MEASUREMENT OF CP PROPERTIES AND ANOMALOUS COUPLINGS OF THE HIGGS BOSON

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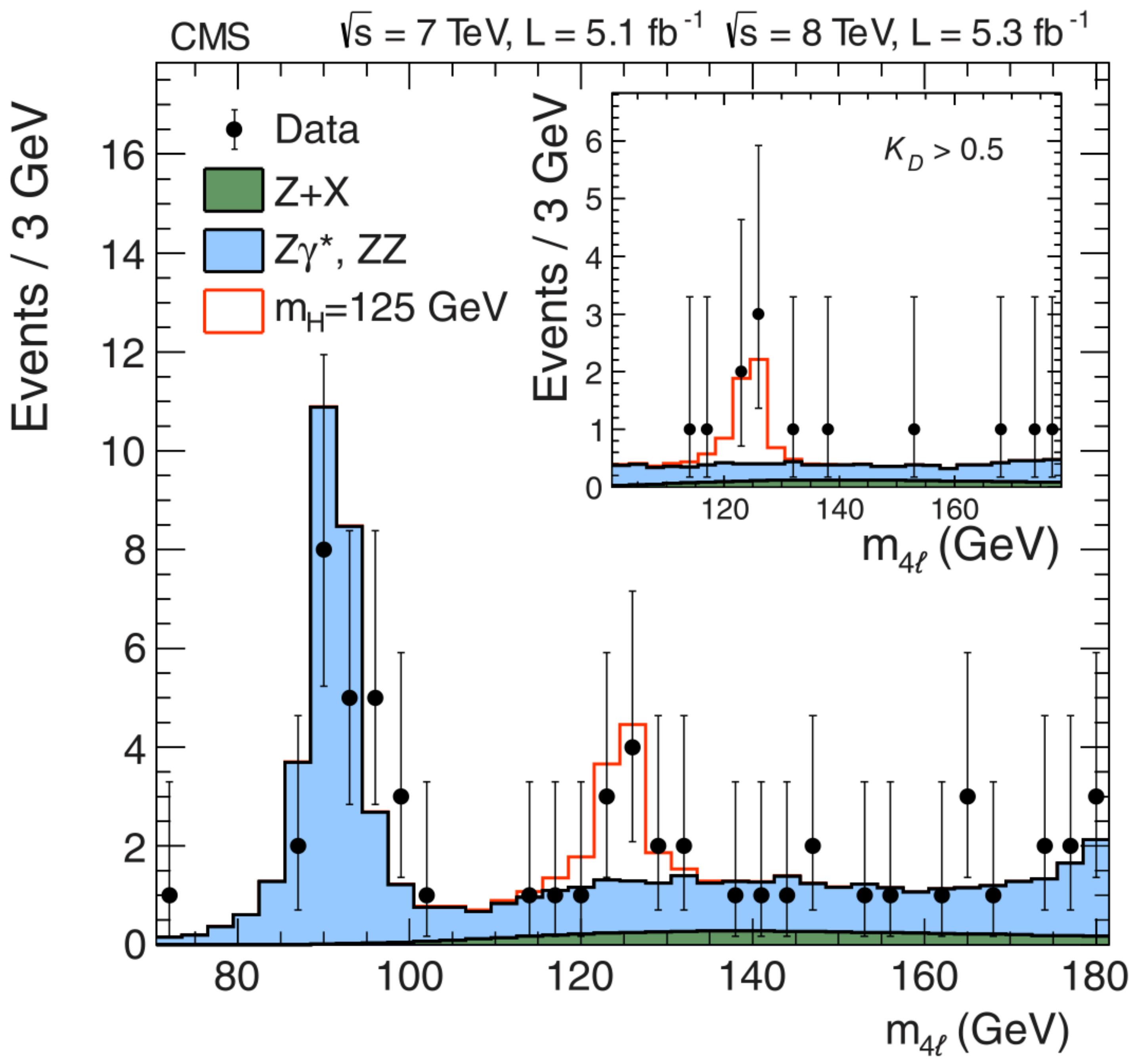
CMS

HIGGS BOSON PROPERTIES



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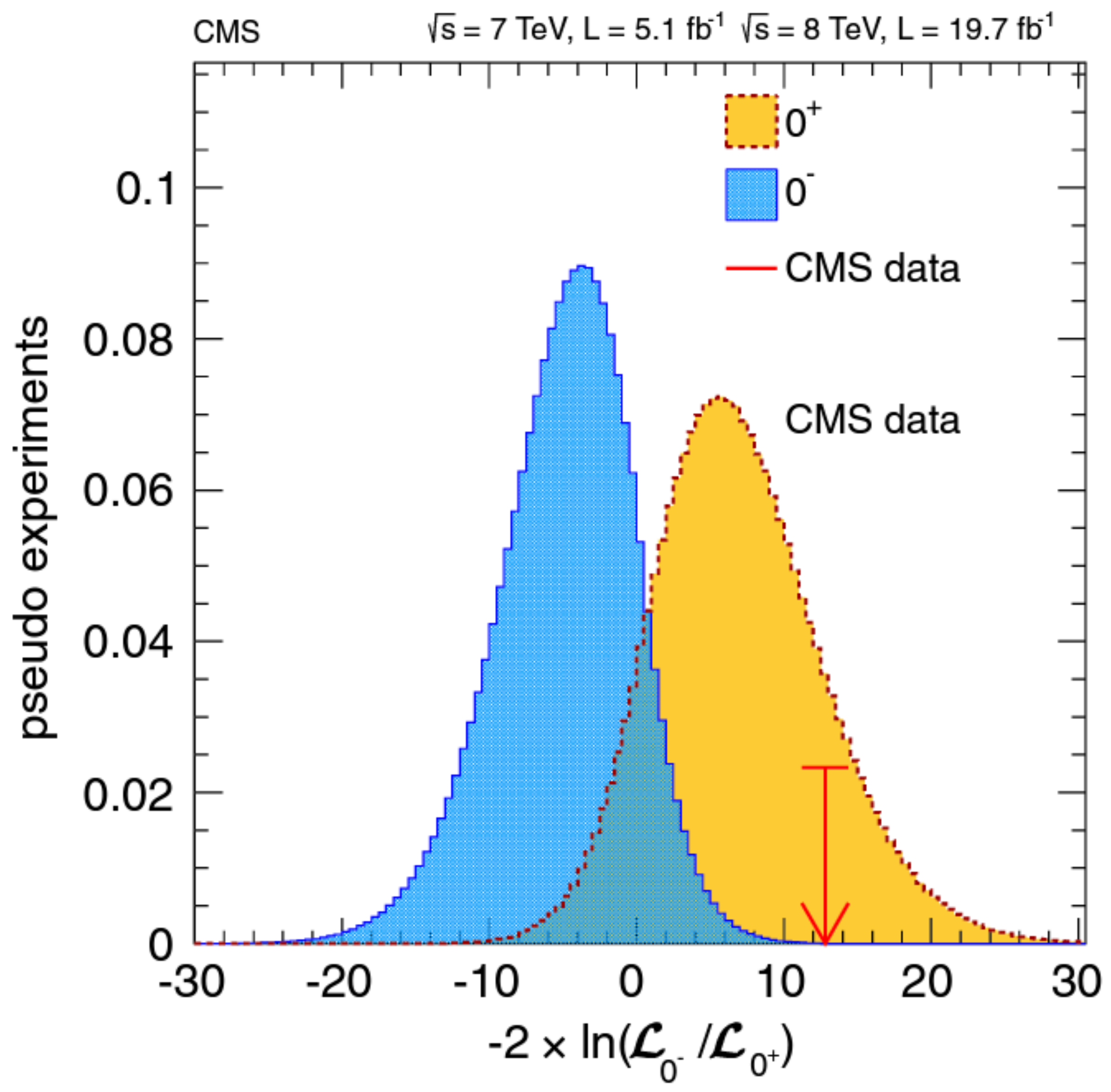
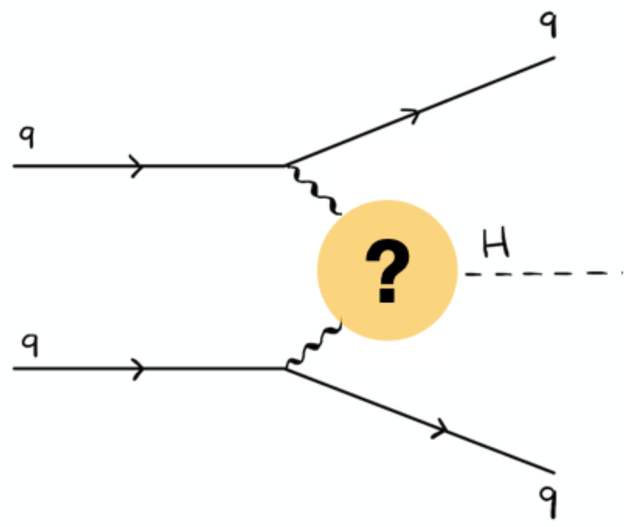


Neutral scalar particle

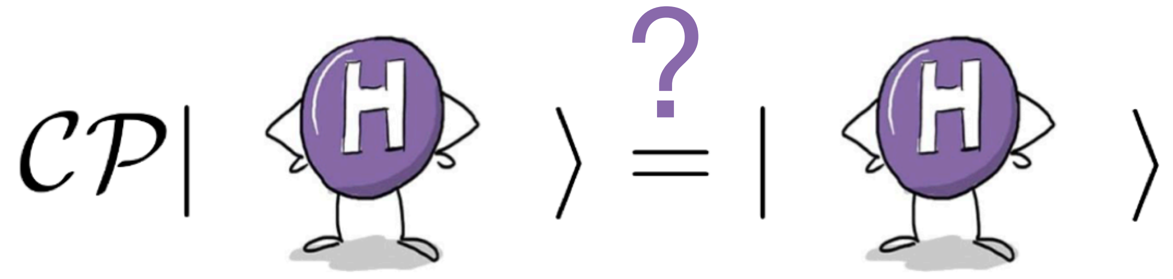
$J^{PC} = 0^{++}$

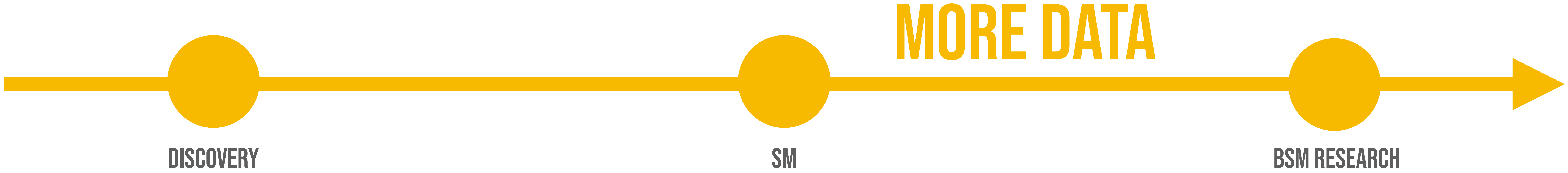
The hypothesis of a pseudoscalar particle has been excluded at 99.95%

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.





