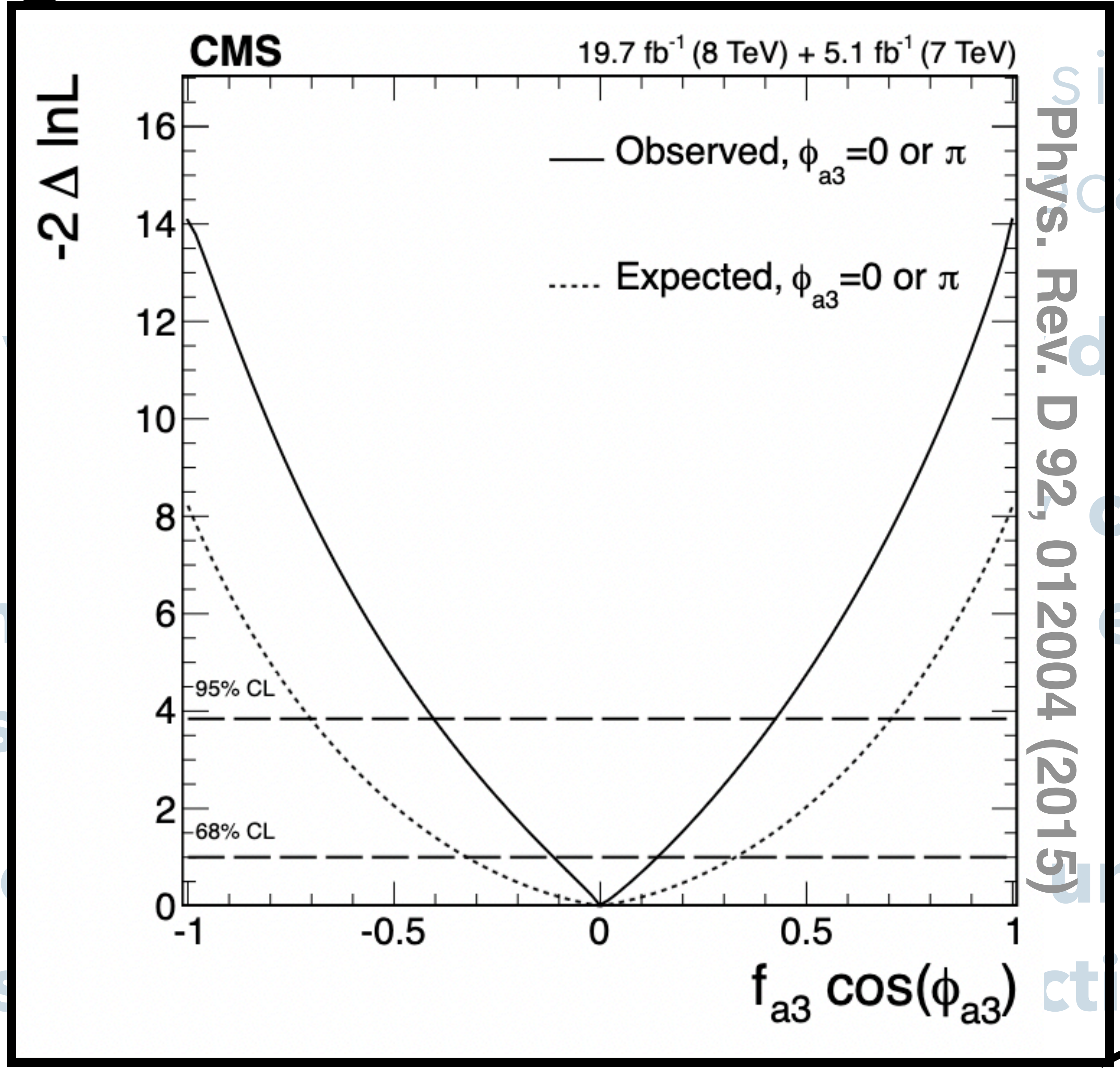
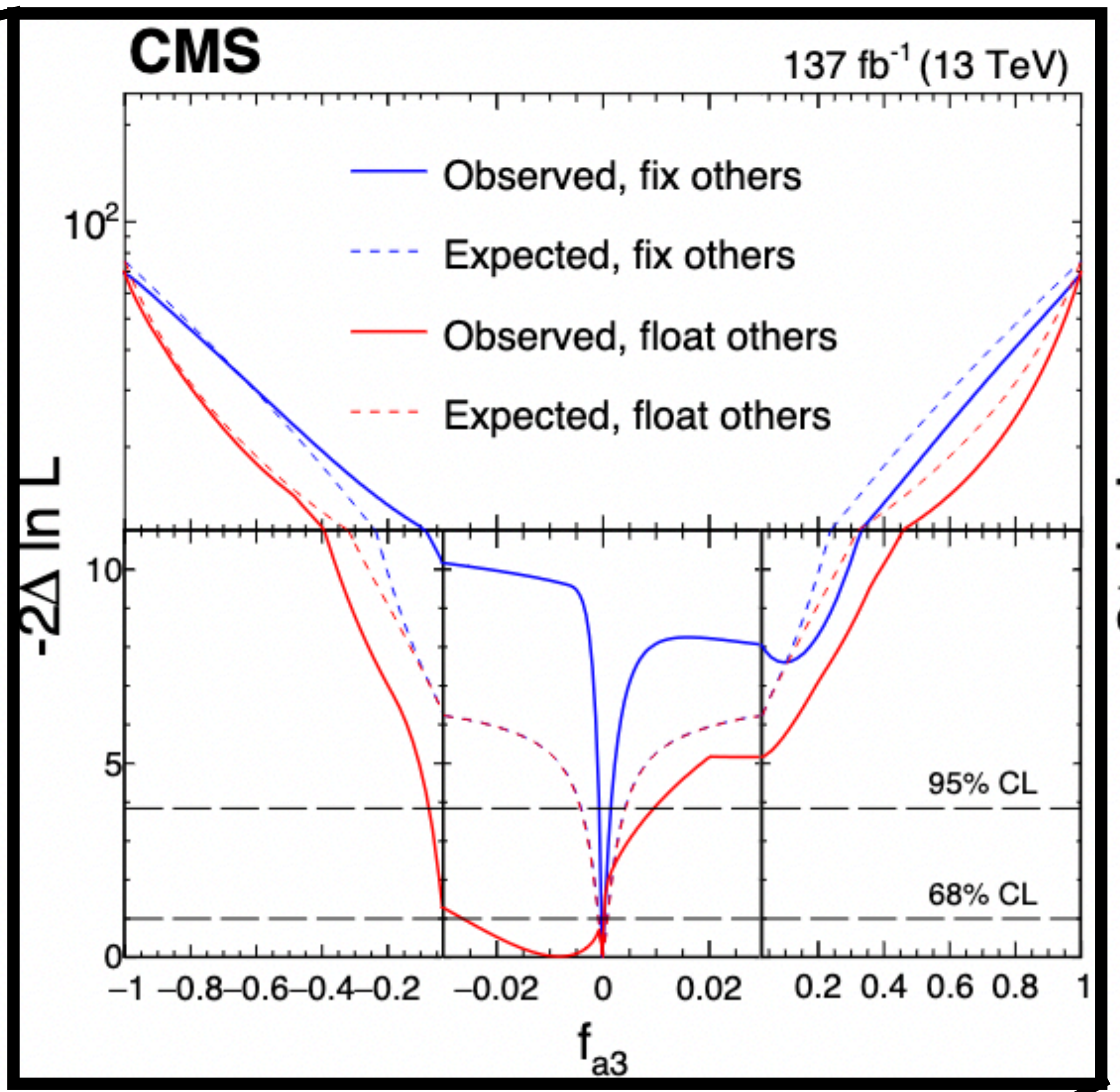


Phys. Rev. D 92, 012004 (2015)

Run-I: HZZ only, $f_{a_3} < 0.40\,(0.43)$



Run-II: HZZ + VBF + VH + ggH, $f_{a_3} < 5.5\times10^{-4}\,(1.68\times10^{-3})$

Substantial improvement in sensitivity wrt Run-I result achieved exploiting production information!

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HVV limits in HZZ, using off-shell

Simultaneous measurement of 4 HVV AC

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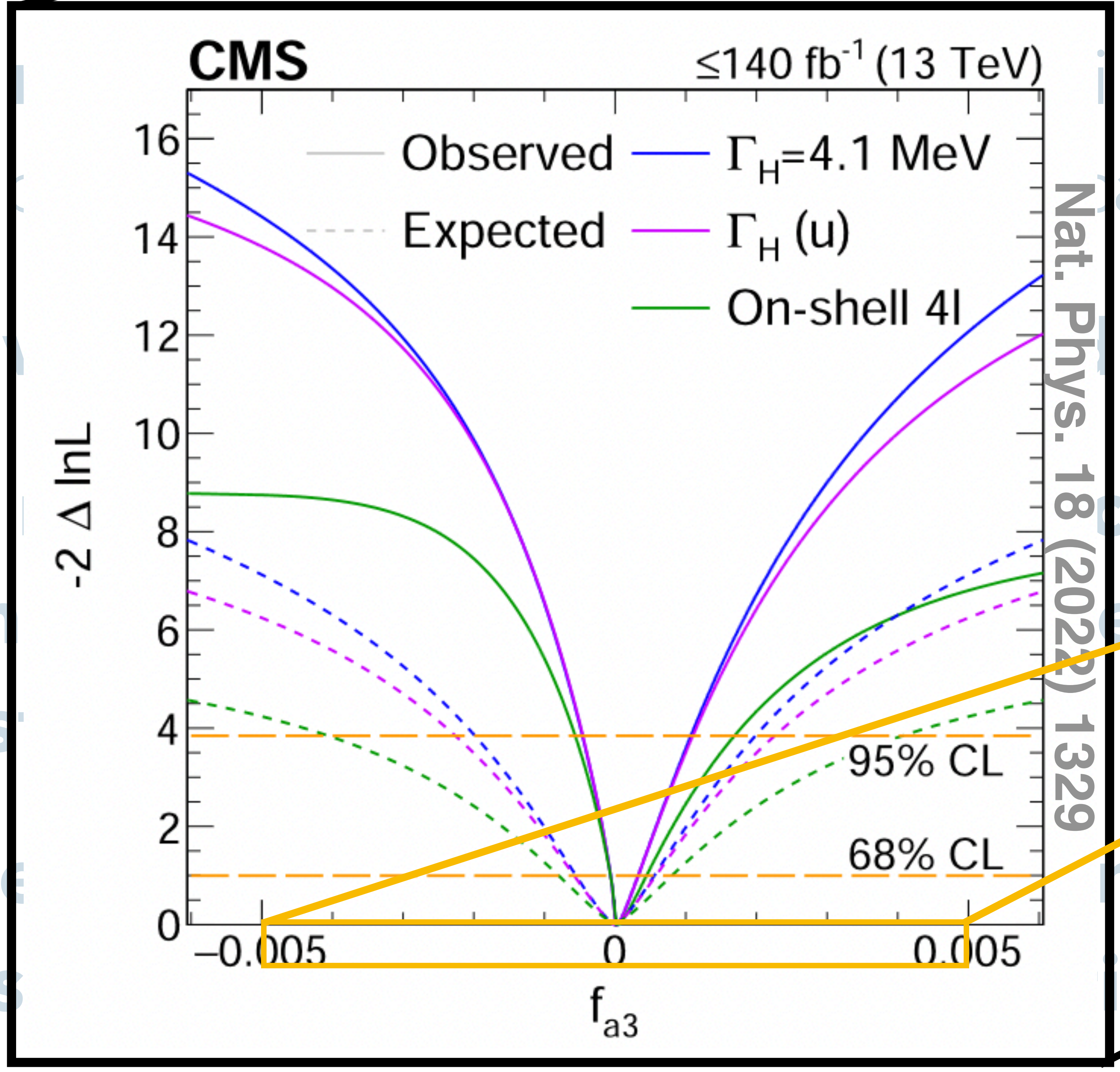
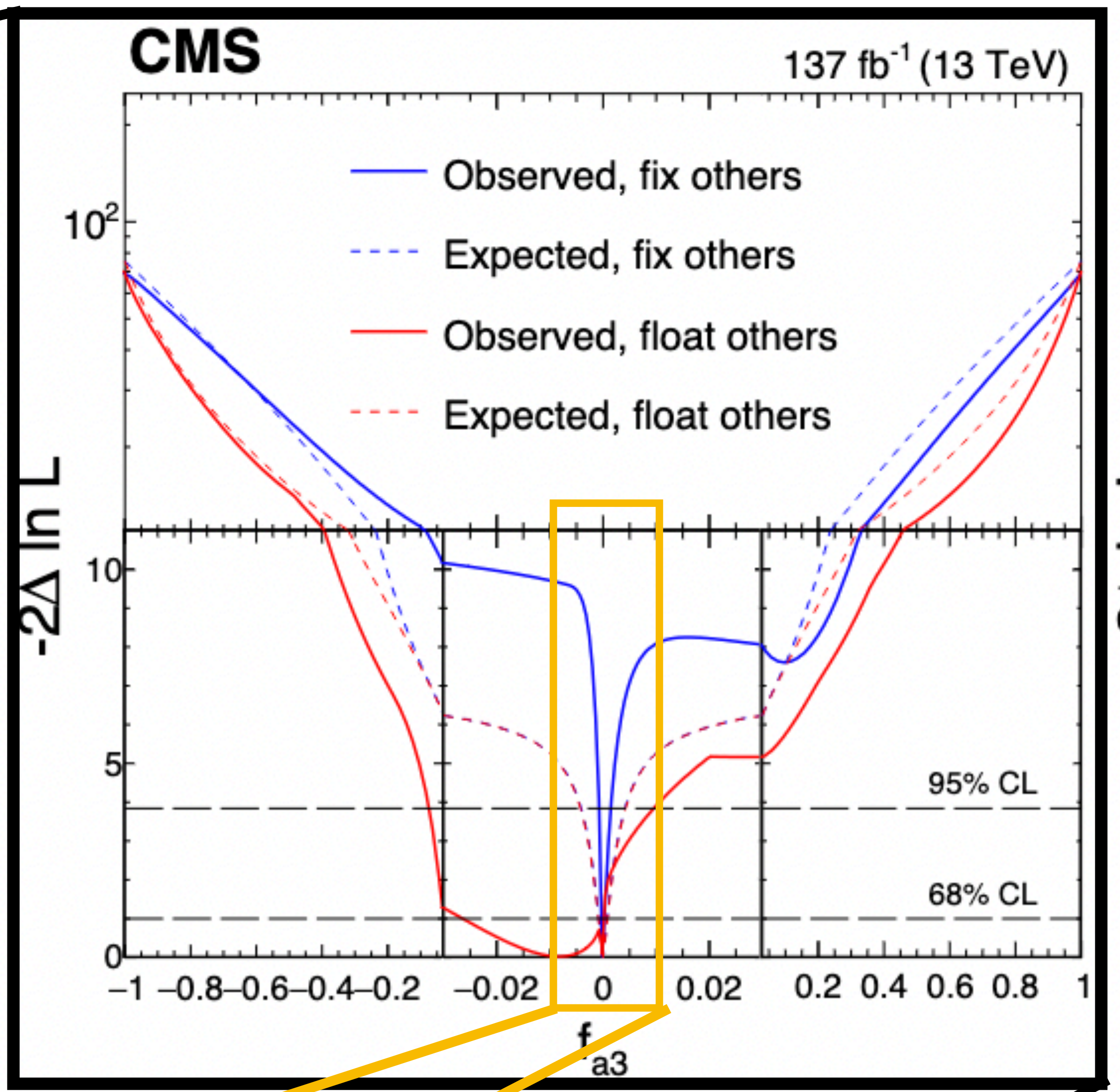


Nat. Phys. 18 (2022) 1329



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Stringent CP-violation test using off-shell data

