CP violation in the Higgs sector

UCL Seminar

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Clara Ramón Álvarez

Universidad de Oviedo

ICTEA
Instituto Universitario de Ciencias
y Tecnologías Espaciales de Asturias

clara.ramon.alvarez@cern.ch

Introduction

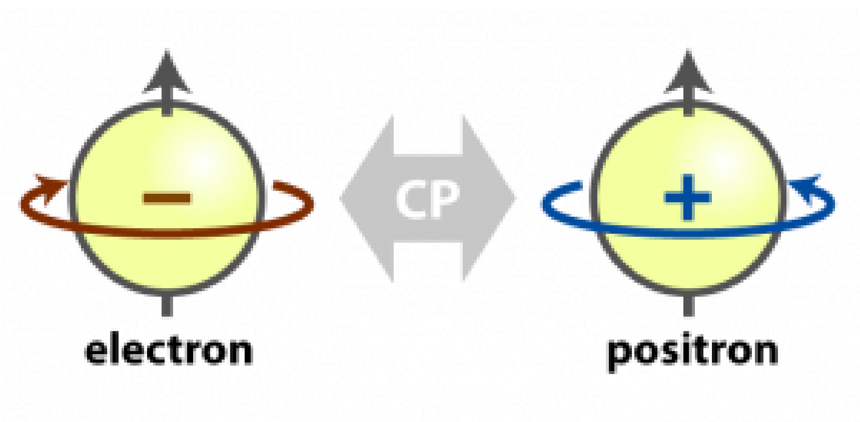
Matter antimatter asymmetry

Observation: in the universe there is much more matter than antimatter

One of Sakharov conditions for Baryogeneis:

“Violation of Charge Conjugation Parity (CP) symmetry in the nonstationary expansion of the hot universe”

CP-symmetry means that a process should occur in the same manner for a particle and its antiparticle (C-symmetry) when its spatial coordinates are inverted (P-symmetry).



CP violation in the SM

In the Standard Model (SM) CP violation is allowed

It originates form the CKM mixing matrix:

quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

anti-quarks

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

This is a complex matrix:
$V_{ud} \neq V^*_{ud}$; $V_{td} \neq V^*_{td}$

Different mixing for quarks and Antiquarks

Origin of CPV violation

CP violation in the SM

In the Standard Model (SM) CP violation is allowed

In the decay of neutral K-mesons:

- Strong eigenstates: $|K^0\rangle = |d\bar{s}\rangle$ & $|\overline{K}^0\rangle = |s\bar{d}\rangle$
- Decay via weak interaction
- Physical states are superposition of K^0 & $\bar{K}^0$, but these are not CP eigenstates

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right), \qquad CP\,|K_1\rangle = +\,|K_1\rangle \qquad \text{"CP even"}$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}^0\rangle\right), \qquad CP\,|K_2\rangle = -\,|K_2\rangle \qquad \text{"CP odd"}$$

$$CP\,|\pi\pi\rangle = +\,|\pi\pi\rangle \qquad \text{CP even}$$

$$CP\,|\pi\pi\pi\rangle = -\,|\pi\pi\pi\rangle \qquad \text{CP odd}$$

For the decay to pions and assuming CP invariance one can find:

$$\text{CP even:} \quad K_1 \rightarrow \pi\pi\,, \qquad K_1 \not\rightarrow \pi\pi\pi$$

$$\text{CP odd:} \quad K_2 \rightarrow \pi\pi\pi\,, \qquad K_2 \not\rightarrow \pi\pi$$

CP violation in the SM

In the Standard Model (SM) CP violation is allowed

In the decay of neutral K-mesons:

CP even:	$K_1 \to \pi\pi\,,$	$K_1 \not\to \pi\pi\pi$	**This should lead to very different lifetimes**
CP odd:	$K_2 \to \pi\pi\pi\,,$	$K_2 \not\to \pi\pi$	

Observation of a long lived and a short lived particle (K_L and K_s) which

$$|K_S\rangle = |K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right)$$

$$|K_L\rangle = |K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}^0\rangle\right)$$

$$\tau_S = 0.9 \cdot 10^{-10} s, \qquad \tau_L = 0.5 \cdot 10^{-7} s$$

Looking for CP violation

So far not enough to explain the asymmetry observed in the universe: Need to search for new CP violation sources. **There are several ways:**

- Quark sector
  - Hadron decays, interference and mixing…
  - Belle II, LHCb
- Neutrino sector
  - CP symmetry can be violated in neutrino oscillation
  - Experiments: T2K, Dune…
- **Higgs sector:**
  - **CMS and ATLAS**

CP violation in the Higgs sector

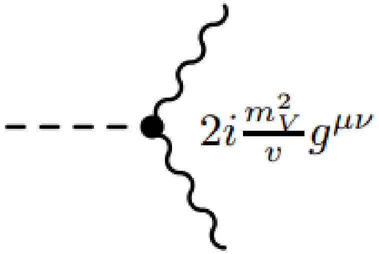
Higgs coupling

- Coupling of the Higgs boson can be read from the Lagrangian:

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

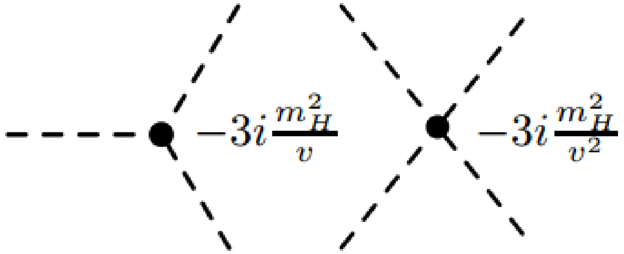
Couplings to EW gauge bosons

$$\left[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2$$



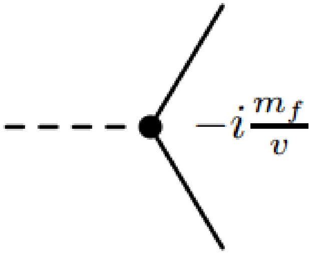
Higgs self-couplings

$$-\mu^2 h^2 - \tfrac{\lambda}{2} v h^3 - \tfrac{1}{8}\lambda h^4$$



Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



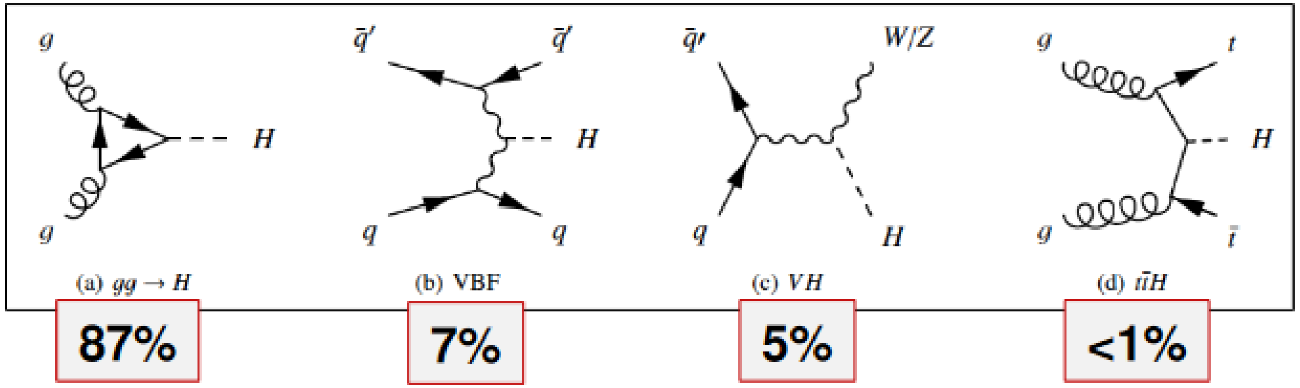
$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value})$$