BSM COUPLINGS | HVV

Tree level — Loop level

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

SM : VV = ZZ,WW

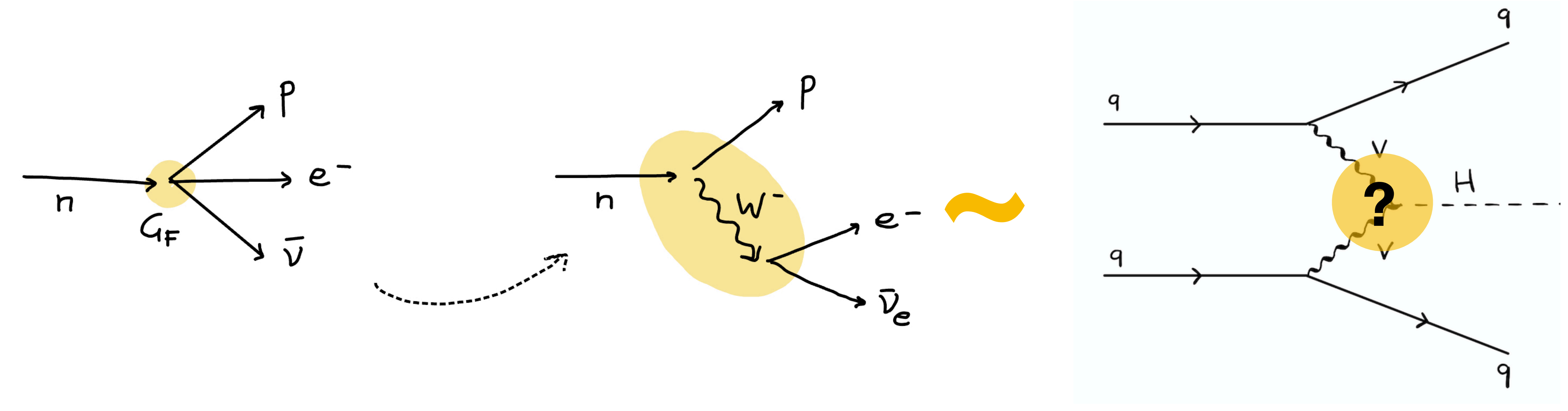
New physics scale

($\Lambda_1 = 1 TeV$)

CP even

CP odd

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



AC Approach (Anomalous Coupligs)

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

4 anomalous couplings

$a_2(CP)$

$\cancel{a_3(CP)}$

$a_{\Lambda_1}(CP)$

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

ACCOPPIAMENTI BSM | HVV

Tree level

Loop level

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

SM : VV = ZZ,WW

Scala di nuova fisica

$(\Lambda_1 = 1 TeV)$

CP pari

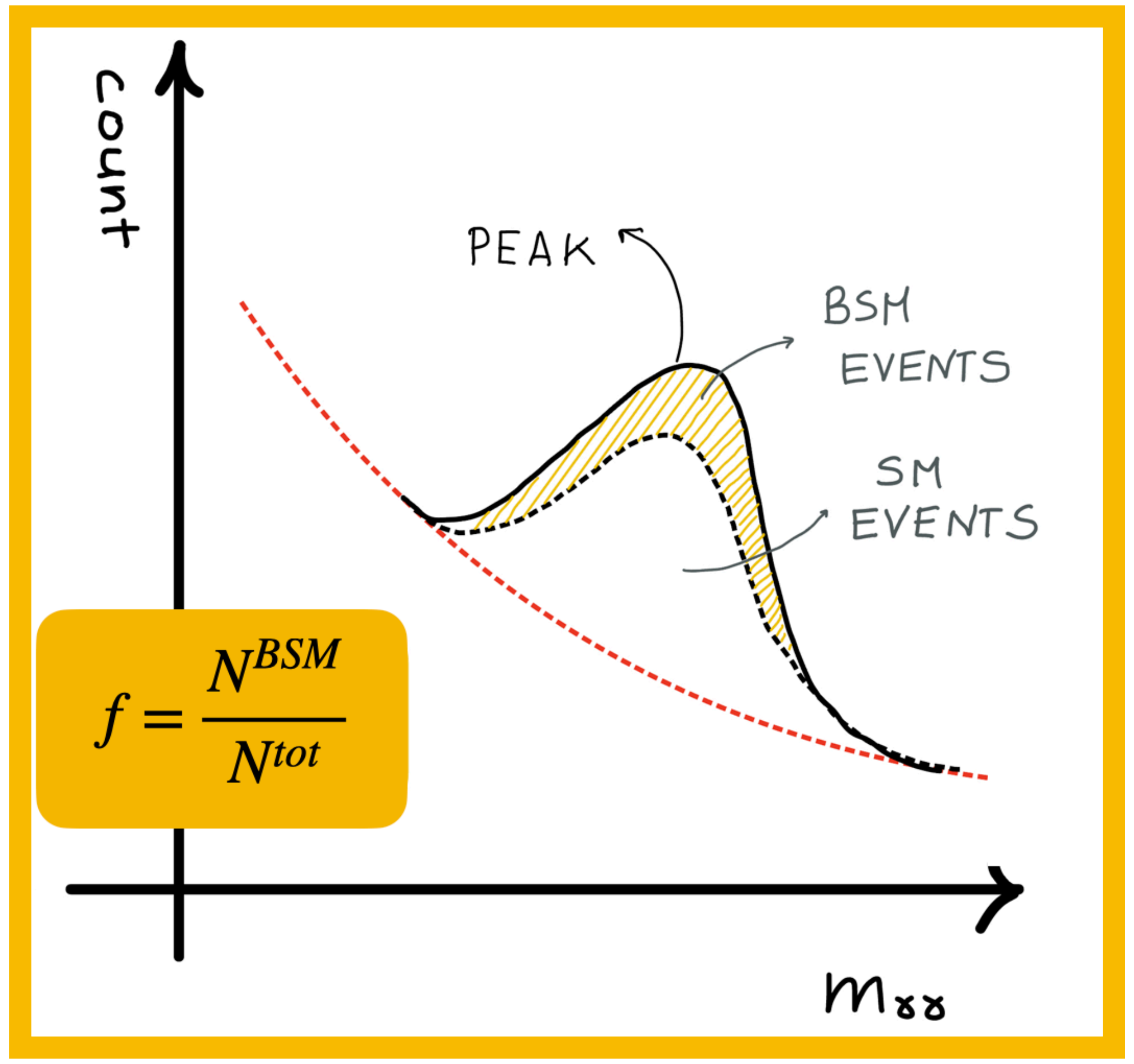
CP dispari

EFFECTIVE CROSS SECTION FRACTIONS

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

- Indipendent of Γ_H
- Limited between [-1,1]

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



σ_i cross section of the process with $a_i = 1$

BSM COUPLINGS | Hff

$\tilde{\psi}_f, \psi_f \rightarrow$ Dirac spinors
$m_f \rightarrow$ fermion mass
$v \rightarrow$ Vacuum expectation value.
$k_f \rightarrow$ CP-even Yukawa coupling modifier.
(SM : $k_f = 1$)
$\tilde{k}_f \rightarrow$ CP-odd Yukawa coupling modifier.
(SM : $\tilde{k}_f = 0$)

$$A(Hff) = -\frac{m_f}{v}\bar{\psi}_f(\underbrace{k_f}_{\text{SM}} + i\underbrace{\tilde{k}_f}_{\text{CP odd}}\gamma_5)\psi_f$$

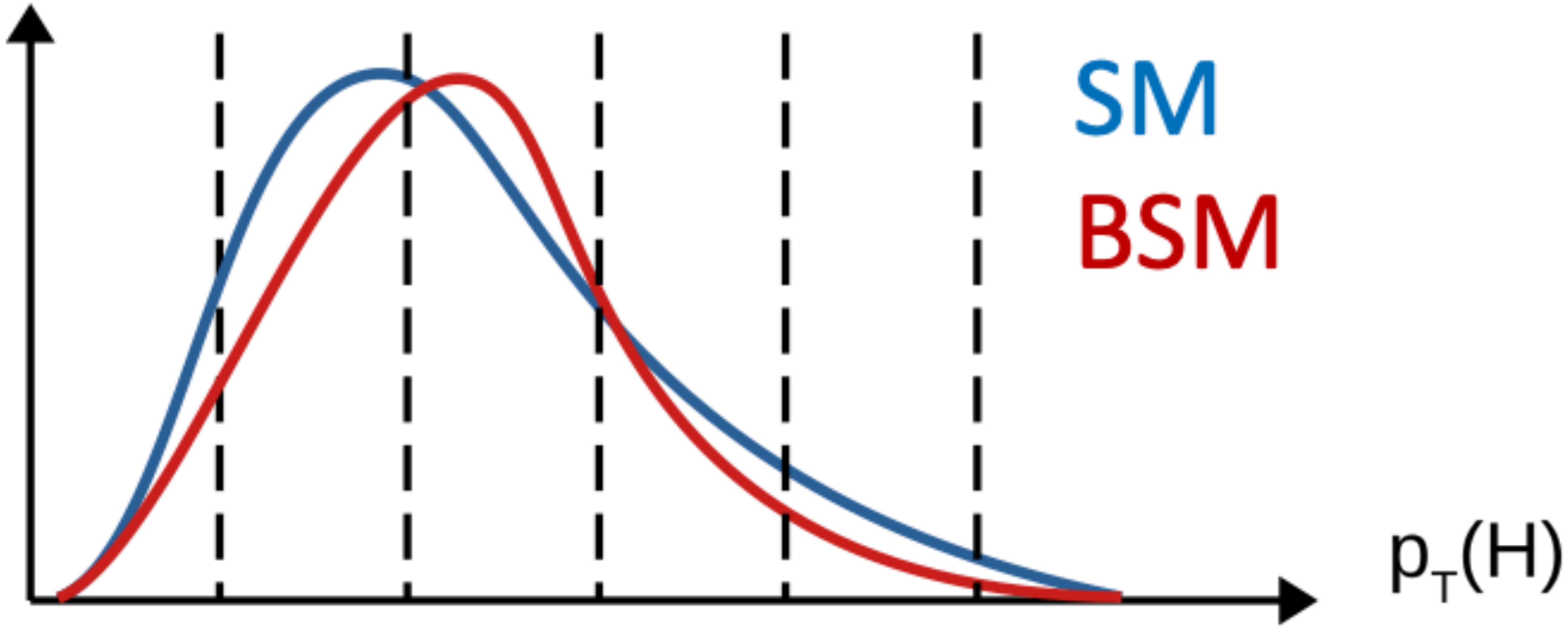
EFFECTIVE CROSS SECTION FRACTIONS

$$f_{CP}^{Hff} = \frac{|\tilde{k}_f|^2}{|k_f|^2 + |\tilde{k}_f|^2} sign\left(\frac{\tilde{k}_f}{k_f}\right) \qquad \alpha^{Hff} = tan^{-1}\left(\frac{\tilde{k}_f}{k_f}\right)$$

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 → $\tau\tau$	HVV,Hff	H → ZZ + H → $\tau\tau$	Phys. Rev. D 108 (2023) 032013

KEY POINT OF ALL THE ANALYSIS



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

Obviously, using all the kinematic variables available would make the analysis very complex so we choose to create ad hoc variables for the problem of interest that summarize the kinematic variables.

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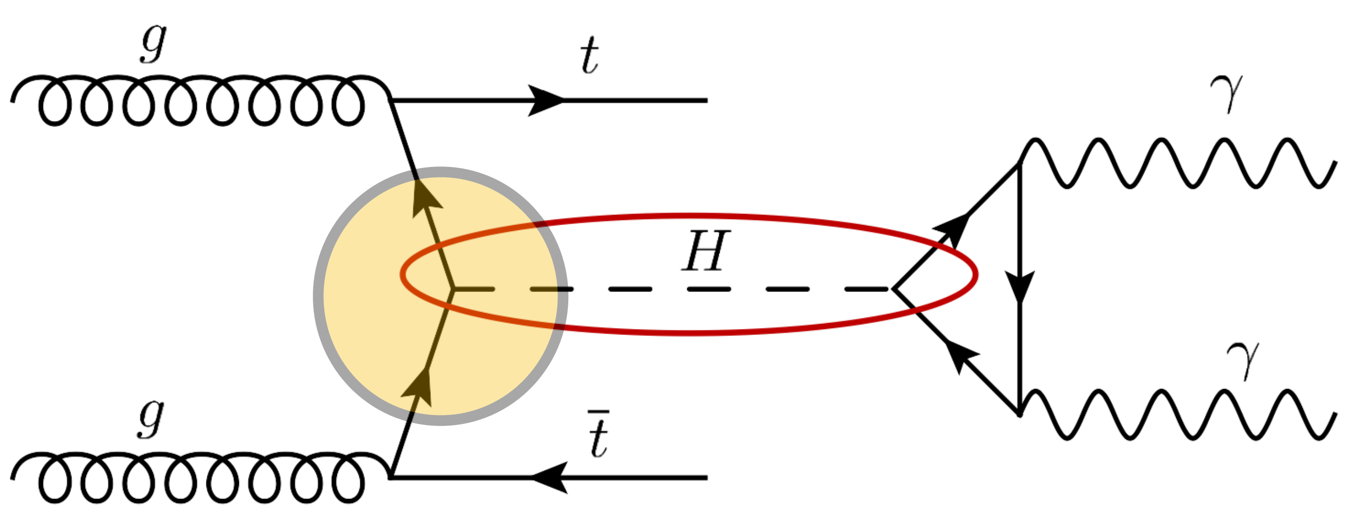
"Measurements of ttH production and the CP structure of the Yukawa interaction between the Higgs boson and the top quark in the diphoton decay channel"