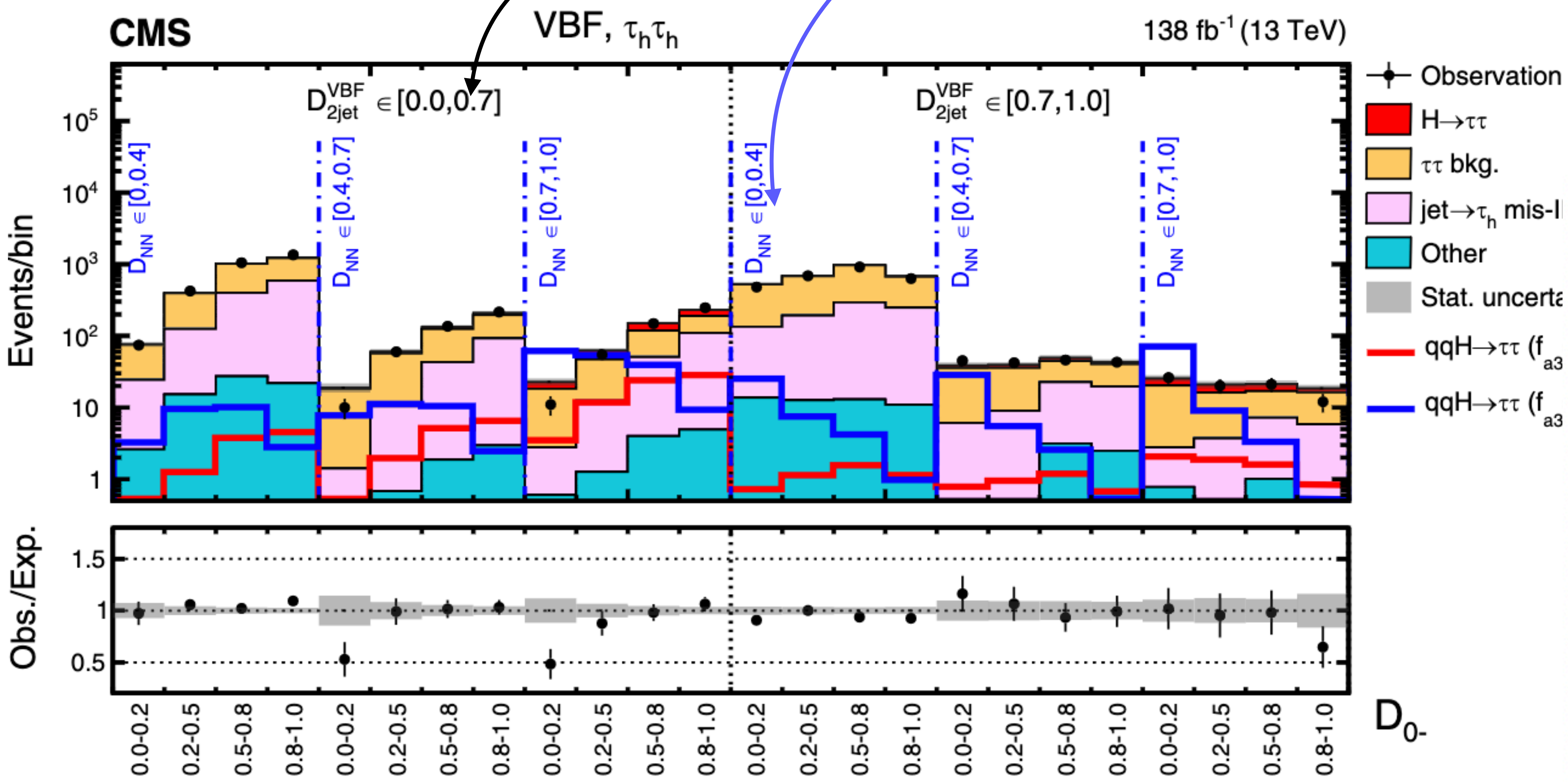
SM: 10% off-shell events vs CP-odd: enhancement of off-shell events

Targeting measurement of f_{a_3} at 10^{-5} level to achieve theory target

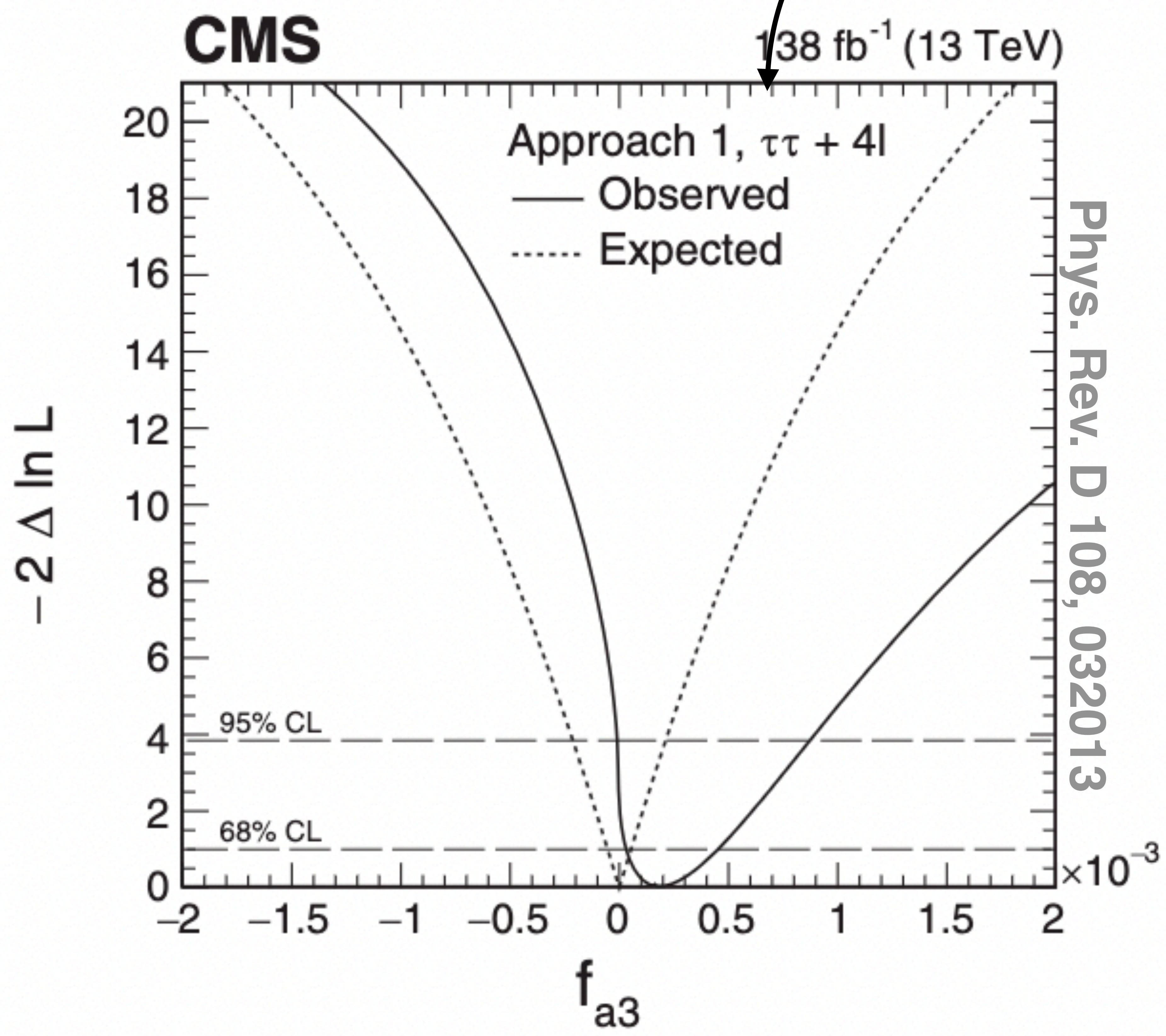
Parameter	Condition	Observed			Expected	
		Best fit	68% CL	95% CL	68% CL	95% CL
f_{a3} ($\times 10^5$)	$\Gamma_H = \Gamma_H^{SM}$	2.2	[−6.4, 32]	[−46, 107]	[−55, 55]	[−198, 198]
	Γ_H (u)	2.4	[−6.2, 33]	[−46, 110]	[−58, 58]	[−225, 225]

Combining production and decay

Combination of MEM and NN discriminants



Combination of production and decay (4ℓ, $\tau\tau$)



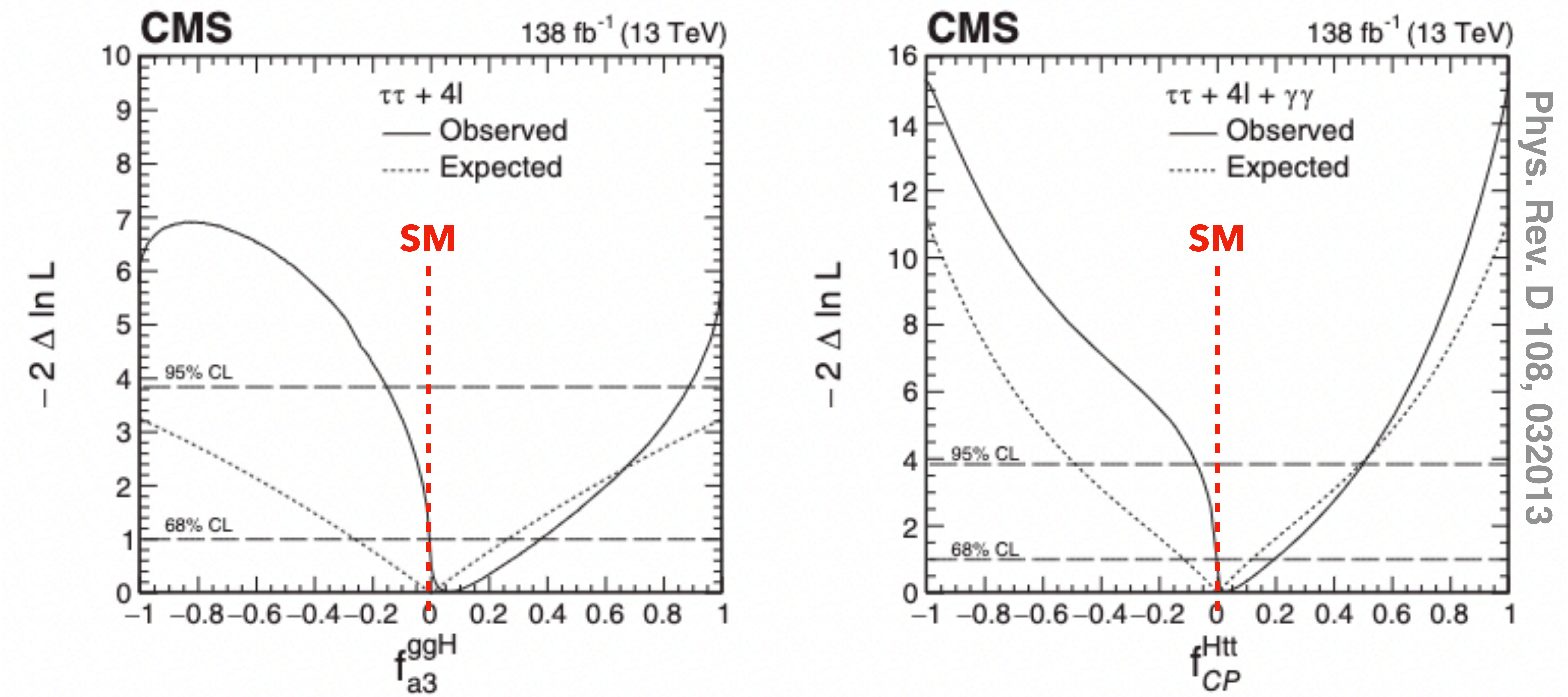
Combining $H\tau\tau + H4\ell$ (prod+dec):

$f_{a_3} < 1 \times 10^{-5}\,(1.3 \times 10^{-3})$

CP measurements in ggH and Htt

Sensitivity to CP-violation effects enhanced combining different decay channels ($\tau\tau, ZZ, \gamma\gamma$)

Combination of MEM and NN increases by 13% precision with respect to cut-based analysis using $\Delta\phi_{jj}$



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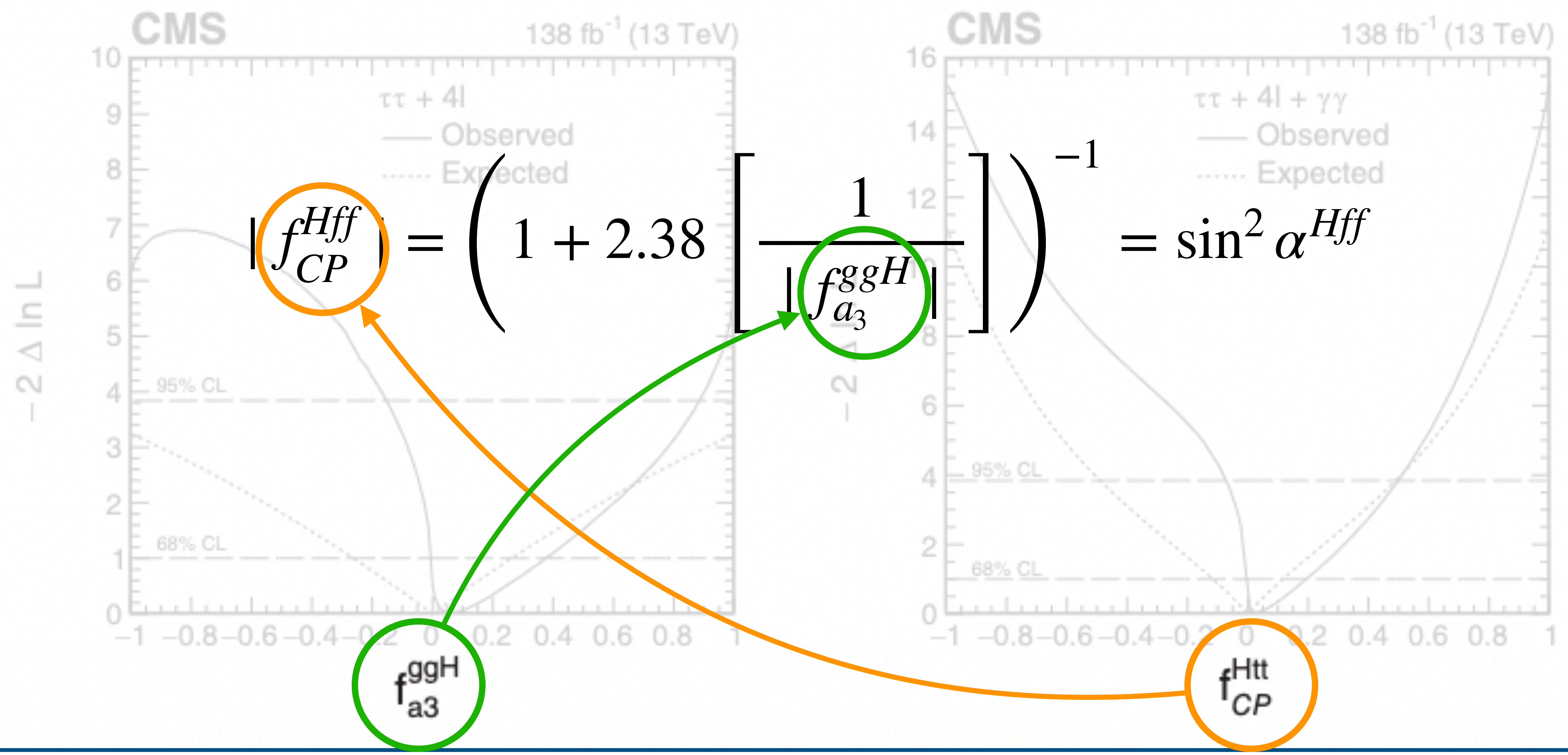
Measurement of $f_{a_3}^{\mathrm{ggH}}$ interpreted in terms of $f_{\mathrm{CP}}^{\mathrm{Htt}}$ assuming $\kappa_b = \kappa_t, \tilde{\kappa}_b = \tilde{\kappa}_t$



$$|f_{CP}^{Hff}| = \left(1 + 2.38\left[\frac{1}{|f_{a_3}^{ggH}|}\right]\right)^{-1} = \sin^2\alpha^{Hff}$$