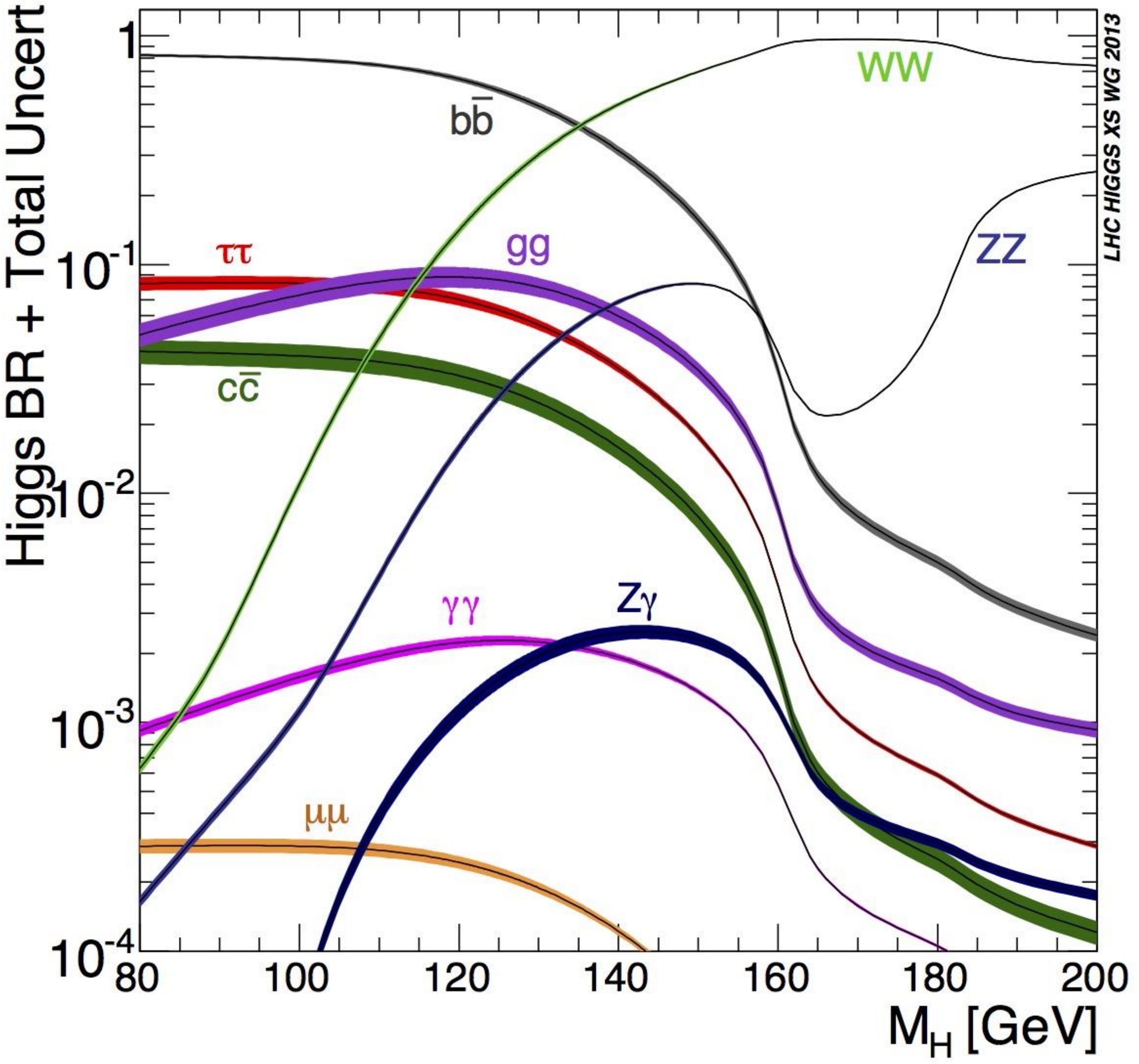
- Bosons: gauge coupling
- Fermions: Yukawa coupling

In the SM Higgs boson is even under CP inversion

Higgs production and deacy modes

- Depending on the production modes and decays selected we can study different couplings
- Experimentally very different signatures and challenges





Run I

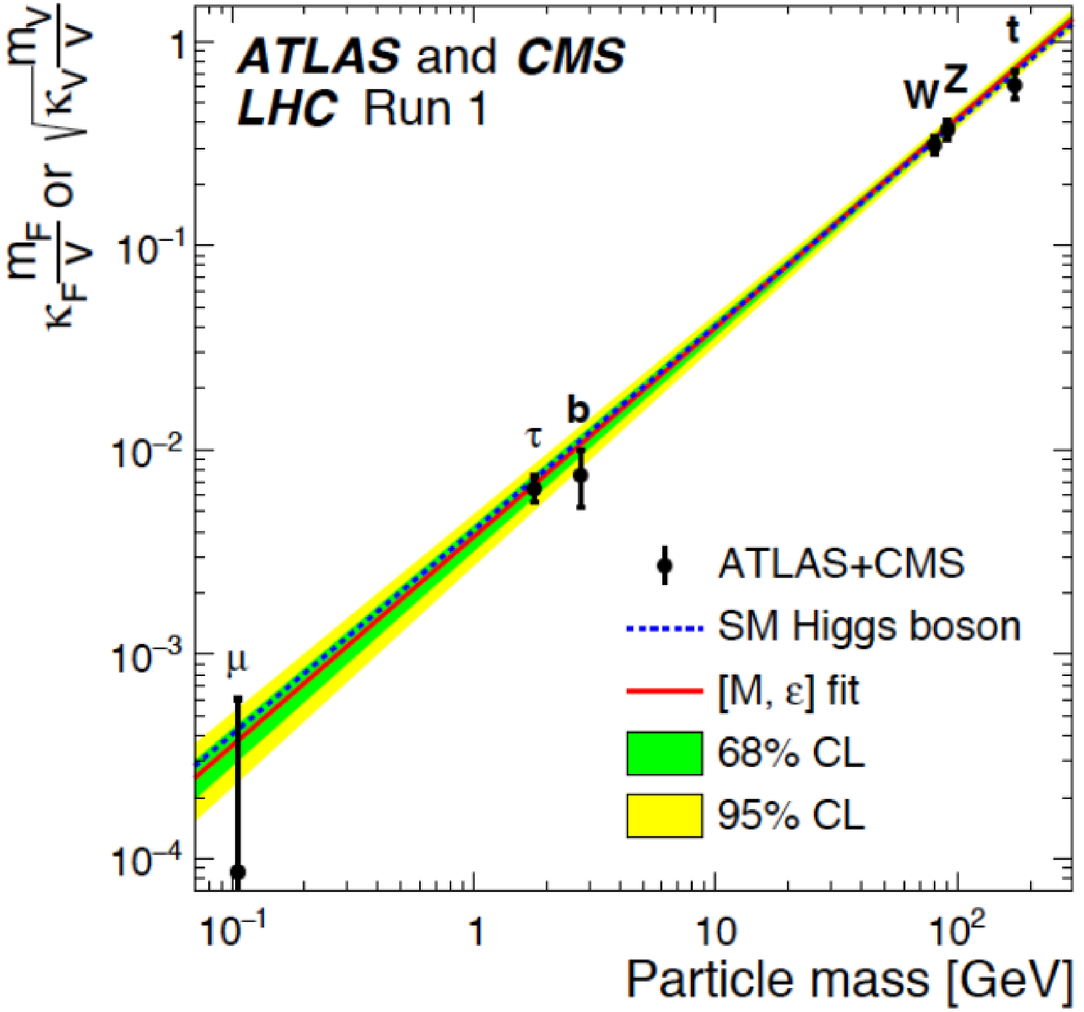
- LHC Run 1: **Discovery of a Higgs Boson** 

- Measure all its properties and interactions → enormous task

- Interaction with bosons well measured in Run 1

- Interactions with fermions established in Run 1

JHEP 08, 045 (2016)