ttH [H]→γγ | Htt coupling

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

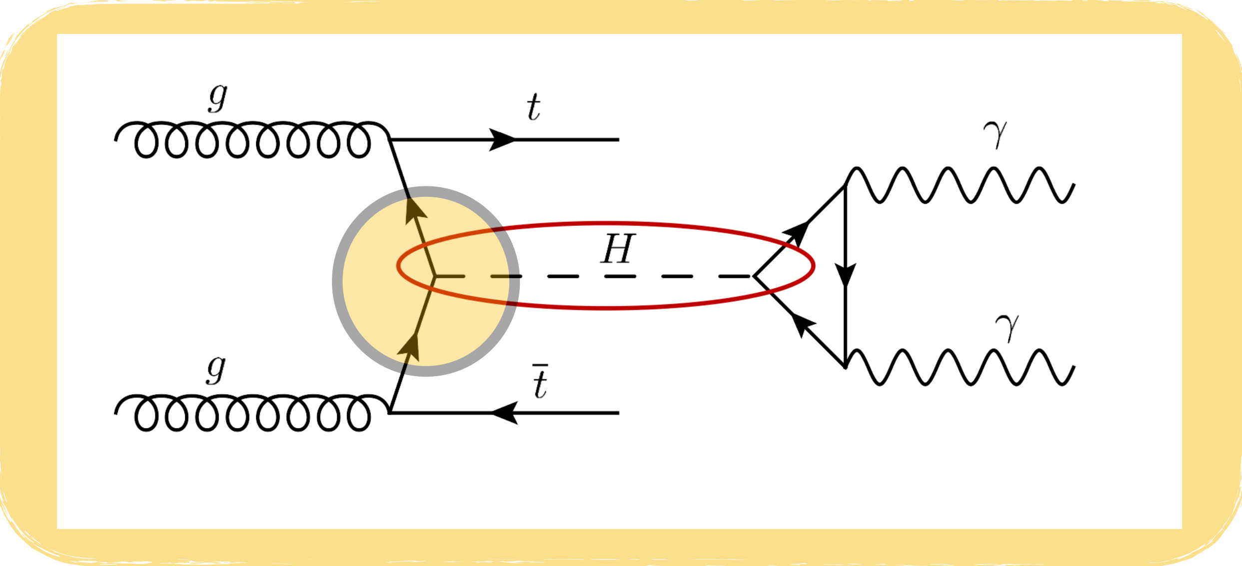


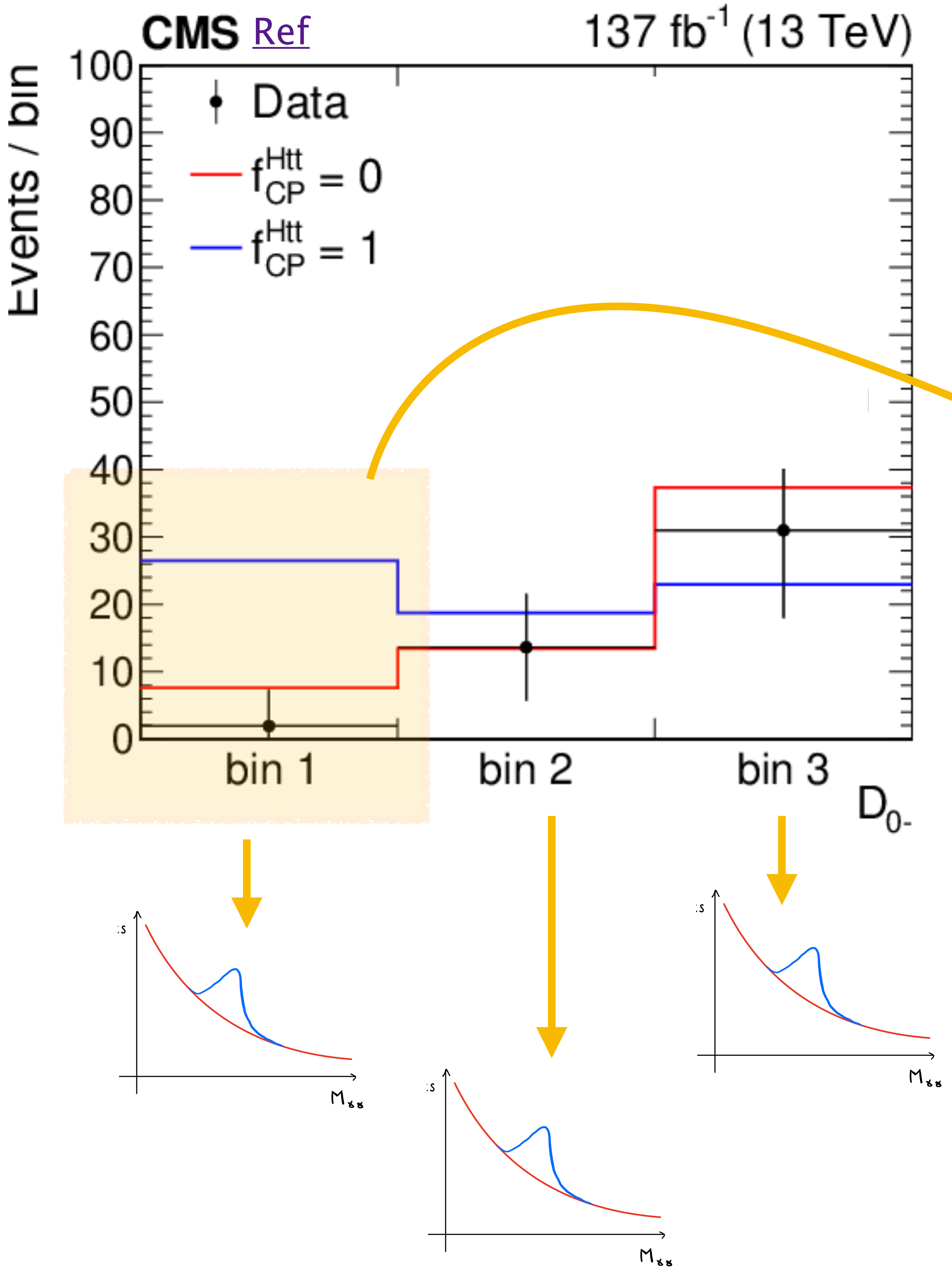
- BDT BKG to distinguish between ttH events and background (γγ + j / tt + γγ).
- Further categorization using MELA variables (Matrix Element Likelihood Analysis).

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

Ω = kinematics information
alt =alternative Hypothesis

ttH [H]→γγ | Htt coupling





D_0^- summerize the kinematics information to maximize the analysis sensitivity to anomalous contributions.

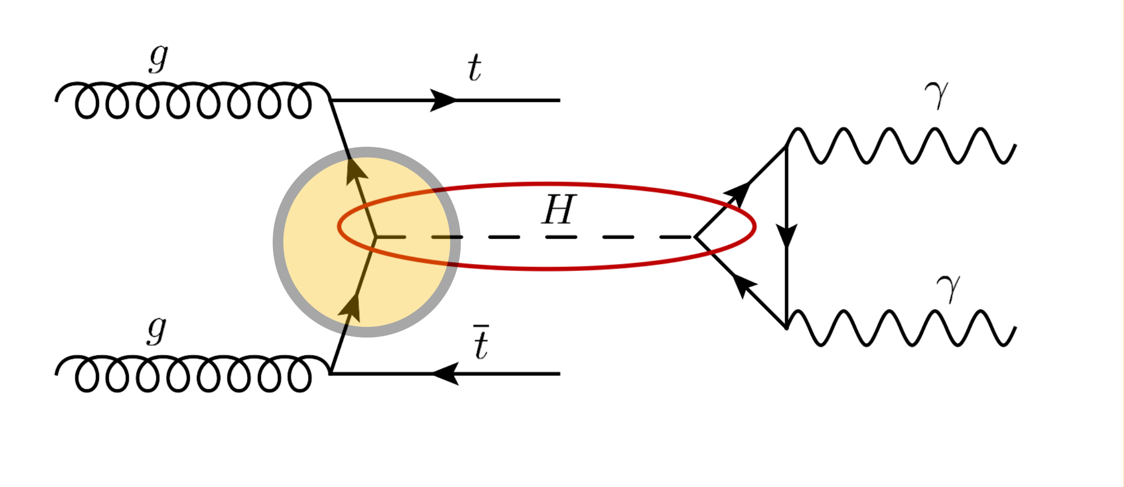
$f_{CP} = 1$ (all BSM type of events) → bin 1 = **26** events

$f_{CP} = 0$ (all SM type of events) → bin 1 = **8** events

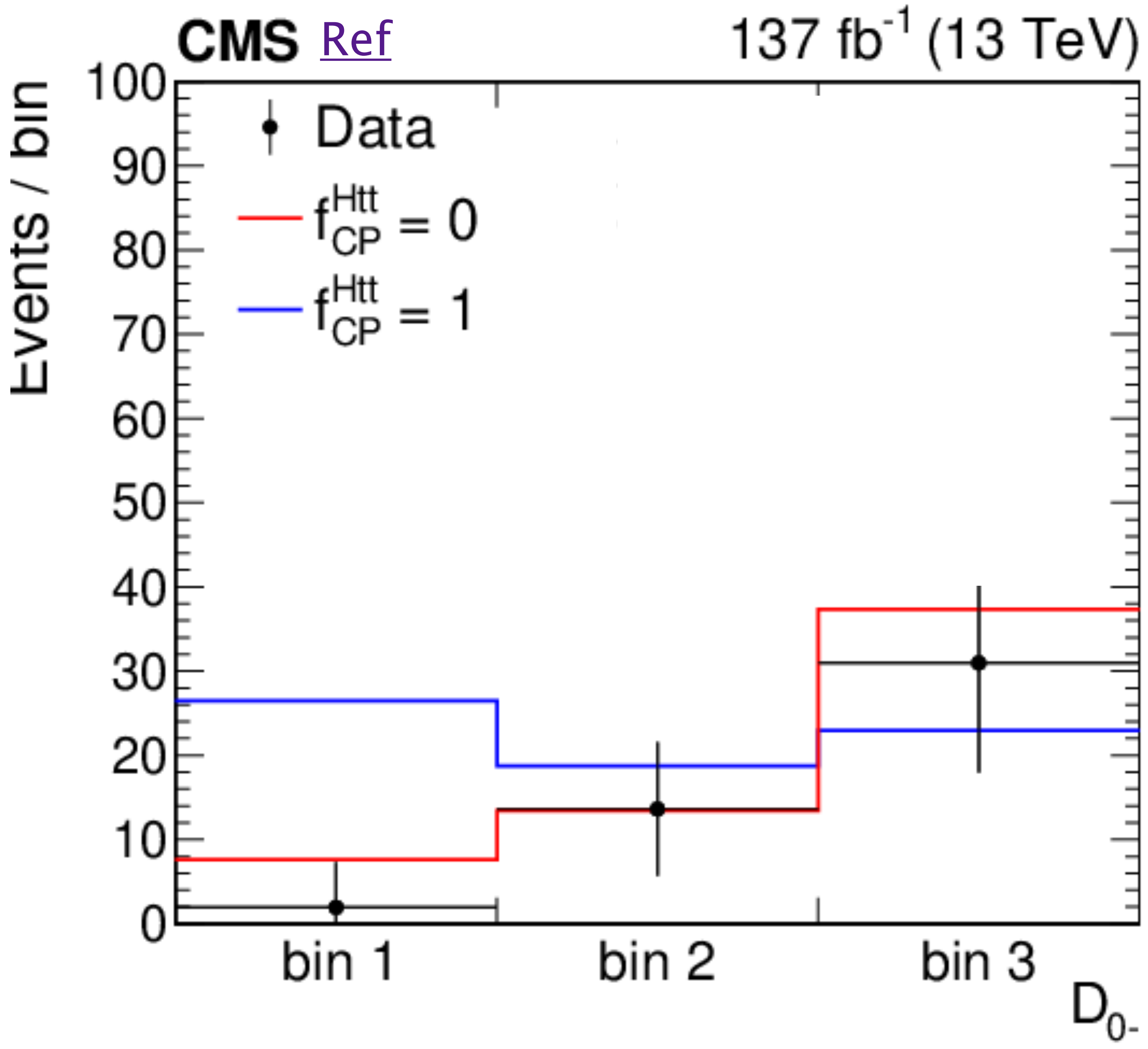
The number of events expected in each bin is the Key point to perform a fit in the $M_{\gamma\gamma}$

