# Anomalous couplings and CP properties at CMS

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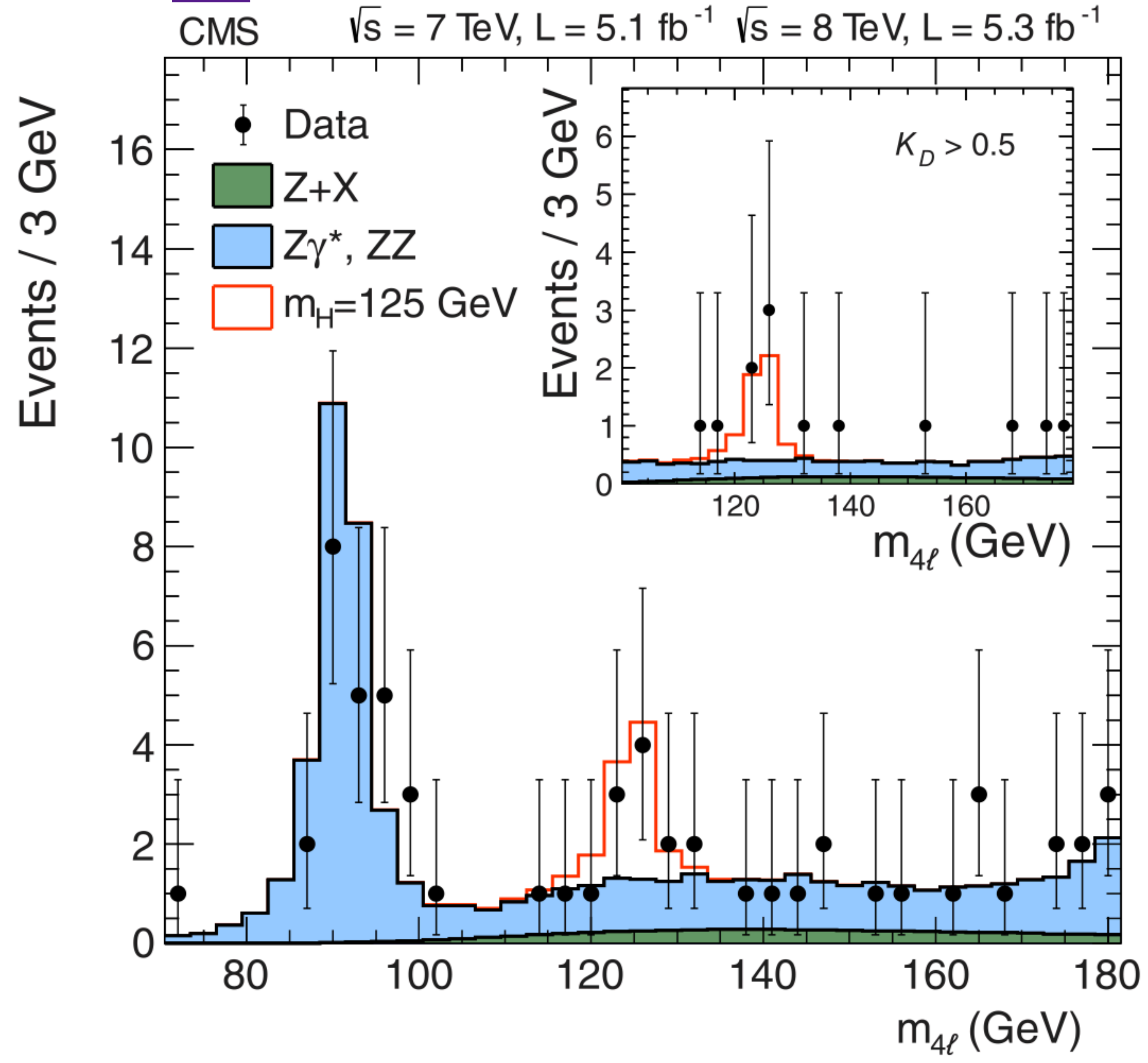
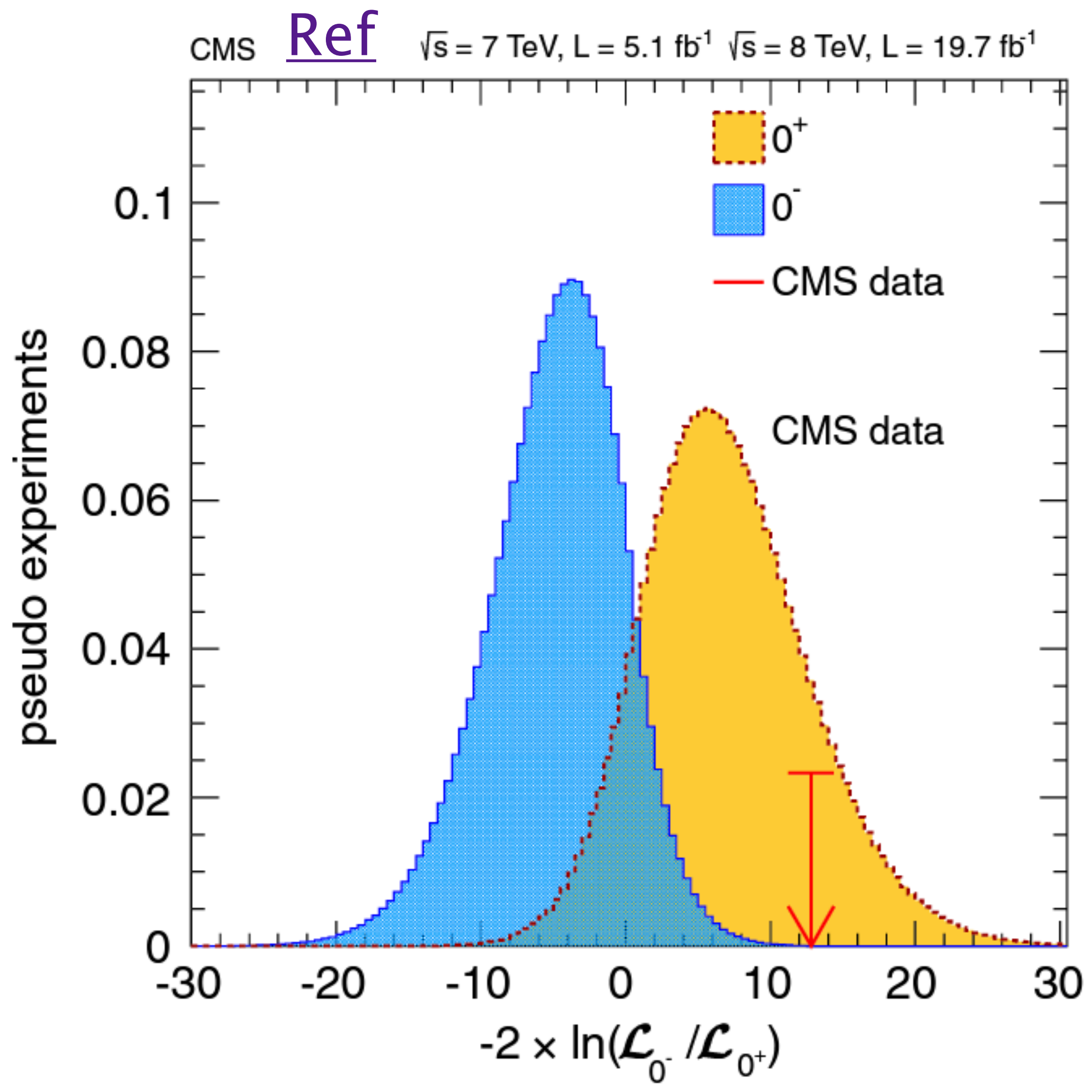
# HIGGS BOSON PROPERTIES

Ref



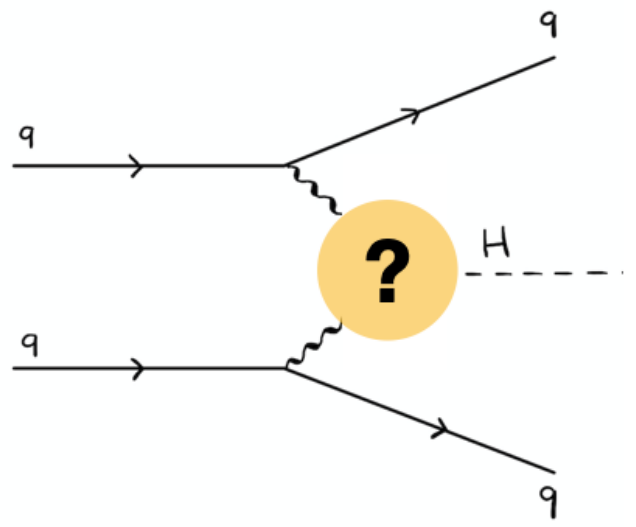




Neutral scalar particle

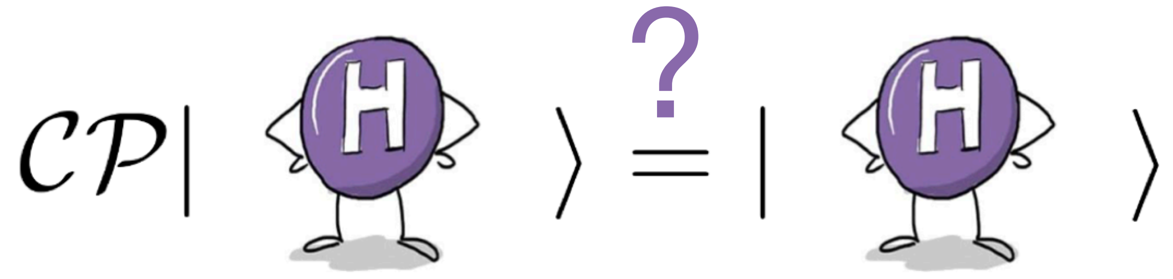
$J^{PC} = 0^{++}$

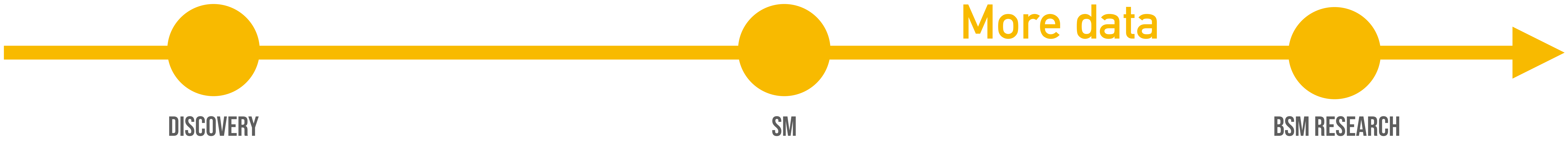
The hypothesis of a pseudoscalar particle has been excluded at 99.95%

**Objective:** to be sensitive to anomalous couplings BSM (Beyond Standard Model).




**What happened to antimatter?** The asymmetry between matter and antimatter implies CP violation. The Standard Model (SM) can only partially explain the CP violation needed → we look for other sources of violation.



# ANOMALOUS COUPLINGS | HVV

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*\mu\nu(2)} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*\mu\nu(2)}$$

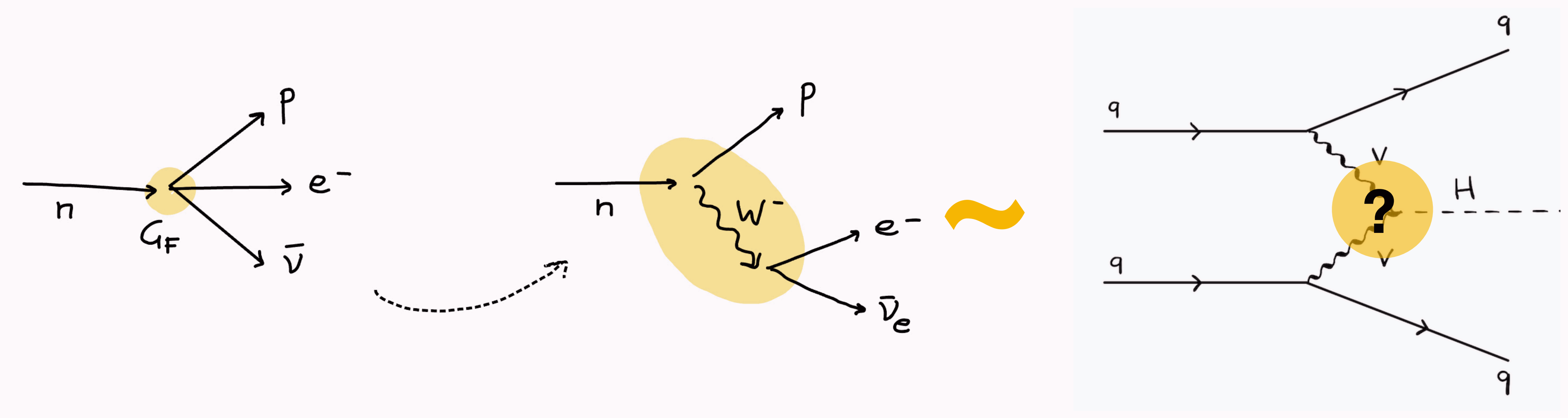
SM : VV = ZZ,WW

**CP Even (higher order couplings)**
($\Lambda_1 = 1TeV$)

**CP Even**

**CP Odd**

The 'point-like' coupling ($G_F$) becomes a complete theory when probing larger scales ($M_W \sim 100GeV$)




AC Approach (Anomalous Coupligs)

$a_i^{ZZ} = a_i^{WW}$

4 anomalous couplings

$a_2(CP)$

~~$a_3(CP)$~~

$a_{\Lambda_1}(CP)$

$a_{\Lambda_1}^{Z\gamma}(CP)$

# ANOMALOUS COUPLINGS | HVV

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*\mu\nu(2)} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*\mu\nu(2)}$$

SM : VV = ZZ,WW

CP Even (higher order couplings)

($\Lambda_1 = 1 TeV$)

CP Even

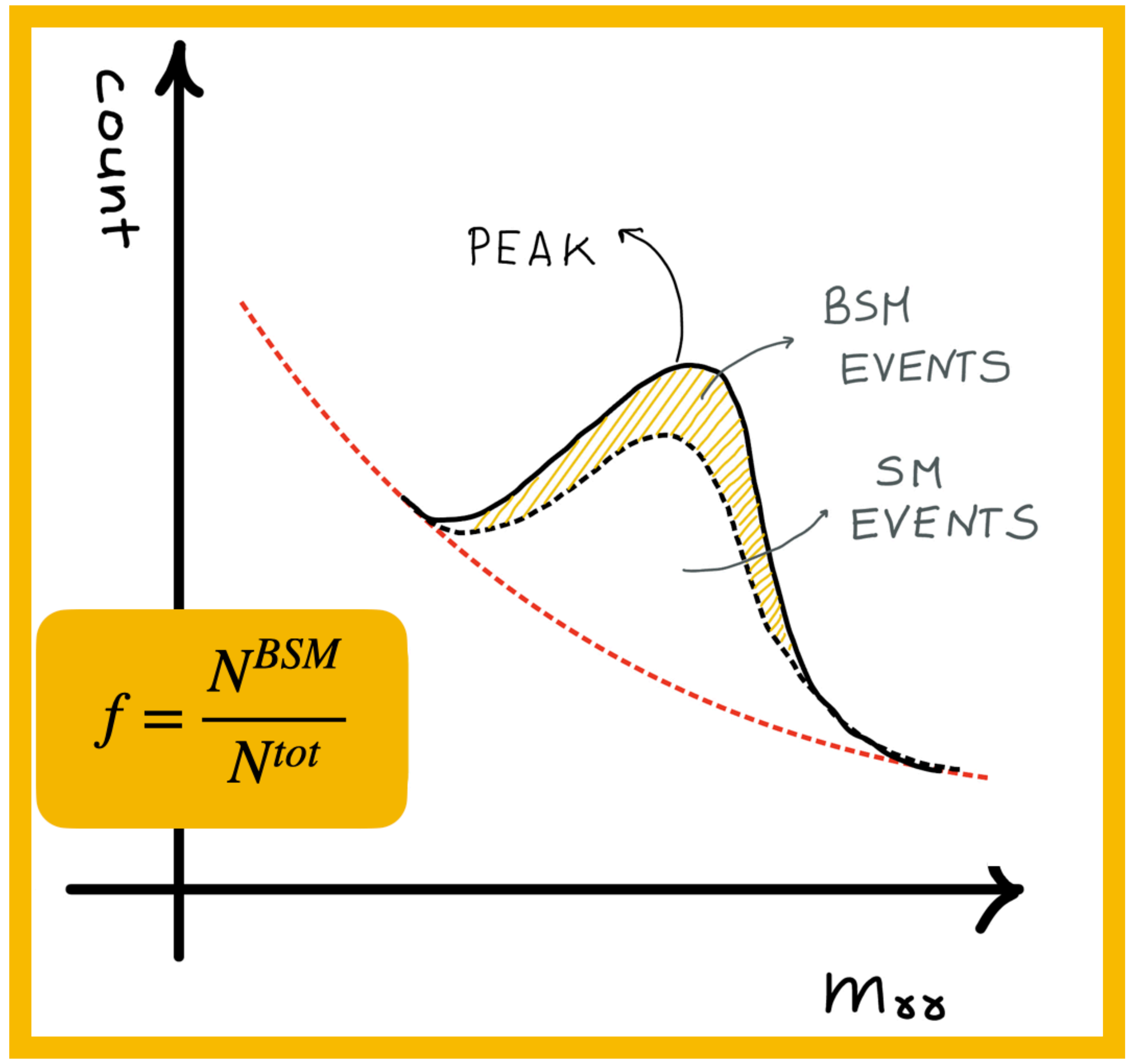
CP Odd

## EFFECTIVE CROSS SECTION FRACTIONS

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3,\Lambda_1} |a_j|^2 \sigma_j} \qquad \phi_{ai} = arg(\frac{a_i}{a_1})$$

- Indipendent $\Gamma_H$
- Limited between [-1,1]

$$f_{ai} = f_{a2}\,,\ f_{a_3}\,,\ f_{\Lambda_1}\,,\ f_{\Lambda_1}^{Z\gamma}$$




$\sigma_i$: cross section of the process with $a_i = 1$

**The sensitivity to Anomalous couplings could be translated into sensitivity to higher dimensionality operators in SM Effective Field Theory (SMEFT)**

$$L = L_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + (O(\Lambda^{-4}))$$

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

$$\begin{aligned}
\delta c_z &= \frac{1}{2}a_1 - 1, \\
c_{z\Box} &= \frac{m_Z^2 s_w^2}{4\pi\alpha}\frac{\kappa_1}{(\Lambda_1)^2}, \\
c_{zz} &= -\frac{s_w^2 c_w^2}{2\pi\alpha}a_2, \\
\tilde{c}_{zz} &= -\frac{s_w^2 c_w^2}{2\pi\alpha}a_3. \\
c_{gg} &= -\frac{1}{2\pi\alpha_S}a_2^{gg}, \\
\tilde{c}_{gg} &= -\frac{1}{2\pi\alpha_S}a_3^{gg},
\end{aligned}$$

# ANOMALOUS COUPLINGS | H-FERMIONS COUPLINGS

$\bar{\psi}_f, \psi_f$ → Dirac spinors

$m_f$ → fermion mass

$v$ → Vacuum expectation value.