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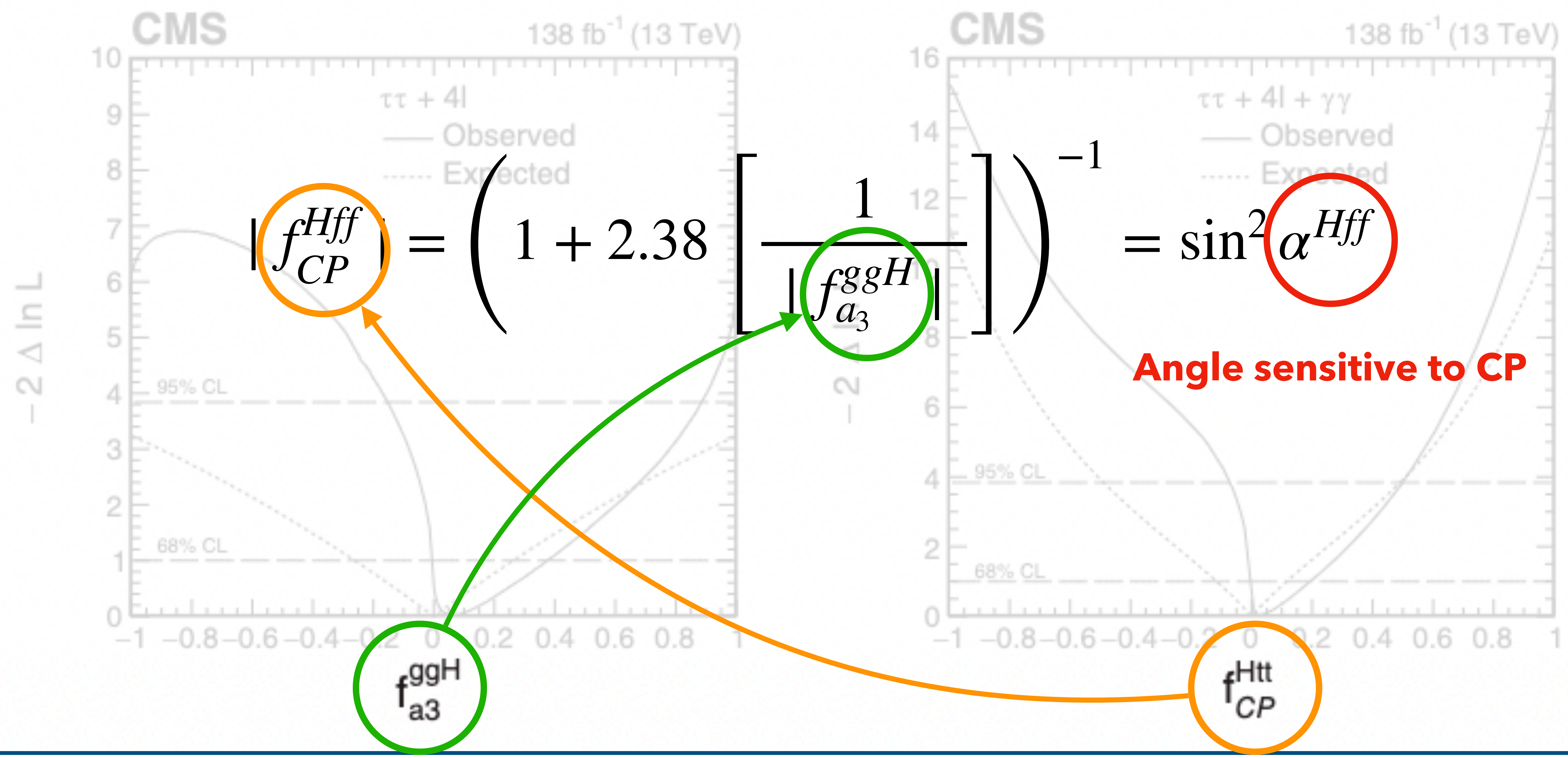
$$|f_{CP}^{Hff}| = \left(1 + 2.38\left[\frac{1}{|f_{a_3}^{ggH}|}\right]\right)^{-1} = \sin^2 \alpha^{Hff}$$

Angle sensitive to CP



CP measurements in Hff

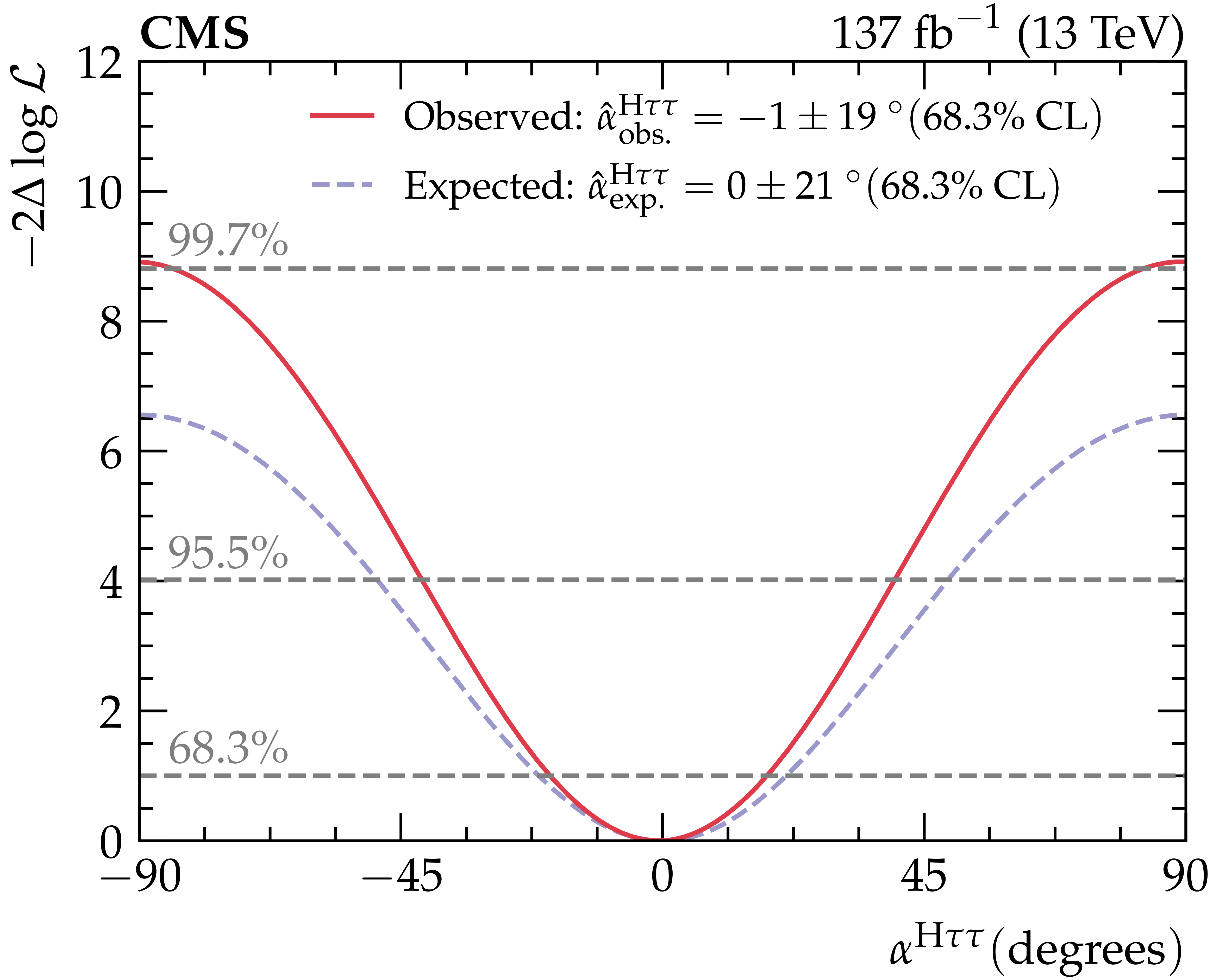
Effective Lagrangian for Yukawa coupling to tau leptons parameterized by **CP-even** and **CP-odd** components

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

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

Table 1: Possible CP scenarios

Scenario	α
Purely CP-even	0° or 180°
Purely CP-odd	90°
Mixed	$\neq 0°, \neq 90°, \neq 180°$



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$\phi_\tau = -1 \pm 19°$ (21° exp)

Pure CP-odd coupling excluded at 3σ

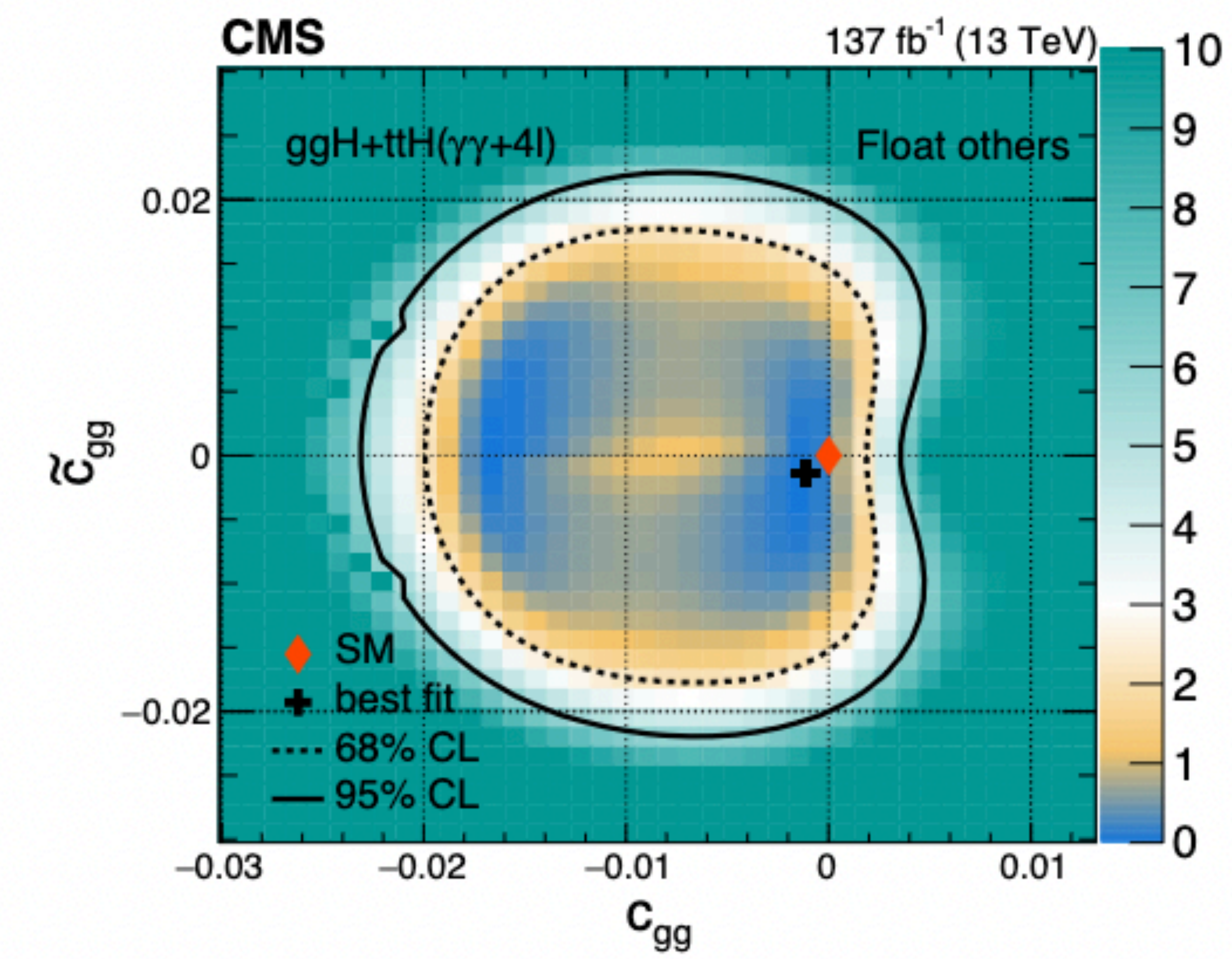
EFT measurements in Hff

Hff and ggH anomalous coupling measurements can be interpreted in SMEFT

Increased sensitivity in limits coming from combination of different production modes and decay channels

Assuming SU(2)xU(1) symmetry, we are left with 4 coefficients in the Hff Lagrangian:

$$c_{gg} = \frac{1}{2\pi\alpha_S} a_2^{gg}, \tilde{c}_{gg} = \frac{1}{2\pi\alpha_S} a_3^{gg}, \kappa_t, \tilde{\kappa}_t$$



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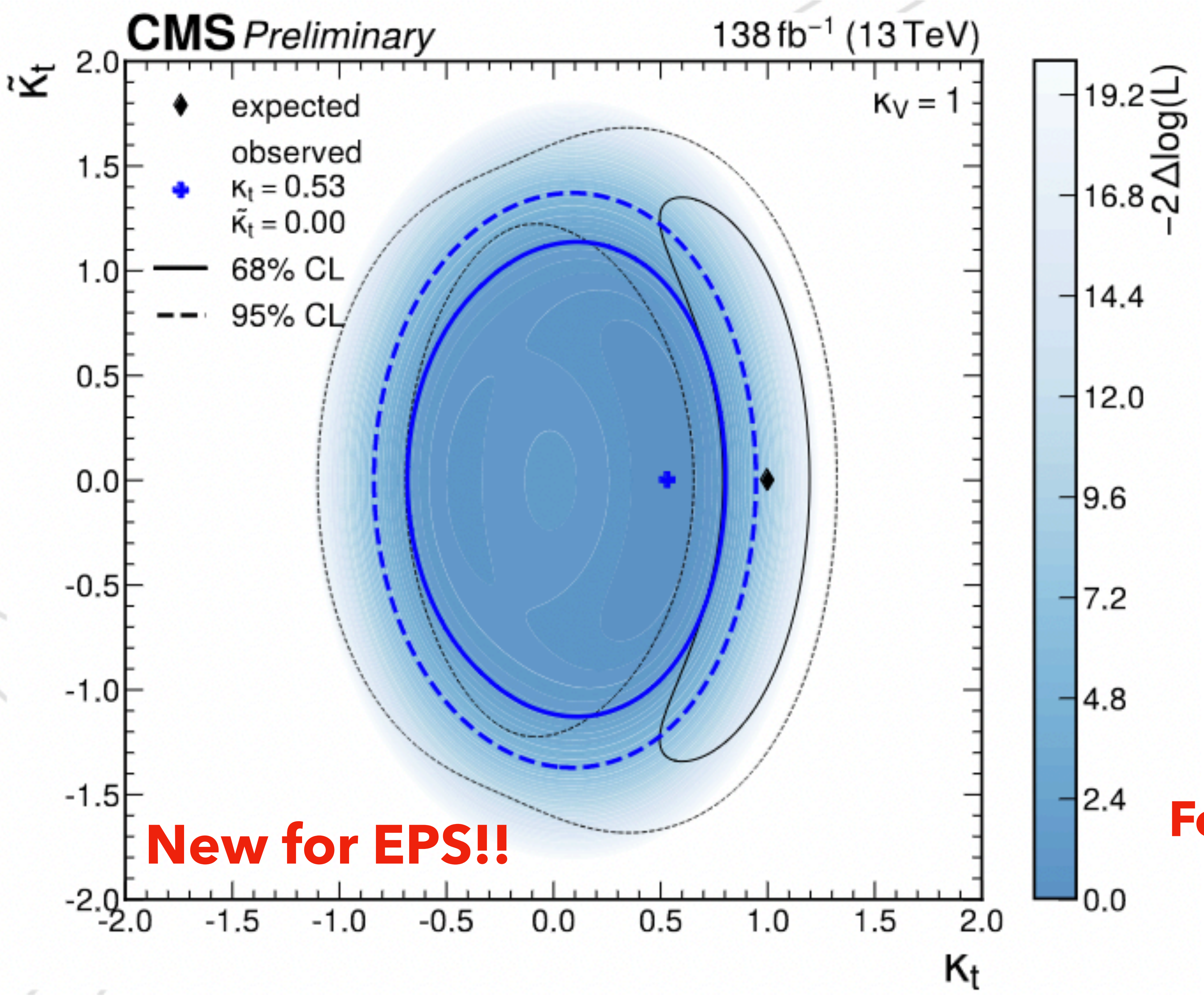