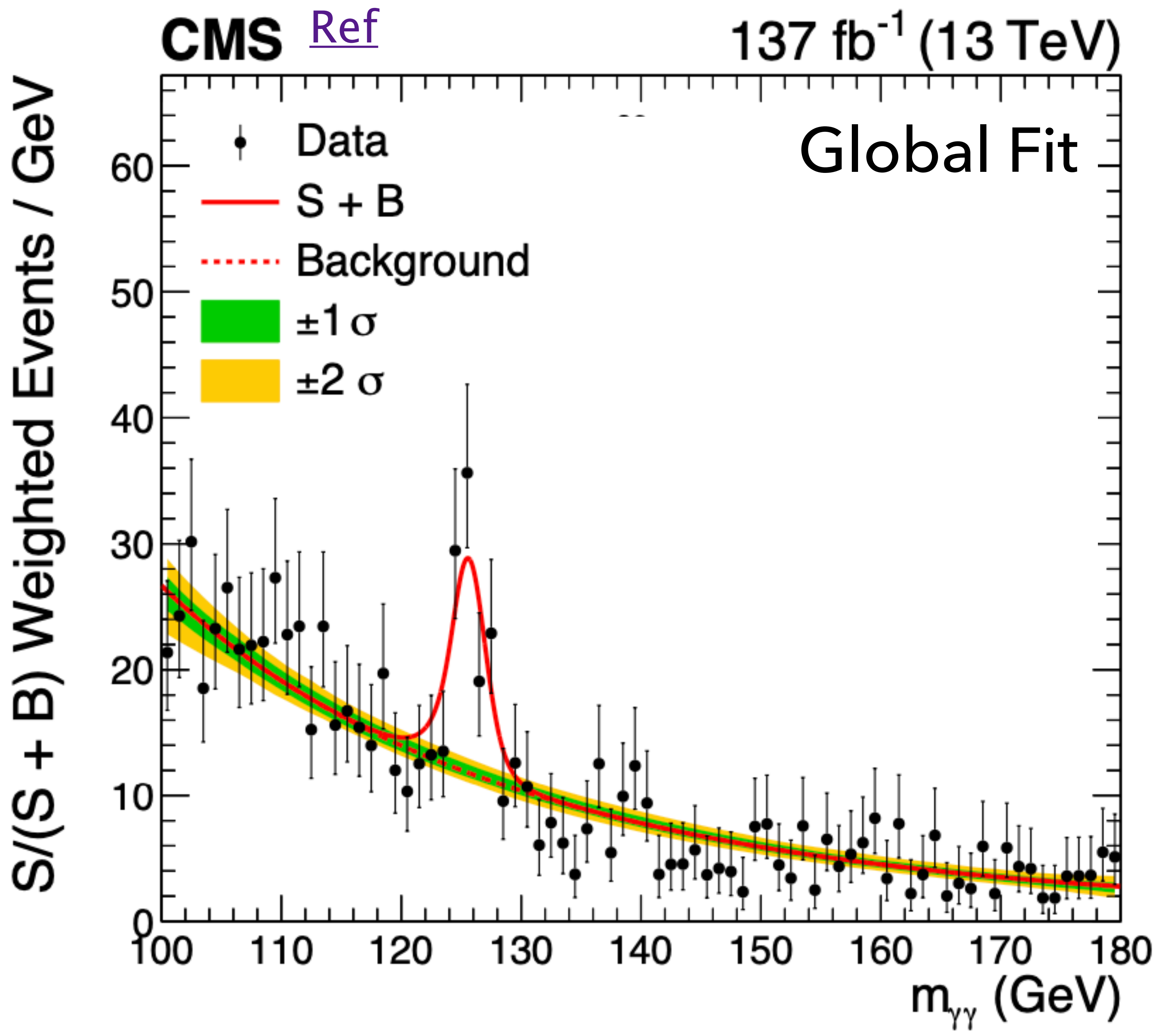
Then the fits will be combined to perform a global fit!

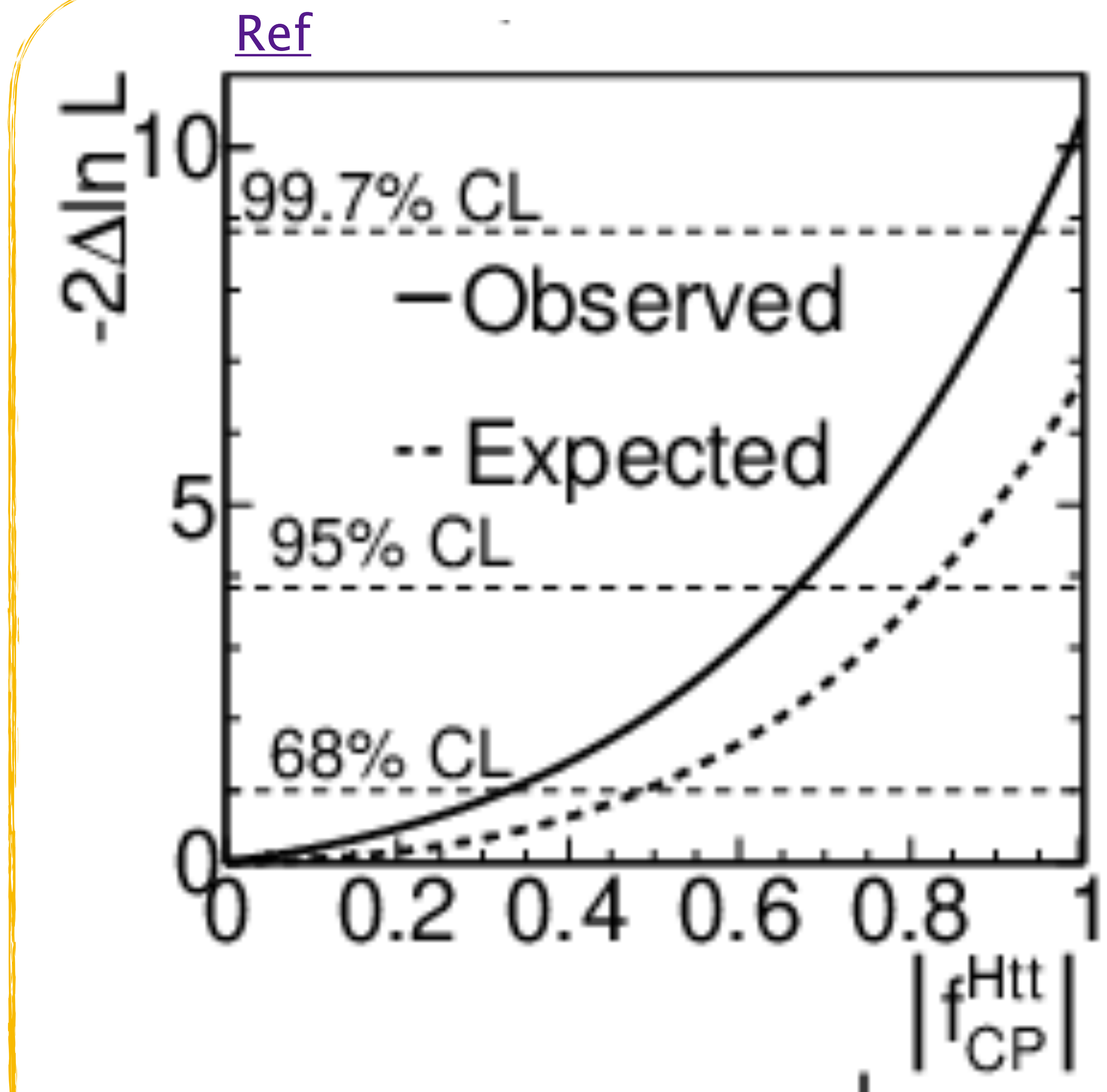
ttH [H]→γγ | Htt coupling



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







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

CMS ANALYSIS

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"Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state"