$k_f$ → CP-even Yukawa coupling modifier.(SM : $k_f = 1$)

$\tilde{k}_f$ → CP-odd Yukawa coupling modifier. **(SM : $\tilde{k}_f = 0$)**

$$A(Hff) = -\frac{m_f}{v}\bar{\psi}_f(k_f + i\tilde{k}_f\gamma_5)\psi_f$$

SM

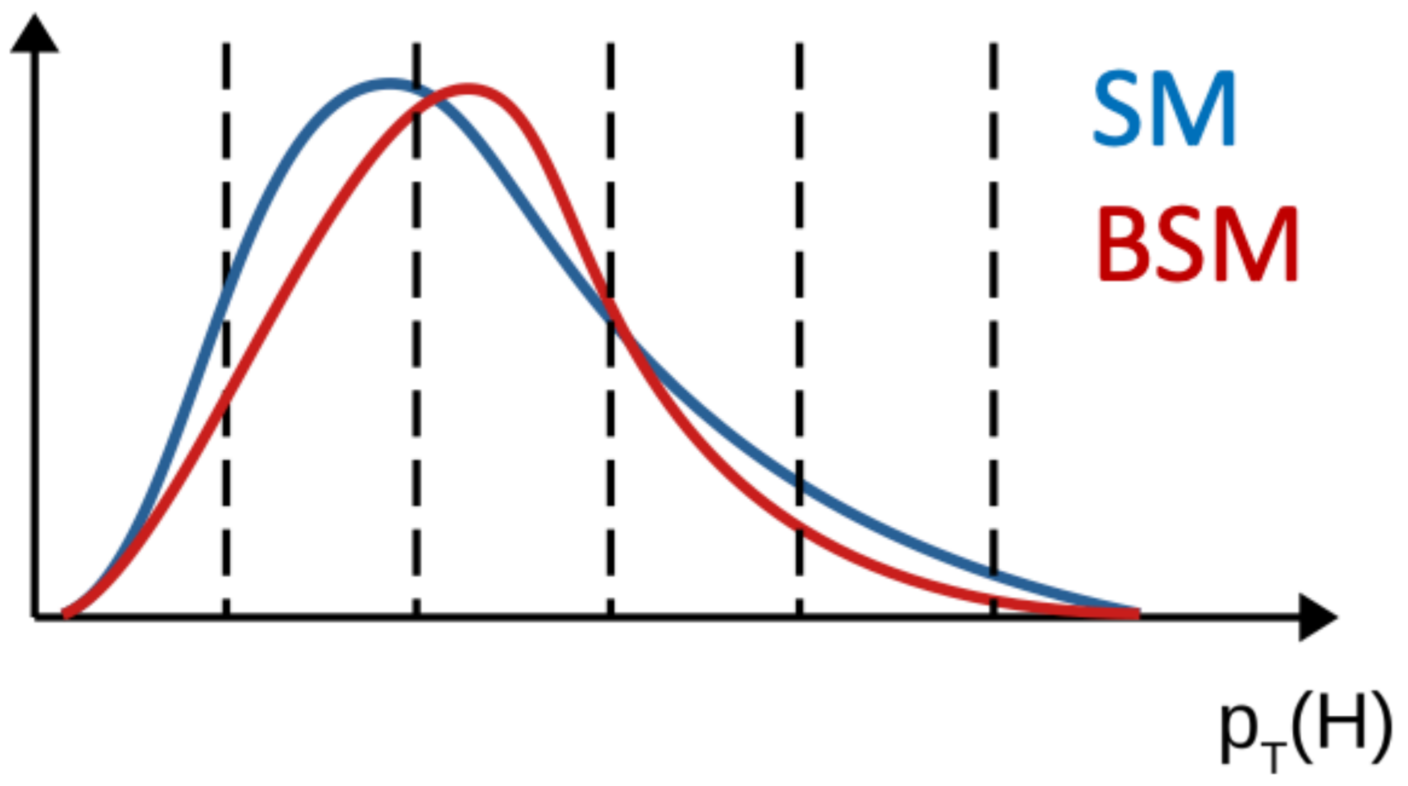
CP odd

## EFFECTIVE CROSS SECTION FRACTIONS

$$f_{CP}^{Hff} = \frac{|\tilde{k}_f|^2}{|k_f|^2 + |\tilde{k}_f|^2} sign\left(\frac{\tilde{k}_f}{k_f}\right)$$

- Sensitivity to CP-odd operators at tree level

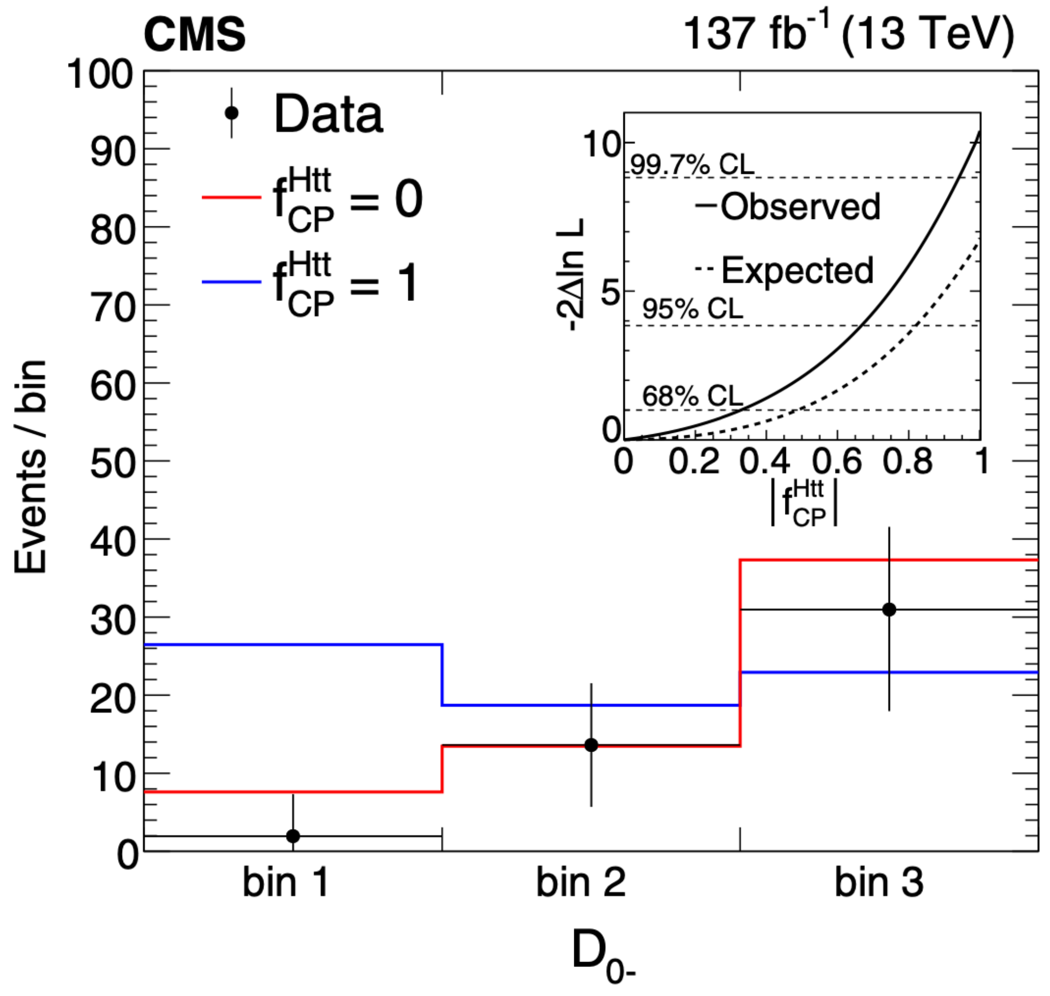
# HOW DO WE MEASURE CP OPERATORS?




The distributions of the kinematic variables are sensitive to Higgs quantum numbers and anomalous couplings

→ CP-sensitive variables ($\Delta\phi_{jj}$, $p_T(H)$ , … )

Phys. Rev. Lett. 125, 061801 (2020)




**Multivariate Analysis:** BDT, DNN, etc. trained to distinguish between SM and BSM type of events

**MELA (Matrix Element Likelihood Approach)** variables :

$$D_{alt}(\Omega) = \frac{P_{SM}(\Omega)}{P_{SM}(\Omega) + P_{alt}(\Omega)}$$

$$D_{0^-}(\Omega) = \frac{P_{SM}(\Omega)}{P_{SM}(\Omega) + P_{0^-}(\Omega)}$$

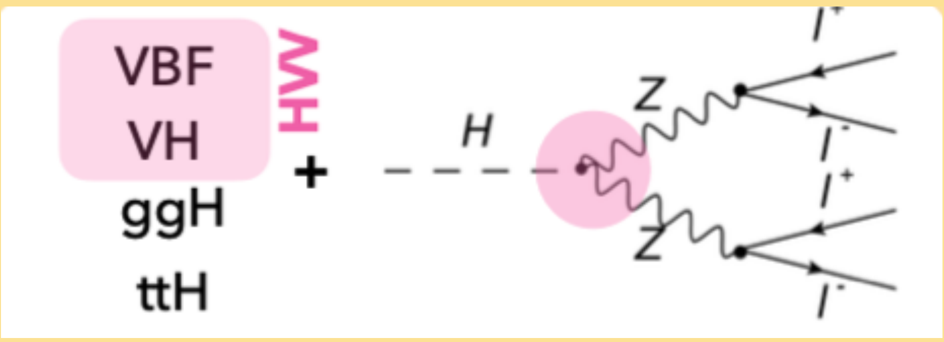
$\Omega$ = kinematics information
alt =alternative Hypothesis

# CMS ANALYSIS

| Channel | Measure | Combined with | REF |
| --- | --- | --- | --- |
| * ttH [H]→ $\gamma\gamma$ | Hff | | Phys. Rev. Lett. 125, 061801 (2020) |
| H → ZZ | HVV,Hff | H → $\gamma\gamma$ | Phys.Rev.D 104 (2021) 5, 052004 |
| H → WW | HVV,Hff | | Eur. Phys. J. C 84 (2024) 779 |
| H → $\tau\tau$ | HVV,Hff | H → ZZ + H → $\gamma\gamma$ | Phys. Rev. D 108 (2023) 032013 |
| ttH tH → WW/$\tau\tau$ | Hff | H → ZZ + H → $\gamma\gamma$ | JHEP 07 (2023) 092 |
| H → $\tau\tau$ | Hff | | JHEP 06 (2022) 012 |
| H → bb | Hff | H → ZZ + H → $\gamma\gamma$ + H → WW//$\tau\tau$ | [Submitted on 15 Jul 2024] |

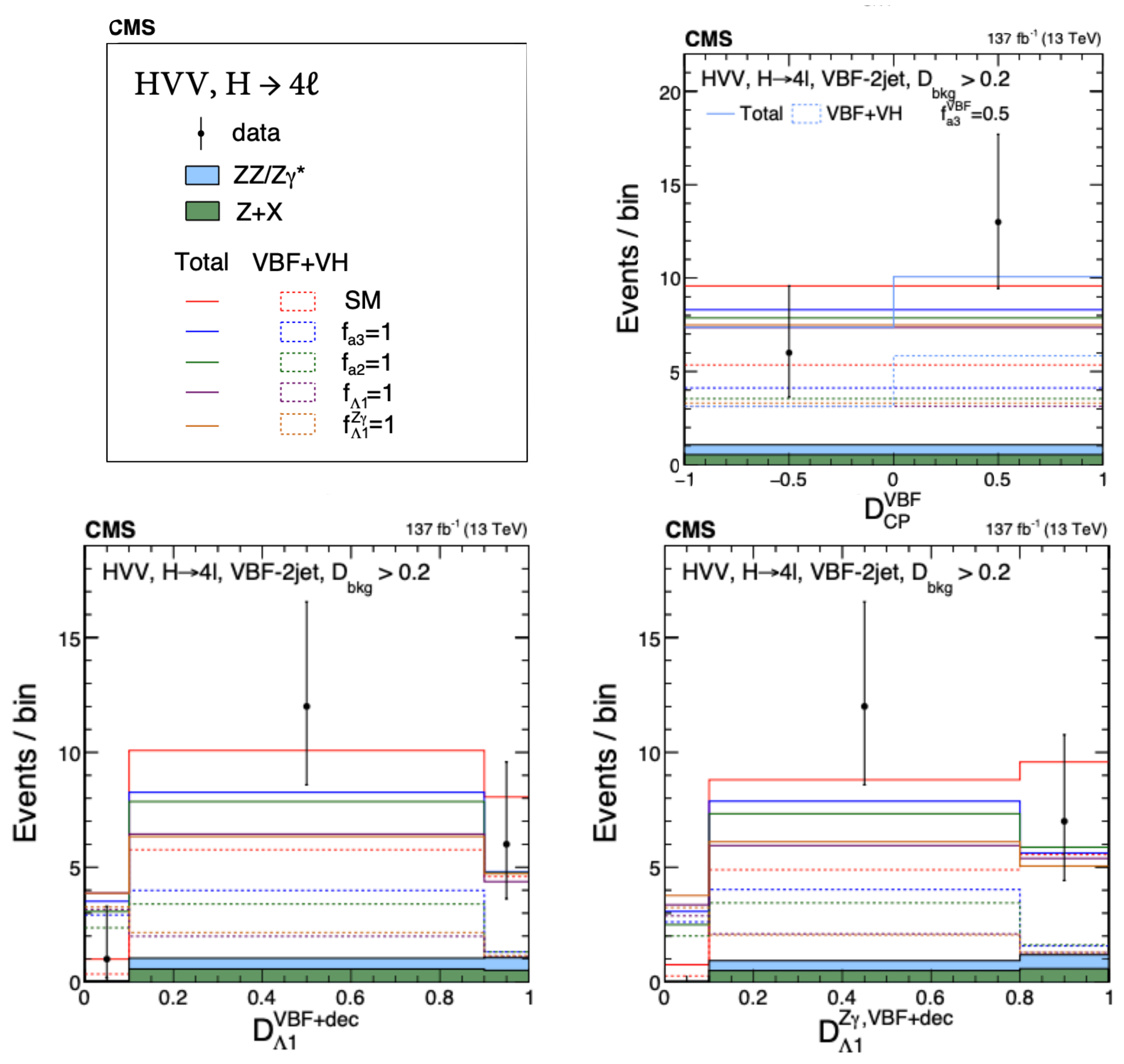
*We can use information both from production and decay to perform studying on HVV and/or Hff*

# H→4l | HVV couplings




Phys.Rev.D 104 (2021) 5, 052004

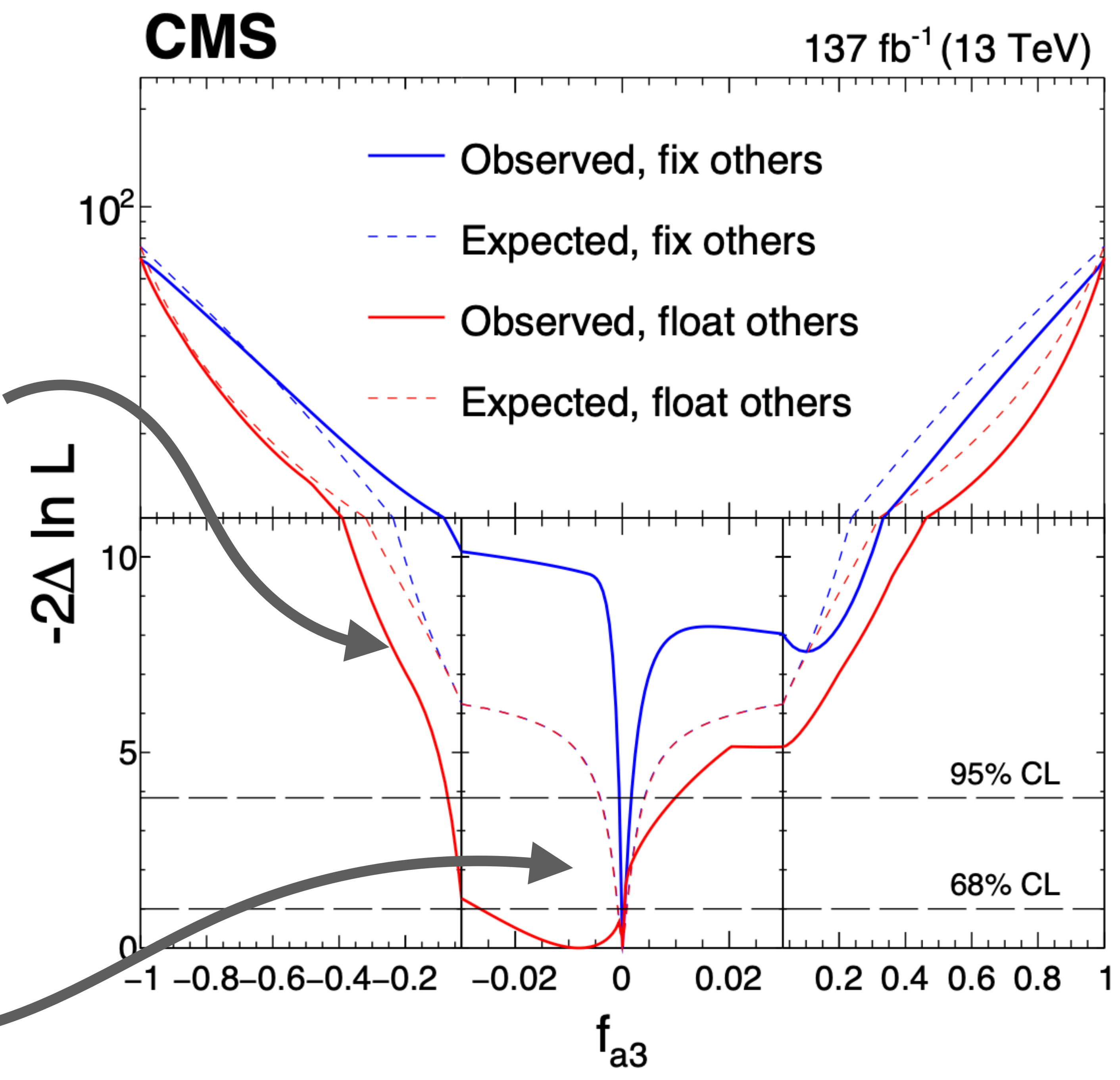
- Channels considered: 2e2μ, 4μ, and 4e in the Higgs decay
- MELA variables used both for S/B discrimination and SM-BSM discrimination
- Definition of specific categories for different anomalous couplings and different HVV