CMS-PAS-HIG-19-011

For more details see Pascal's talk and Valeria's poster

CP measurements in Hff

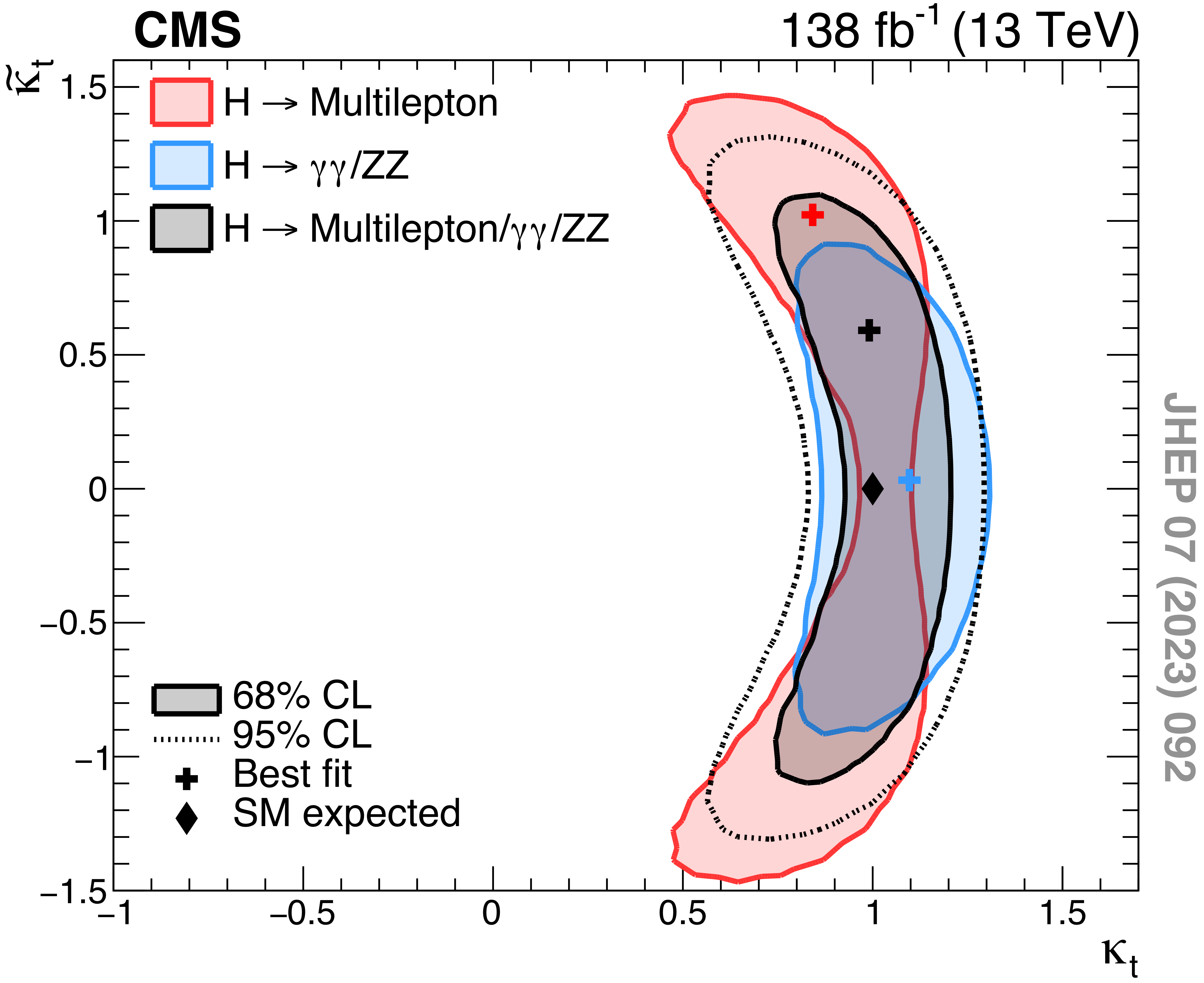
Effective Lagrangian for Yukawa coupling to top quarks parameterized by **CP-even** and **CP-odd** components

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

$$f_{CP}^{Htt} = \frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2} \qquad |f_{CP}^{Htt}| = (\sin\alpha)^2$$

Table 1: Possible *CP* scenarios

Scenario	α
Purely *CP*-even	0° or 180°
Purely *CP*-odd	90°
Mixed	$\neq 0°, \neq 90°, \neq 180°$



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

Pure CP-odd coupling excluded at 3.7σ

EFT in the Higgs combination

Extend SM Lagrangian with higher-dim operators in the **HEL[1] model:**

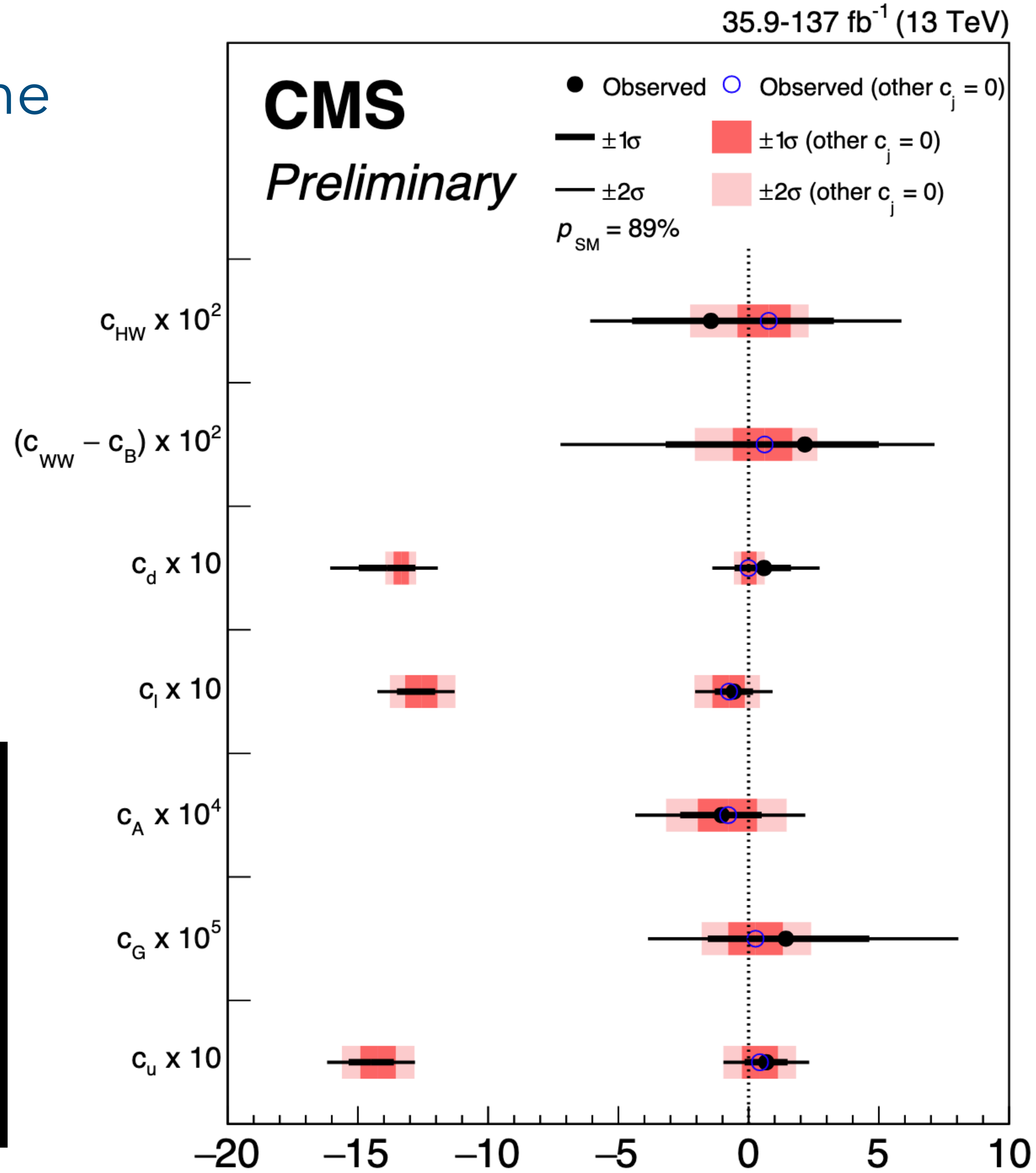
$$\mathscr{L}_{\text{HEL}} = \mathscr{L}_{\text{SM}} + \sum_j \mathcal{O}_j f_j / \Lambda^2$$

⇓

$$\sigma_i^{\text{EFT}} = \sigma_i^{\text{SM}} + \sigma_i^{\text{int}} + \sigma_i^{\text{BSM}}$$

Scaling depending on $c_j = f_j/\Lambda^2$ for each STXS bin:

$$\mu_i(c_j) = \frac{\sigma_i^{\text{EFT}}}{\sigma_i^{\text{SM}}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$



CMS-HIG-PAS-19-005

[1]: Higgs Effective Lagrangian

EFT in the Higgs combination

Extend SM Lagrangian with higher-dim operators in th

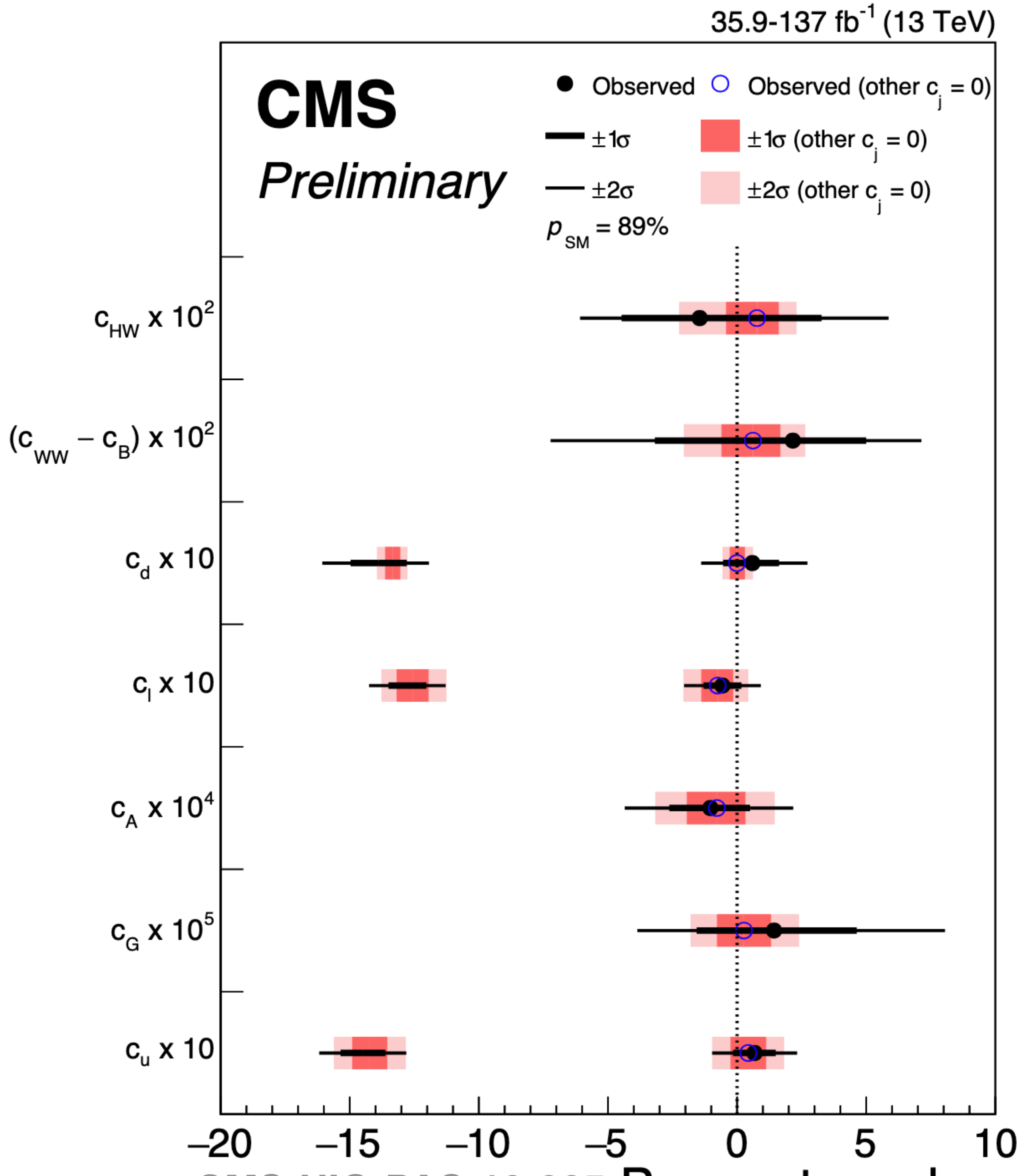
HEL[1] model:

$H \to \mu\mu$ and boosted $H \to bb$ analyses not considered

Alternative and complementary approach to AC, but complementary limits on EFT parameters (+ possibility of basis rotation)

Simultaneous fit of the 8 leading CP-even terms

Stringent constraints on HEL parameters coming from combination of production and decay



CMS-HIG-PAS-19-005

[1]: Higgs Effective Lagrangian

Conclusion

We have come a long way in the characterization of the Higgs Boson, but:

- The **presence of** small CP-violating **anomalous couplings** in the SM or new BSM scenarios including CP-odd terms are **not excluded yet**
- CMS targets this quest by **setting constraints on anomalous couplings** and reinterpreting them in the context of EFT theories (SMEFT) $\Rightarrow$ **Pure CP-odd Higgs excluded at 3.7 SD**
- **An alternative approach**, based on the re-interpretation of STXS measurements, allows to **set direct constraints to EFT coefficients** (HEL basis)
- So far, **all the results are in agreement with the predictions of the SM** and no sign of CP-violation in the Higgs sector has been found …

Conclusion

We have come a long way in the characterization of the Higgs Boson, but:

- The **presence of** small CP-violating **anomalous couplings** in the SM or new BSM scenarios including CP-odd terms are **not excluded yet**
- CMS targets this quest by **setting constraints on anomalous couplings** and reinterpreting them in the context of EFT theories (SMEFT) ⇒ **Pure CP-odd Higgs excluded at 3.7 SD**
- **An alternative approach**, based on the re-interpretation of STXS measurements, allows to **set direct constraints to EFT coefficients** (HEL basis)
- So far, **all the results are in agreement with the predictions of the SM** and no sign of CP-violation in the Higgs sector has been found …

… Combination of different production modes and decay channels w/ Run-III stat will improve the precision of the results and possibly unveil new physics!