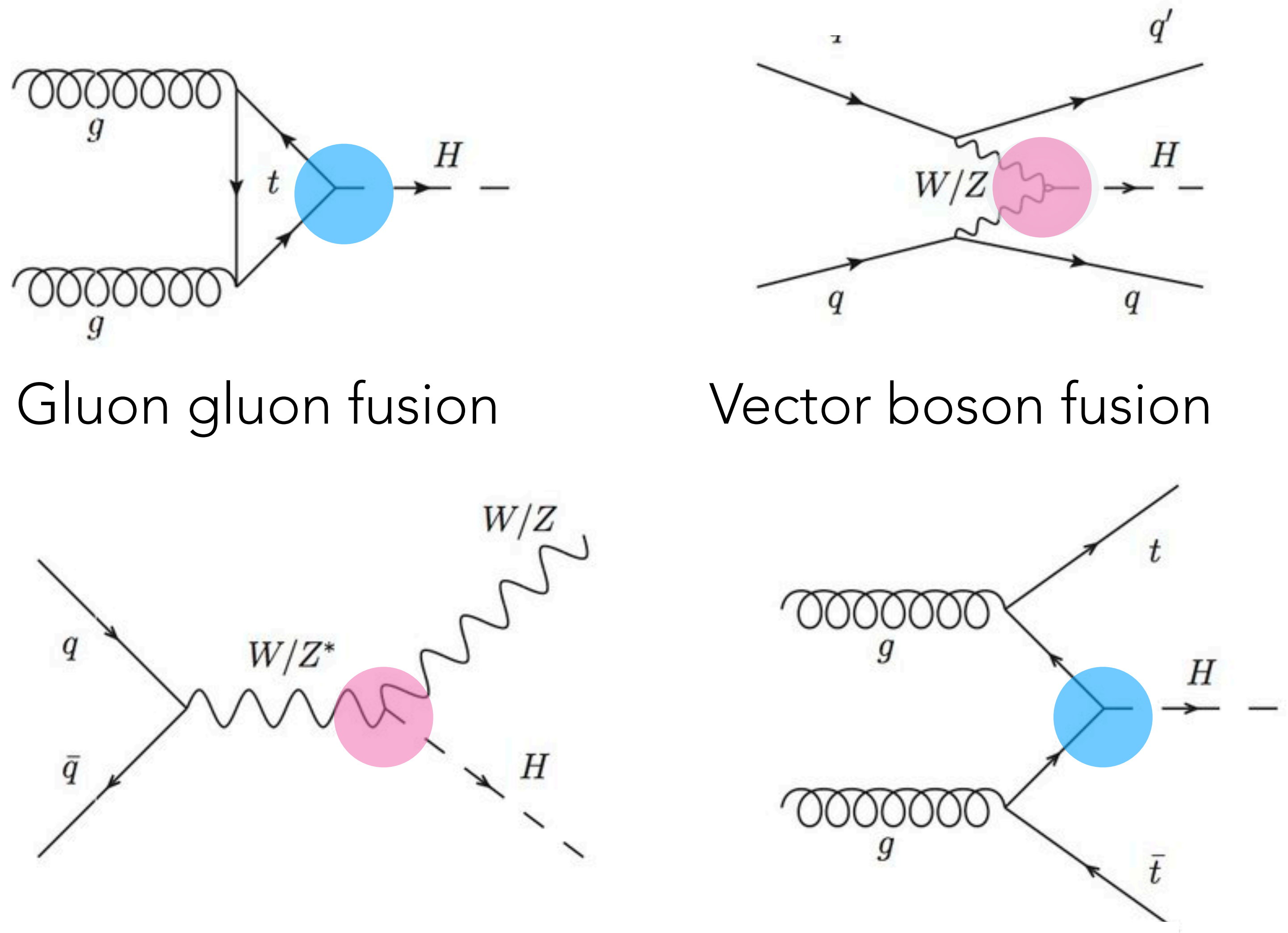
ON SHELL H-4l | HVV, Hff couplings

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

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

Htt : production

PRODUCTION



Gluon gluon fusion

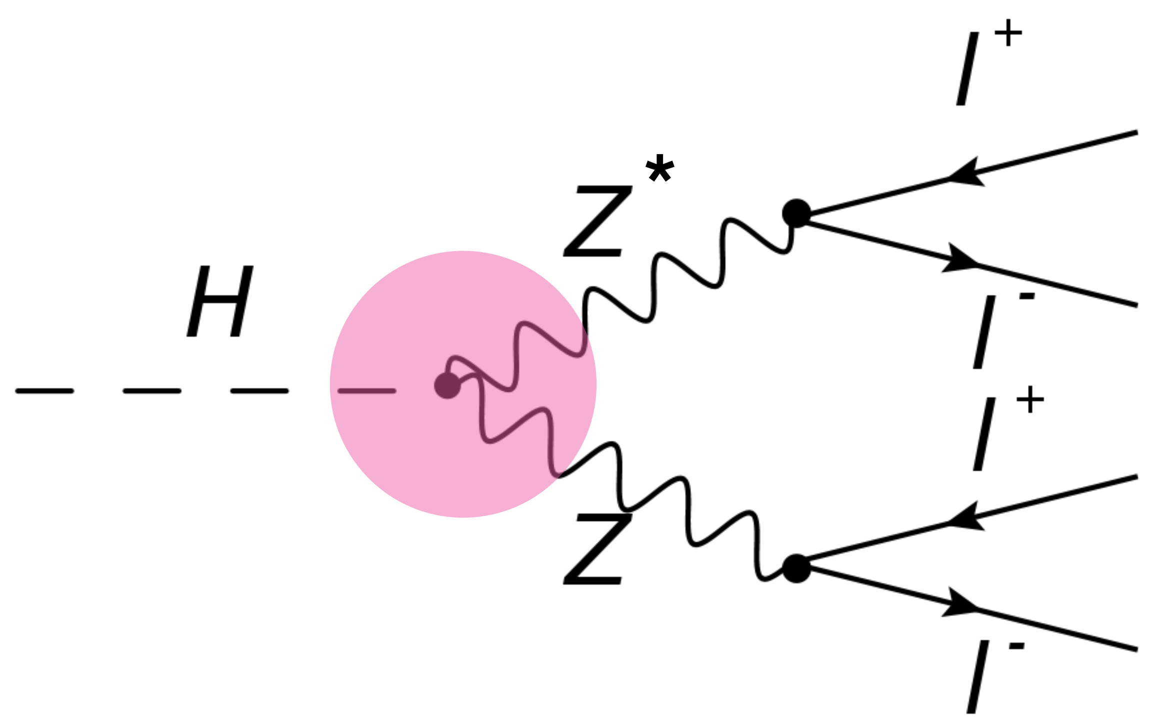
Vector boson fusion

WW/ZZ bremsstrahlung

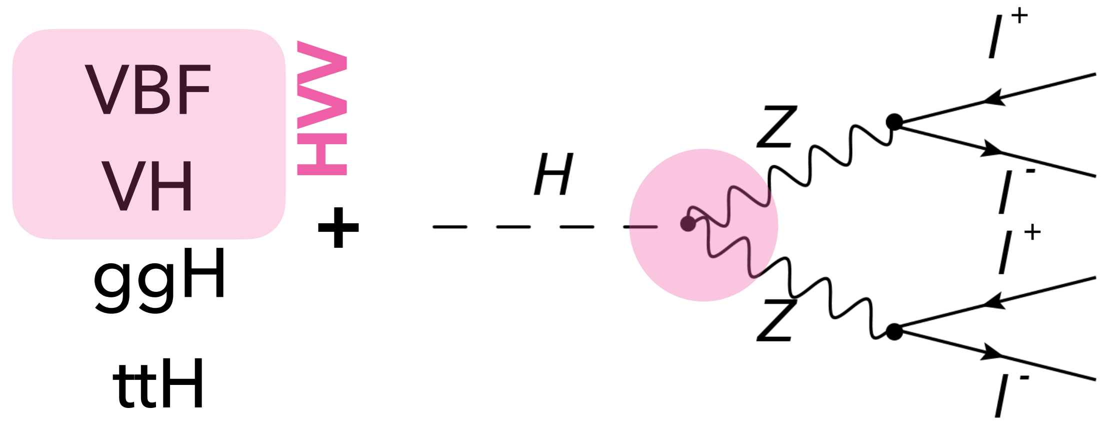
t-quark fusion

+

DECAY

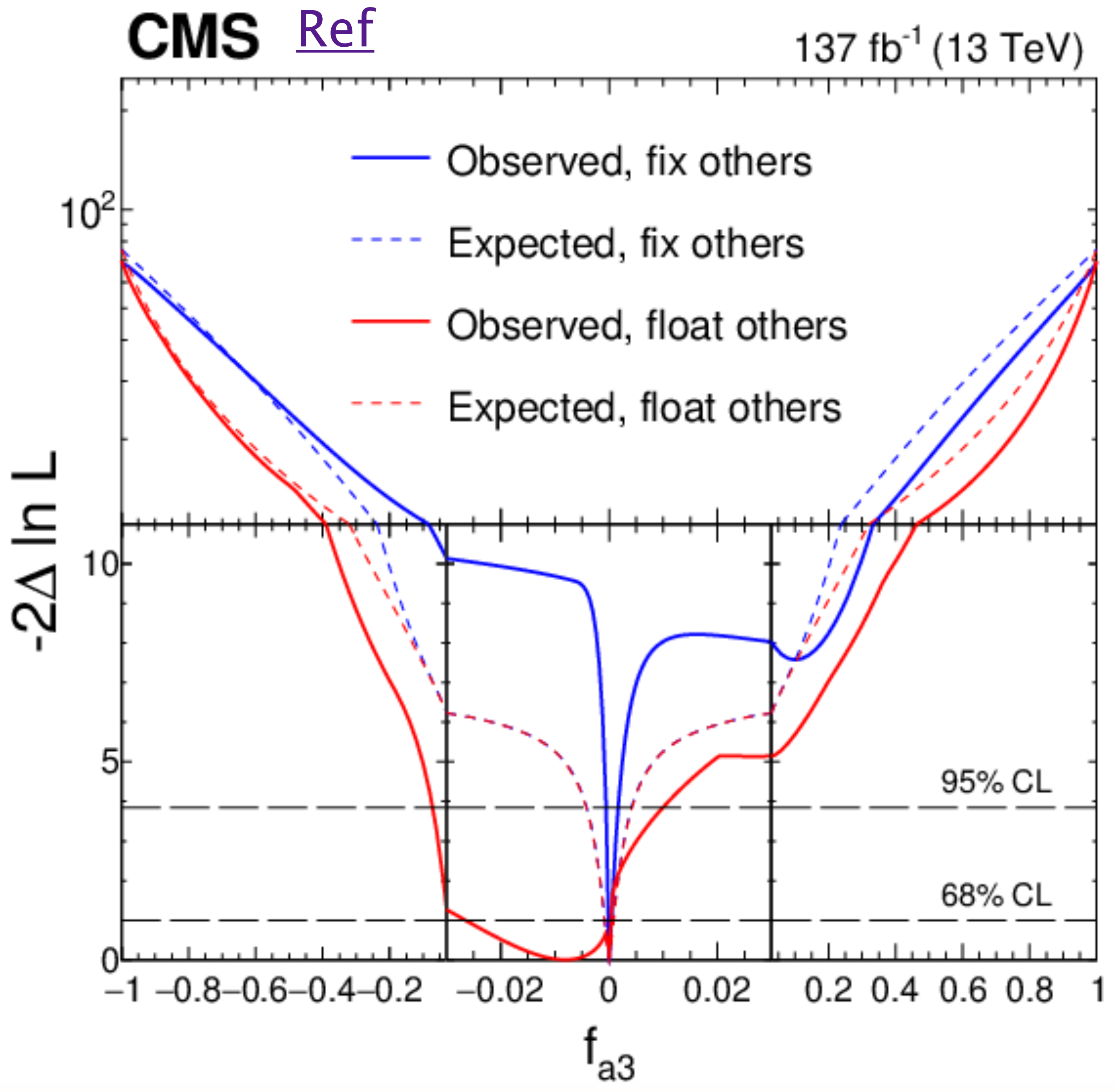


ON SHELL H-4l | HVV coupling

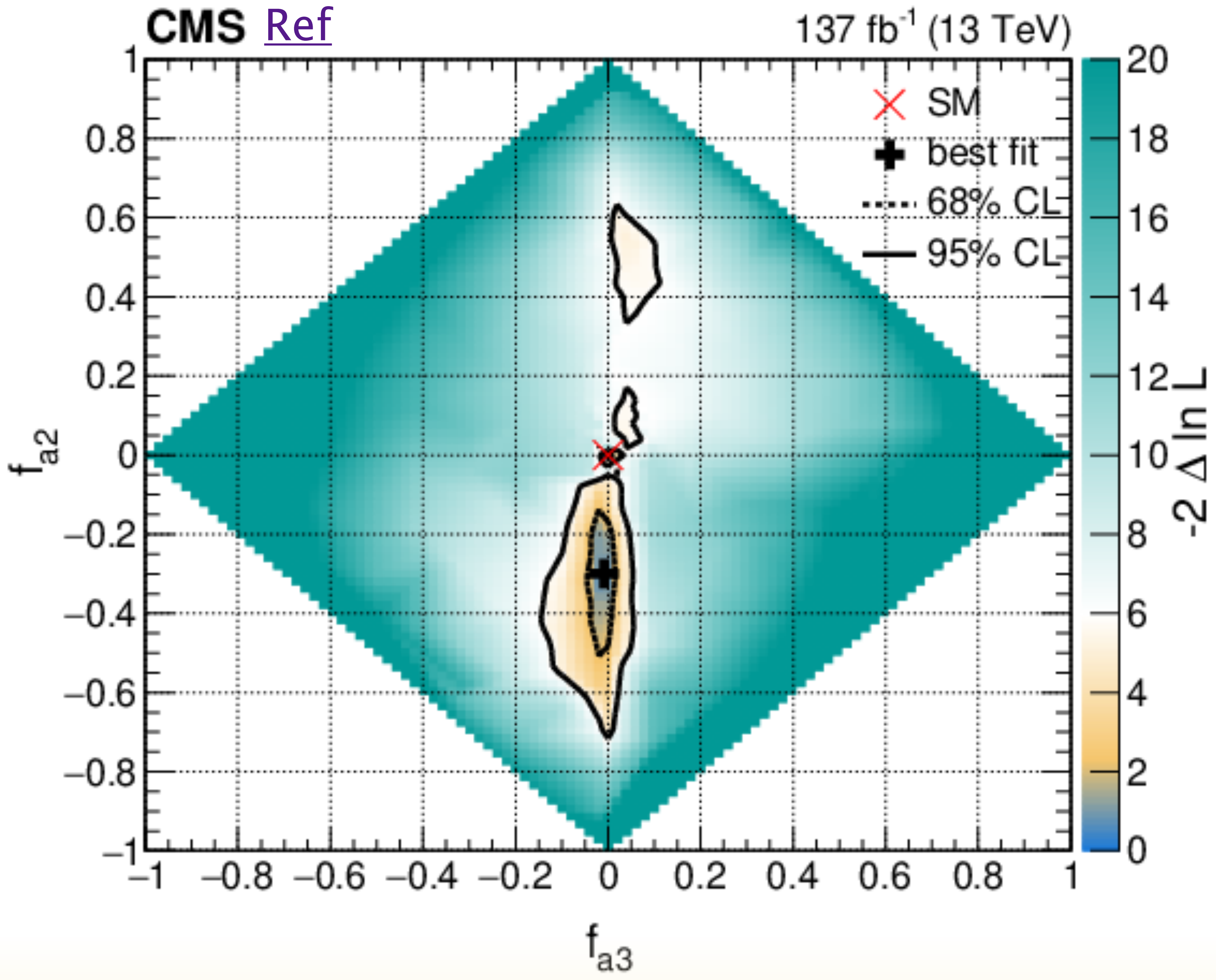


Fix others: only on of $f_{ai} \neq 0$; the others fixed to 0

Floating others: $f_{ai} \neq 0$; the others free to change in the fit

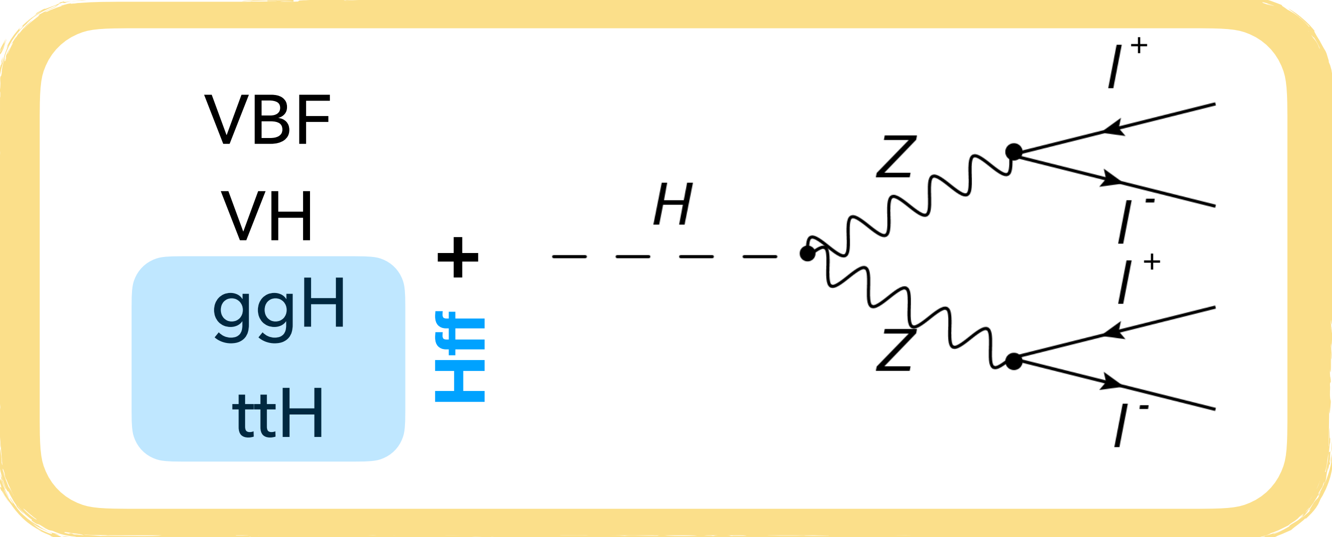


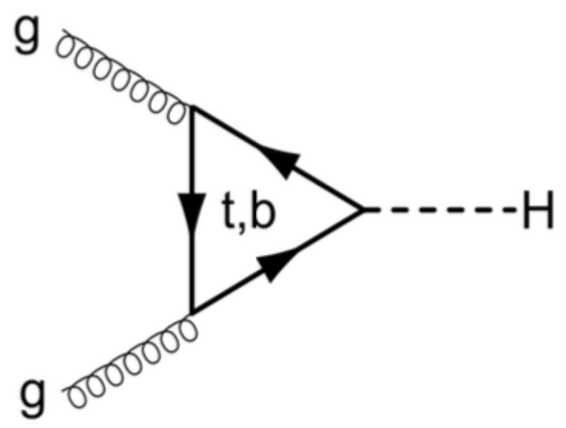
Scan 2D 2 couplings free to change in the fit