Variables used to enhance sensitivity to VBF BSM events

*Decay information* becomes relevant around 0.2

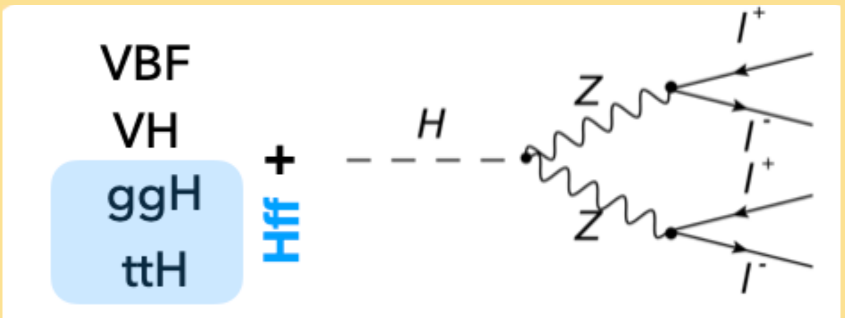
Narrow minimum from *production* information



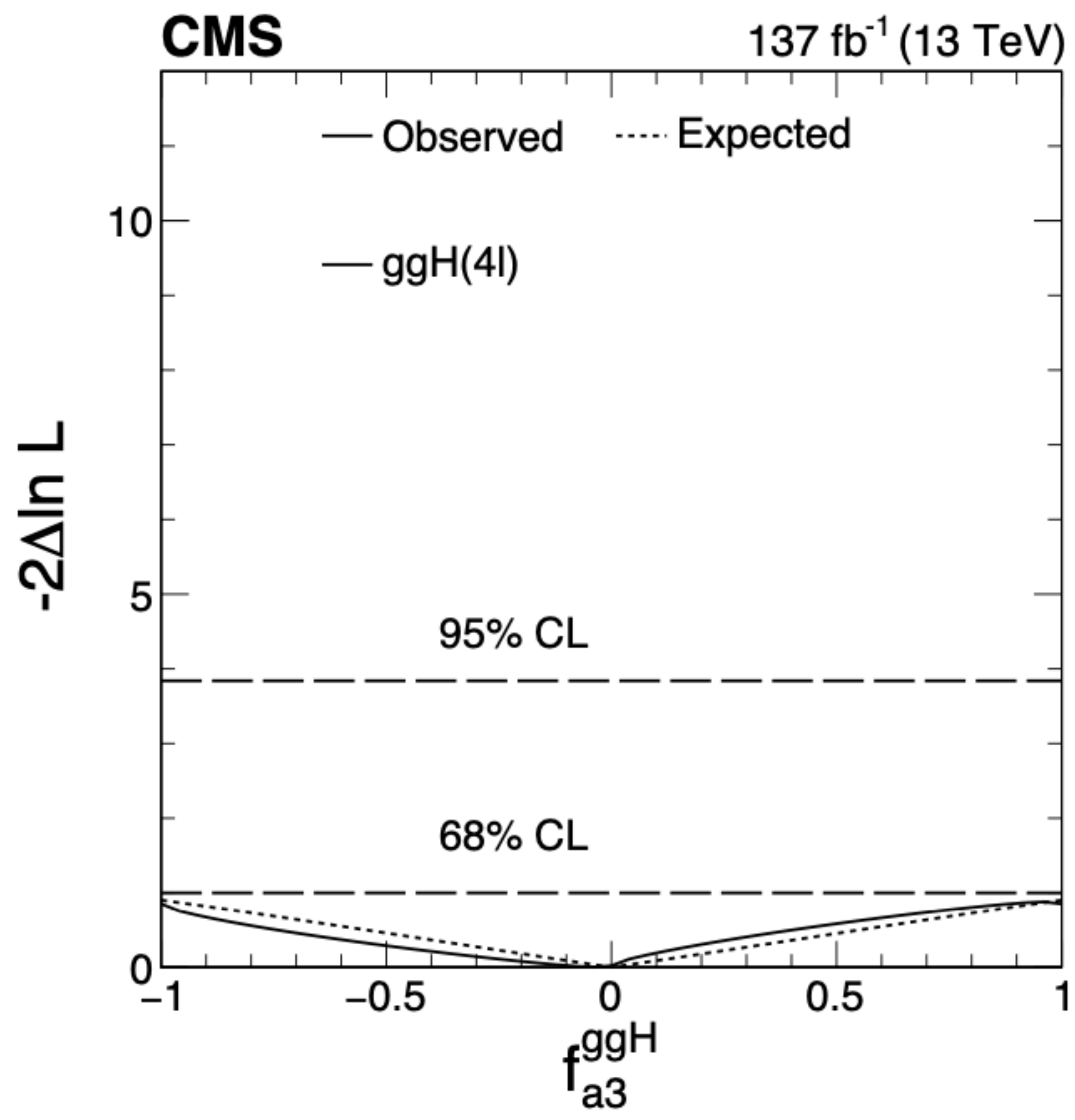

**Fix others:** only one of $f_{ai} \neq 0$ → 95% CL [-0.00055, 0.00168]

**Float others**: all $f_{ai}$ free parameters → 95% CL [-0.07191, 0.00990]

# H→4l | Hgg & Hff couplings

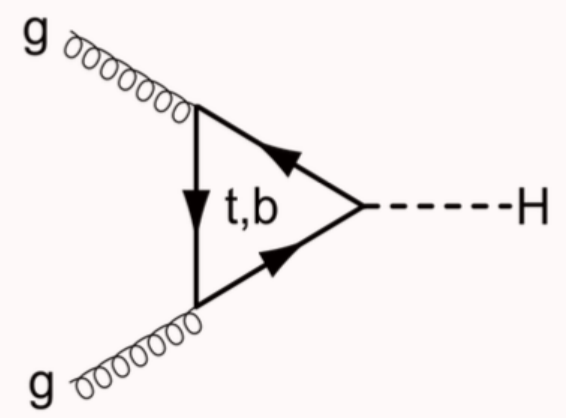



Phys.Rev.D 104 (2021) 5, 052004




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

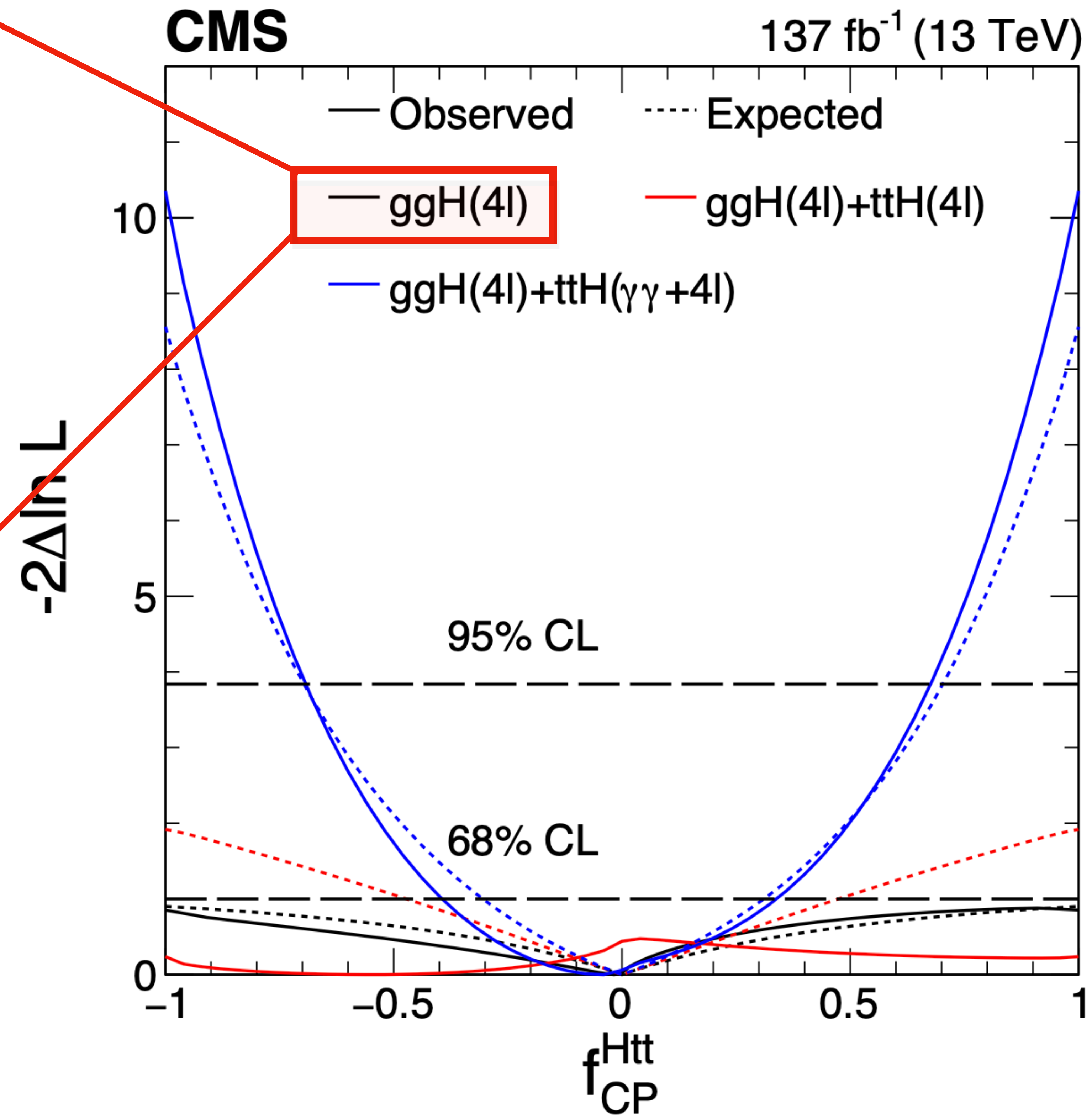
Limit on the Htt coupling using the ttH and Hgg production methods



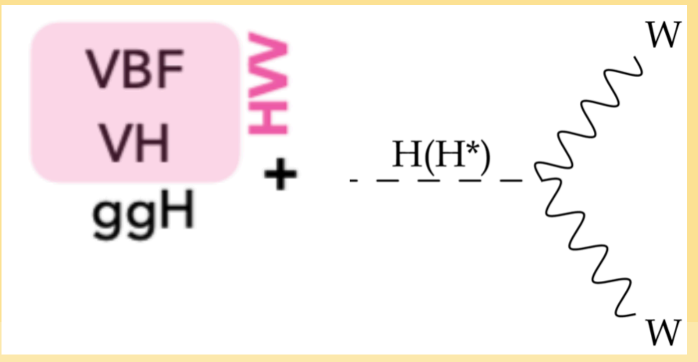

**ggH loop dominated by the top quark**

*Observed @ 95% CL*

[−0.69, 0.68]

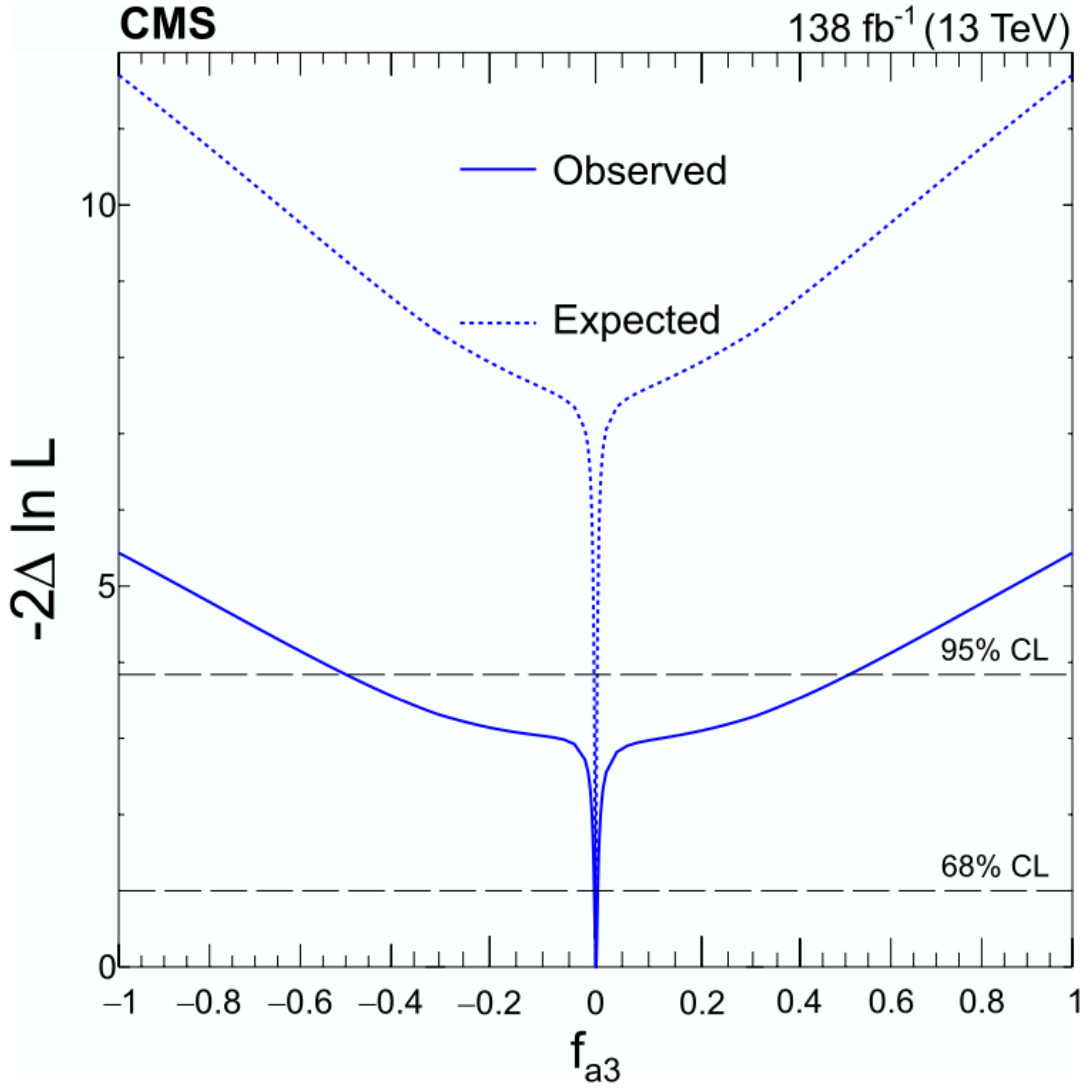


# H ⟶ WW | HVV couplings

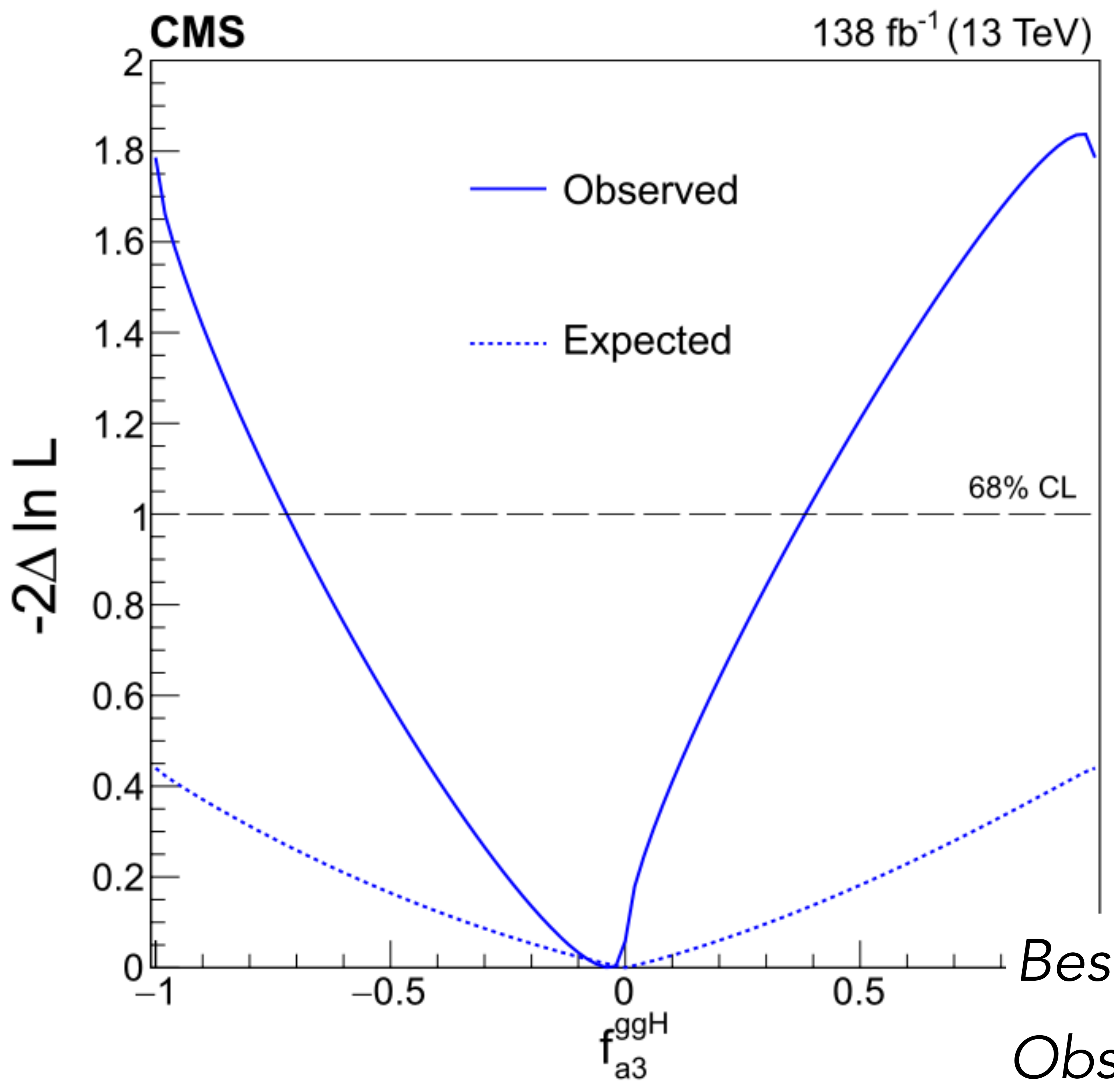



Eur. Phys. J. C 84 (2024) 779

- Final state H ➝WW ➝ μνeν
- Production modes considered ggH, VBF, VH (resolved and boosted)
- Main background: tt , DY, non-resonant WW and W-Jet (estimated from data)