BACKUP SLIDES

HVV and Hff Lagrangians

The sensitivity to Higgs AC can be translated into sensitivity to higher- dimensional operators in EFT

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k c_k^{(5)}\mathscr{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)}\mathscr{O}_k^{(6)} + \mathscr{O}\left(\frac{1}{\Lambda^3}\right)$$

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

$$\begin{aligned}\mathcal{L}_{hvff} = 2e\frac{h}{v}\Big\{ & \frac{W_\mu^+}{\sqrt{2}s_w}\left(\bar{u}_L\gamma^\mu\delta g_L^{hWq}d_L + \bar{u}_R\gamma^\mu\delta g_R^{hWq}d_R + \bar{\nu}_L\gamma^\mu\delta g_L^{hW\ell}e_L\right) \\ + & \frac{W_\mu^-}{\sqrt{2}s_w}\left(\bar{d}_L\gamma^\mu\delta g_L^{hWq}u_L + \bar{d}_R\gamma^\mu\delta g_R^{hWq}u_R + \bar{e}_L\gamma^\mu\delta g_L^{hW\ell}\nu_L\right) \\ + & \frac{Z_\mu}{s_w c_w}\left(\sum_{f=u,d,e,\nu}\bar{f}_L\gamma^\mu\delta g_L^{hZf}f_L + \sum_{f=u,d,e}\bar{f}_R\gamma^\mu\delta g_R^{hZf}f_R\right)\Big\}.\end{aligned}$$

Modifications of Γ_H

- When measuring ai or EFT coefficients, need to consider their modification to the overall width Γ_H
- Assuming unknown particle contribution 0
  - Each partial width is modified by a ratio calculated by JHUGen, MCFM and HDECAY

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

$$R_{ZZ/Z\gamma^*/\gamma^*\gamma^*} = \left(\frac{g_1^{ZZ}}{2}\right)^2 + 0.1695\left(\kappa_1^{ZZ}\right)^2 + 0.09076\left(g_2^{ZZ}\right)^2 + 0.03809\left(g_4^{ZZ}\right)^2$$
$$+0.8095\left(\frac{g_1^{ZZ}}{2}\right)\kappa_1^{ZZ} + 0.5046\left(\frac{g_1^{ZZ}}{2}\right)g_2^{ZZ} + 0.2092\kappa_1^{ZZ}g_2^{ZZ}$$
$$+0.1023\left(\kappa_2^{Z\gamma}\right)^2 + 0.1901\left(\frac{g_1^{ZZ}}{2}\right)\kappa_2^{Z\gamma} + 0.07429\kappa_1^{ZZ}\kappa_2^{Z\gamma} + 0.04710 g_2^{ZZ}\kappa_2^{Z\gamma}$$

$$R_{gg} = 1.1068\kappa_t^2 + 0.0082\kappa_b^2 - 0.1150\kappa_t\kappa_b + 2.5717\tilde{\kappa}_t^2 + 0.0091\tilde{\kappa}_b^2 - 0.1982\tilde{\kappa}_t\tilde{\kappa}_b$$

channel (f)	$\Gamma_f^{\text{SM}}/\Gamma_{\text{tot}}^{\text{SM}} = \mathcal{B}_f^{\text{SM}}$	$\Gamma_f/\Gamma_f^{\text{SM}} = R_f(\vec{g}_j)$
$H \to b\bar{b}$	0.5824	$(\kappa_b^2 + \tilde{\kappa}_b^2)$
$H \to W^+W^-$	0.2137	$R_{WW}(\vec{g}_j)$
$H \to gg$	0.08187	$R_{gg}(\vec{g}_j)$
$H \to \tau^+\tau^-$	0.06272	$(\kappa_\tau^2 + \tilde{\kappa}_\tau^2)$
$H \to c\bar{c}$	0.02891	$(\kappa_c^2 + \tilde{\kappa}_c^2)$
$H \to ZZ/Z\gamma^*/\gamma^*\gamma^*$	0.02619	$R_{ZZ/Z\gamma^*/\gamma^*\gamma^*}(\vec{g}_j)$
$H \to \gamma\gamma$	0.002270	$R_{\gamma\gamma}(\vec{g}_j)$
$H \to Z\gamma$	0.001533	$R_{Z\gamma}(\vec{g}_j)$
$H \to \mu^+\mu^-$	0.0002176	$(\kappa_\mu^2 + \tilde{\kappa}_\mu^2)$

SMEFT Symmetry relations

The sensitivity to Higgs AC can be translated into sensitivity to higher- dimensional operators in EFT

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k c_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)}\mathcal{O}_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

$$a_1^{\mathrm{WW}} = a_1^{\mathrm{ZZ}} + \frac{\Delta m_{\mathrm{W}}}{m_{\mathrm{W}}},$$

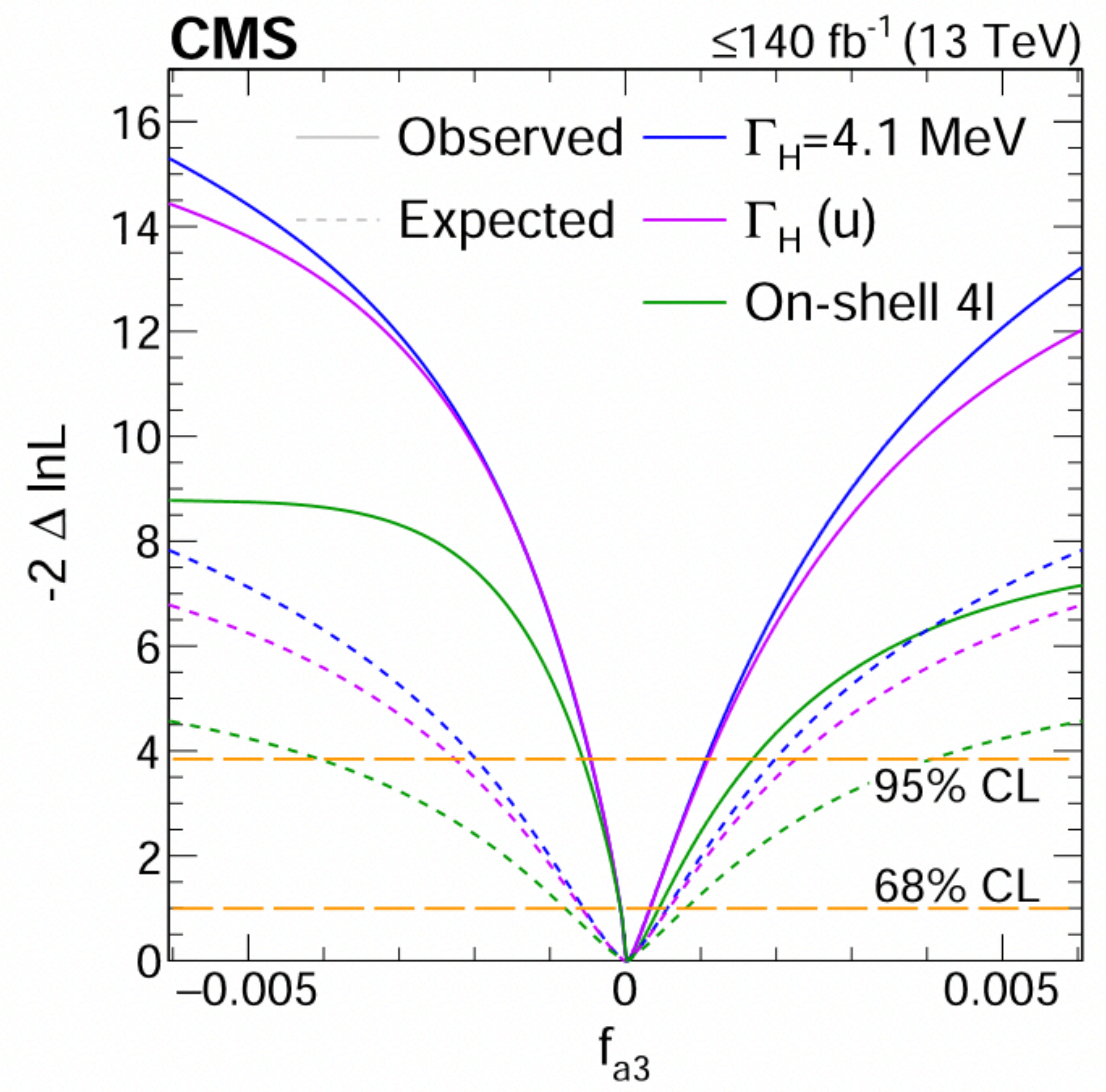
$$a_2^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_2^{\mathrm{ZZ}} + s_{\mathrm{w}}^2 a_2^{\gamma\gamma} + 2 s_{\mathrm{w}} c_{\mathrm{w}} a_2^{\mathrm{Z}\gamma},$$

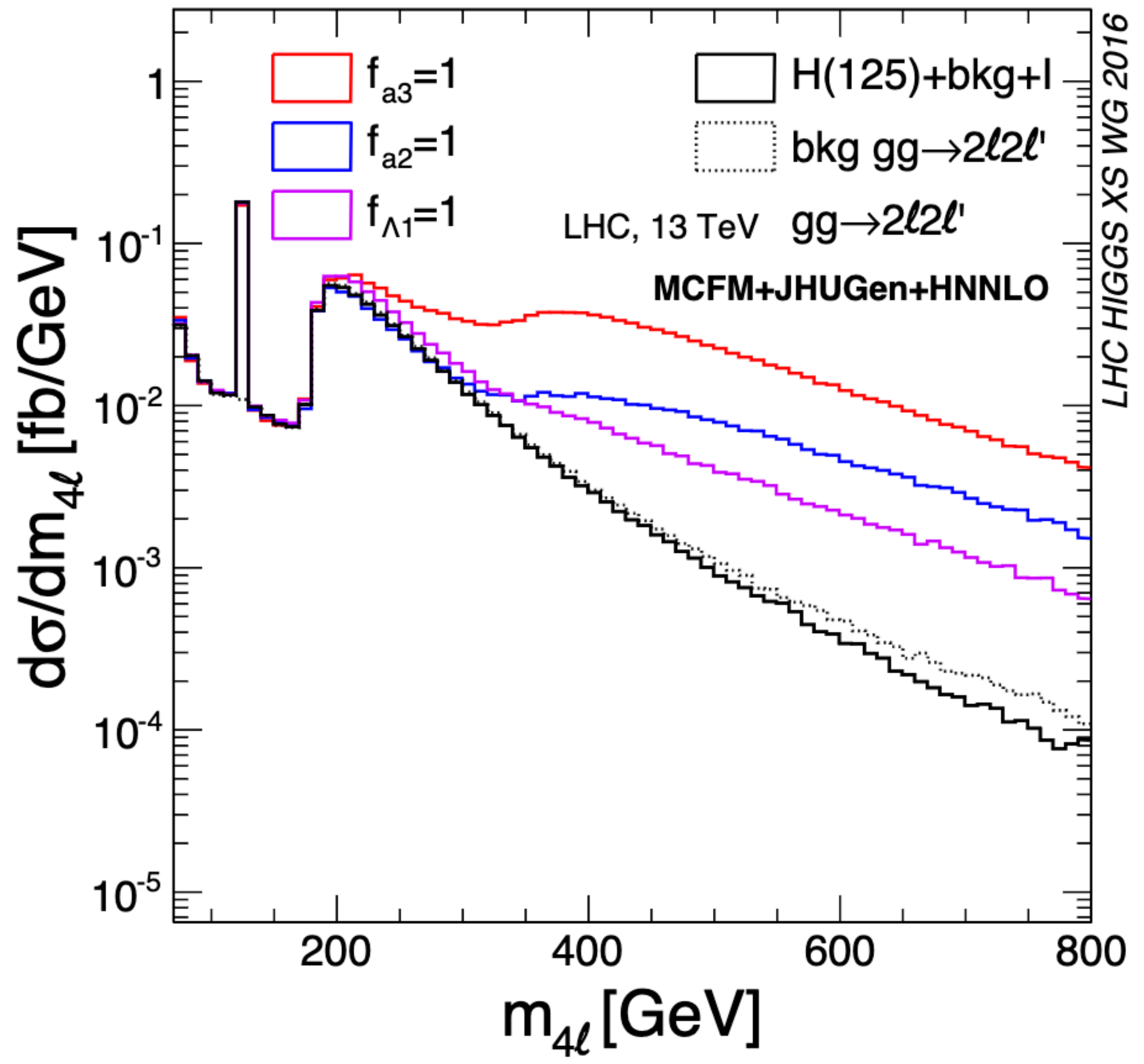
$$a_3^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_3^{\mathrm{ZZ}} + s_{\mathrm{w}}^2 a_3^{\gamma\gamma} + 2 s_{\mathrm{w}} c_{\mathrm{w}} a_3^{\mathrm{Z}\gamma},$$

$$\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) = \frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + 2 s_{\mathrm{w}}^2 \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} + 2\frac{s_{\mathrm{w}}}{c_{\mathrm{w}}}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_{\mathrm{Z}}^2},$$

$$\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) = 2 s_{\mathrm{w}} c_{\mathrm{w}}\left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2}\right) + 2(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_{\mathrm{Z}}^2},$$

HVV limits in HZZ off-shell





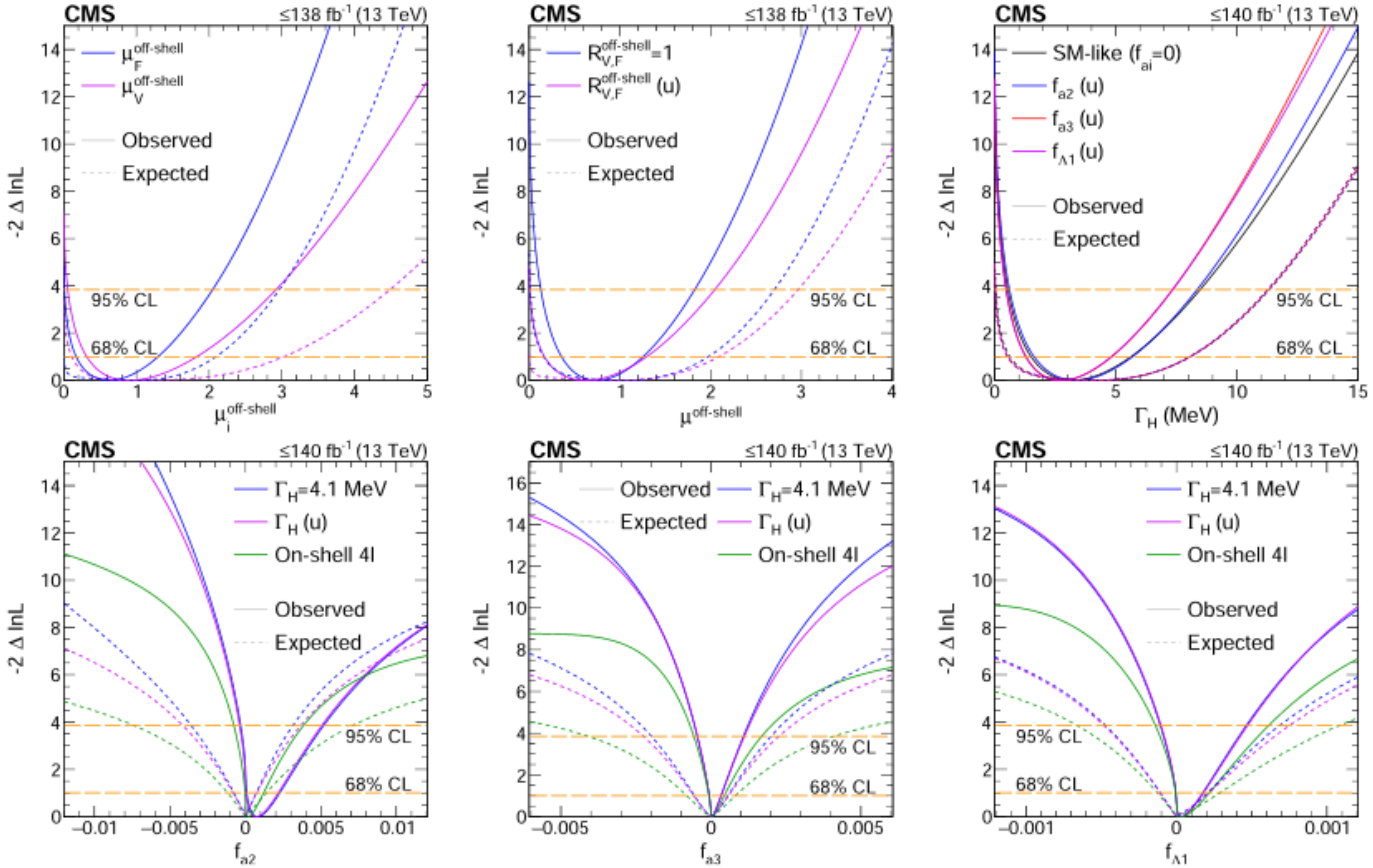
Stringent CP-violation test using off-shell data

SM: 10% off-shell events vs CP-odd: enhancement of off-shell events

Targeting measurement of f_{a_3} at 10^{-5} level to achieve theory target

Parameter	Condition		Observed		Expected	
		Best fit	68% CL	95% CL	68% CL	95% CL
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]

What about the off-shell?