		Expected	Observed
Fix Others :	f_{a3}	$0.4^{+4.4}_{-0.7} \times 10^{-4}$	$(0 \pm 8) \times 10^{-4}$

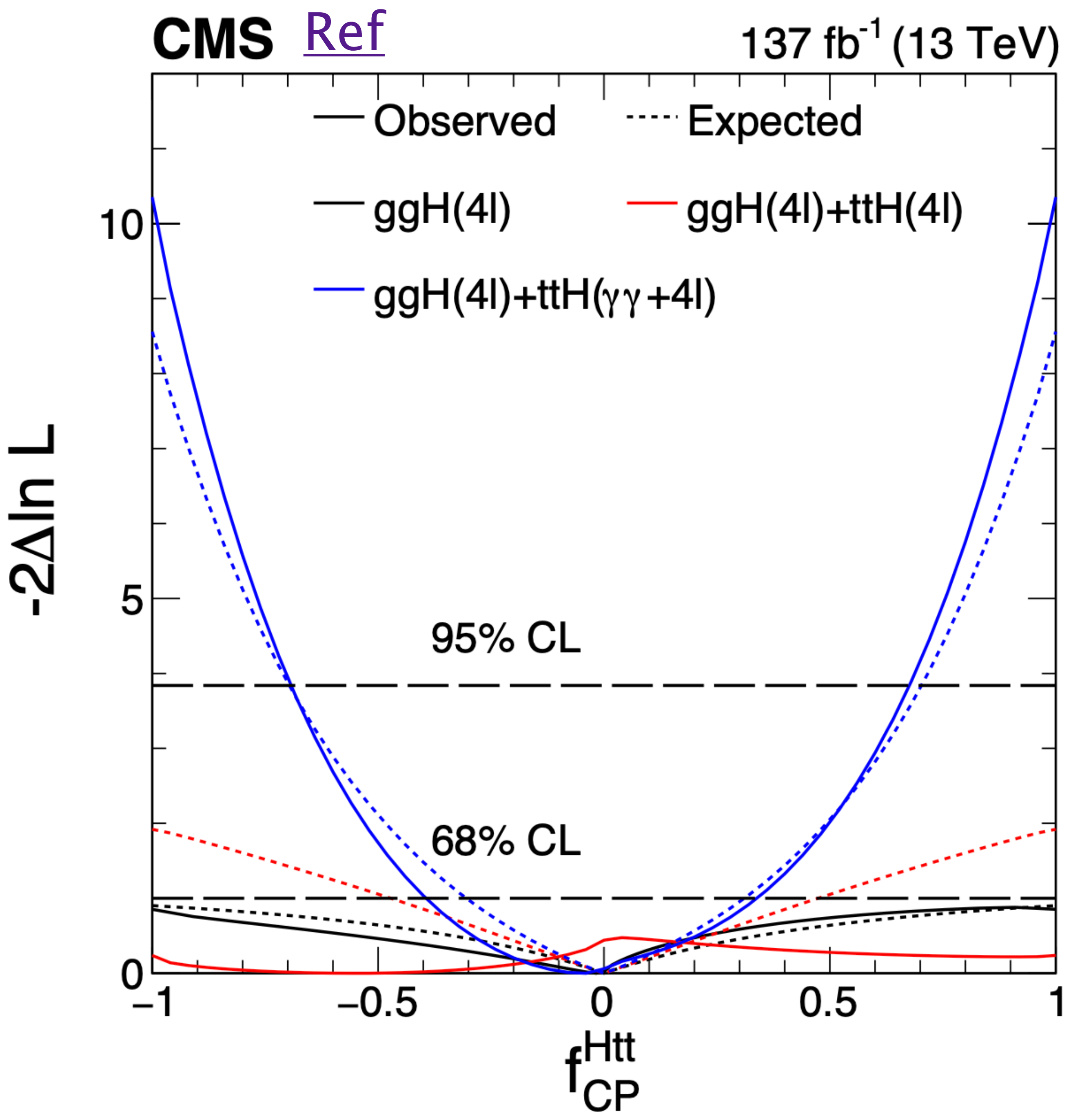
ON SHELL H-4l | Htt coupling

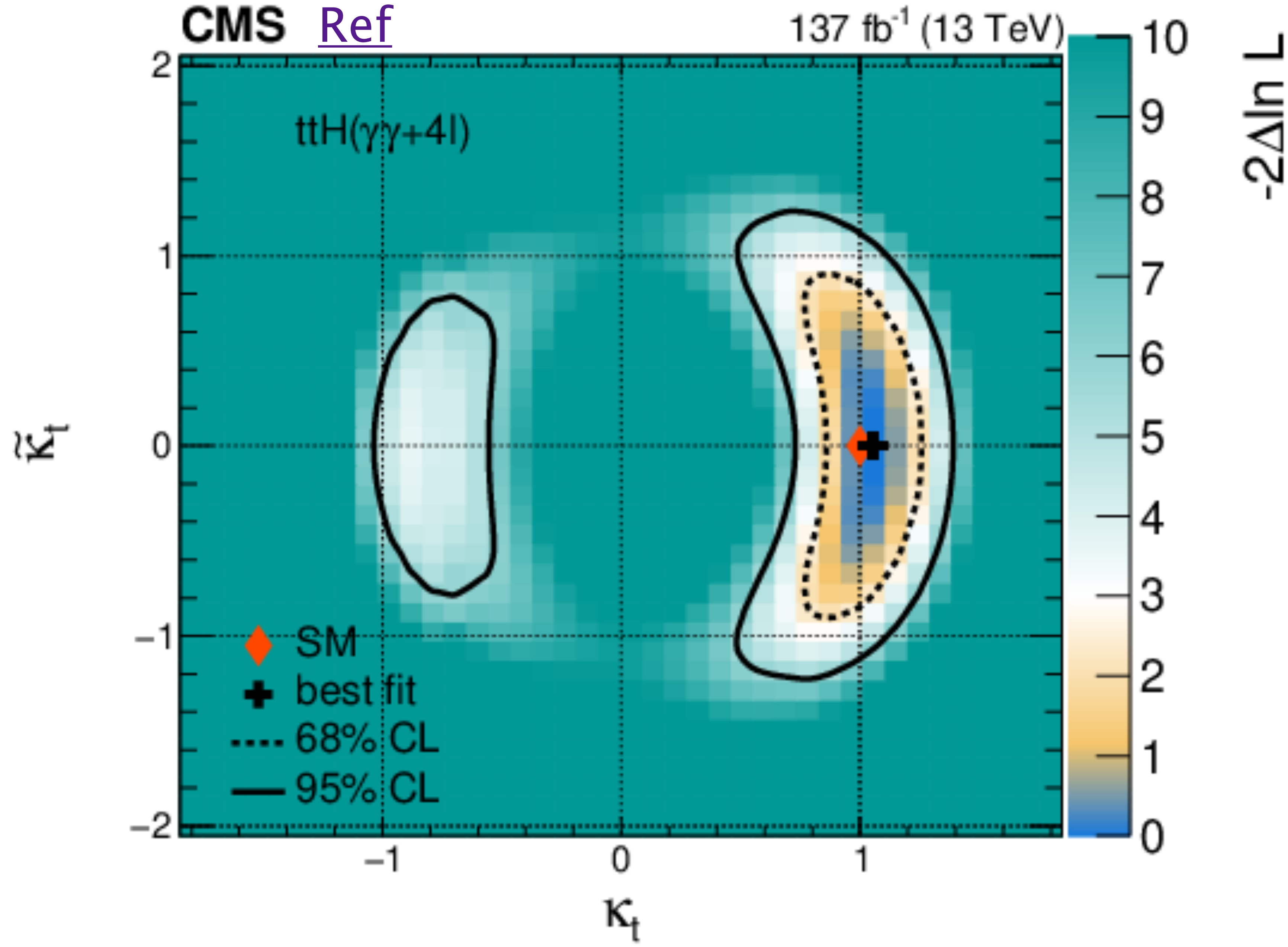




ggH loop dominated by the top quark

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





		Expected	Observed
f_{CP}^{Htt}	ggH & tH & $t\bar{t}$H (H $\rightarrow 4\ell$ & $\gamma\gamma$)	$-0.04^{+0.38}_{-0.36}$	-0.0 ± 0.3

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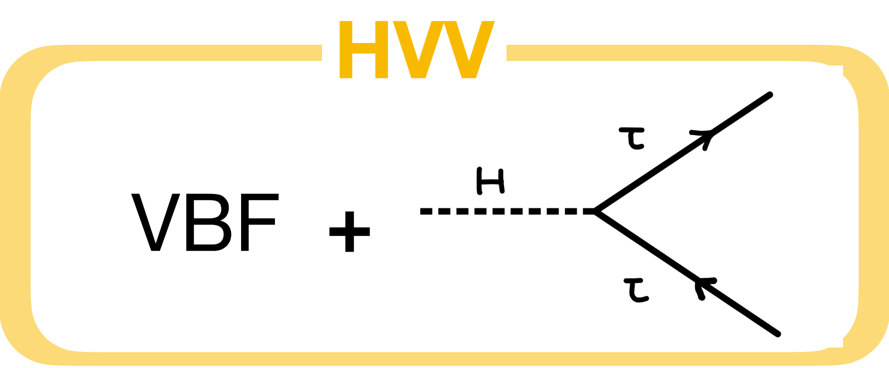
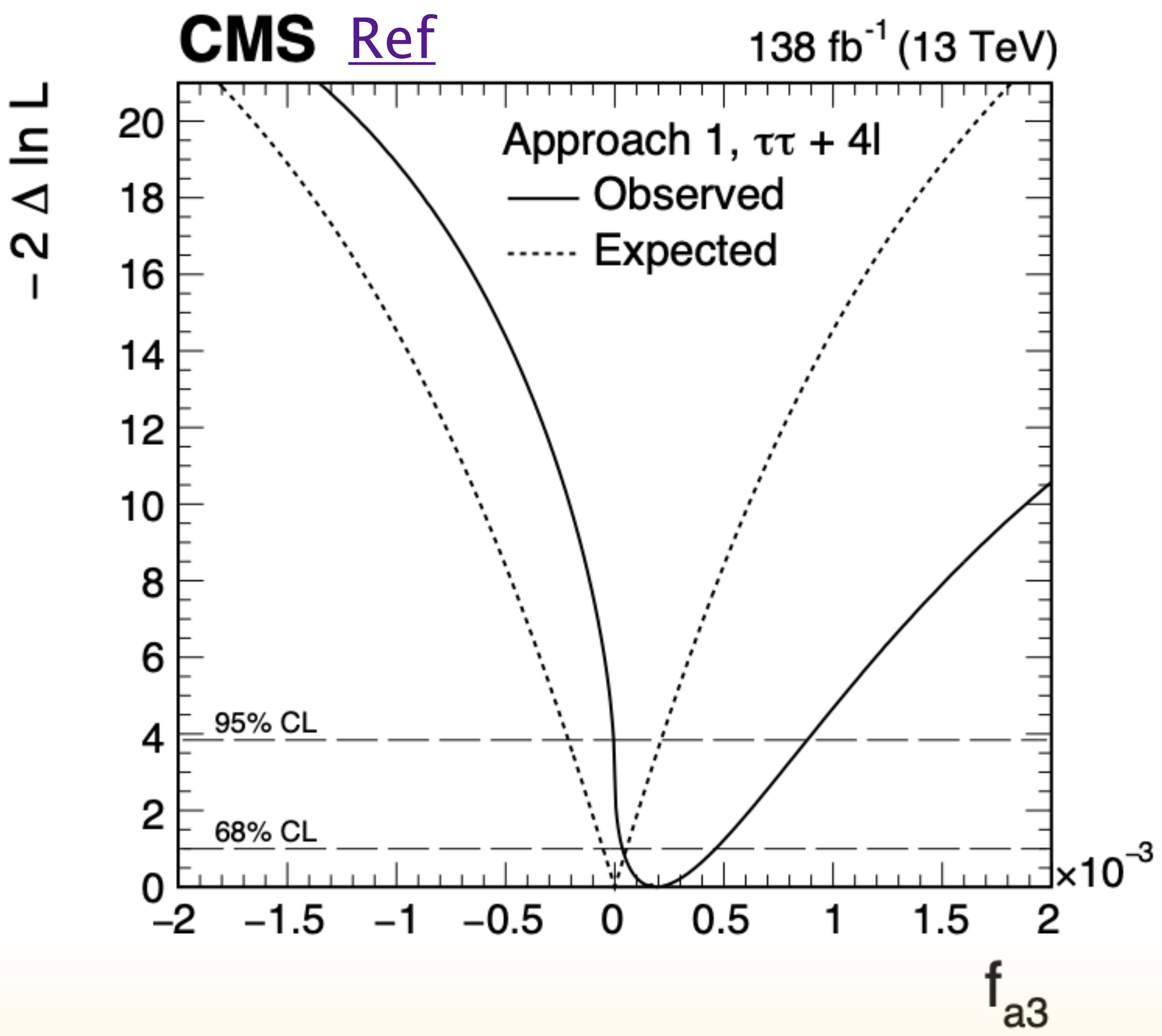
"Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\boldsymbol{\tau\tau}$ *final state"*