*Fix others* ➝ *95% CL [−0.553, 0.561]*

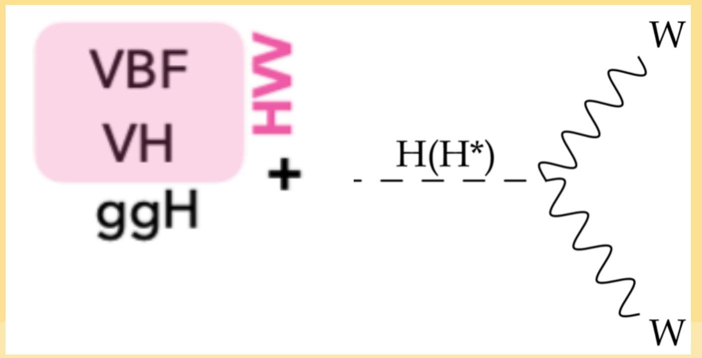



*Best Value = -0.034*

*Observed @68% CL*

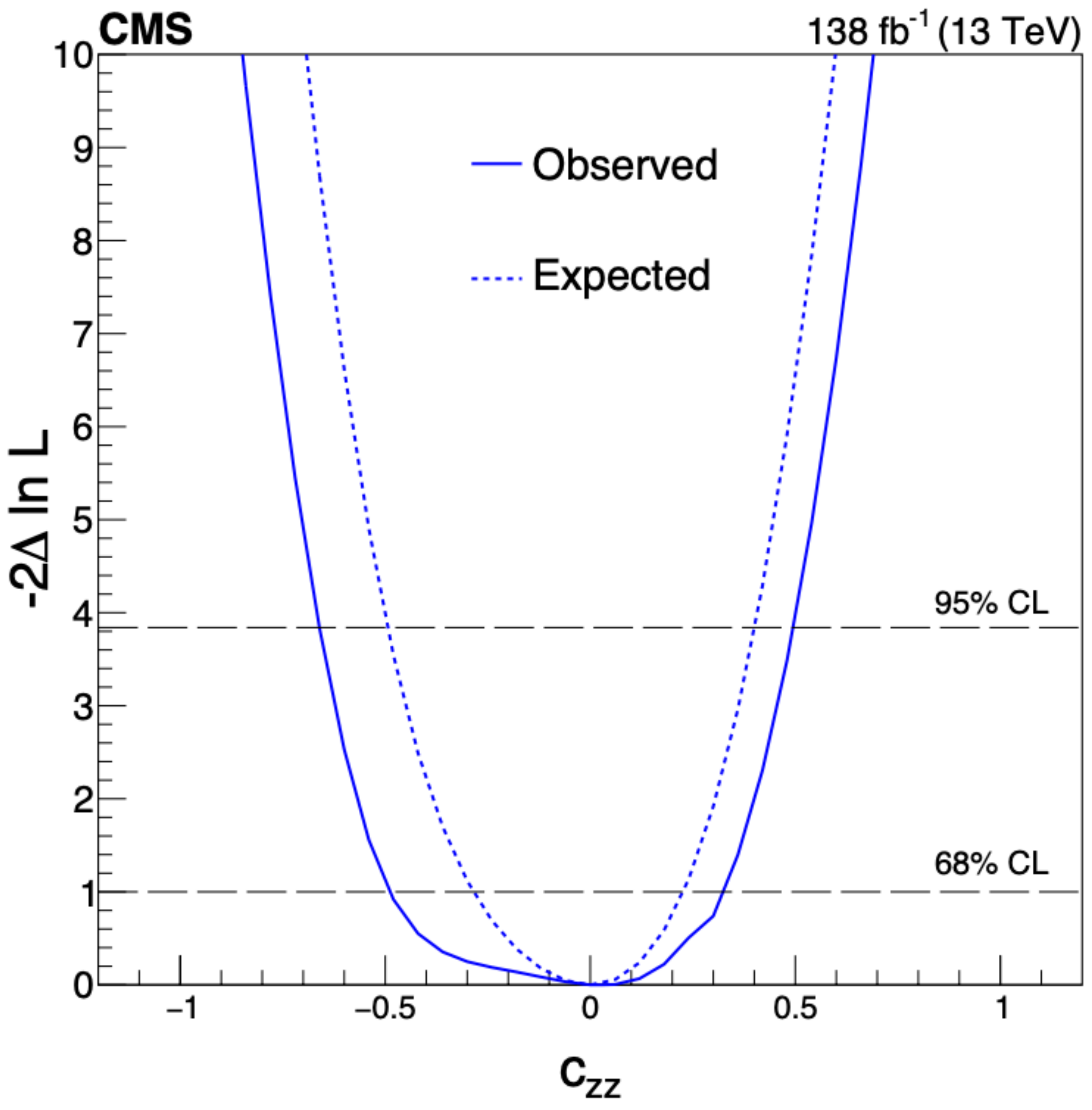
*[68% CL [−0.721, 0.383]]*

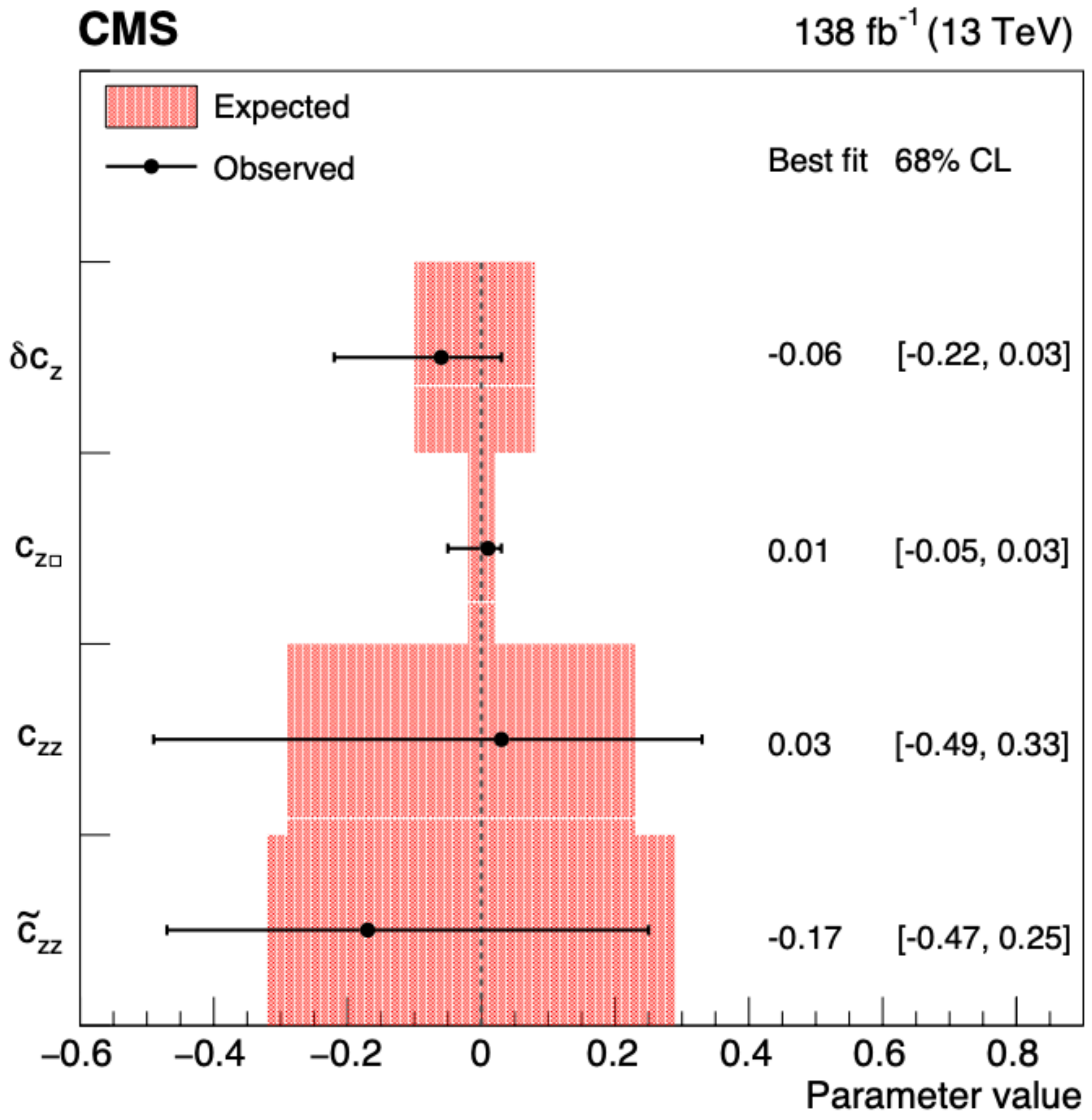
# H → WW | HVV couplings (SMEFT interpretation)

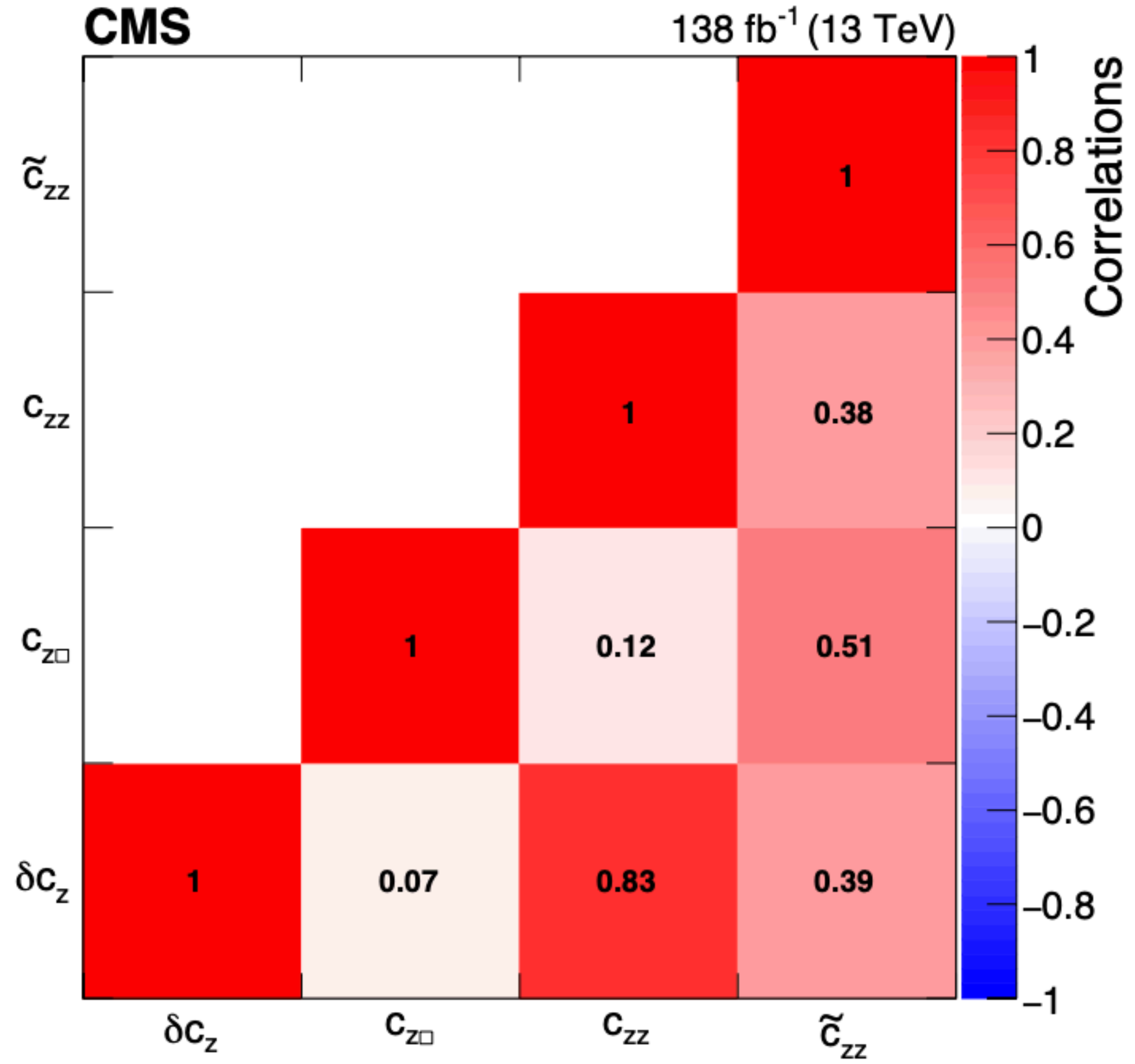



Eur. Phys. J. C 84 (2024) 779

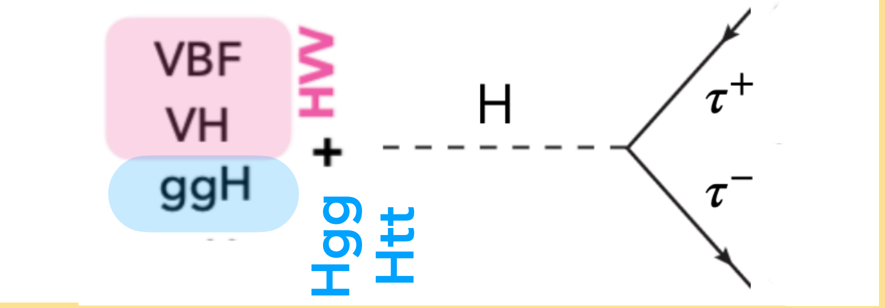
- A simultaneous measurement of four Higgs boson couplings to electroweak vector bosons has been performed in the framework of SMEFT