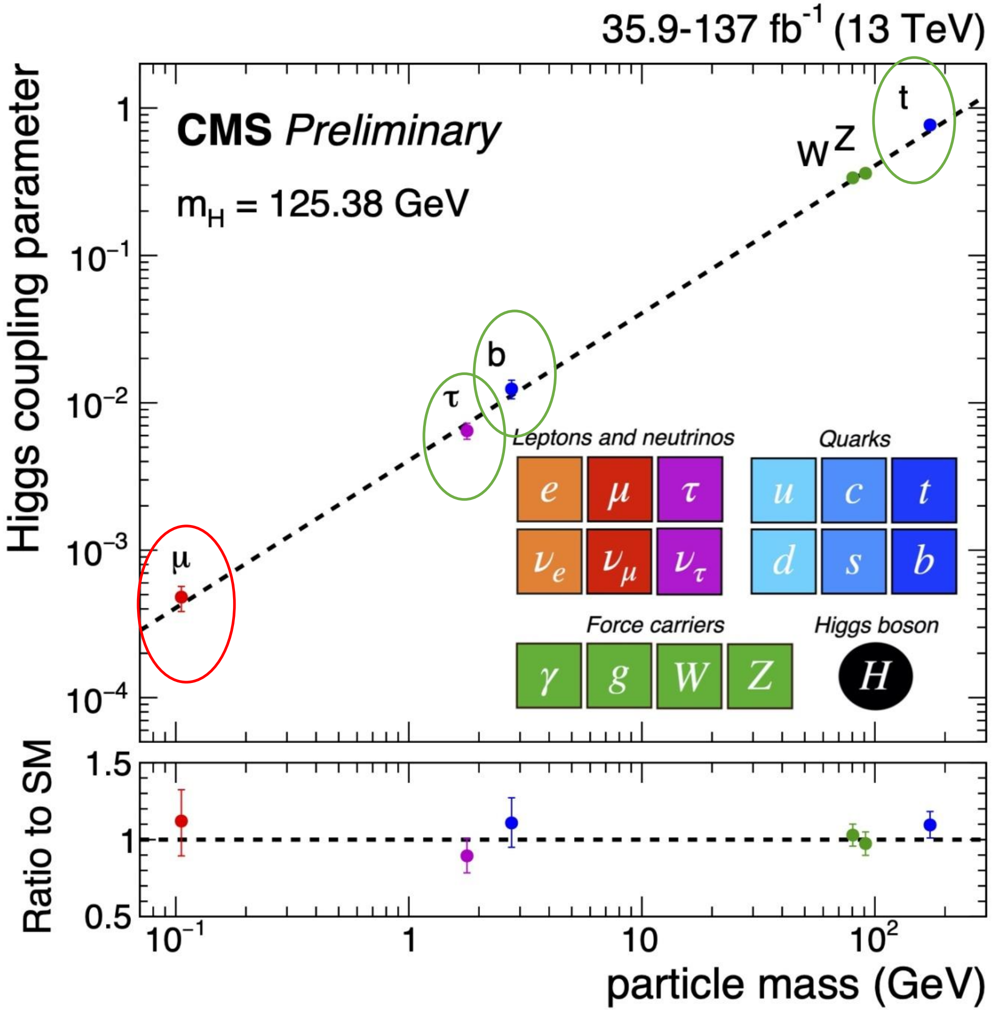


Run II

- Run 2 has been very productive measuring the interaction of **the H to fermions**:
  - Observation of Higgs couplings to all third-generation charged fermions
  - Evidence of H coupling to μ
  - Significant improvements in Hcc coupling search
  - Ongoing search for H→ee

- **Time to check the CP properties of the Higgs Boson!**
  - Measurements still dominated by stats

CMS-PHO-GEN-2020-002



CP estructure of Higgs coupling

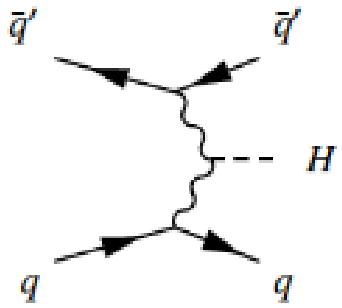
Depending on the decay mode and production mode we can study the coupling to bosons or fermions:

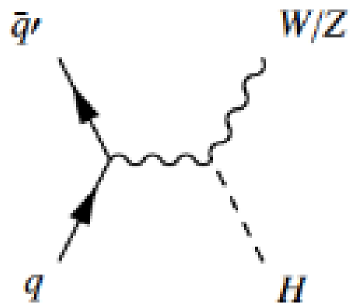
Hgg ggH production.

HVV

- VH production
- VBF
- H→ ZZ → 4l

CP-odd contributions enter at high order operators,
Amplitude expansion up to (q^2/Λ_1^2)





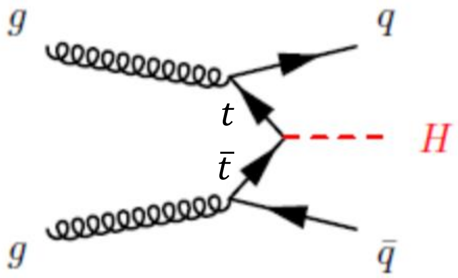
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}}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

Hff

- Good handle: ttH, tH and H→ $\tau\tau$

$$L_Y = \frac{m_f}{v} H(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i\gamma_5 f)$$

- ggH is purely loop induced process,
Bottom quarks → indirect constrain on Htt



Run II results on Higgs CP violation

How to design a CP analysis?

Need to decided which coupling to study:
Hff, HVV, Hgg

Target production mode or decay mode
Make assumptions: What happens to other couplings and branching ratios?

Need to isolate your signal – many times this is very challenging:
Machine learning can help

Look for an observable sensitive to coupling modifications:

- Kinematic information usually sensitive
- In many cases too much information to be handle only with 1 observable:
  Machine learning (again) can help

In this talk…

HVV/Hgg coupling:

- Anomalous H couplings (H $\rightarrow \tau\,\tau$) **CMS-HIG-PAS-20-007**
  Accpeted PRD
- Anomalous H couplings (H $\rightarrow 4l$) **Phys. Rev. D 104 (2021) 052004**

Hff coupling:

- H$\tau\tau$ coupling **JHEP 06 (2022) 012**
- Htt coupling (ttH, H$\rightarrow \gamma\gamma$) **Phys. Rev. Lett. 125, 061801**
- Htt coupling (ttH, H$\rightarrow 4l$) **Phys. Rev. D 104 (2021) 052004**
- Htt coupling (ttH, H$\rightarrow$ multileptons) **CMS-PAS-HIG-21-006**
  Submitted JHEP

Anomalous couplings to VV ($H \to \tau\tau$) I

Strategy:

CMS-HIG-PAS-20-007

- Constrain anomalous **HVV**, **Hgg** and Hff (including CP effects)
- $H \to \tau\tau$
- Constrain on effective cross section ratios:

HVV

- Assuming custodial and SU(2)xU(1) symmetries:

$$a_3^{WW} = \cos^2\theta_W \, a_3^{ZZ}$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_3}{a_1}\right)$$

Hgg

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

Anomalous couplings to VV (H → $\tau\tau$) II

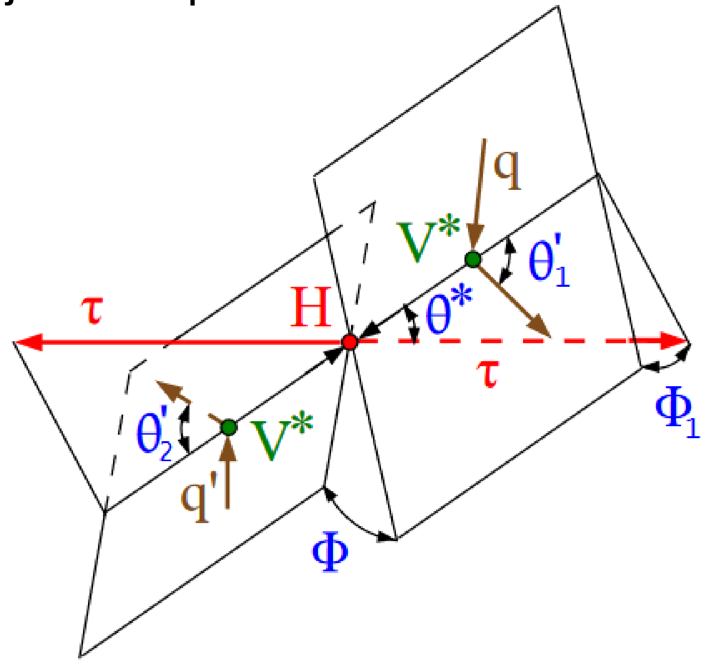
CMS-HIG-PAS-20-007

Strategy:

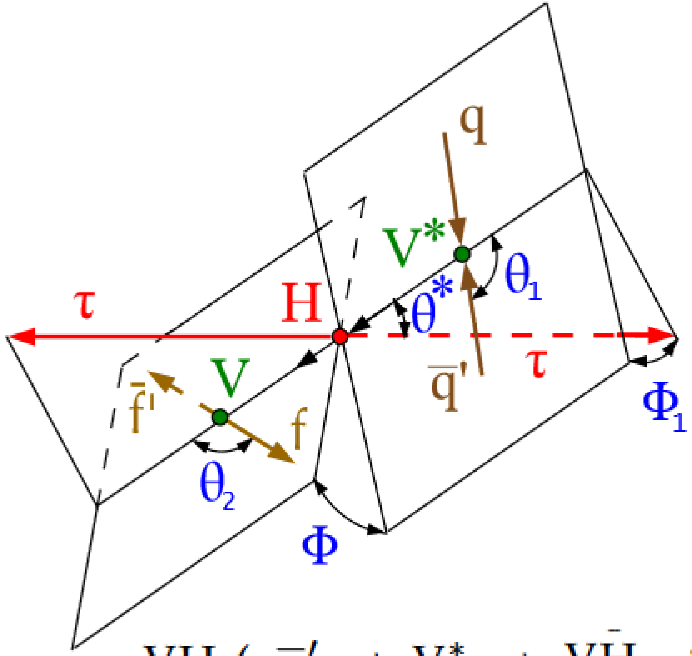
- Constrain anomalous **HVV**, **Hgg** and Hff (including CP effects)
- H → $\tau\tau$

- From the kinematic of the final state several observables can be defined
  - correlation of H and two quark jets or leptons

- $\Delta\phi_{jj}$: provides good discrimination (Hgg)
- Many other kinematic observables -> we need to select and combine the most discriminating ones:
  - Matrix element likelihood approach (MELA)



VBF ($qq' \to qq'H$)