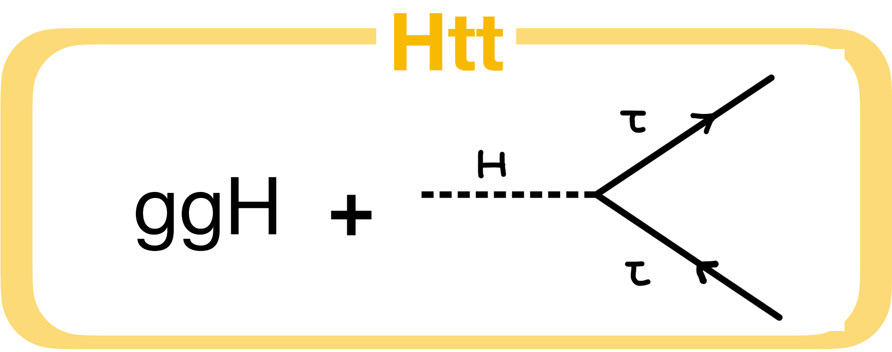
ON SHELL H-$\tau\tau$ | HVV & Htt coupling

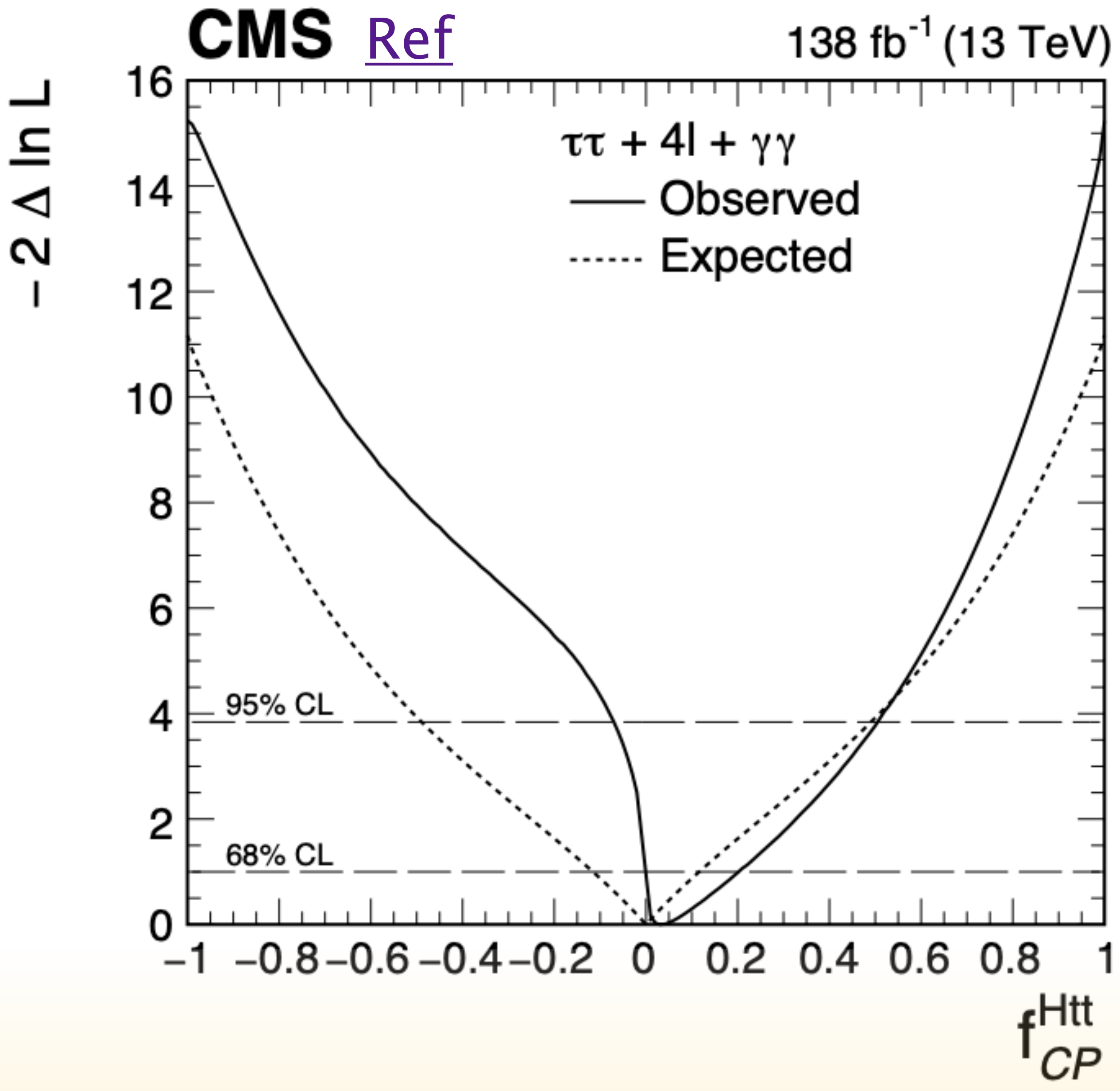
Considered channel: $\tau_h\tau_h, \mu\tau_h, e\tau_h, e\mu$





	Observed	Expected
f_{a3}	$0.20^{+0.26}_{-0.16}$	0.00 ± 0.05





	Observed	Expected
f_{CP}^{Htt}	$0.03^{+0.17}_{-0.03}$	0.00 ± 0.12

SUMMARY

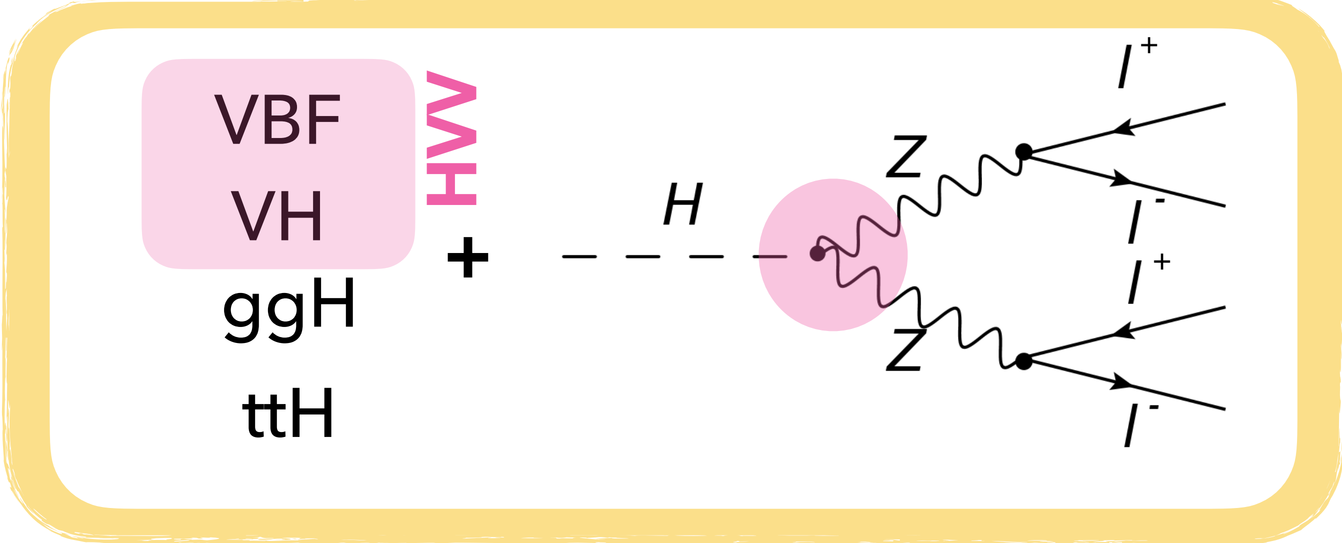
- Studies on anomalous couplings are essential to understand the nature of the Higgs boson
- Analyses with the most stringent limits on CP violation and anomalous couplings presented by the CMS experiment have been addressed
- A rapidly growing field with recent advances and possibilities for new interpretations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

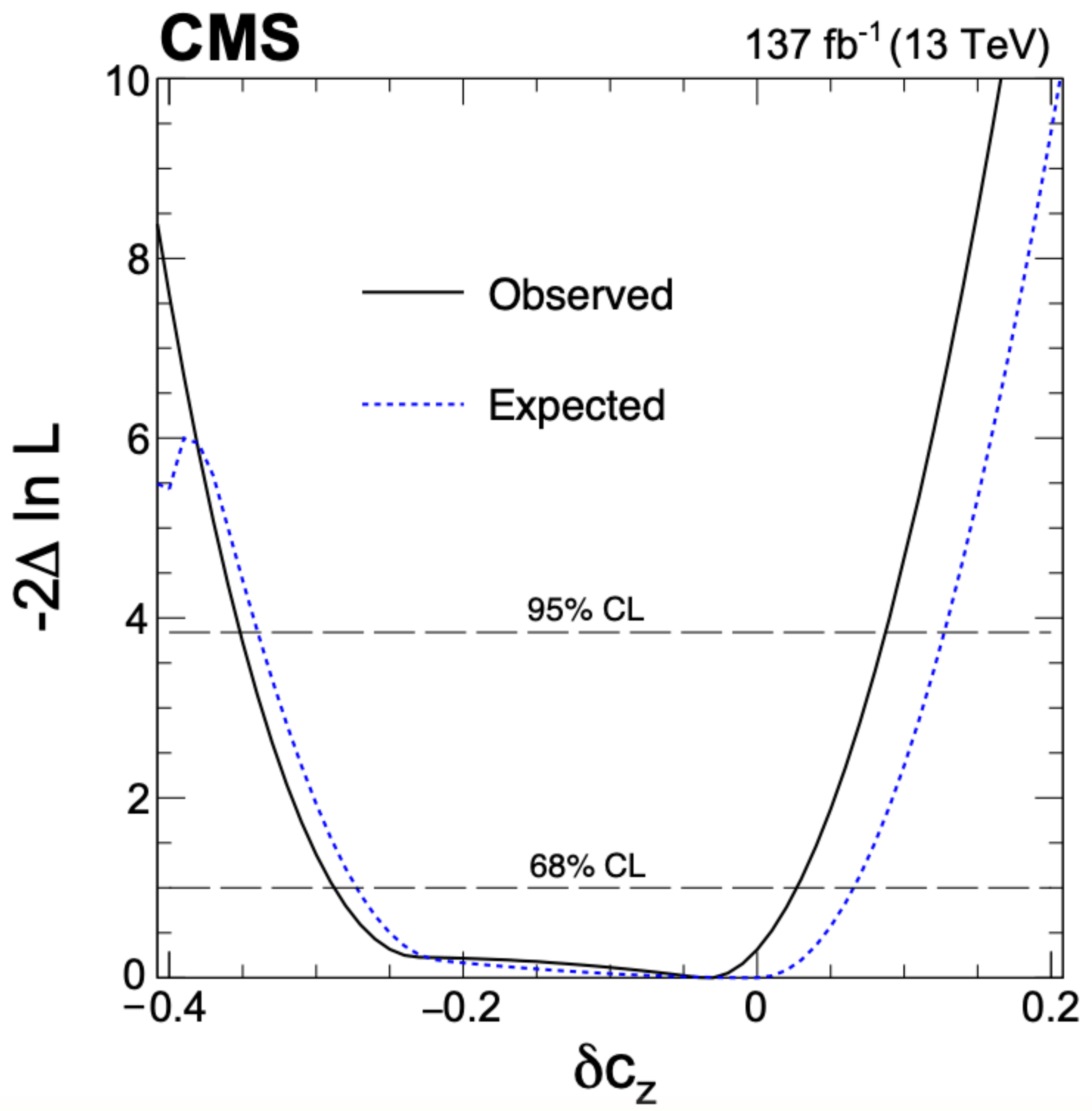
SUMMARY

- 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
- <u>A rapidly growing field with recent advances and possibilities for new interpretations</u>
- Analyses are limited by statistical uncertainties, so we expect improvements from the increase in data.

Thanks for the attention!