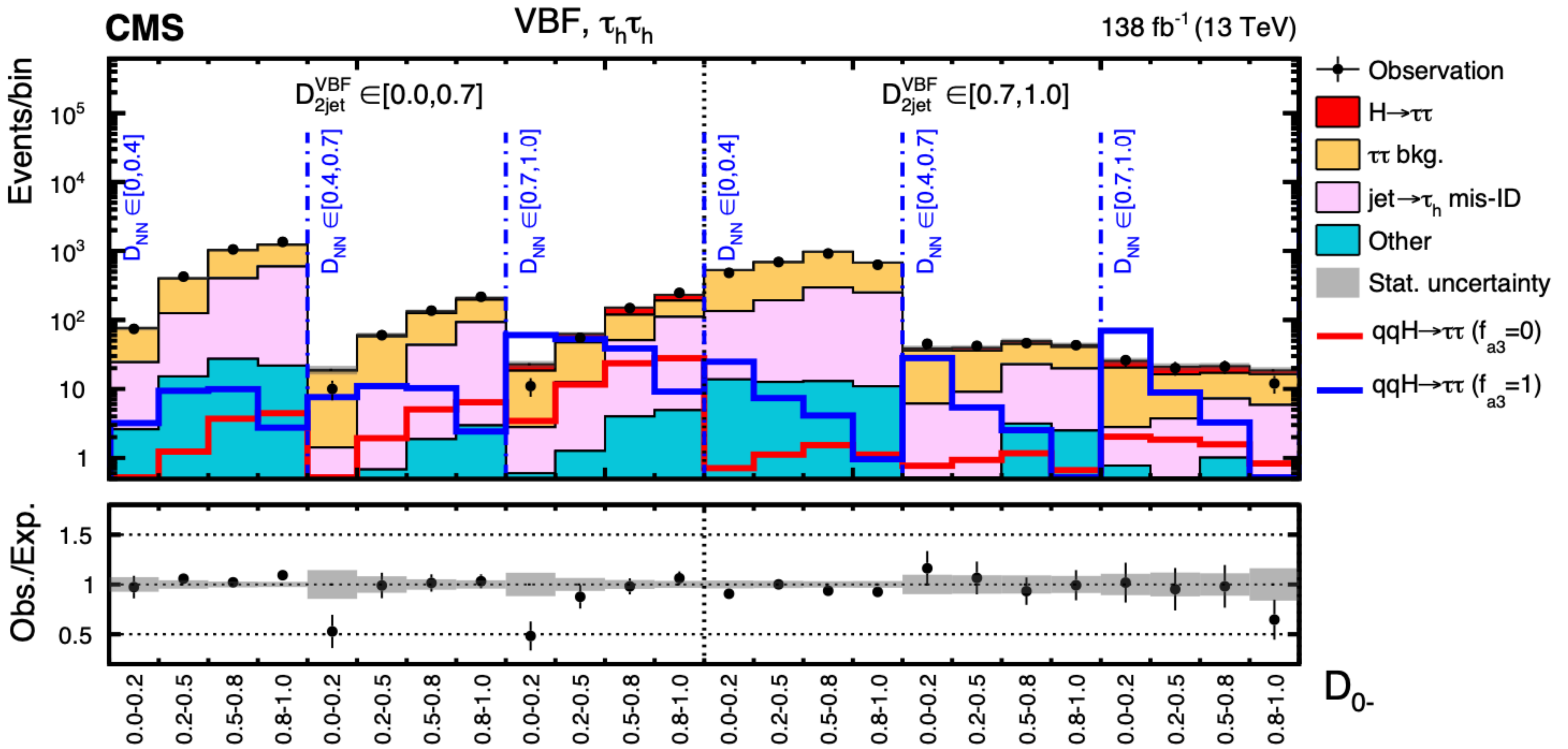



# $H \rightarrow \tau\tau$ | HVV & Hgg & Htt couplings

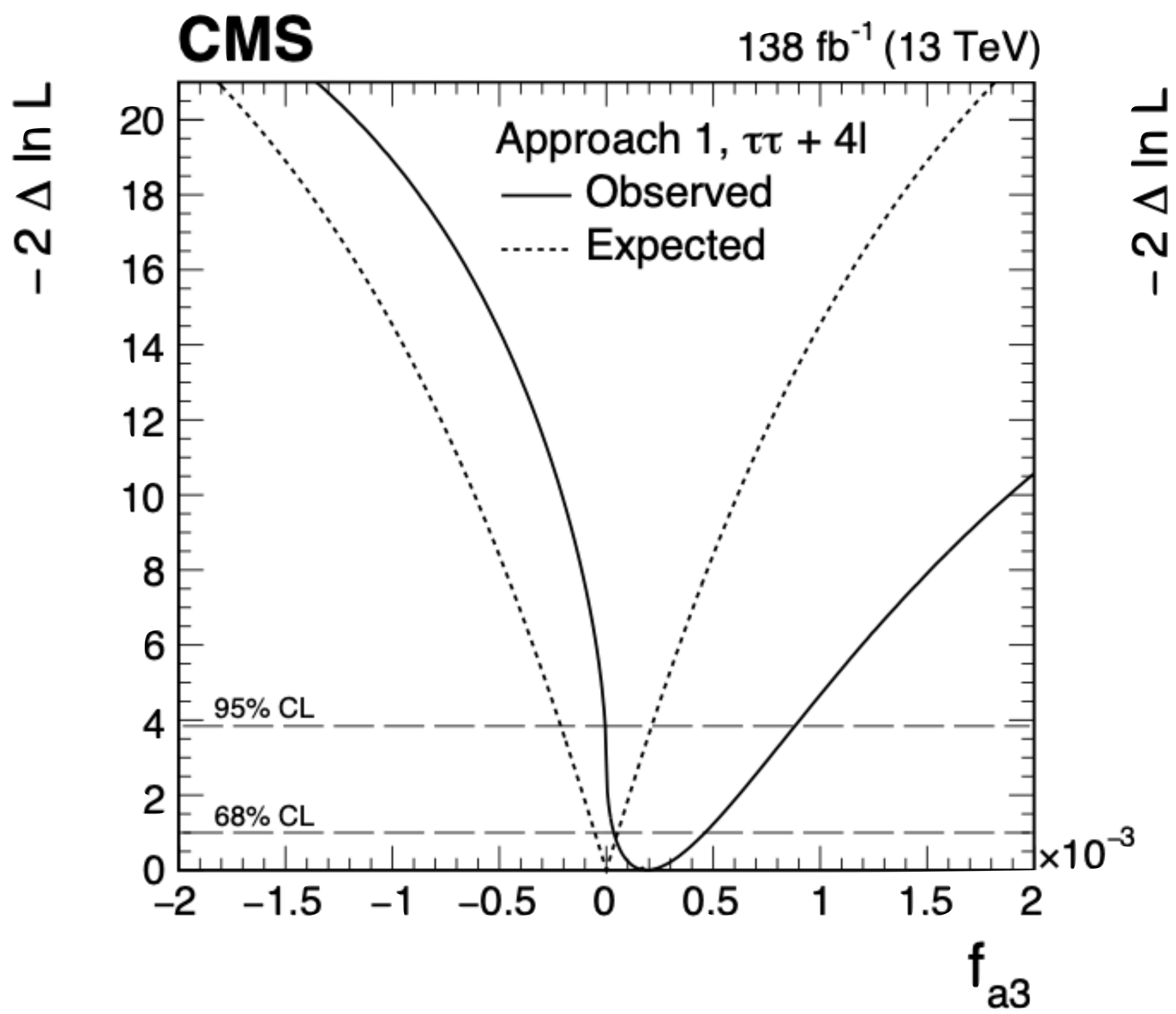



Phys. Rev. D 108 (2023) 032013

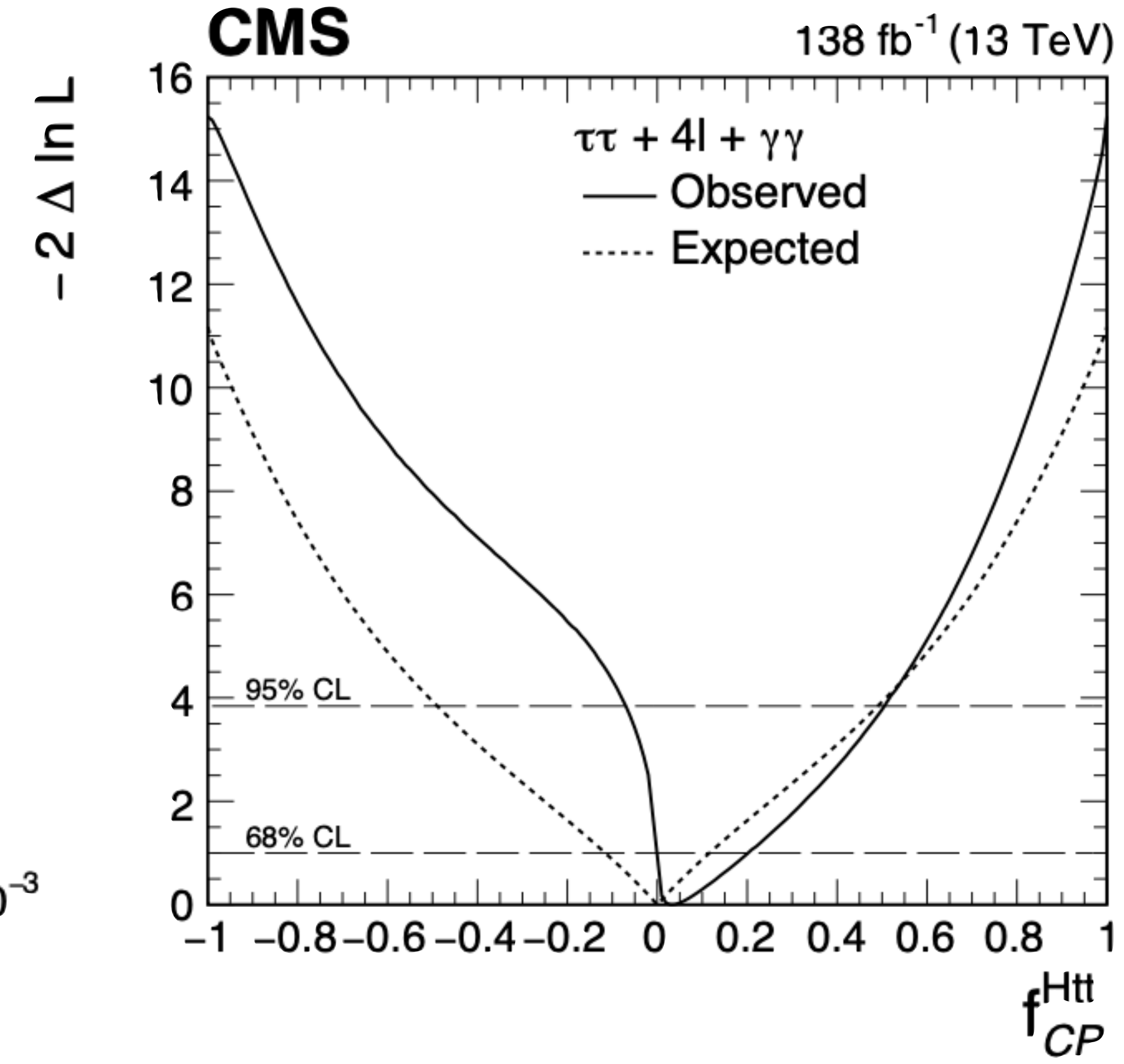
- Considered channel : $\tau_h\tau_h, \mu\tau_h, e\tau_h, e\mu$
- Both MVA and MELA used to discriminate background, BSM, SM events
- The combination improves the limits on the anomalous coupling parameters typically by about 20–50%

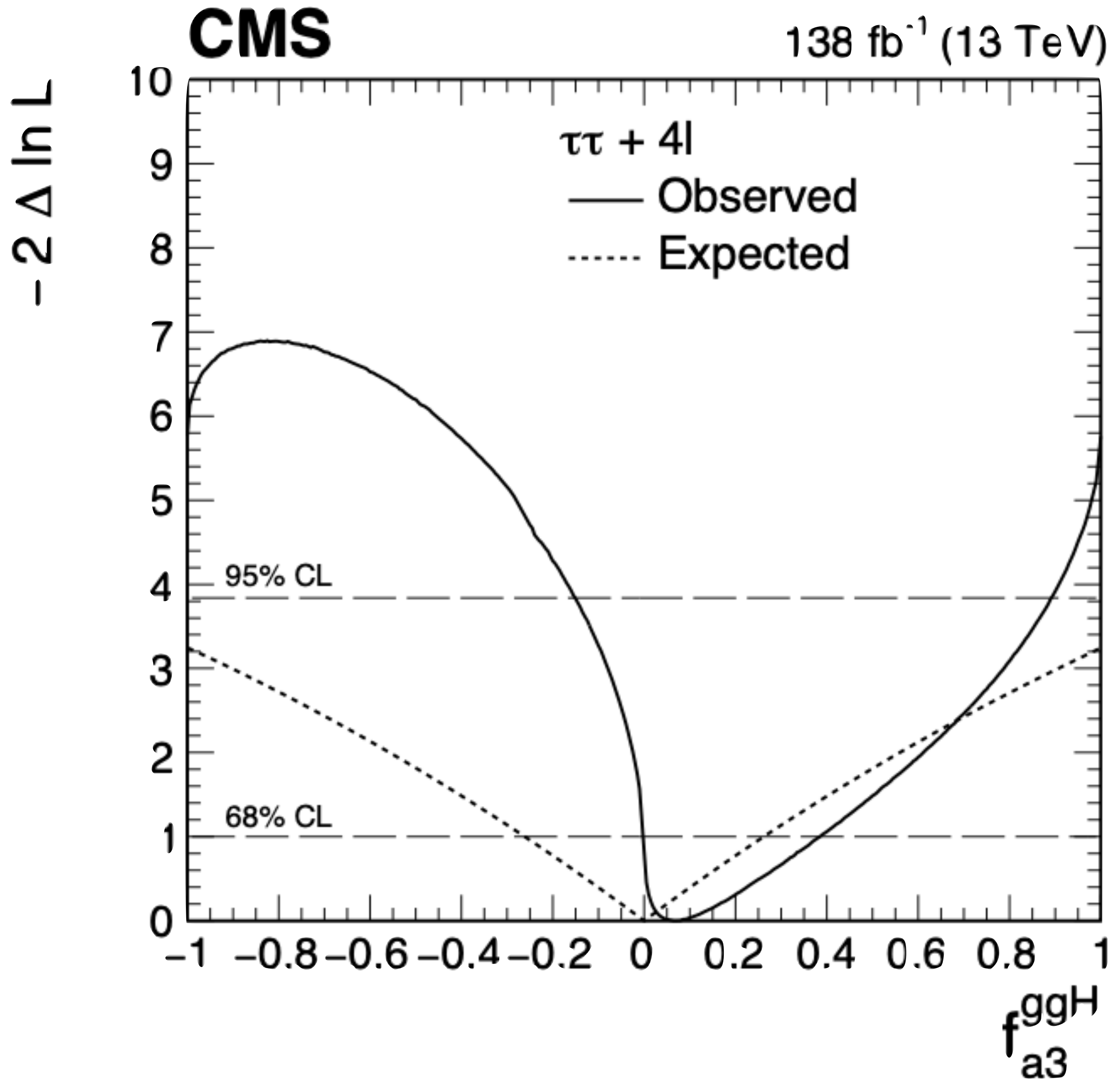



*Observed @ 95% CL*
*[0.00001,0.00013]*




*Observed @ 95% CL*
*[−0.07, 0.51]*



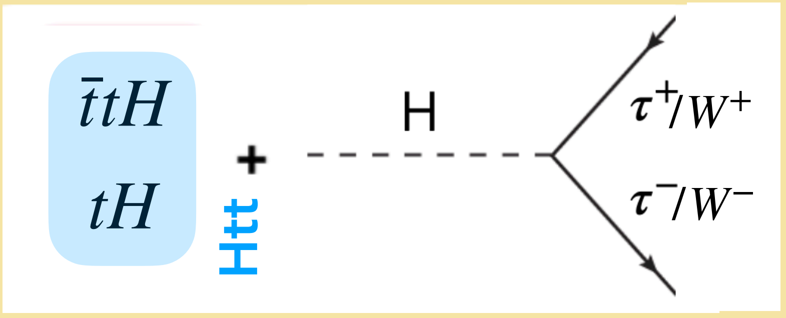




pure CP-odd Hgg excluded at 2.4σ

*Observed @ 95% CL*
*[−0.15, 0.89]*

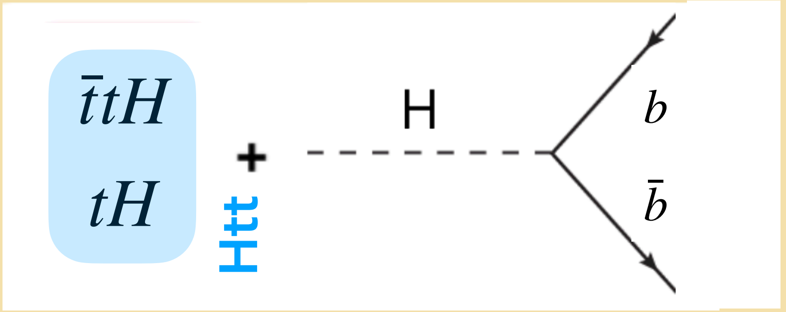
# $t\bar{t}H$ AND tH PRODUCTION | Htt couplings

- Higgs couplings are proportional to the mass so $\bar{t}tH$ and $tH$ channel are very sensitive



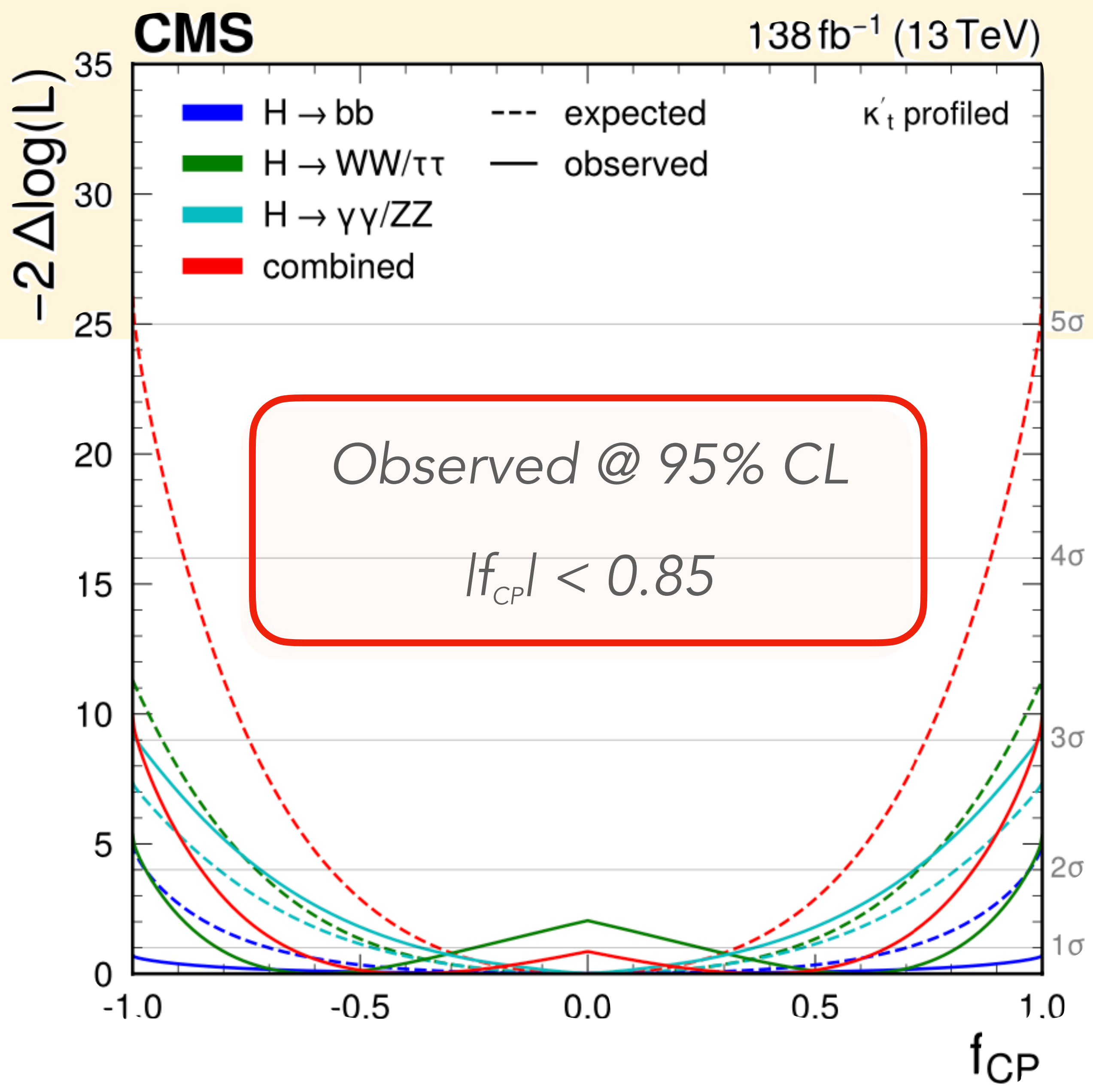

[JHEP 07 (2023) 092]