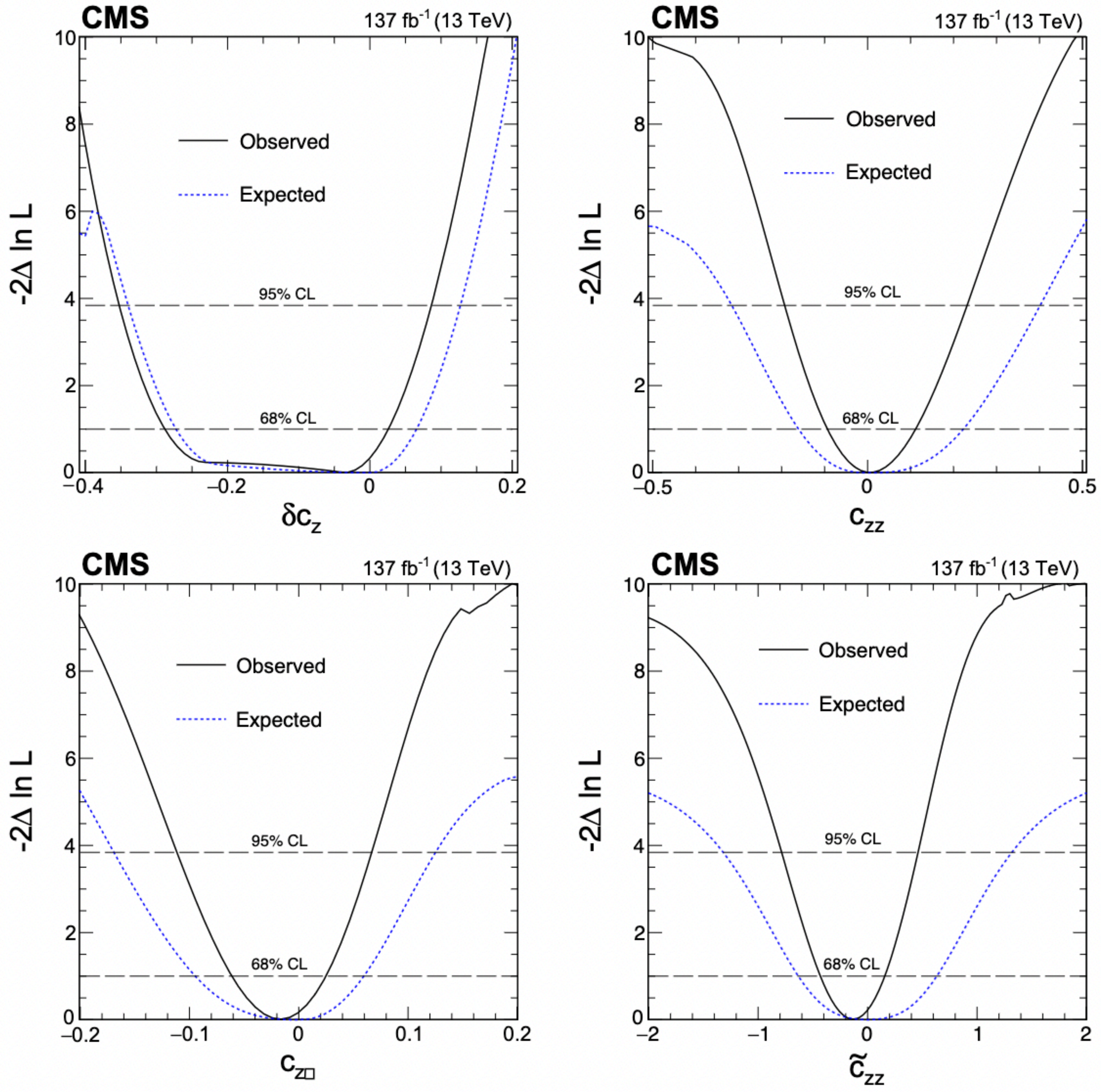


From AC to SMEFT

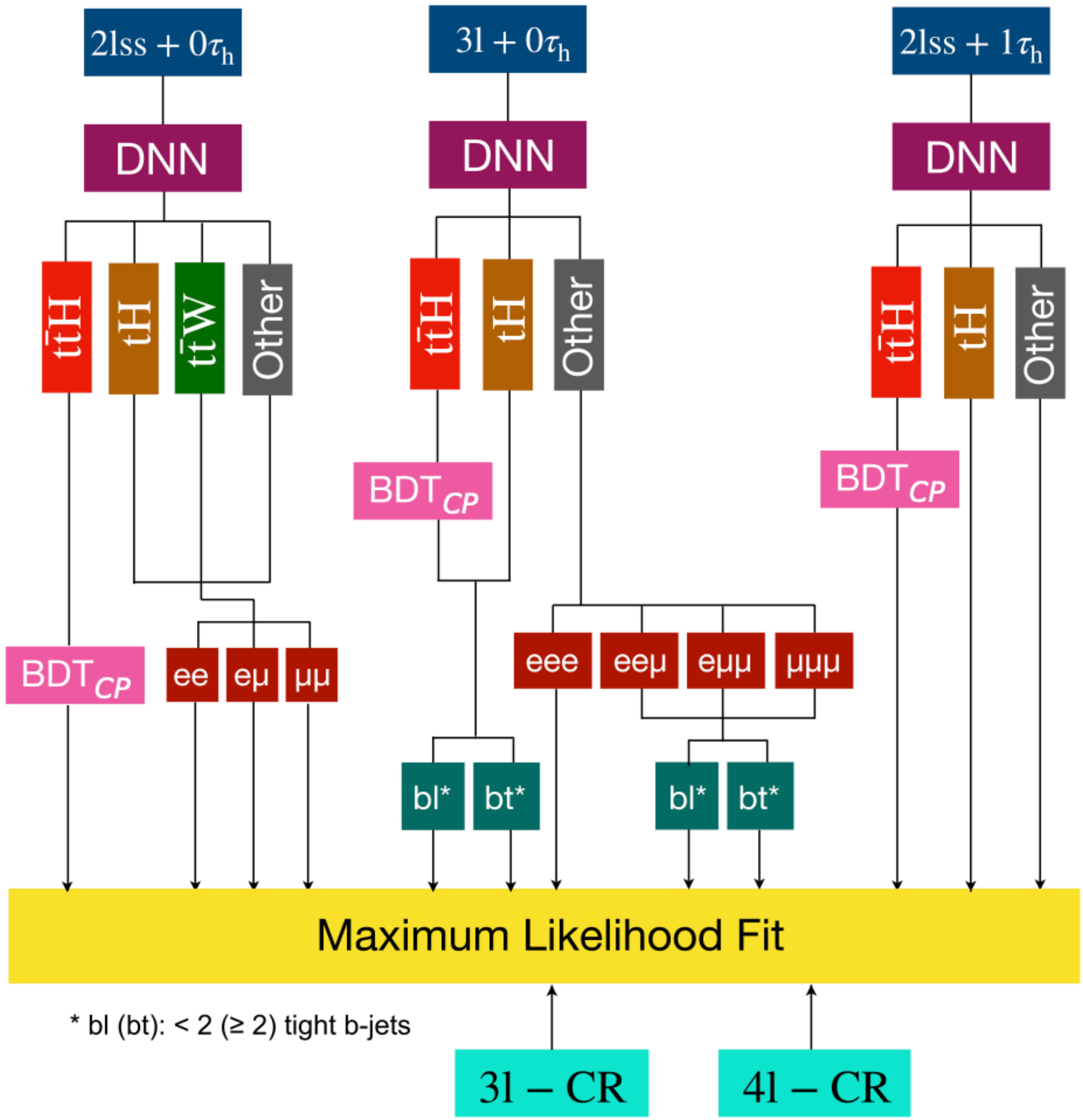
Simultaneous fit of Higgs basis in SMEFT

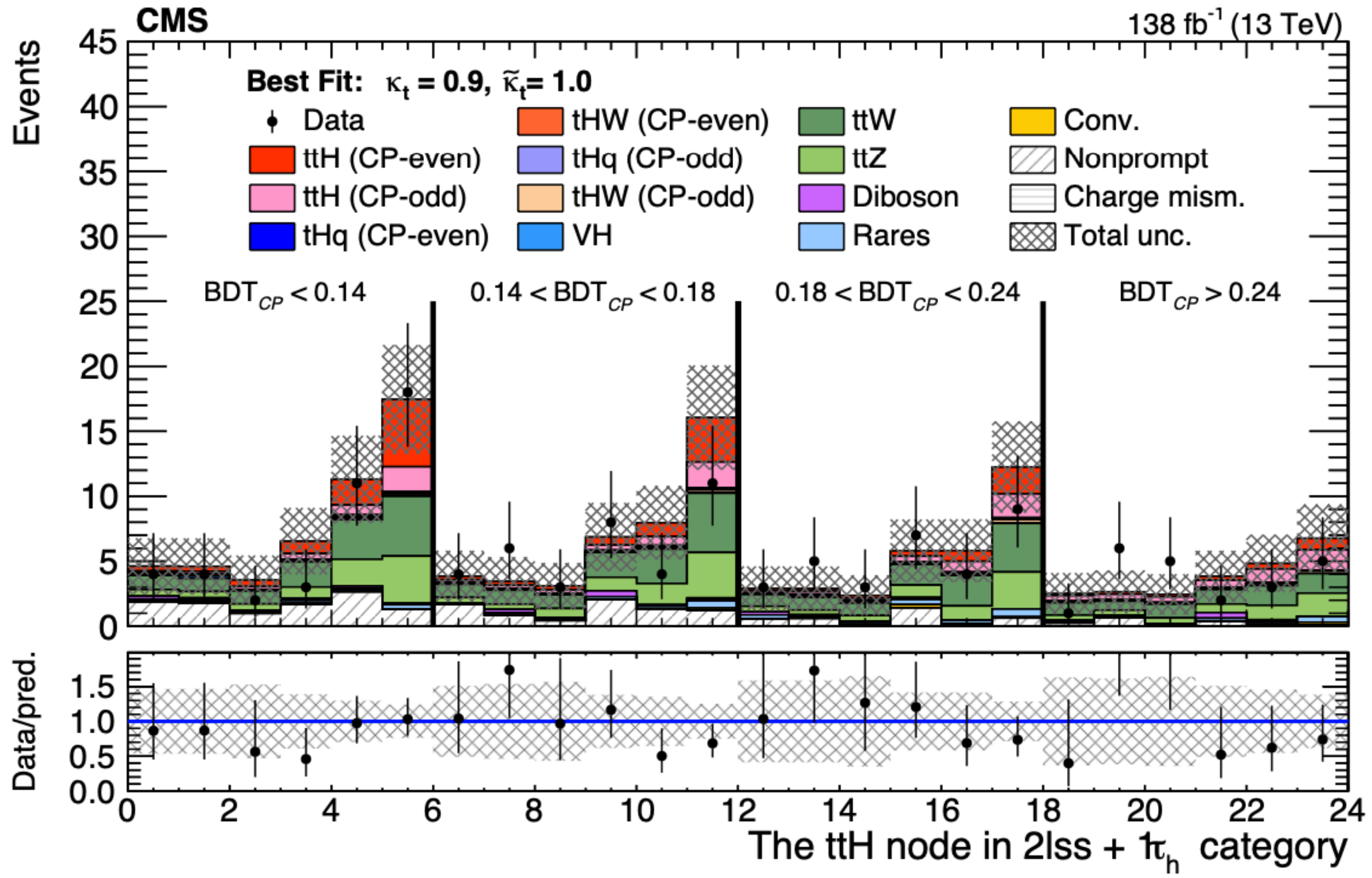
- Assuming the relations of Slide 14
- **These constraints in the Higgs basis can be converted into constraints in the Warsaw basis**
  - **Capability of "rotating" bases and converting constraints from one to the other!**

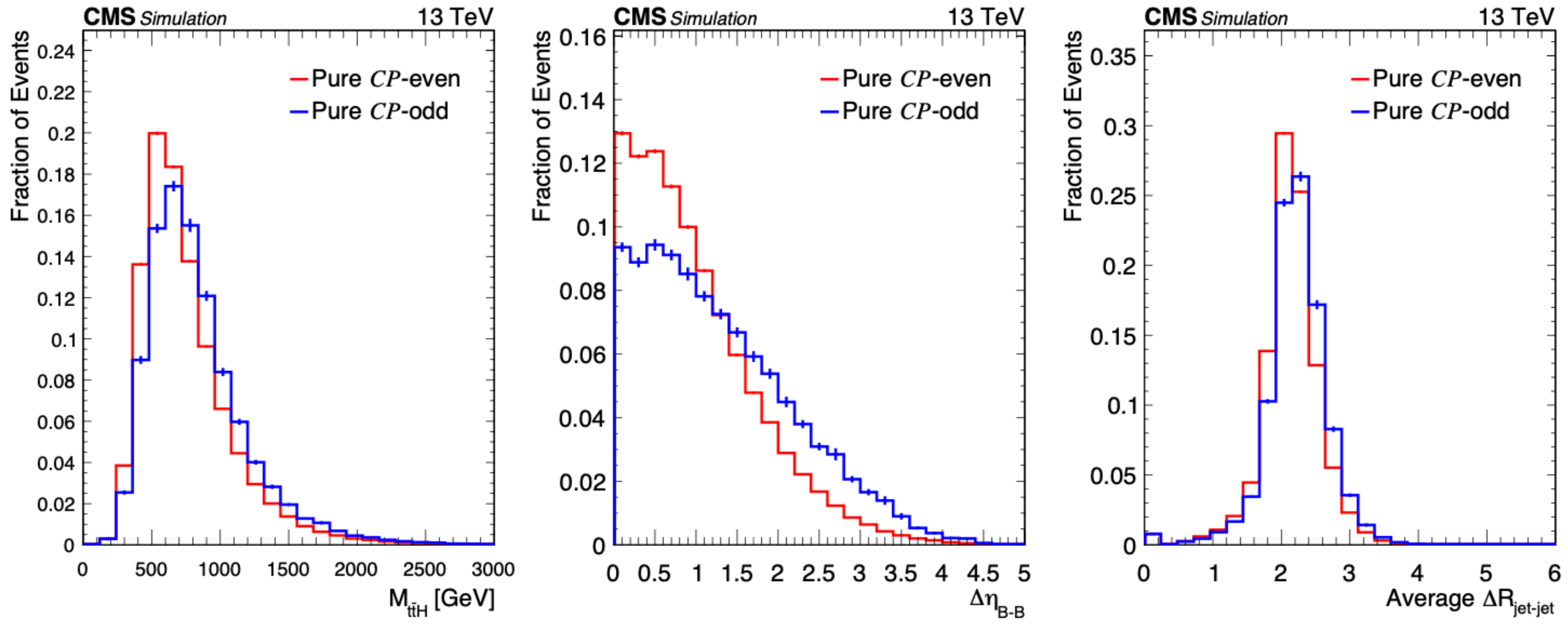
Channels	Coupling	Observed	Expected
VBF & VH & $H \to 4\ell$	$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
	c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
	c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
	c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
	c_{HB}	$0.00^{+0.05}_{-0.05}$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