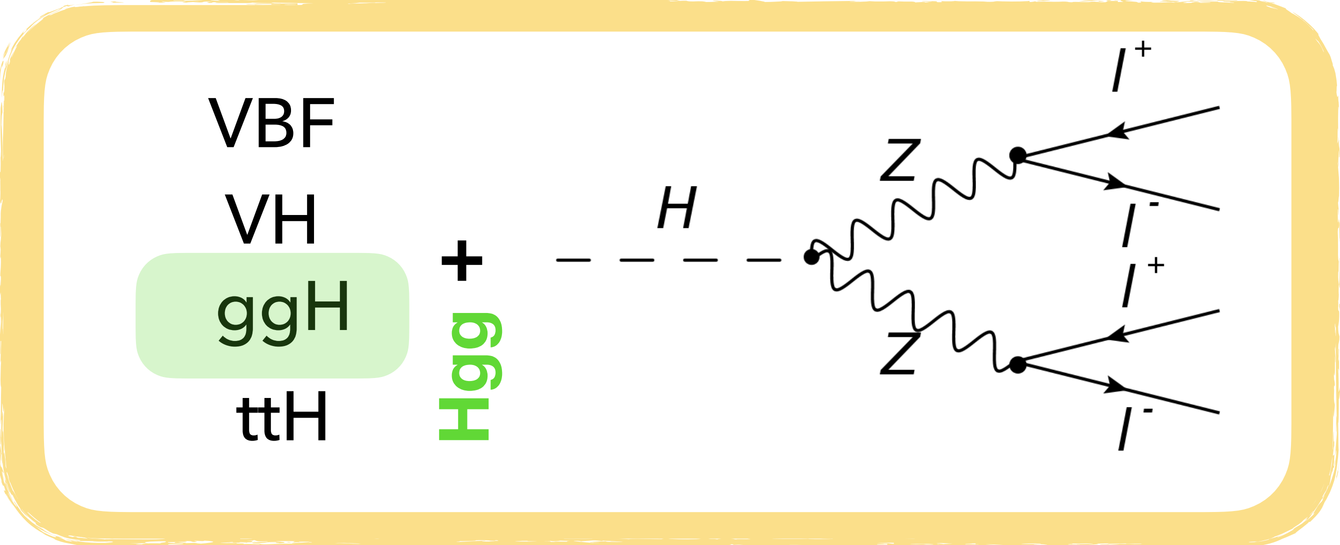
ON SHELL H-4l | accoppiamento HVV

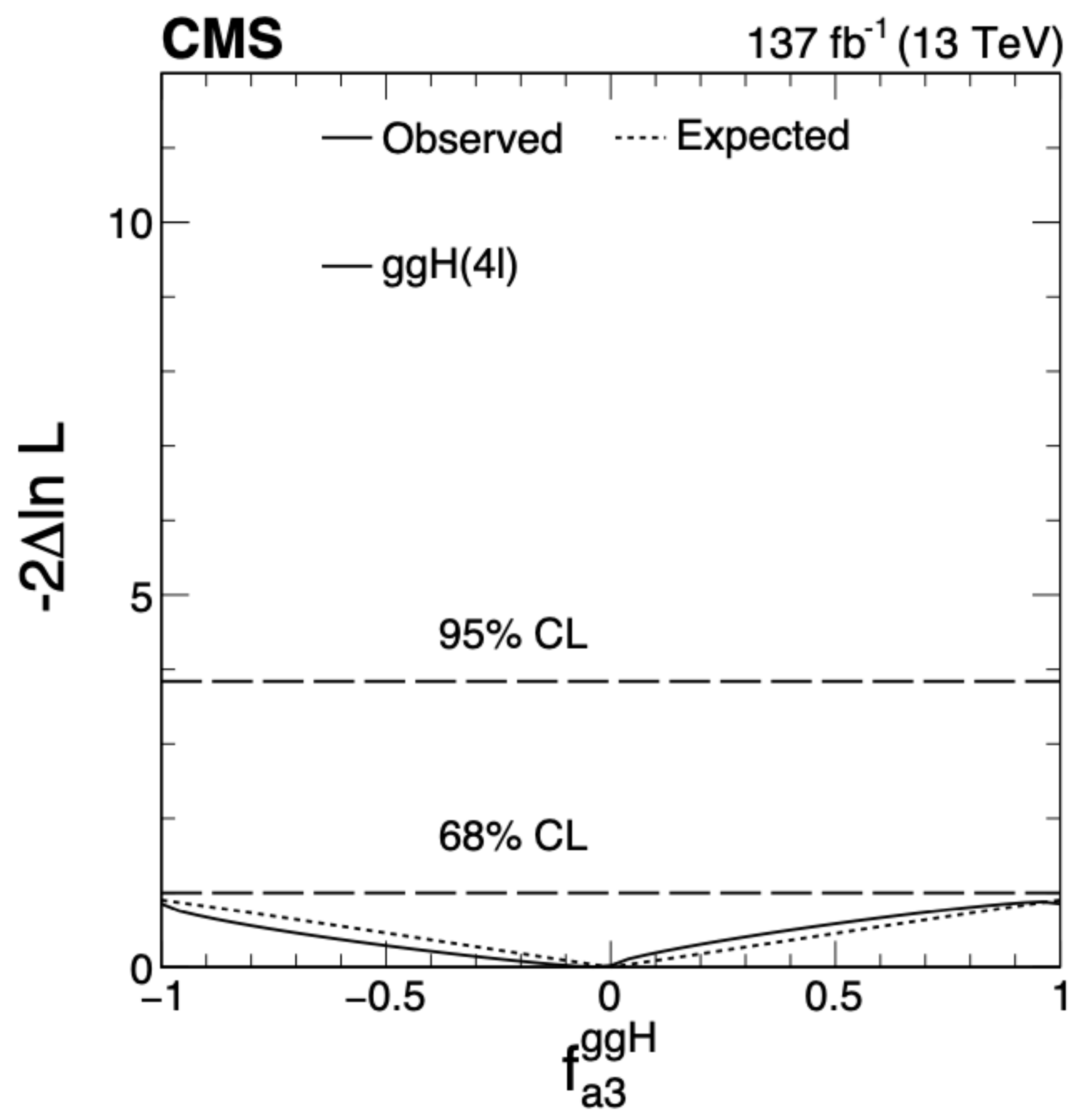




interpretazione in termini di accoppiamento

ON SHELL H-4l | accoppiamento HVV





Il canale di produzione può essere sfruttato per l'analisi dell'accoppiamento Hgg

	Expected	Observed
f_{a3}^{ggH}	$-0.04^{+1.04}_{-0.96}$	0 ± 1

ACCOPPIAMENTI BSM | Hff

$\tilde{\psi}_f, \psi_f \to$ Dirac Spinors

$m_f \to$ mass

$v \to$ valore

$k_t \to$ accop

$\tilde{k}_t \to$ accop

FRAZIO

$$\mathcal{L}_{\mathrm{hvv}} = \frac{h}{v}\Big[(1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}$$

$$+ (1+\delta c_w)\frac{g^2v^2}{2}W^+_\mu W^-_\mu + c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu} + c_{w\Box}g^2(W^-_\mu\partial_\nu W^+_{\mu\nu} + \mathrm{H.c.}) + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}$$

$$+ c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu}$$

$$+ c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu} + \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\Big],$$

$\Rightarrow$

$$\delta c_z = \frac{1}{2}a_1 - 1,$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{4\pi\alpha}\frac{\kappa_1}{(\Lambda_1)^2},$$

$$c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha}a_2,$$

$$\tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha}a_3.$$

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

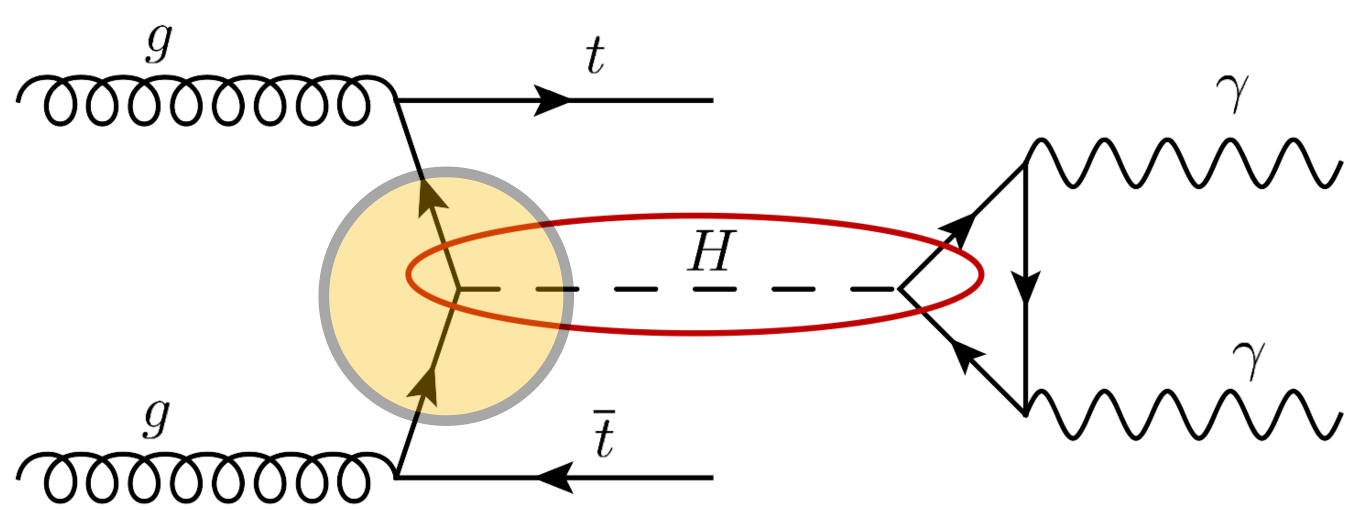
$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S}a_3^{gg},$$

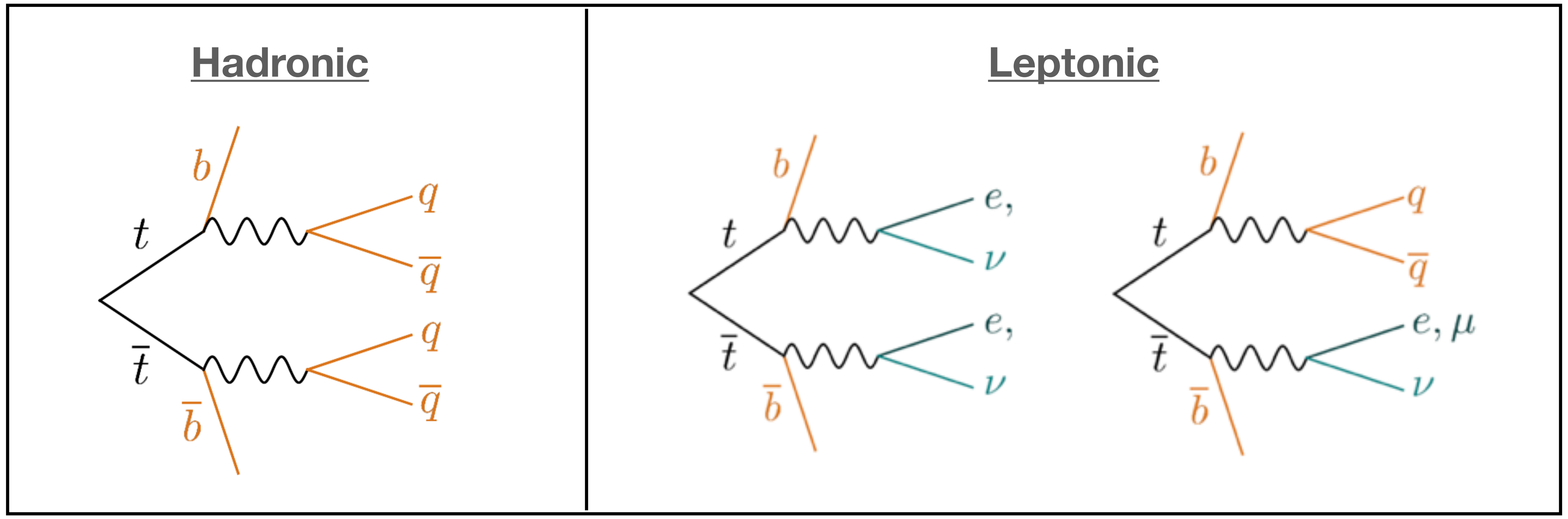
Gli accoppiamenti possono essere reinterpretati in **coefficienti della Lagrangiana effettiva**

$$f_{CP}^{Hff} = \frac{\ldots}{|k_f|^2 + |\tilde{k}_f|^2}\,\mathrm{sign}\left(\frac{\ldots}{k_f}\right) \qquad \alpha^{Hff} = \tan^{-1}\left(\frac{\ldots}{k_f}\right)$$

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).

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Ω = kinematics information
alt =alternative Hypothesis