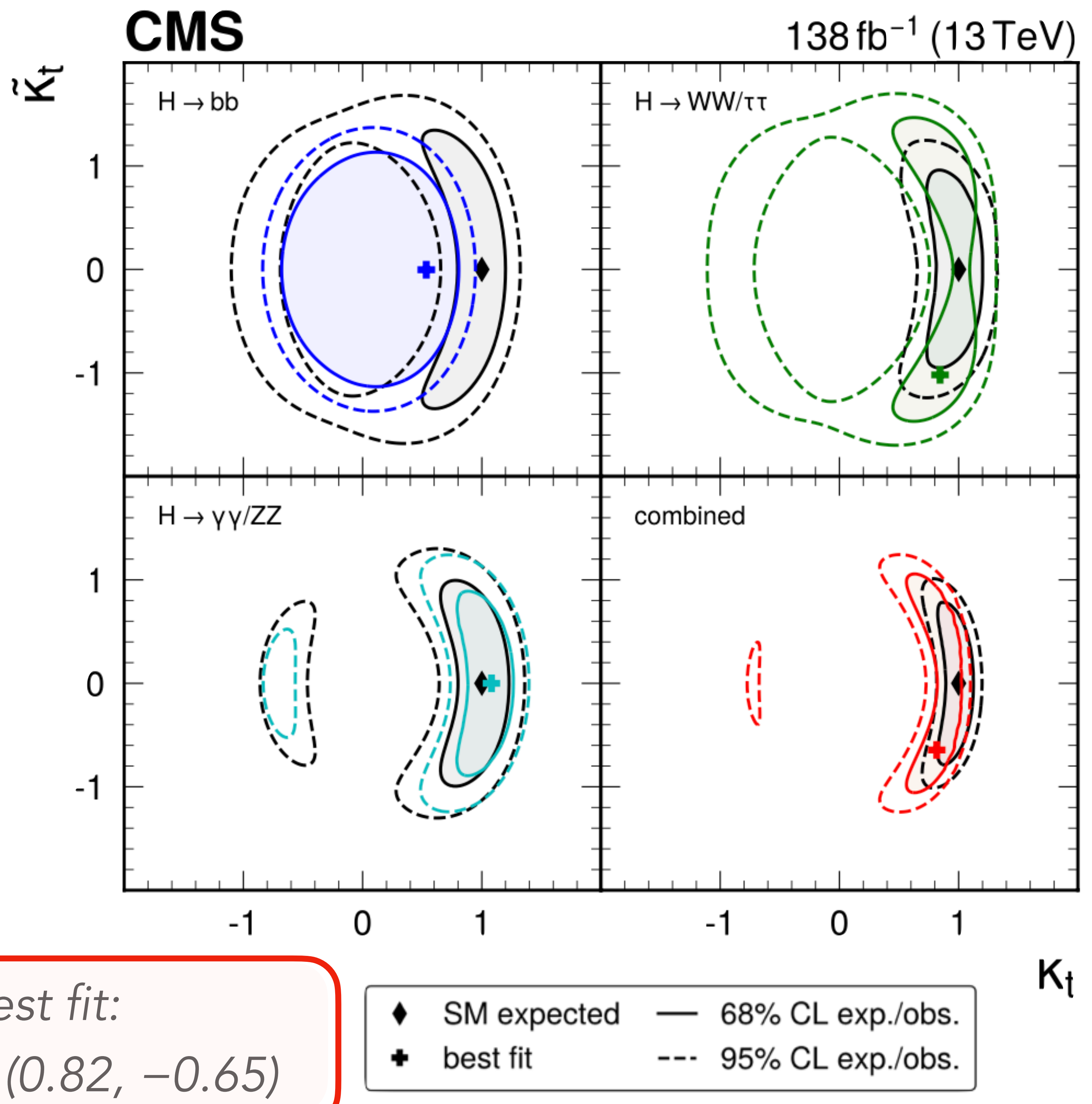
- H boson decays via H→WW+H→$\tau\tau$ (multi lepton) final states characterized by the presence of at least two leptons are studied




[Submitted on 15 Jul 2024]

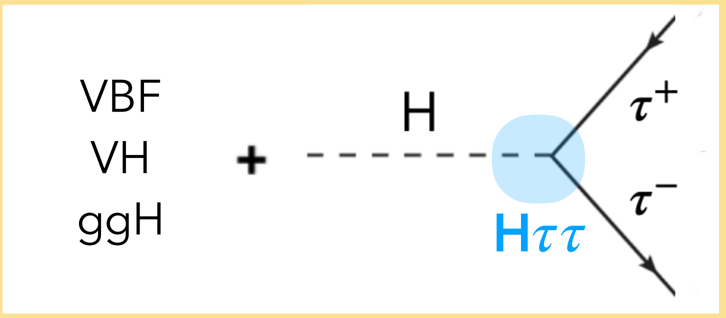
- $\bar{t}tH$ and $tH$ production with the Higgs boson decay into a bottom quark-antiquark pair (H → bb)
- three different final states of the t quark considered, defined by the number of leptons ($e/\mu$) in the event




Best fit:
$(k_t, \tilde{k}_t) = (0.82, -0.65)$

# $H \rightarrow \tau\tau$ | $H\tau\tau$ couplings

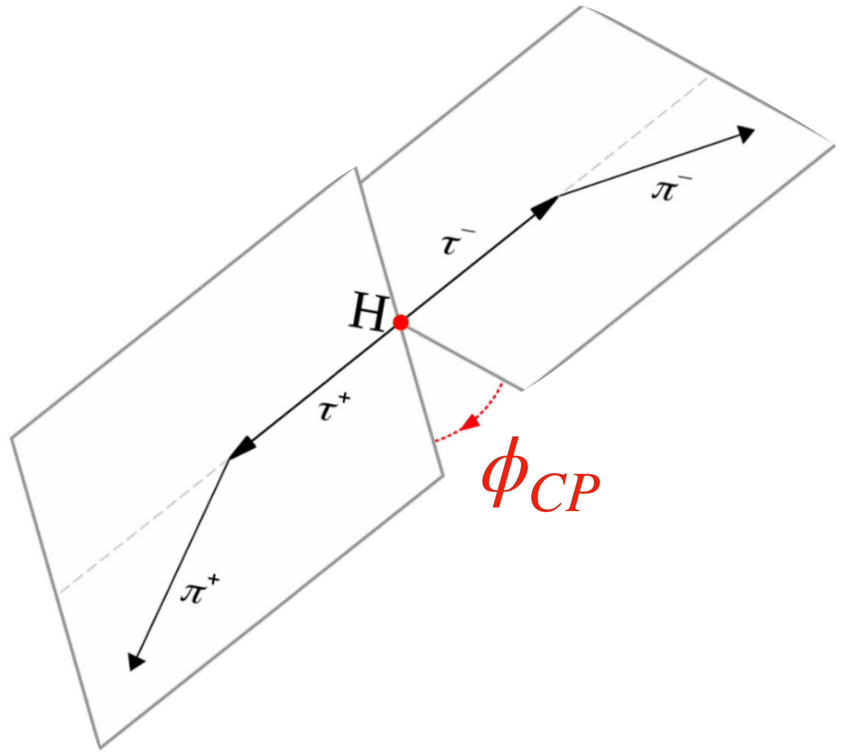



JHEP 06 (2022) 012

- To study the Hff couplings we can also target the $H\tau\tau$ coupling

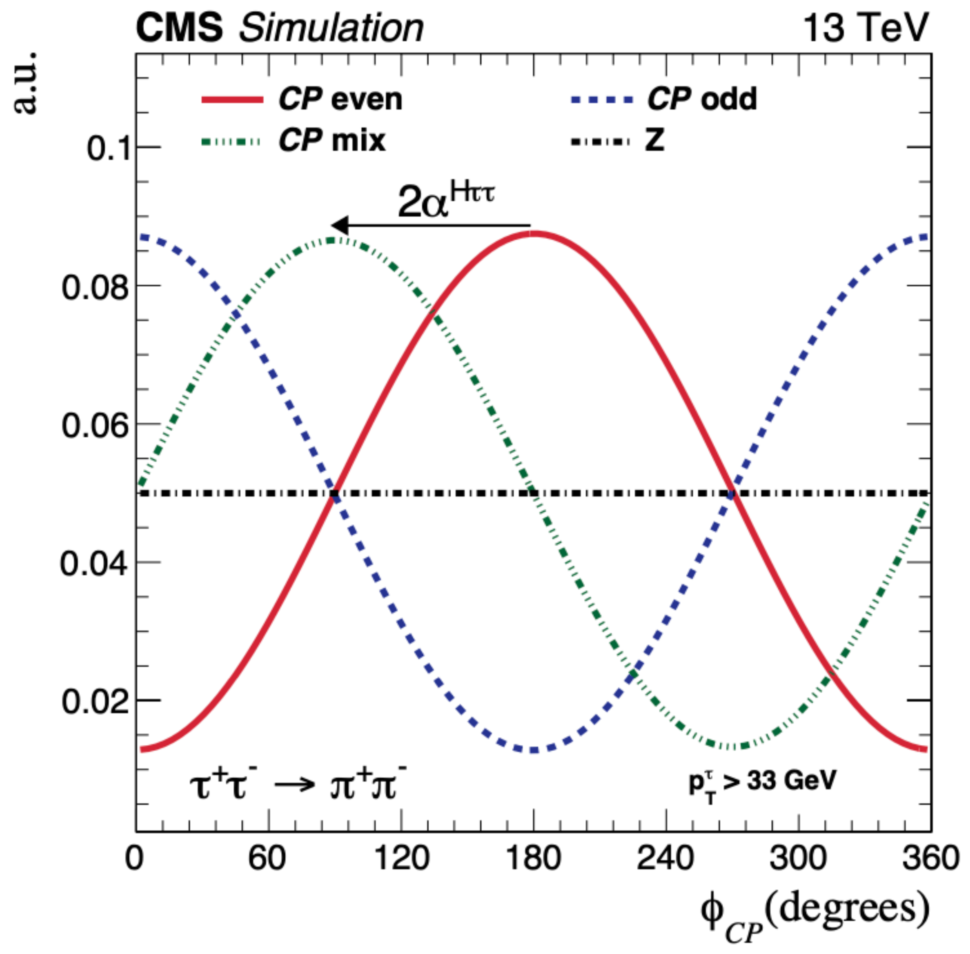
$$\mathscr{L}_Y = -\frac{m_\tau}{v} H(k_\tau \bar{\tau}\tau + \tilde{k}_\tau \bar{\tau} i\gamma^5 \tau)$$

- CP violation appears as a  phase shifting the cross section differential distribution in respect to $\phi_{CP}$: the angle between the τ lepton decay planes in the H rest frame



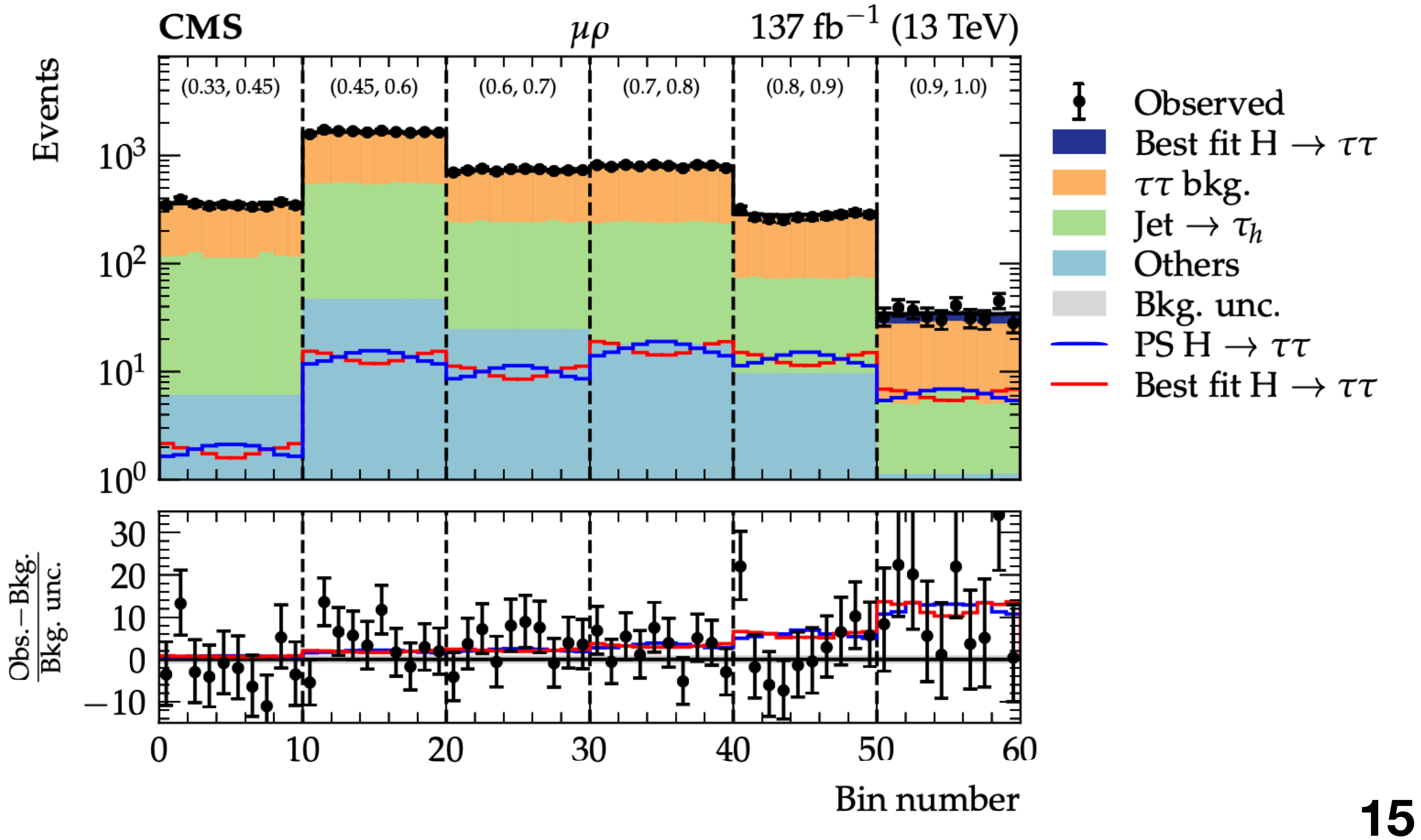

$$\frac{d\Gamma}{d\phi_{CP}}(H \rightarrow \tau^+\tau^-) \propto -cos(\phi_{CP} - 2\alpha^{H\tau\tau}) \qquad tan(\alpha^{H\tau\tau}) = \frac{\tilde{k}_\tau}{k_\tau} \longrightarrow$$

- $|\alpha^{H\tau\tau}|$ = 0° pure CP even
- $|\alpha^{H\tau\tau}|$ = 90° pure CP odd
- $|\alpha^{H\tau\tau}|$ = 45° maximal CP mixing

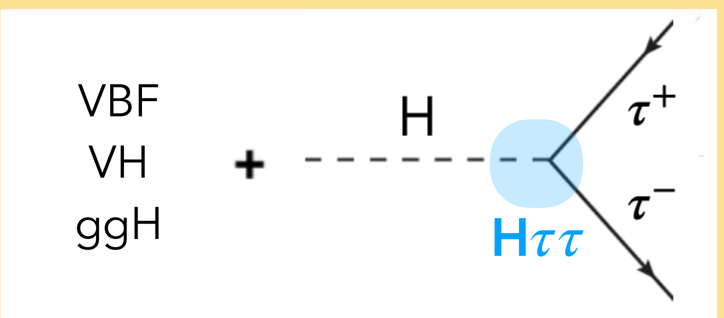



*Drell-Yan is flat in this distribution*

| | |
|---|---|
| $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ | |
| $\tau^- \rightarrow h^- \nu_\tau$ | |
| $\tau^- \rightarrow \rho(770)^- \nu_\tau$ | $\rho(770) \rightarrow h^- \pi^0 \nu_\tau$ |
| $\tau^- \rightarrow a_1(1260)^- \nu_\tau$ | $a_1(1260) \rightarrow h^- \pi^0 \pi^0 \nu_\tau$ |
| | $a_1(1260) \rightarrow h^- h^- h^+ \nu_\tau$ |