Higgs boson CP properties: ttH







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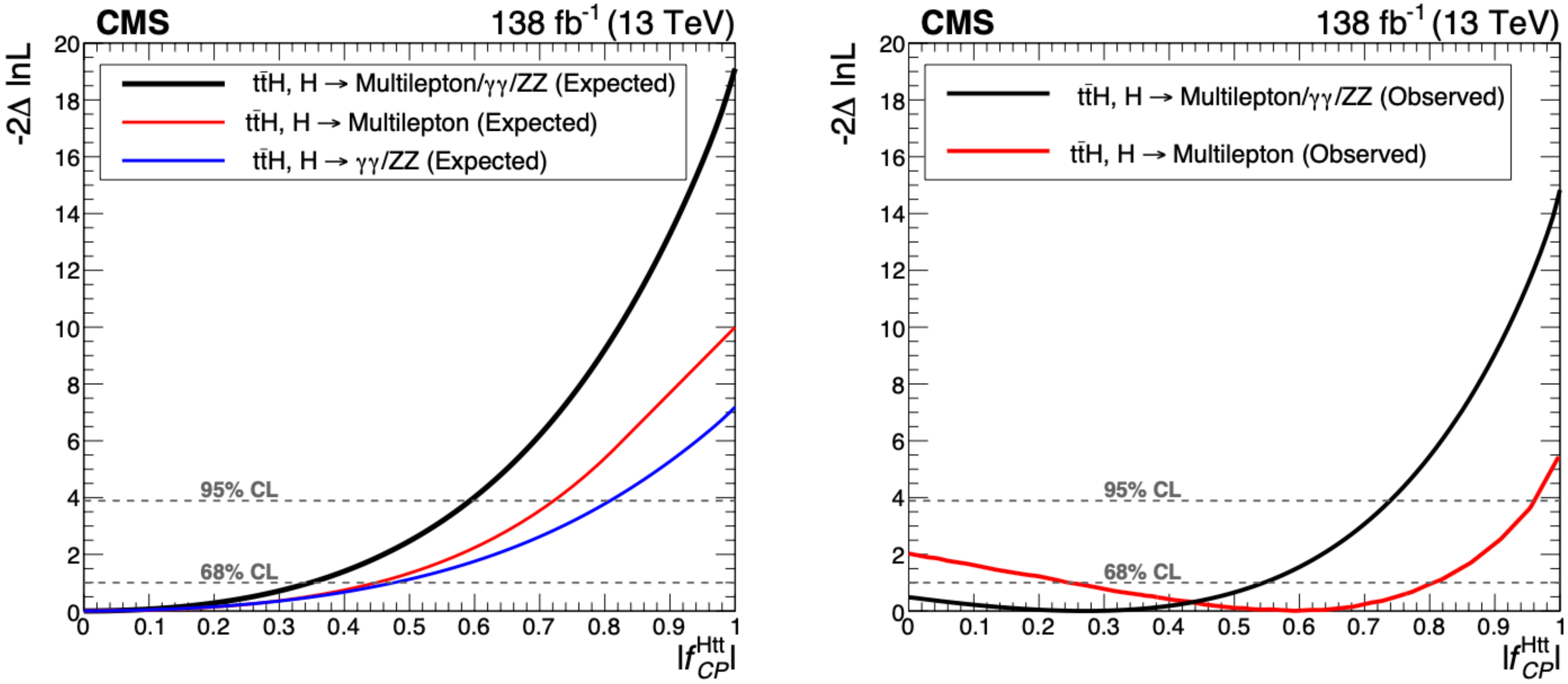
Higgs boson CP properties: ttH



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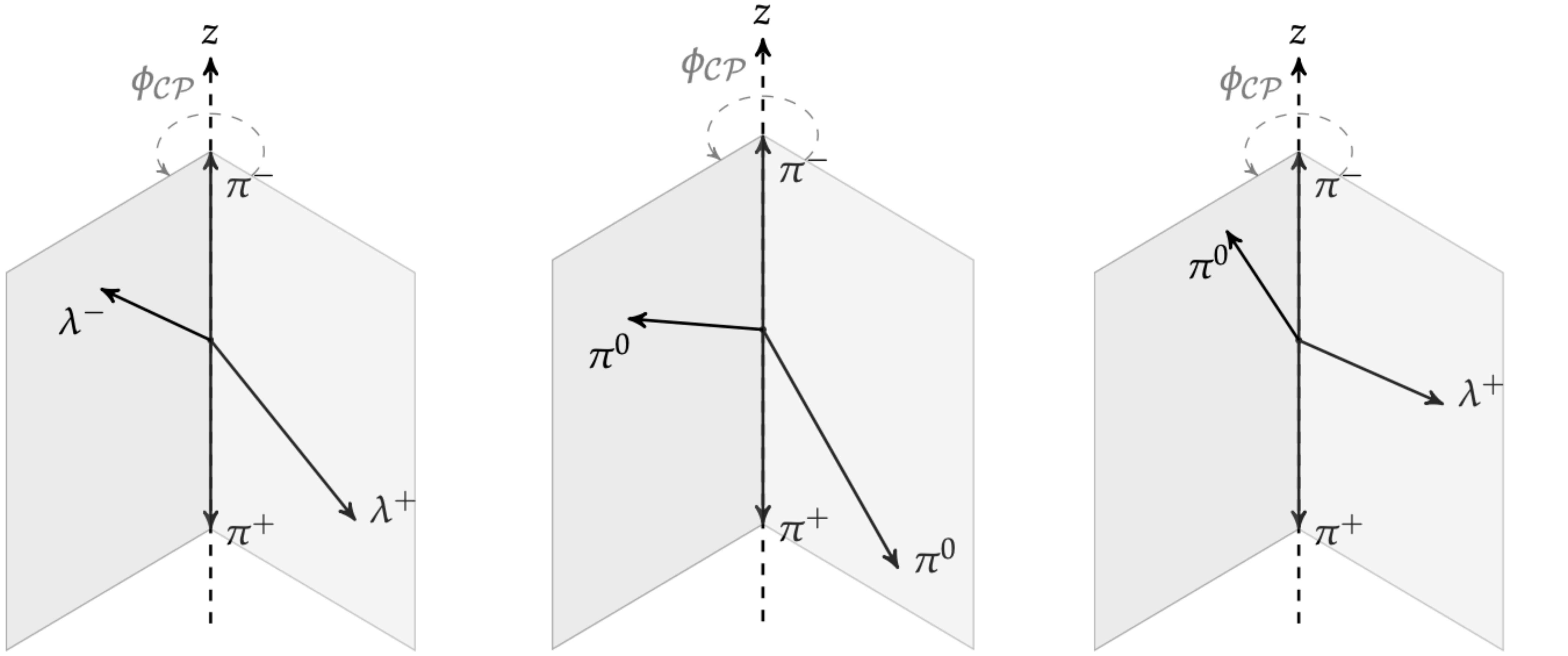
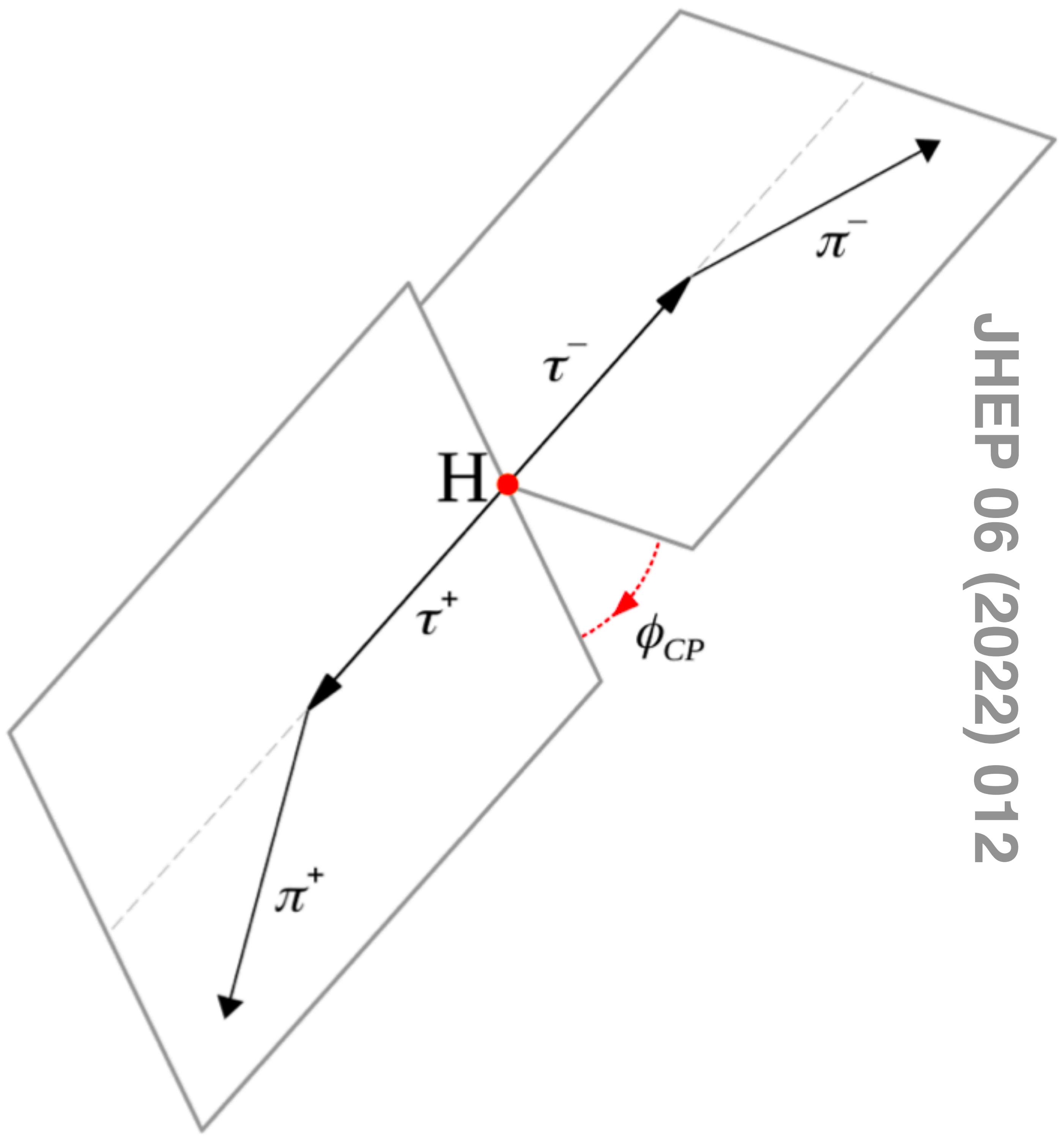
Higgs boson CP properties: $H\tau\tau$





To reconstruct ϕ_{CP}, we first define the angle ϕ^{ZMF} and O^{ZMF} as

$$\begin{aligned} \phi^{ZMF} &= \arccos(\hat{\lambda}_\perp^{ZMF+} \cdot \hat{\lambda}_\perp^{ZMF-}), \text{ and} \\ O^{ZMF} &= \hat{q}^{ZMF-} \cdot (\hat{\lambda}_\perp^{ZMF+} \times \hat{\lambda}_\perp^{ZMF-}). \end{aligned} \tag{6.1}$$

From ϕ^{ZMF} and O^{ZMF} we reconstruct ϕ_{CP} in a range $[0, 360^\circ]$ as

$$\phi_{CP} = \begin{cases} \phi^{ZMF} & \text{if } O^{ZMF} \geq 0 \\ 360^\circ - \phi^{ZMF} & \text{if } O^{ZMF} < 0 \end{cases}. \tag{6.2}$$

The τ lepton spectral functions have opposite signs for single-pion decays and leptonic decays in the kinematic regions considered in this analysis. This causes a phase flip between the ϕ_{CP} distributions for single pion decays and leptonic decays when the impact parameter method is used [40]. An illustration of the definition of the ϕ_{CP} observable using the impact parameter method is shown in figure 3 (left).

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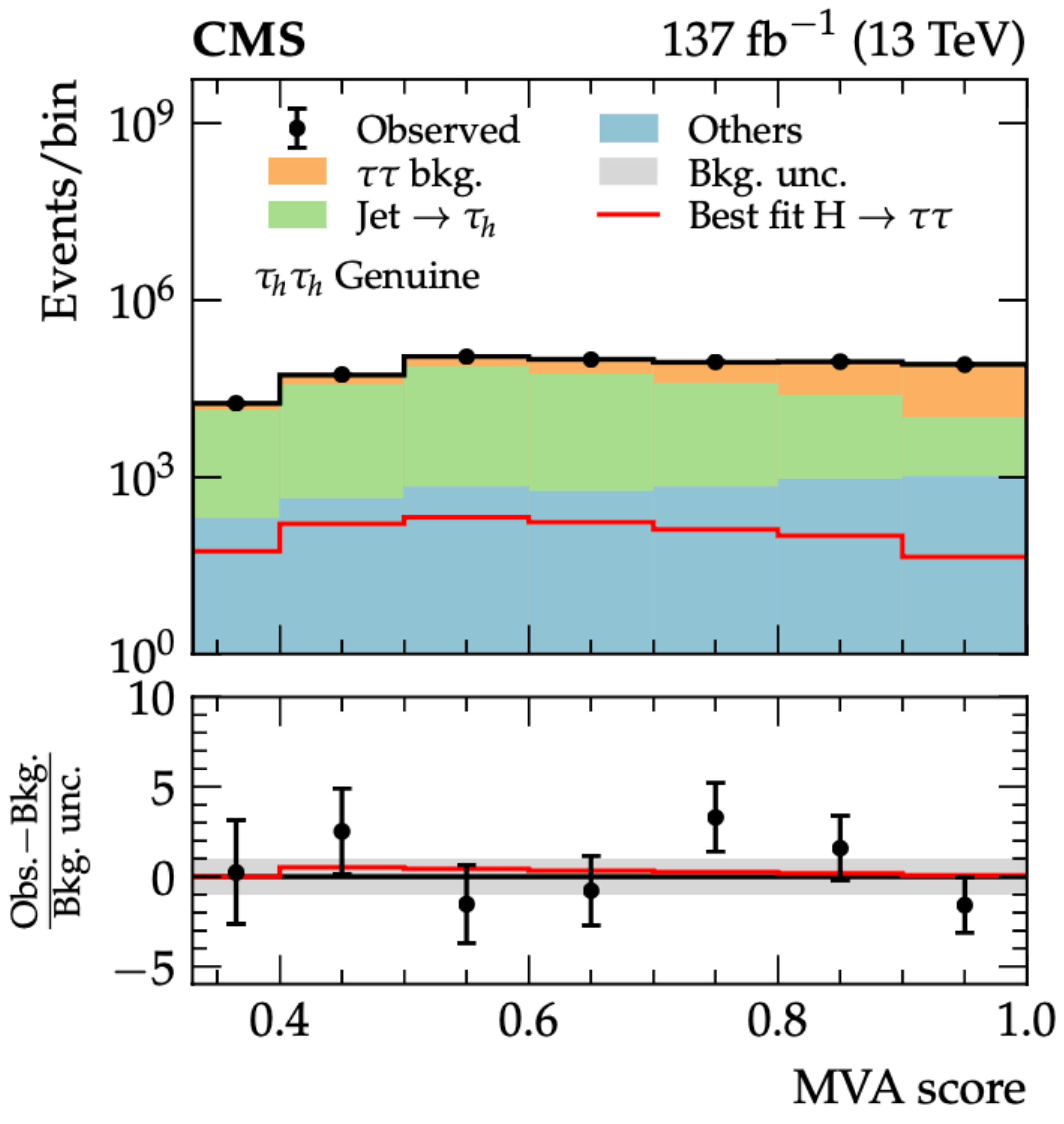
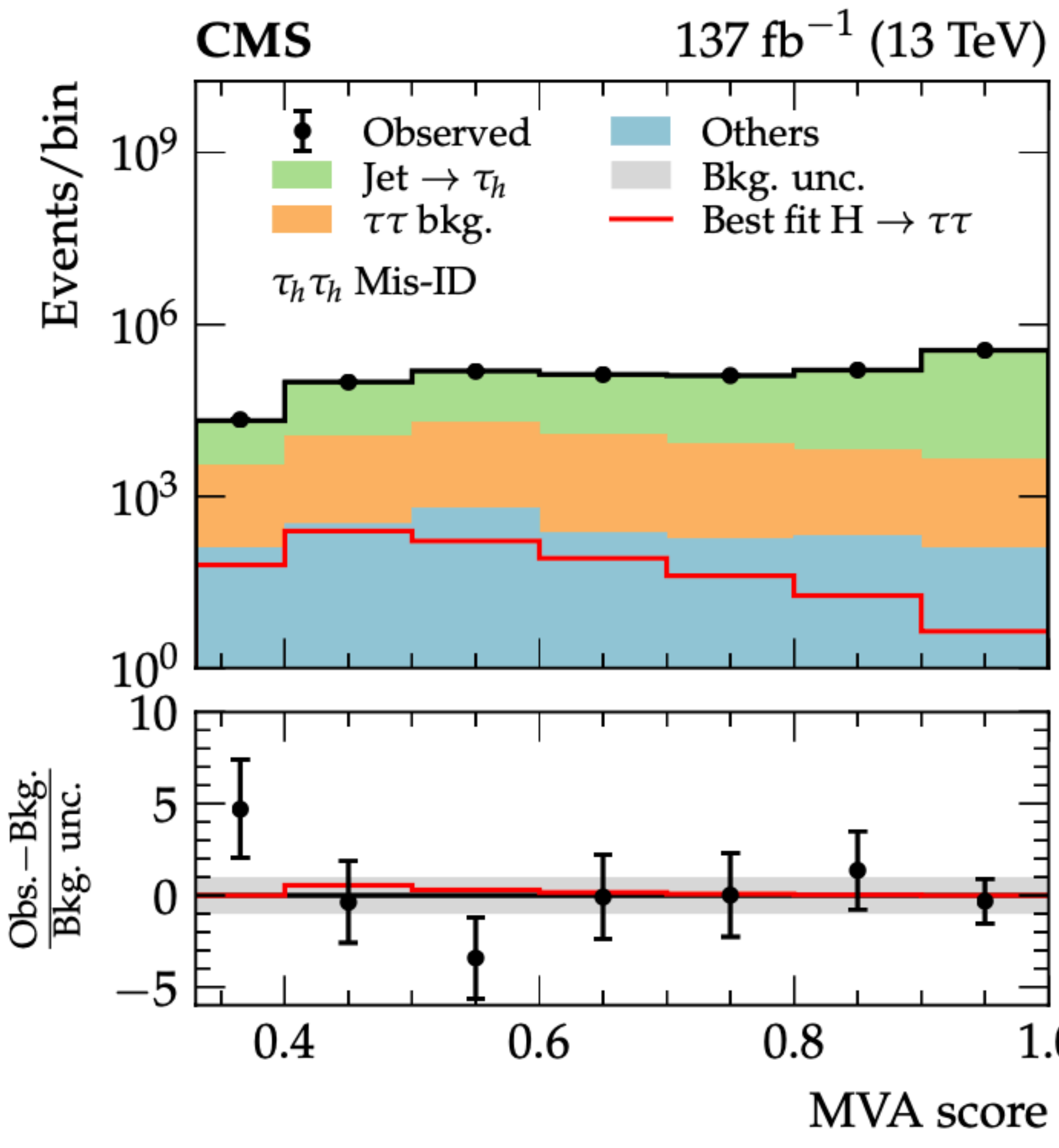
Higgs boson CP properties: $H\tau\tau$