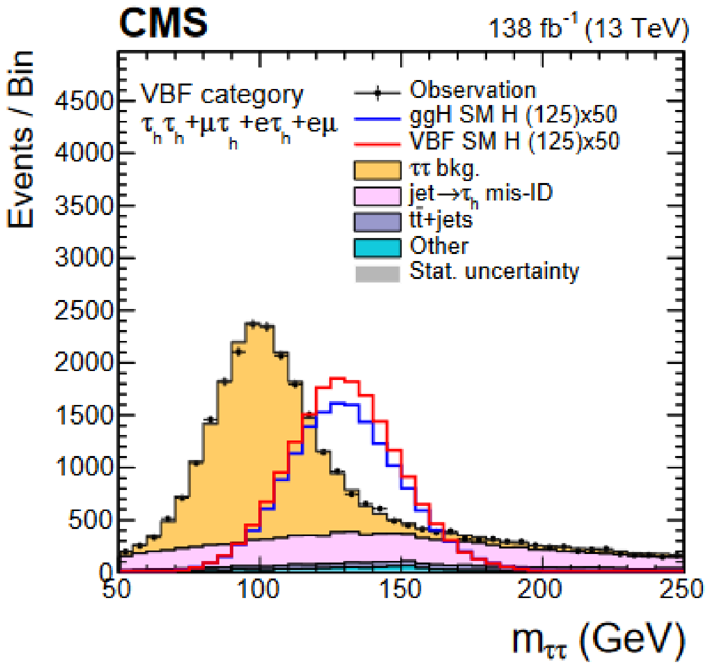
VH ($q\bar{q}' \to V^* \to VH \to qq'H$)

Anomalous couplings to VV ($H \rightarrow \tau\tau$) II

CMS-HIG-PAS-20-007

Event categorization:

- Channels: $\tau_h\tau_h, \tau_e\tau_\mu, \tau_e\tau_h$ and $\tau_\mu\tau_h$
- 3 analysis categories:
  - ggH production: 0 jet
  - VBF: at least 2 jet & mjj > 300 GeV **(most sensitive to CP)**
  - Boosted: events that do not enter in the previous ones



Simulations:

- Anomalous VH & VBF production generated with JHUGEN
- Anomalous ggH (NLO QCD) using MADGRAPH5 aMC@NLO

Backgrounds:

- DY $\rightarrow \tau\tau$
- Jets identified as τ (W+Jets and QCD)

Main systematics:

- Tau identification
- Background modelling
- Jet energy resolution

Anomalous couplings to VV ($H \to \tau\tau$) II

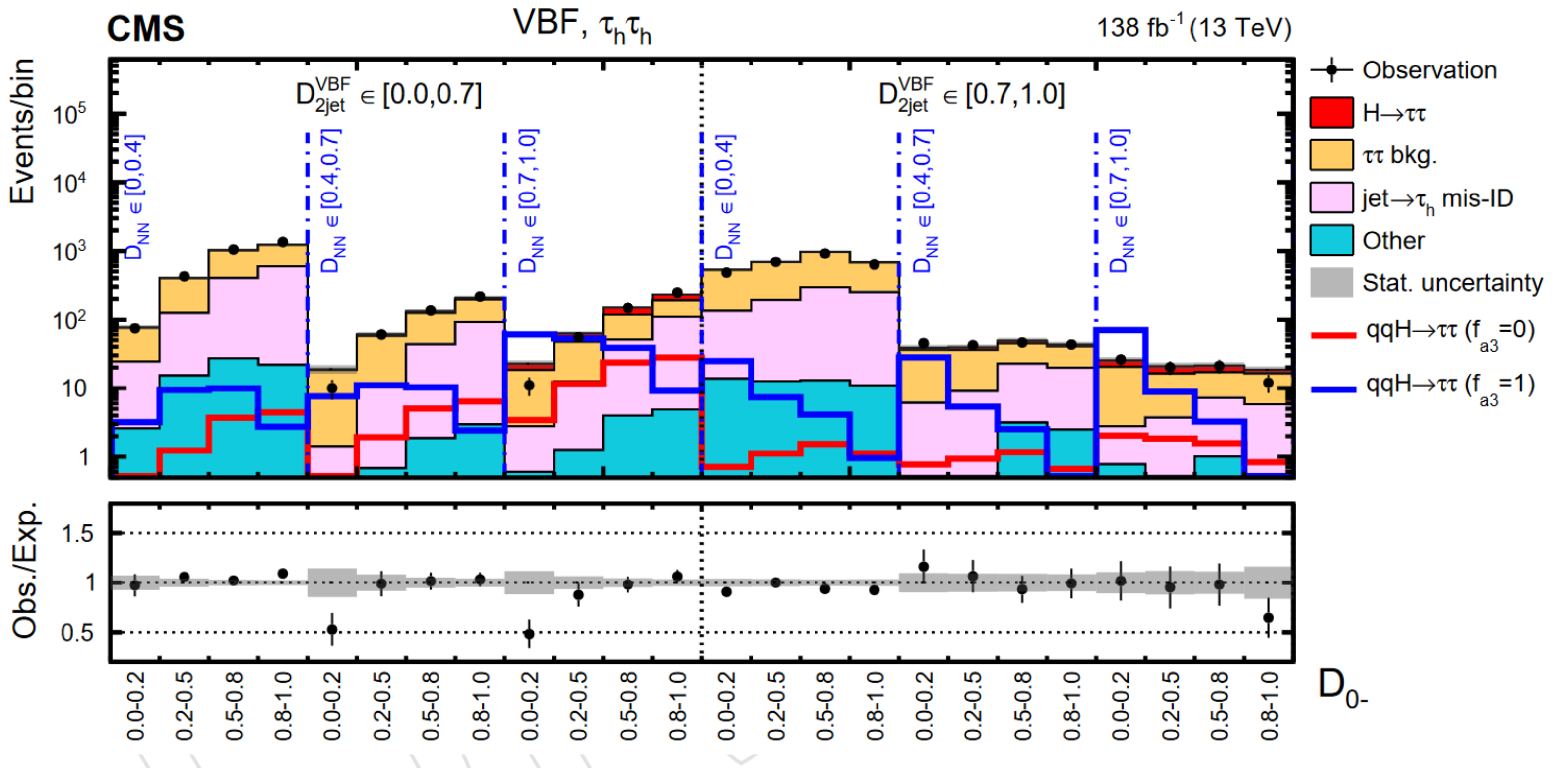
HVV:

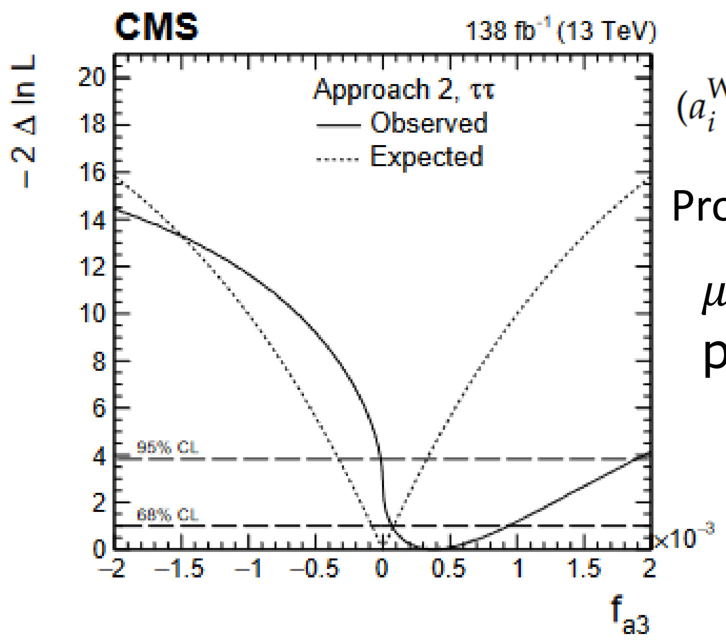
Neural Networks to separate signal and Bkg.
Discriminant to separate signal processes (VBF vs ggH)
Discriminant dedicated to CP

Maximum Likelihood fit is performed using the three discriminators

CMS-HIG-PAS-20-007

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





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

Profiling f_{a3}^{ggH}

μ_{ggH}, μ_{qqH} profiled

$$f_{a3} = 0.40^{+0.53}_{-0.33}$$

Anomalous couplings to VV (H → τ τ) III

Hgg:

Neural Networks to separate signal and Bkg.
Discriminant to separate signal processes (VBF vs ggH)
Discriminant dedicated to CP