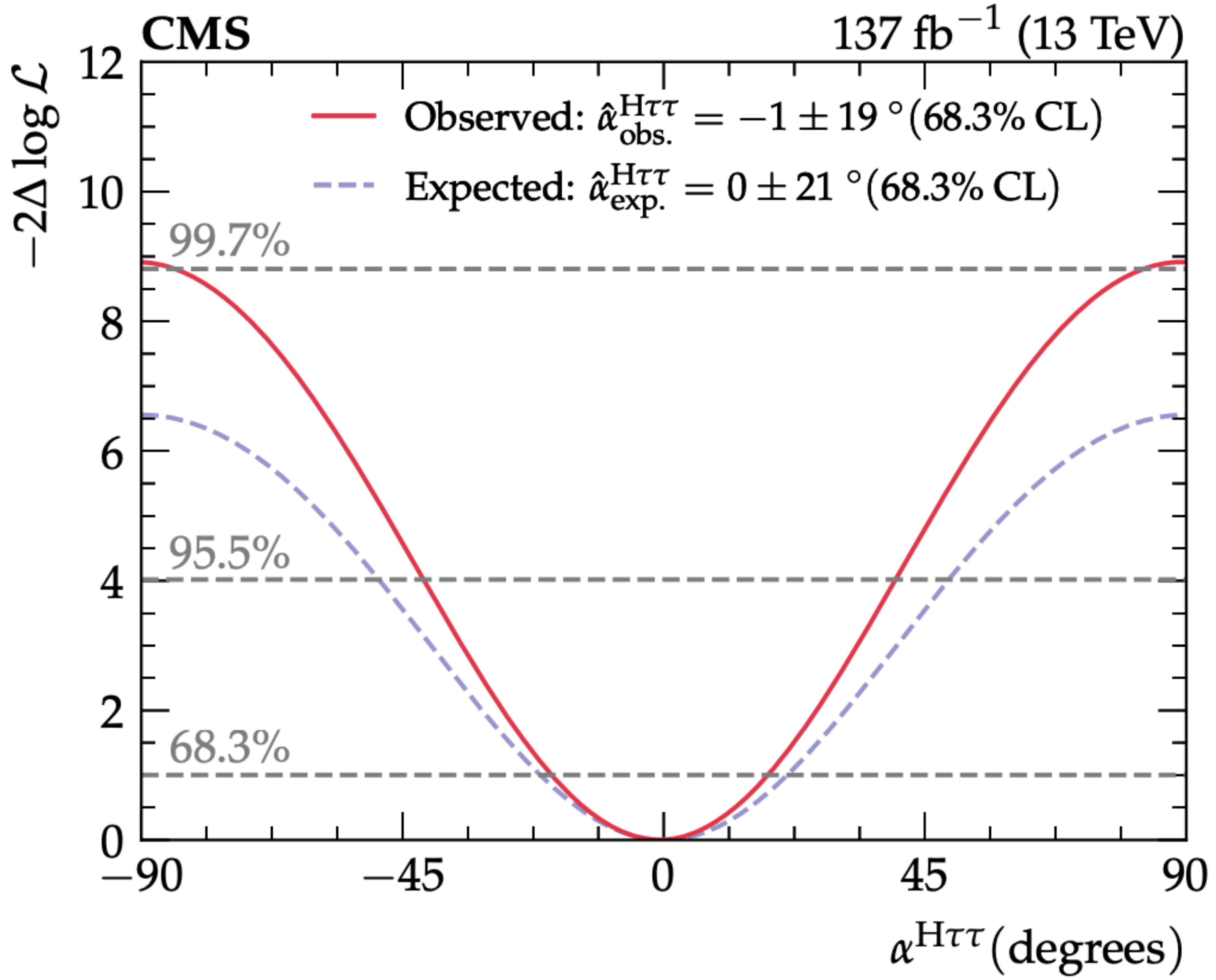


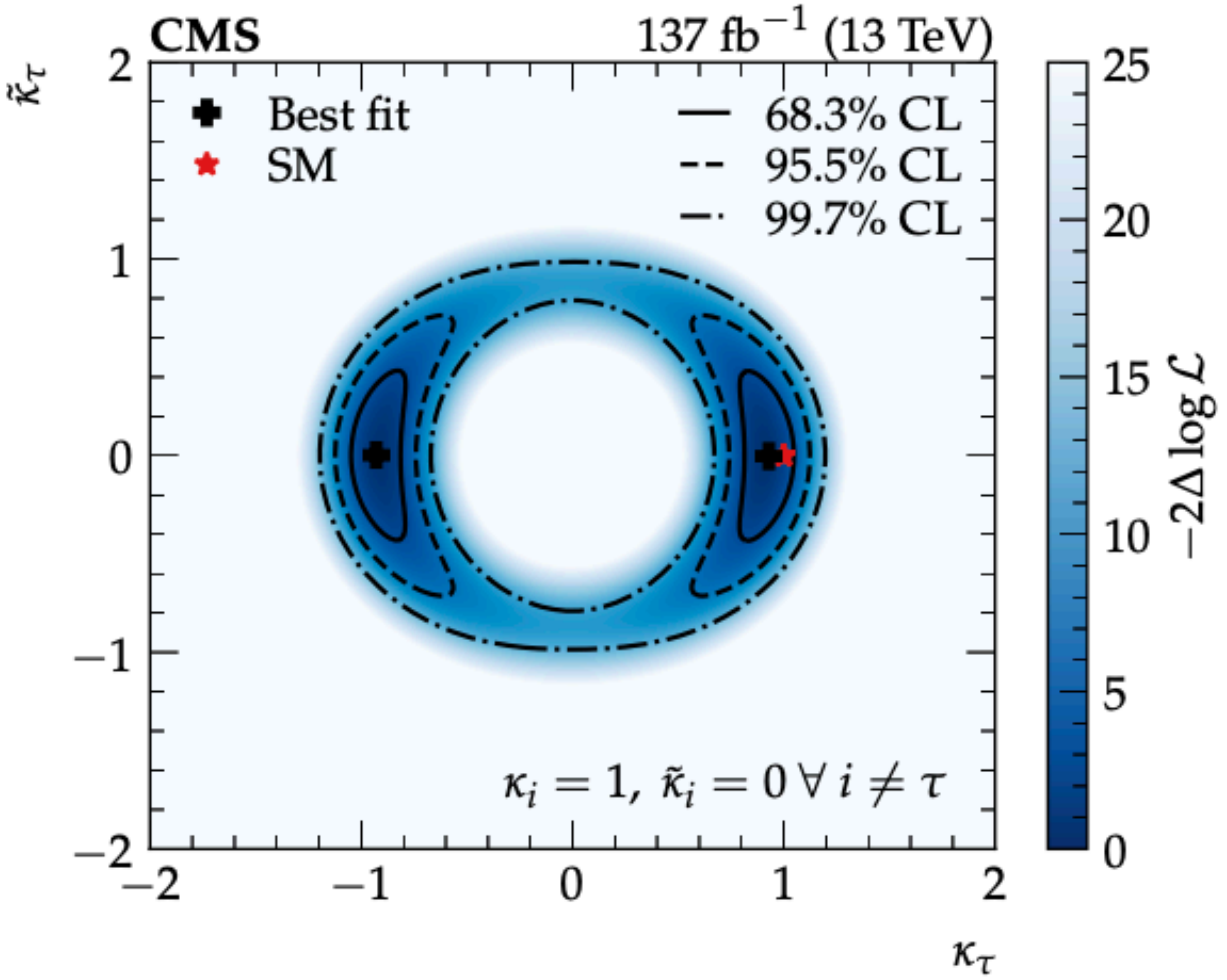
# $H \to \tau\tau$ | $H\tau\tau$ couplings




JHEP 06 (2022) 012

$$\alpha^{H\tau\tau} = -1 \pm 19\,(\text{stat}) \pm 1\,(\text{syst}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{theo})^\circ.$$




Exclusion of a pure CP-odd hypothesis at 3σ

# SUMMARY

- Studies on anomalous couplings are essential to understand the nature of the Higgs boson
- Analyses with the most stringent limits on CP violation and anomalous couplings presented by the CMS experiment have been addressed, all the results are in agreement with the SM
- A rapidly growing field with recent advances and possibilities for new interpretations
- Analyses are limited by statistical uncertainties, so we expect improvements from the increase in data.

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- Analyses are limited by statistical uncertainties, so we expect improvements from the increase in data.

Thanks for the attention!

# CP VIOLATION IN HVV

- Higgs anomalous couplings could be studied both in production and decay modes
- Decay:

  H → VV → 4 leptons [target -> HVV]
- Production:

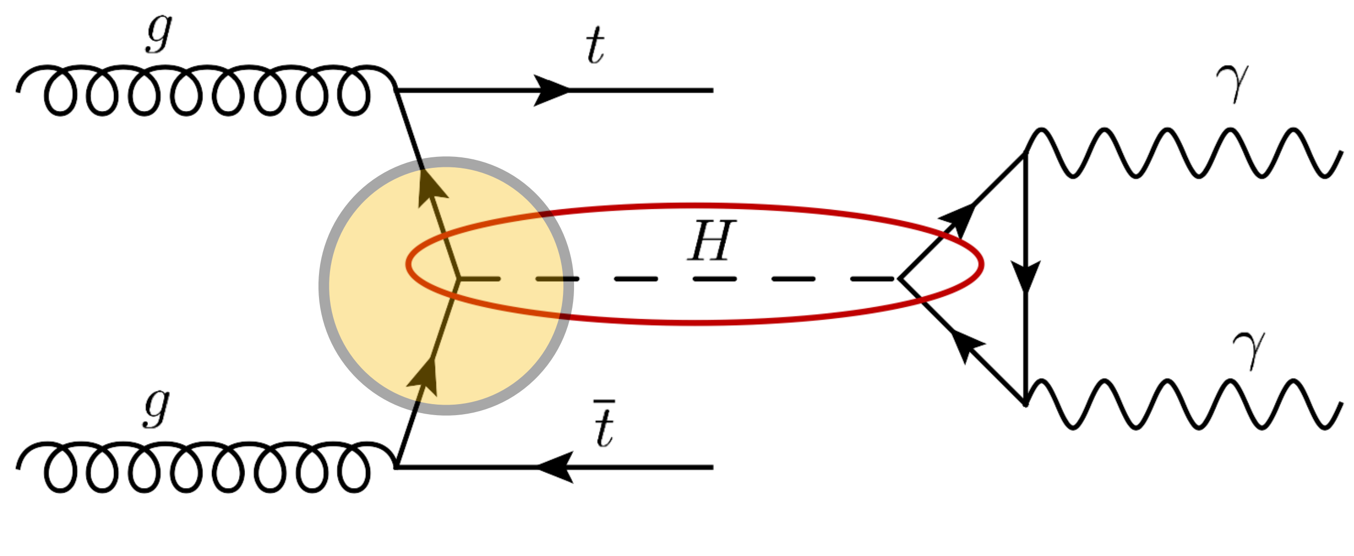
  Vector Boson fusion (VBF)  [HVV]

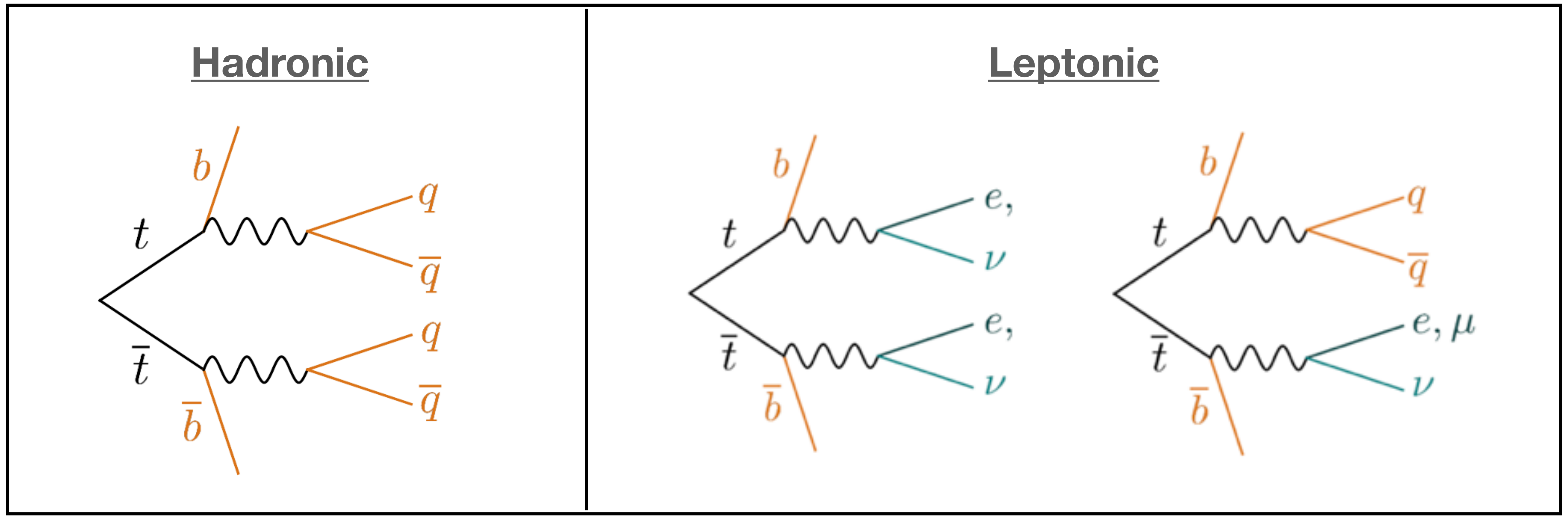
  Higgs production in association of a vector boson (VH)

  Studied in Higgs's decay in $\tau\tau$, ZZ and WW

# ttH [H]→γγ | Htt coupling

- First observation of the Htt coupling in a single decay channel.
- First analysis of the CP structure in ttH.



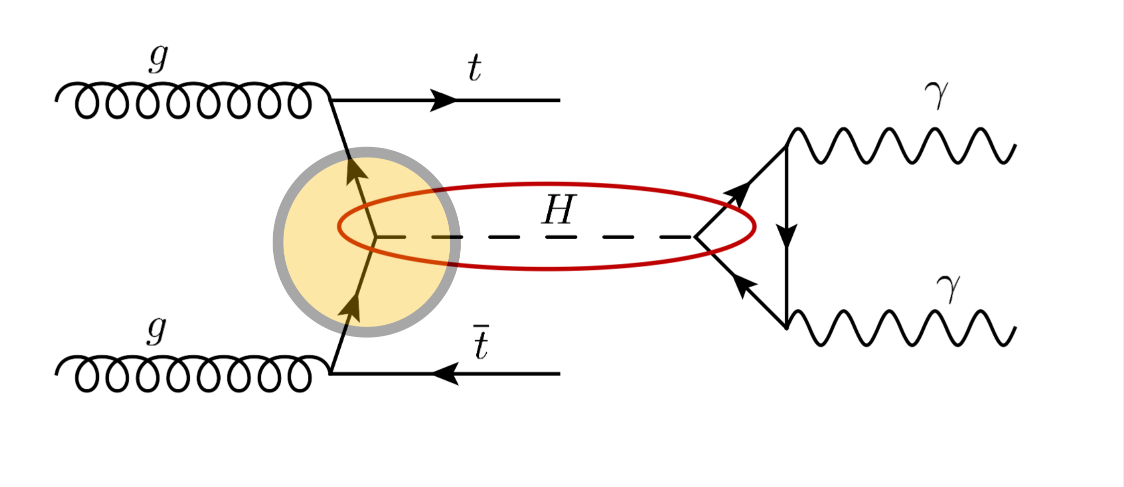




- BDT BKG to distinguish between ttH events and background (γγ + j / tt + γγ).
- Further categorization using MELA variables (Matrix Element Likelihood Analysis).

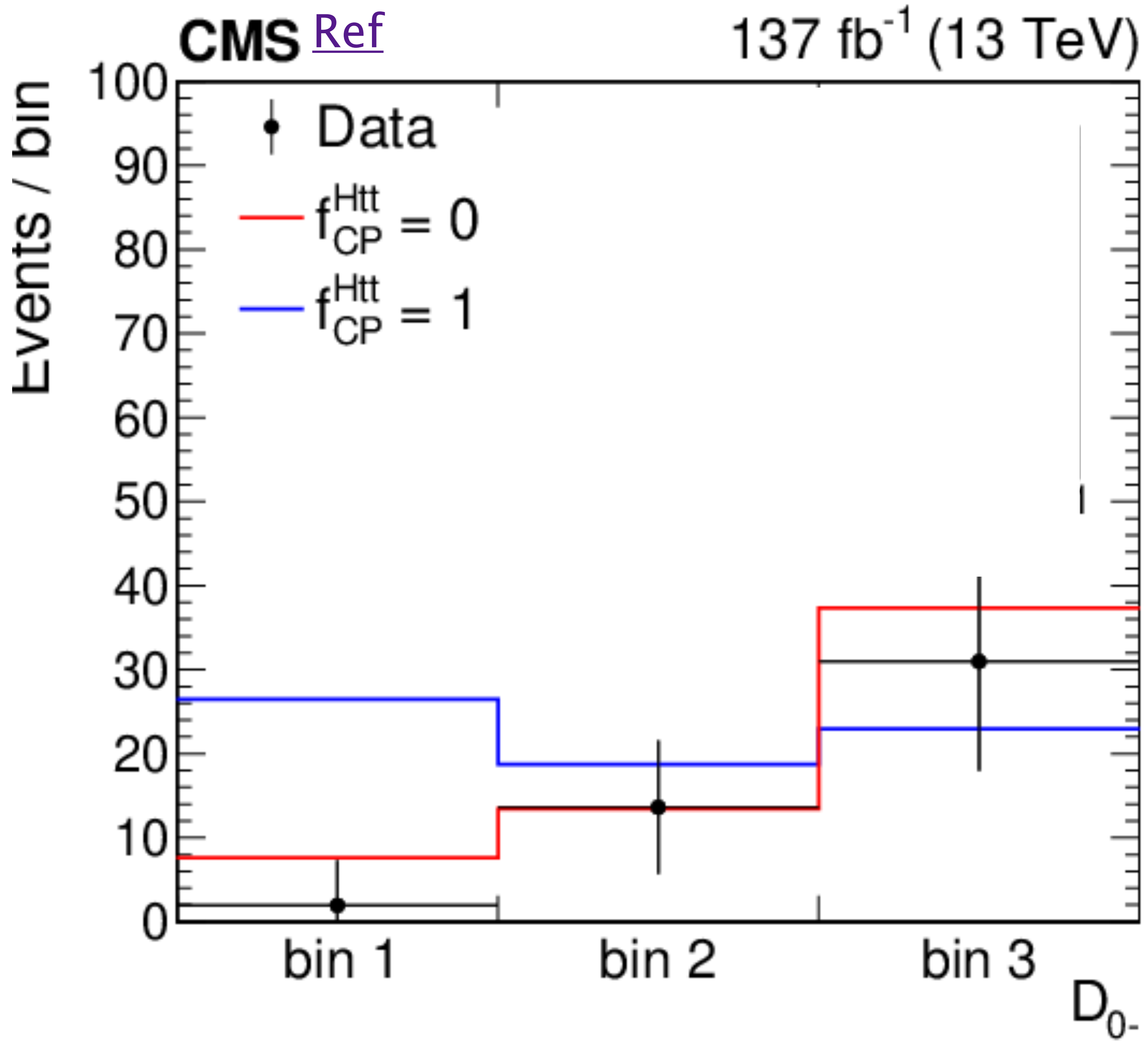
$$D_{alt}(\Omega) = \frac{P_{SM}(\Omega)}{P_{SM}(\Omega) + P_{alt}(\Omega)} \qquad D_{0^-}(\Omega) = \frac{P_{SM}(\Omega)}{P_{SM}(\Omega) + P_{0^-}(\Omega)}$$