Observable	$\tau_\ell\tau_h$	$\tau_h\tau_h$
p_T of leading τ_h	✓	✓
p_T of trailing τ_h	—	✓
p_T of τ_ℓ	✓	—
p_T of visible di-τ	✓	✓
p_T of di-τ_h + p_T^{miss}	—	✓
p_T of $\tau_\ell\tau_h$ + p_T^{miss}	✓	—
Visible di-τ mass	✓	✓
Di-τ mass (using SVFIT)	✓	✓
Leading jet p_T	✓	✓
Trailing jet p_T	✓	
Jet multiplicity	✓	✓
Dijet invariant mass	✓	✓
Dijet p_T	✓	
Dijet $\lvert\Delta\eta\rvert$	✓	
p_T^{miss}	✓	✓





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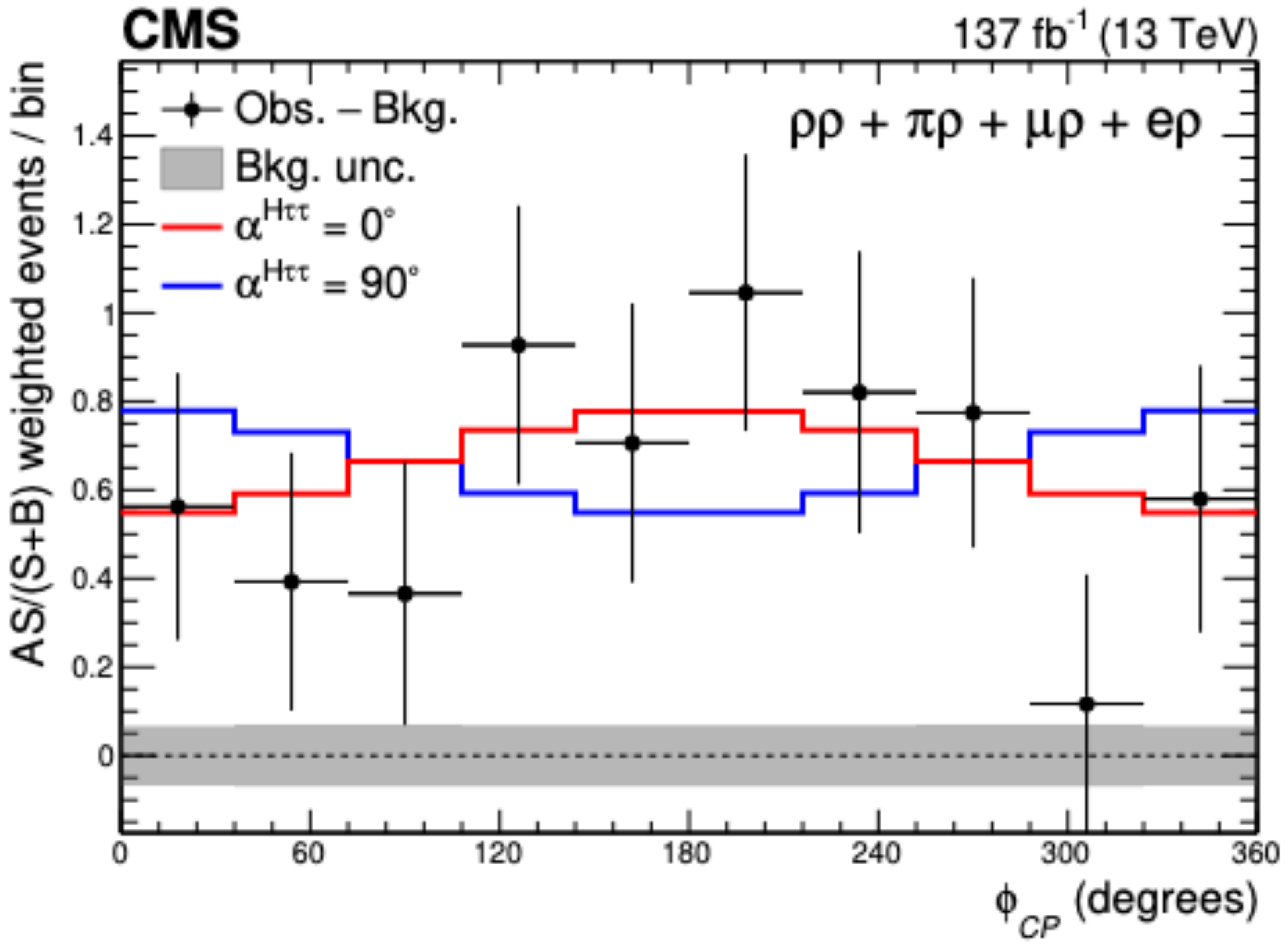
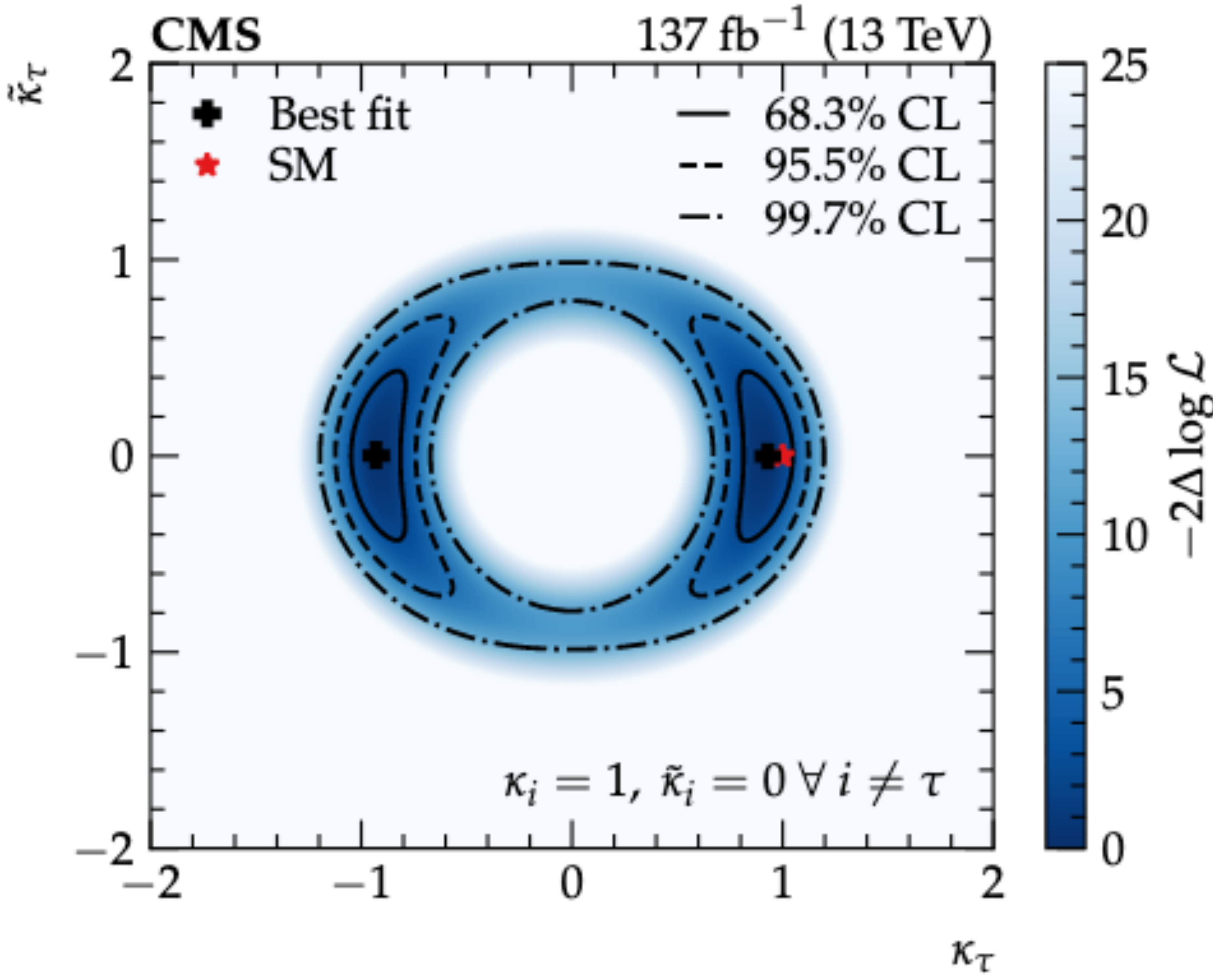
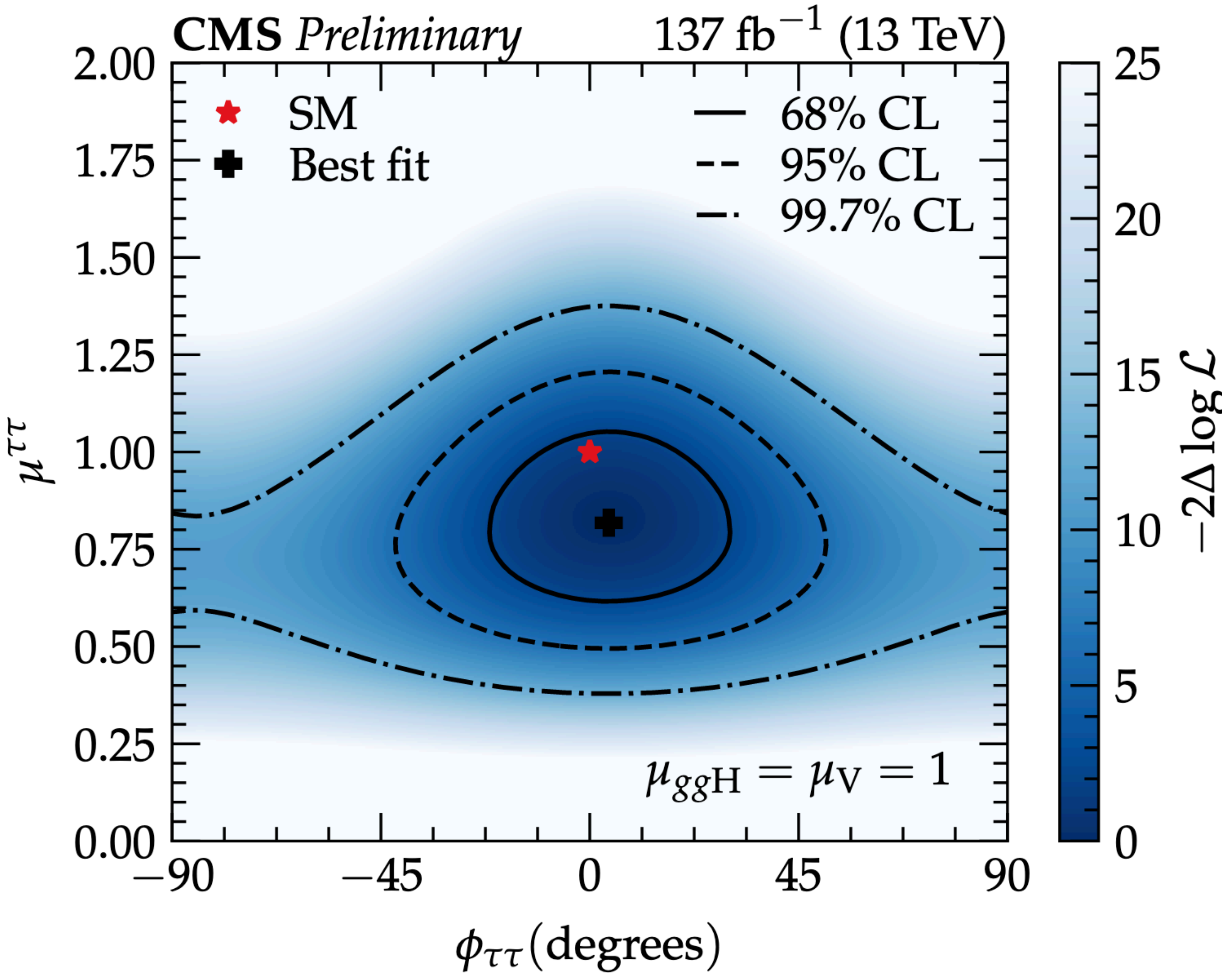
Higgs boson CP properties: $H\tau\tau$







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