Maximum Likelihood fit is performed using the three discriminators

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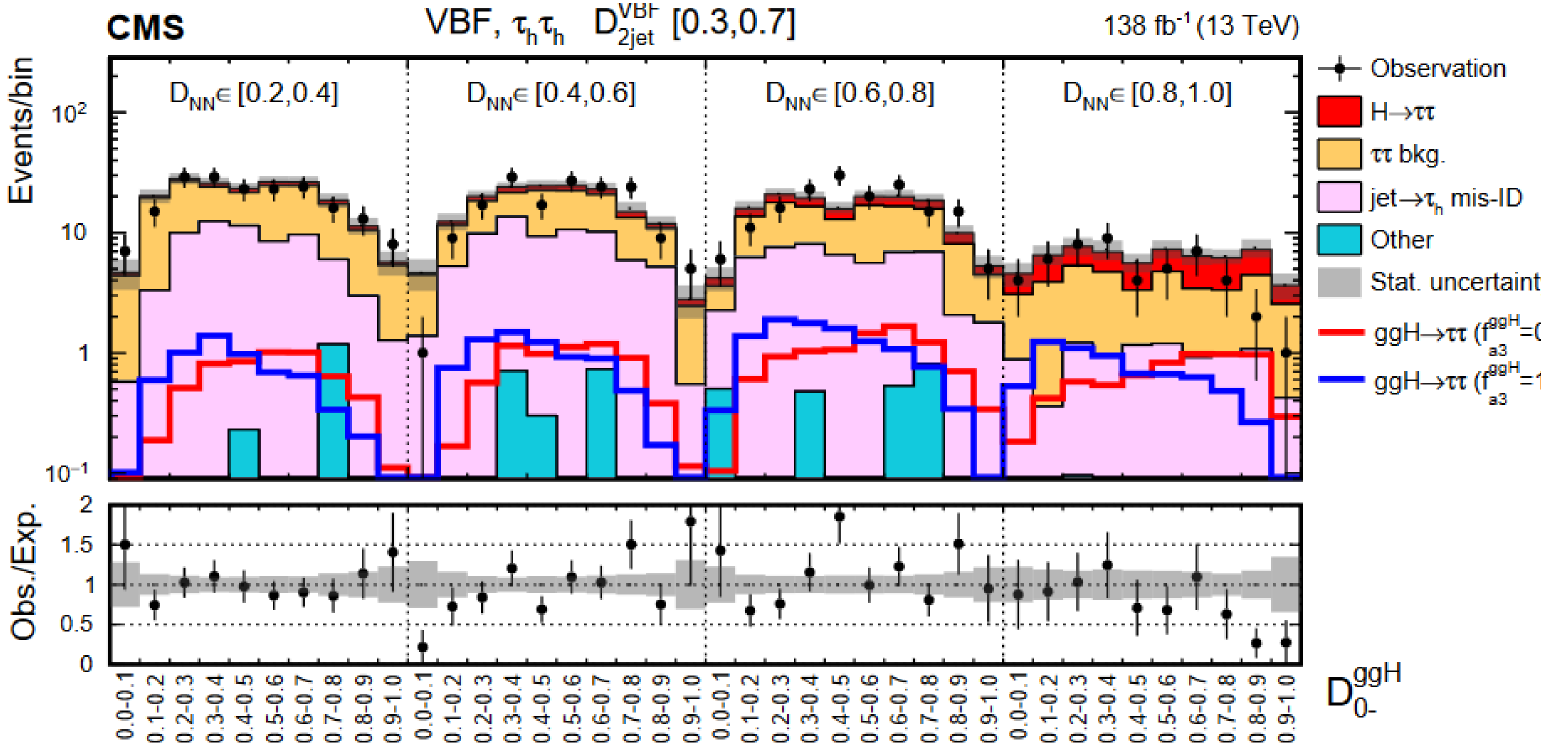
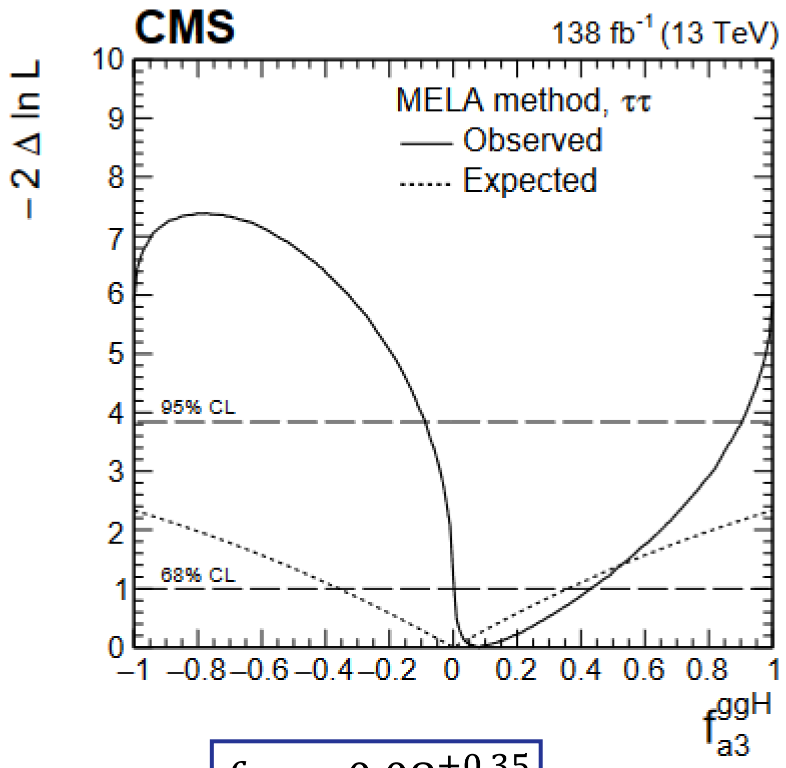




Profiling:
f_{a3}
μ_{ggH}, μ_{qqH}

$$f_{a3} = 0.08^{+0.35}_{-0.08}$$

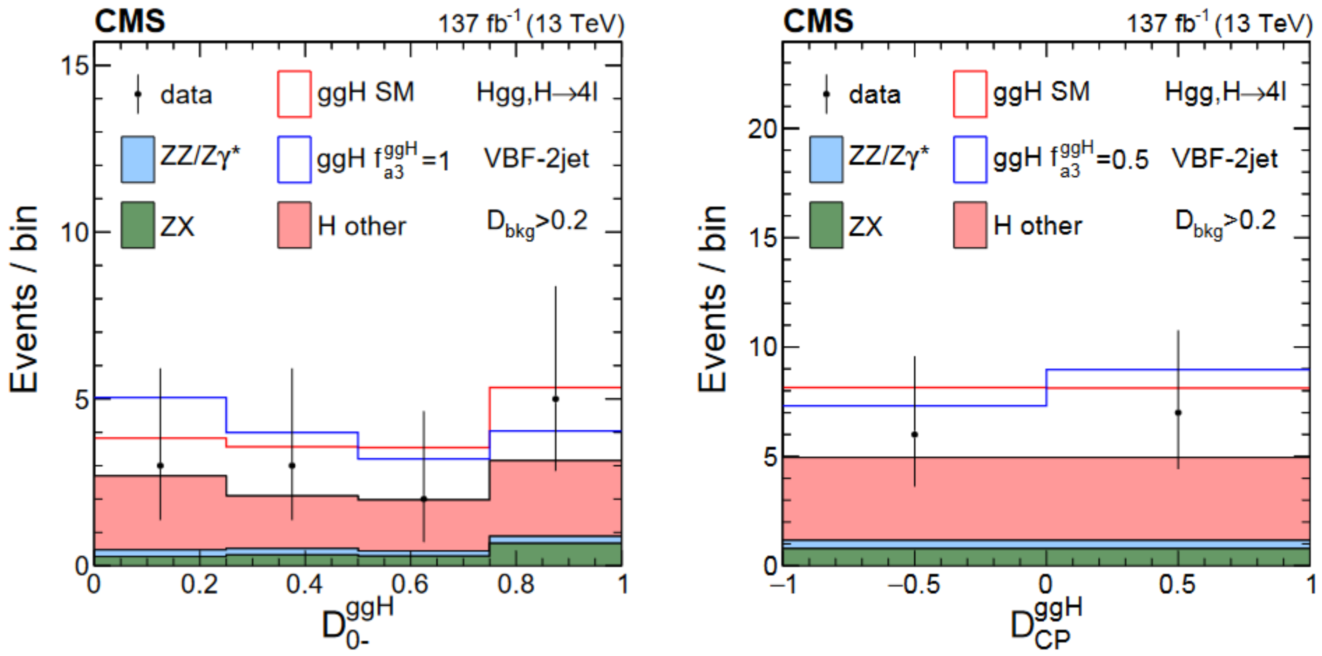
Anomalous couplings to VV ($H \rightarrow ZZ$) I

Phys. Rev. D 104 (2021) 052004

- Anomalous couplings studies in final states with 4ℓ
- **$H \rightarrow ZZ \rightarrow 4l$**

Strategy

- Production modes: **ggF, VBF, VH,** ttH, tH
- Parametrization as in previous analysis
- Full kinematic information is extracted using discriminants from matrix element calculations (using MELA)
    - Bkg vs signal
    - Signal production mode
    - CP