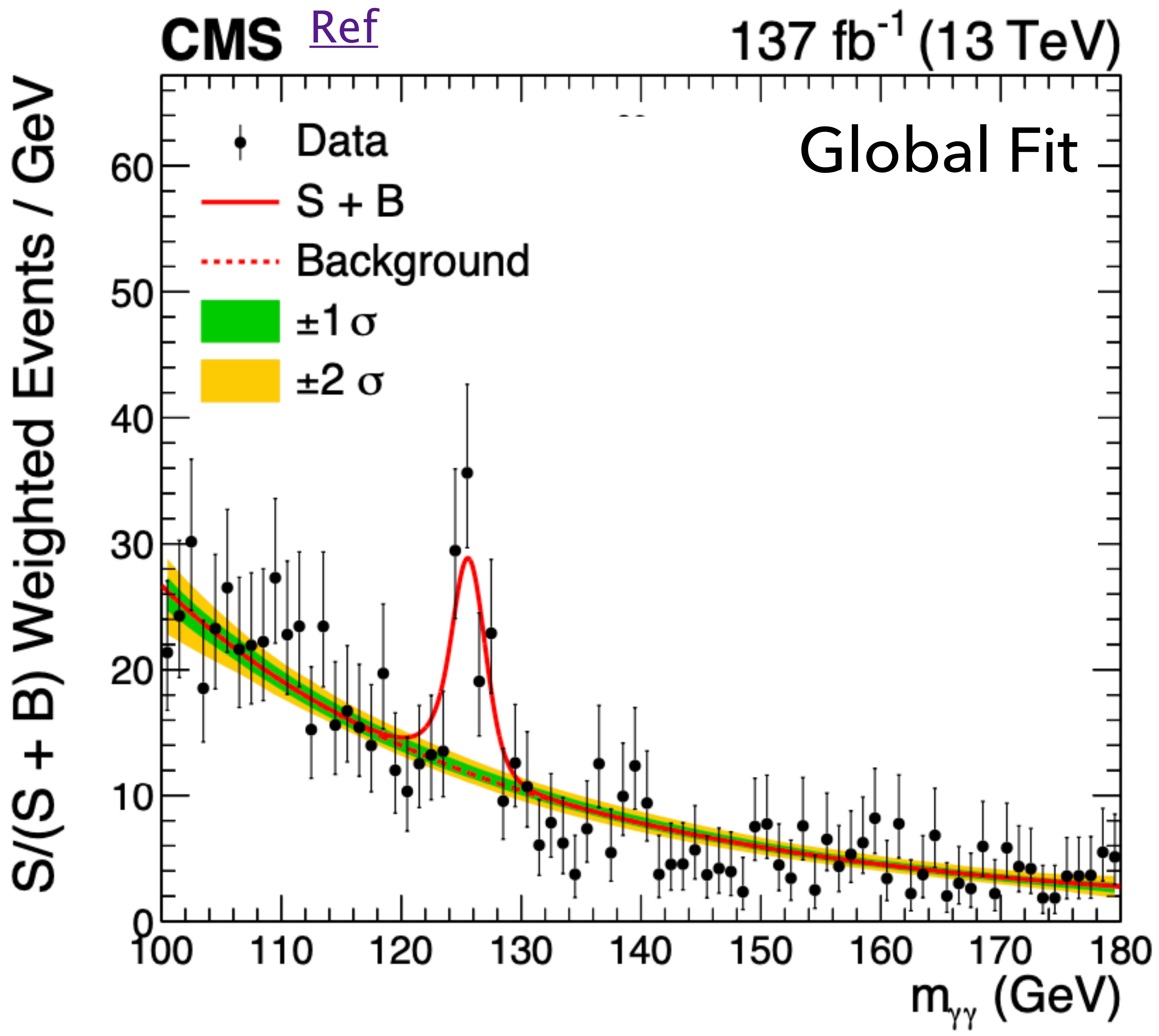
Ω = kinematics information
alt =alternative Hypothesis

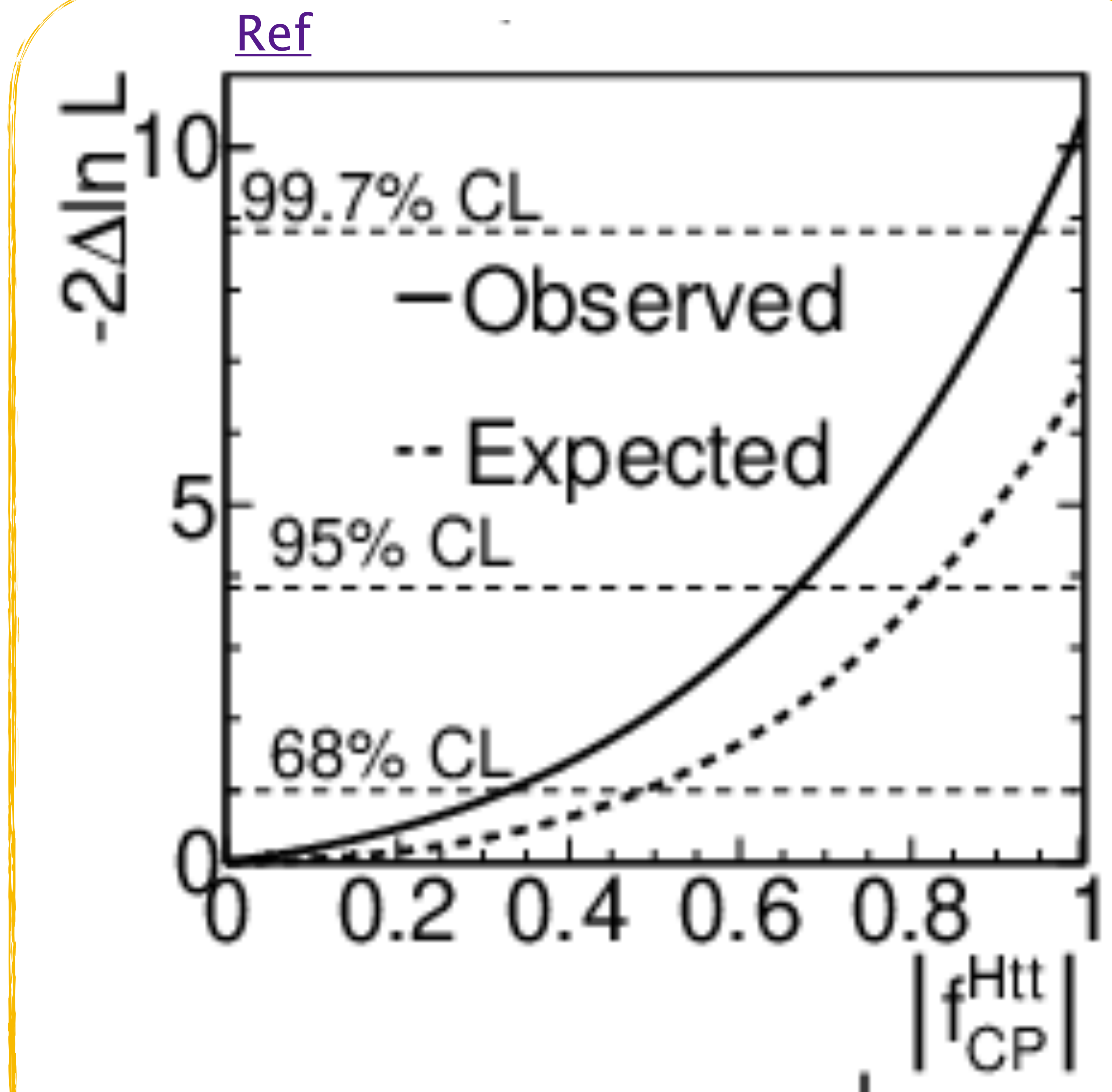
# ttH [H]→γγ | Htt coupling




The categories were defined using the output of the BDT (BDT bkg) and $D_0^-$ maximizing the analysis sensitivity to anomalous contributions.

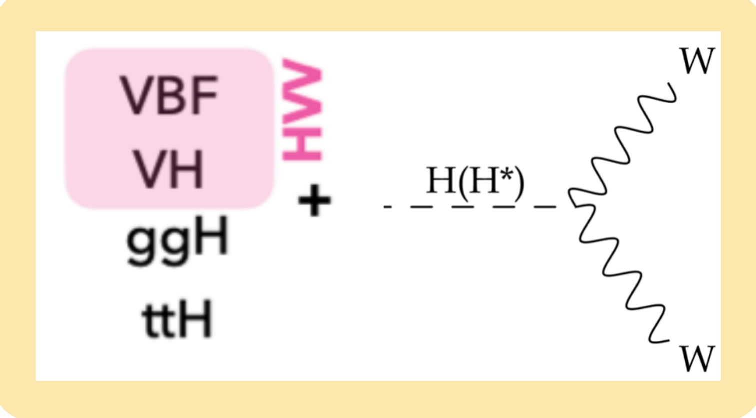


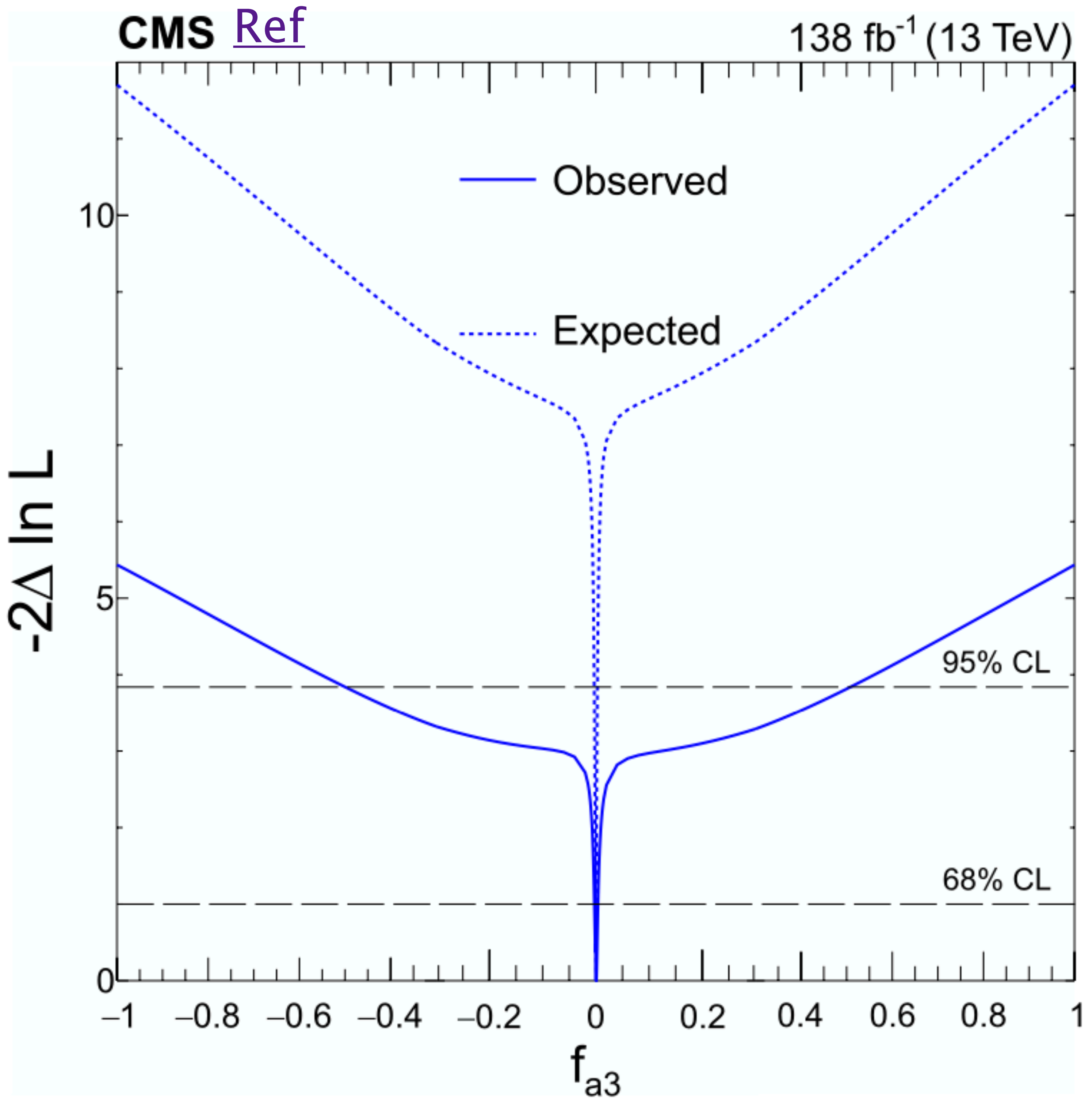




$f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% CL.

# H → WW | HVV couplings

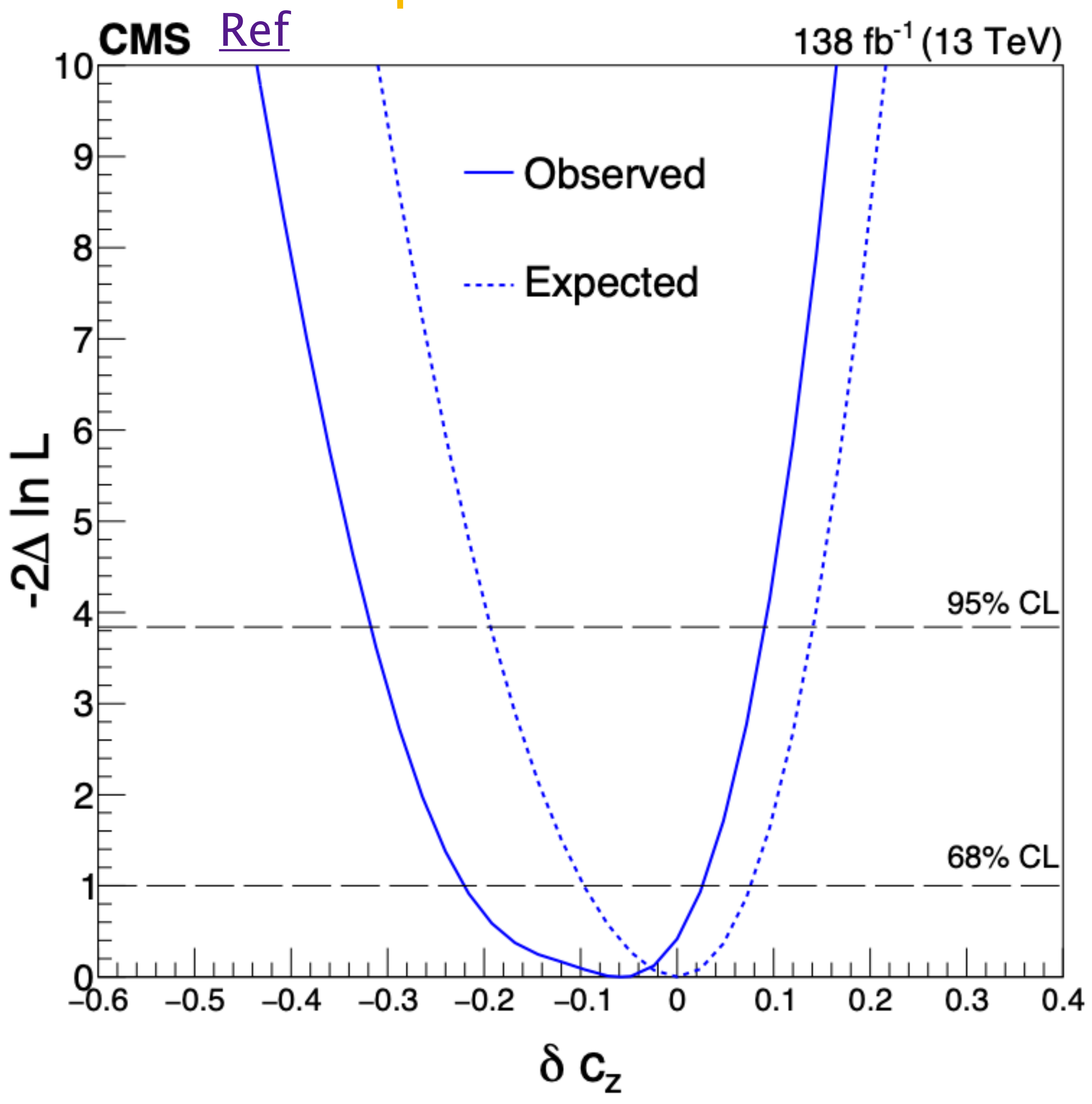



- Final state H → WW → μνeν
- Production modes considered ggH, VBF, VH (resolved and boosted)




*Fix others* → *95% CL [−0.553, 0.561]*

SMEFT interpretation



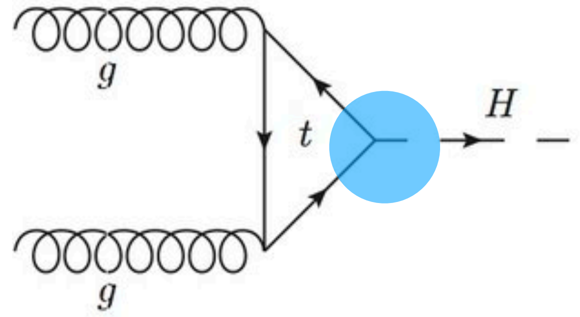
# ON SHELL H-4l | HVV, Hff couplings

1. Channels considered: 2e2μ, 4μ, and 4e in the Higgs decay
2. MELA variables to distinguish signal from background
3. Definition of specific categories for different anomalous couplings and different HVV and Hff interaction

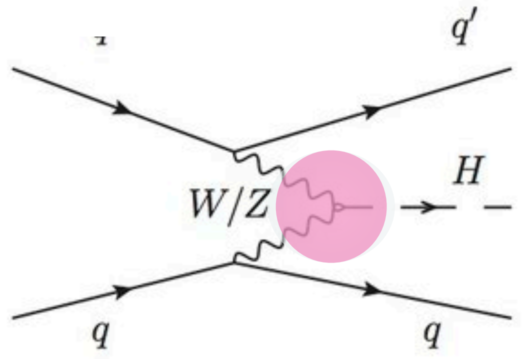
HVV : production and decay (V=ZZ,WW)

Htt : production

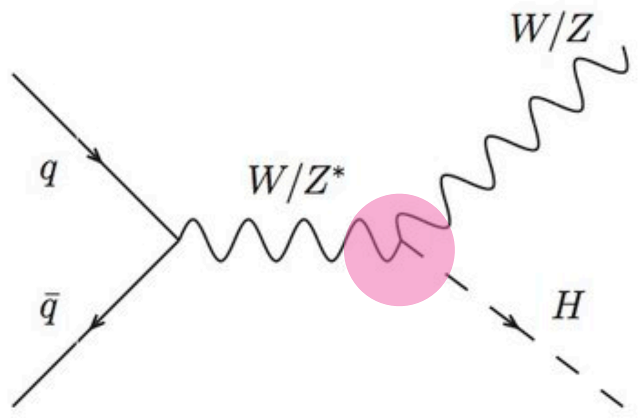
## PRODUCTION



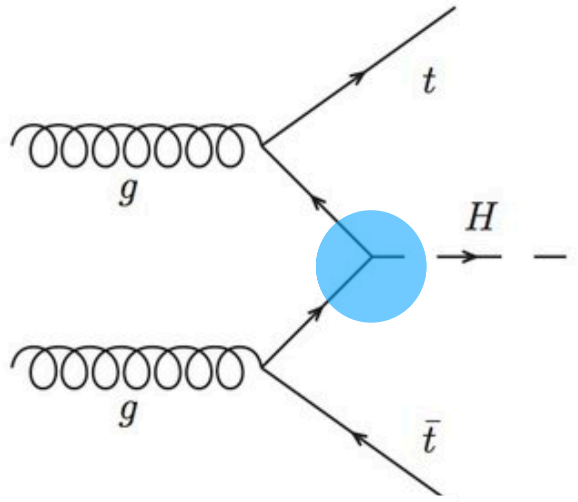

Gluon gluon fusion




Vector boson fusion




WW/ZZ bremsstrahlung




t-quark fusion

+

## DECAY