Several categories:
VBF: 1jet and 2jet
VH: hadronic and leptonic
ttH: hadronic and leptonic→Htt coupling
Untagged

Simulations:
JHUGEN used to describe kinematic distributions in the VBF, VH, ttH, tH

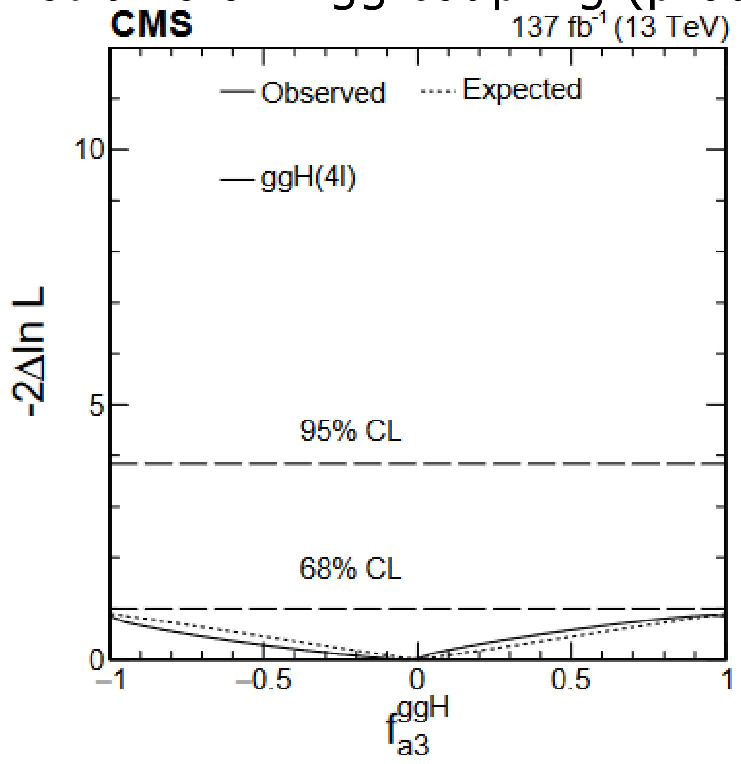
Anomalous couplings to VV ($H \to ZZ$) II

Results

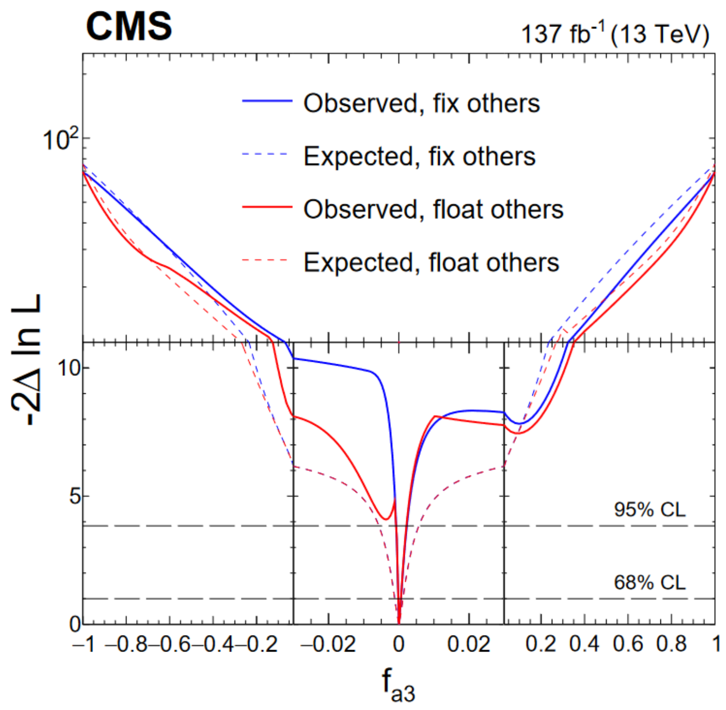
Phys. Rev. D 104 (2021) 052004

Perform multi-dimensional fit to extract parameters sensitive to CP

Constrains on Hgg coupling (production)



Constrain in HVV coupling (Decay)



Best value compatible with SM

Anomalous couplings: combination

Results:

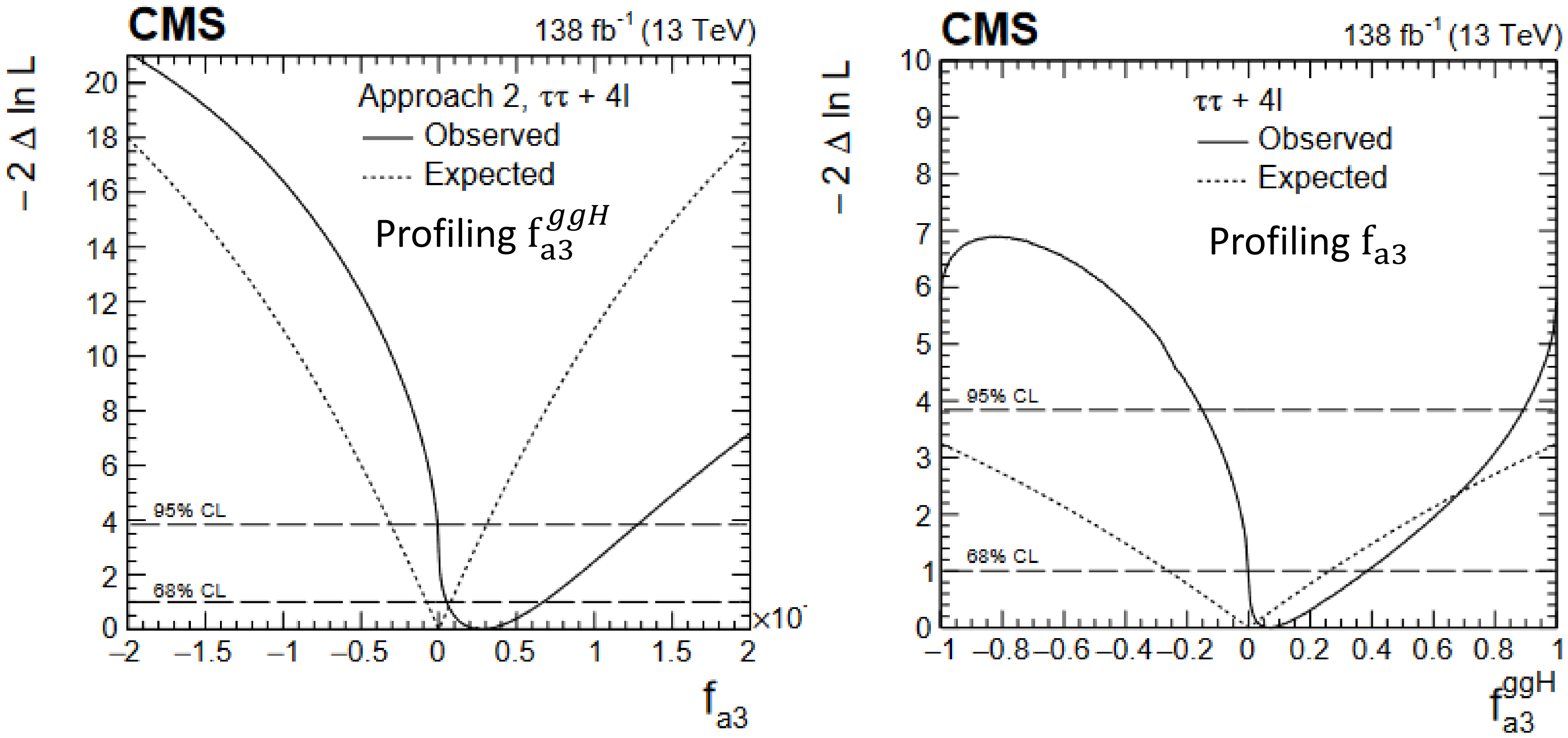
Combining the two decay modes $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \tau\tau$

Constrains are improved

$(a_i^{WW} = a_i^{ZZ})$ μ_{ggH}, μ_{qqH} profiled

CMS-HIG-PAS-20-007

Excludes pure CP-odd scenario
Hgg at 2.4 σ.



Hττ I

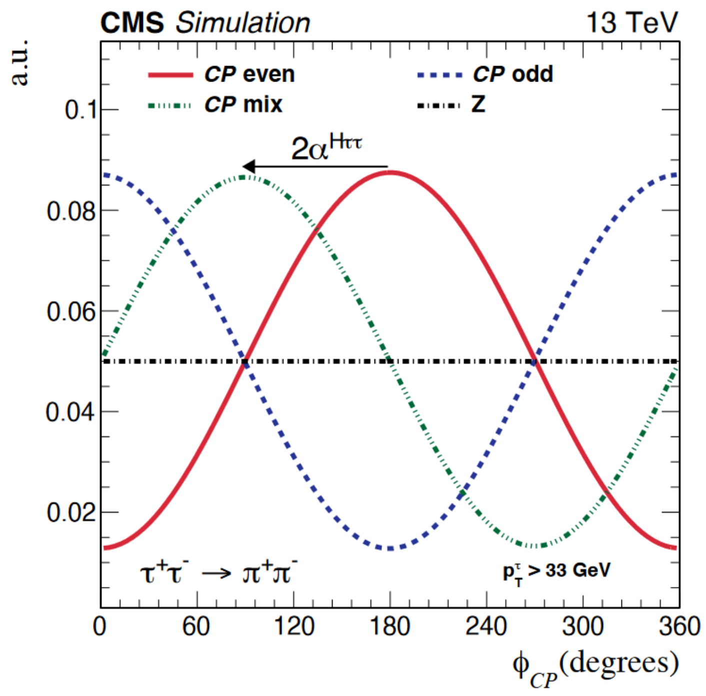
JHEP 06 (2022) 012

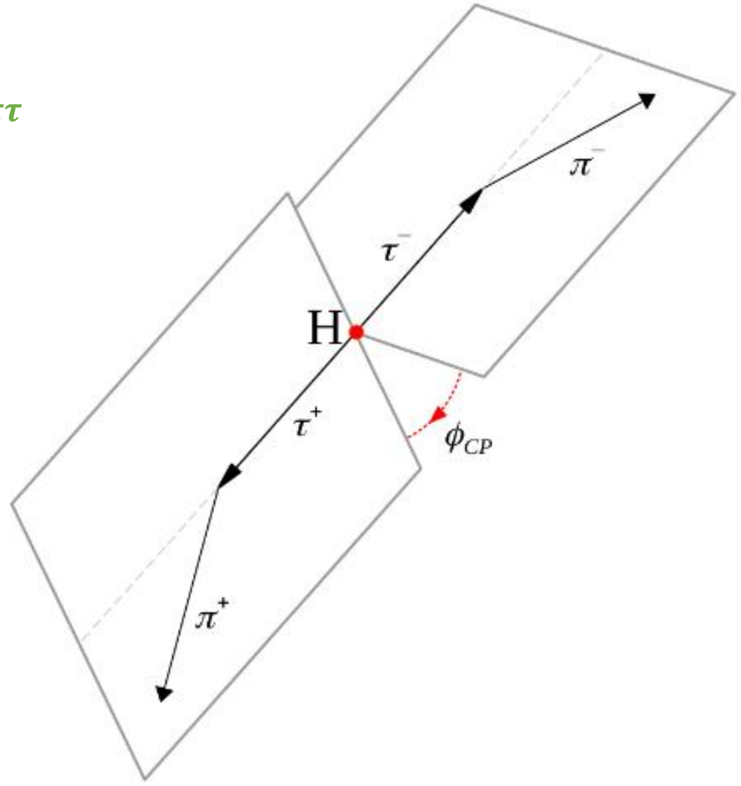
- First measurement of the CP structure of the H-τ Yukawa coupling
- ggH, VBF and VH production modes
- Channels: $\tau_h\tau_h, \tau_e\tau_h$ and $\tau_\mu\tau_h$ (70% of decay modes)

Methodology

$\alpha^{H\tau\tau}$: effective mixing angle $\tan(\alpha^{H\tau\tau}) = \frac{\widetilde{\kappa}_\tau}{\kappa_\tau}$

ϕ_{CP} : angle between the τ decay plane, **sensitive to** $\alpha^{H\tau\tau}$





$H\tau\tau$ I

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- Channels: $\tau_h\tau_h, \tau_e\tau_h$ and $\tau_\mu\tau_h$ (70% of decay modes)

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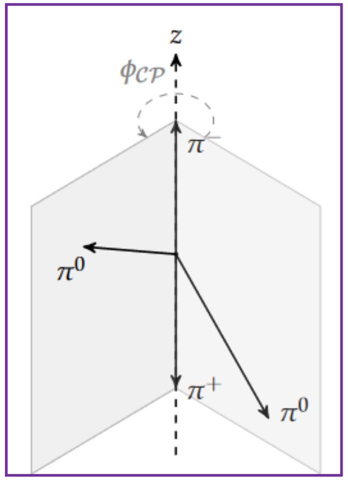
Methodology

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

ϕ_{CP} : angle between the τ decay plane, **sensitive to $\alpha^{H\tau\tau}$**



- Need to reconstruct the decay, several methods planes depending on the target decay:

$\tau_\mu \rightarrow \mu^\pm\nu\nu$ $\tau_e \rightarrow e^\pm\nu\nu$

$\tau_h \rightarrow \pi^\pm\nu$

} Impact parameter method

$\tau_h \rightarrow \rho^\pm\nu \rightarrow \pi^\pm\pi^0\nu$

$\tau_h \rightarrow a_1^{1pr}\nu \rightarrow \pi^\pm\pi^0\pi^0\nu$

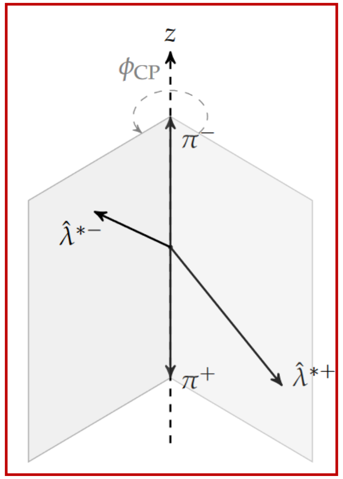
$\tau_h \rightarrow a_1^{3pr}\nu \rightarrow \pi^\pm\rho^0\nu \rightarrow \pi^\pm\,\pi^\pm\,\pi^\pm\,\nu$

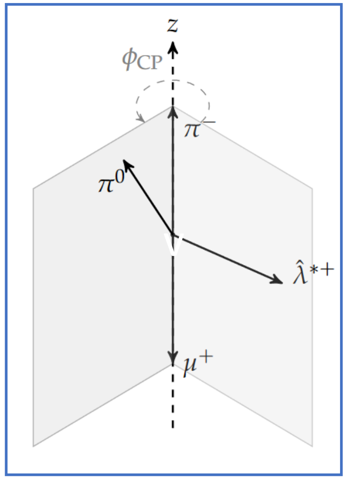
} Neutral pion method (more than 1 hadron)

} Combined

Polatimetric

In principle all, but:
Need to reconstruct well the p_T of the tau in the rest frame of the H



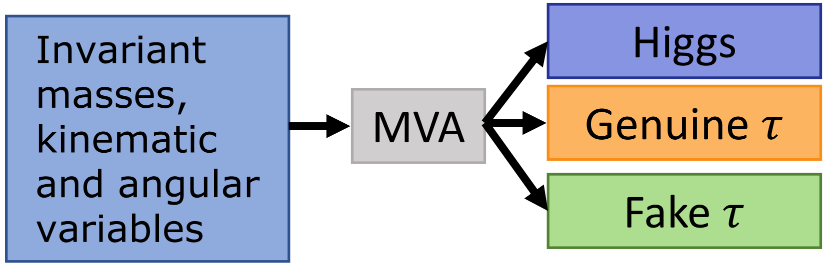


Hττ II

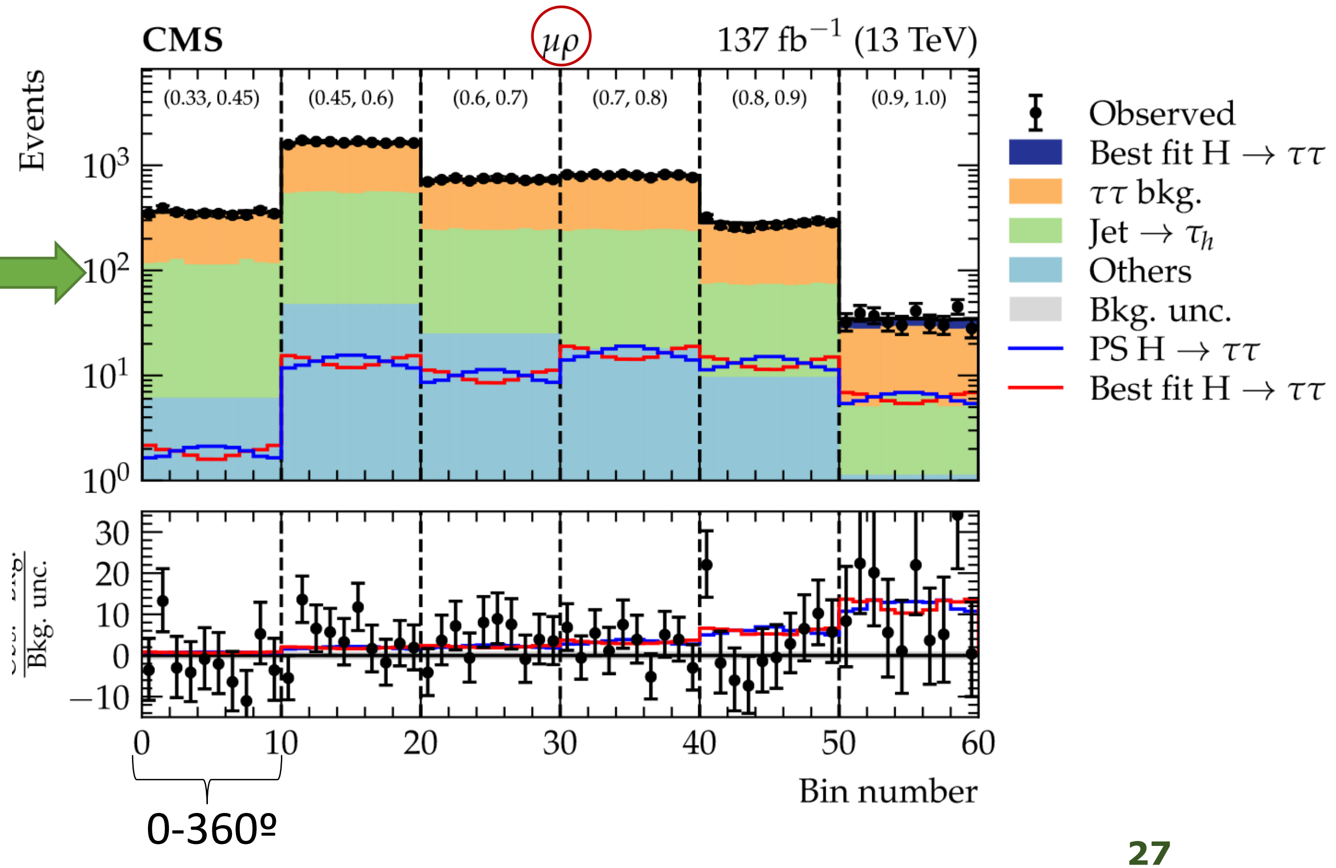
JHEP 06 (2022) 012

Analysis strategy

- Selection: τ pair of opposite charge
- Main Background: Z/W+Jet and $t\bar{t}$ → genuine τ or misID as τ
- Signal vs. Background discrimination using multiclass MVA in each channel



- In order to extract CP information: For the signal (Higgs) category ϕ_{CP} distribution is used in windows of the MVA discriminant for each of the (13) decay modes.



Systematic Unc:

Tau misID rate

Hadronic tau energy scale

Hττ III

JHEP 06 (2022) 012

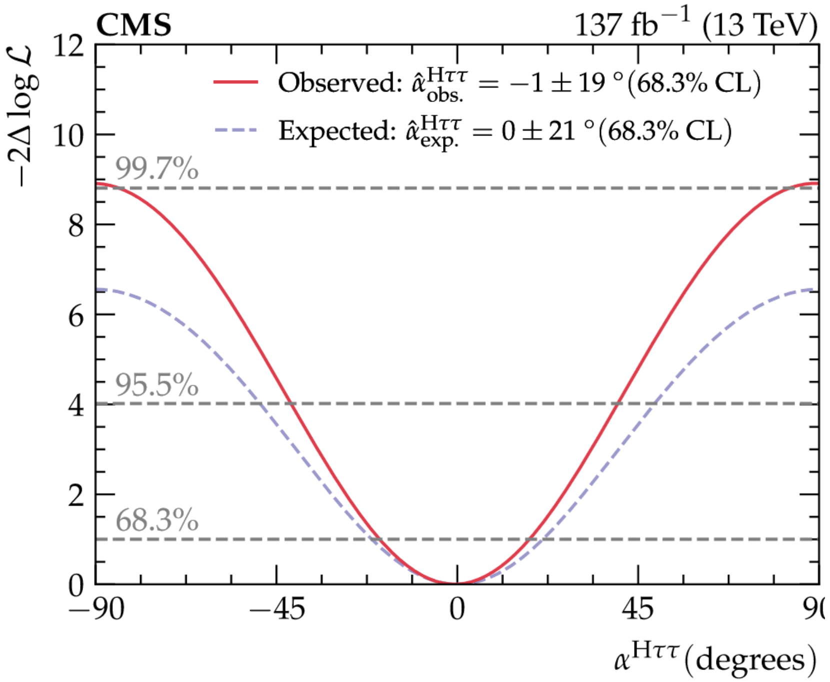
Results

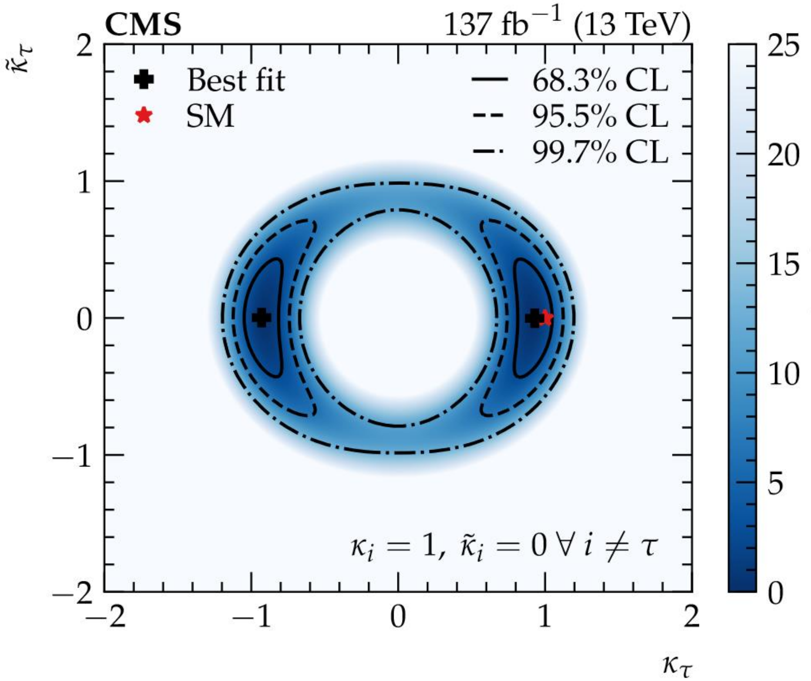
Maximum Likelihood fit to all Signal $\phi_{CP} - \mathrm{MVA}$ distributions and control regions:

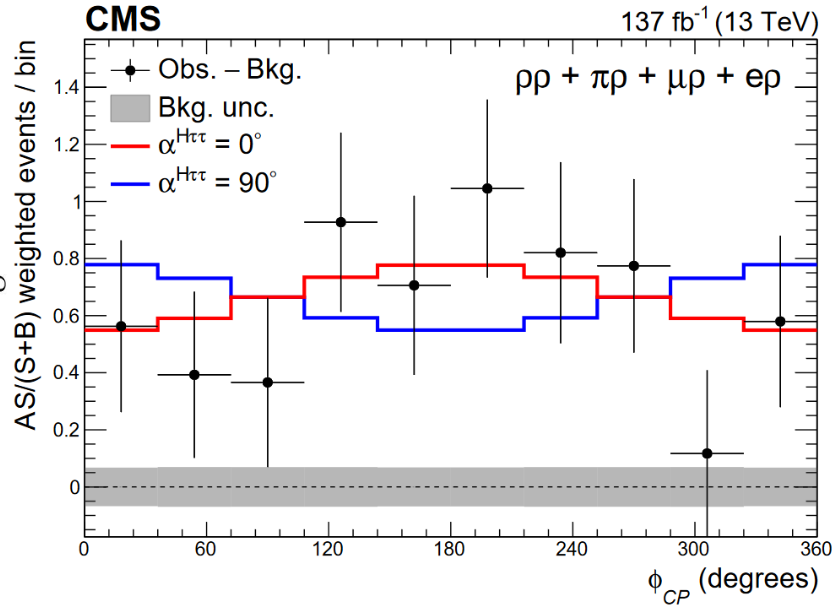
$$L(\mathcal{L}, \vec{\mu}, \alpha^{H\tau\tau}, \vec{\theta}) \quad \text{with} \quad \vec{\mu} = (\mu_{ggH}, \mu_{qqH})$$

Two dim limits parametrizing the L as a function of κ_τ and $\tilde{\kappa}_\tau$. Fixing other κ to the SM.

- $\alpha^{H\tau\tau}$ **=(-1±19)° @68%CL. Dominated by statistical uncertainties**.
- Pure CP odd **H$\tau\tau$** coupling excluded with **3.0σ** (2.6σ expected)







Htt: ttH→ $\gamma\gamma$ I

Phys. Rev. Lett. 125, 061801

Selection & Event Categorization

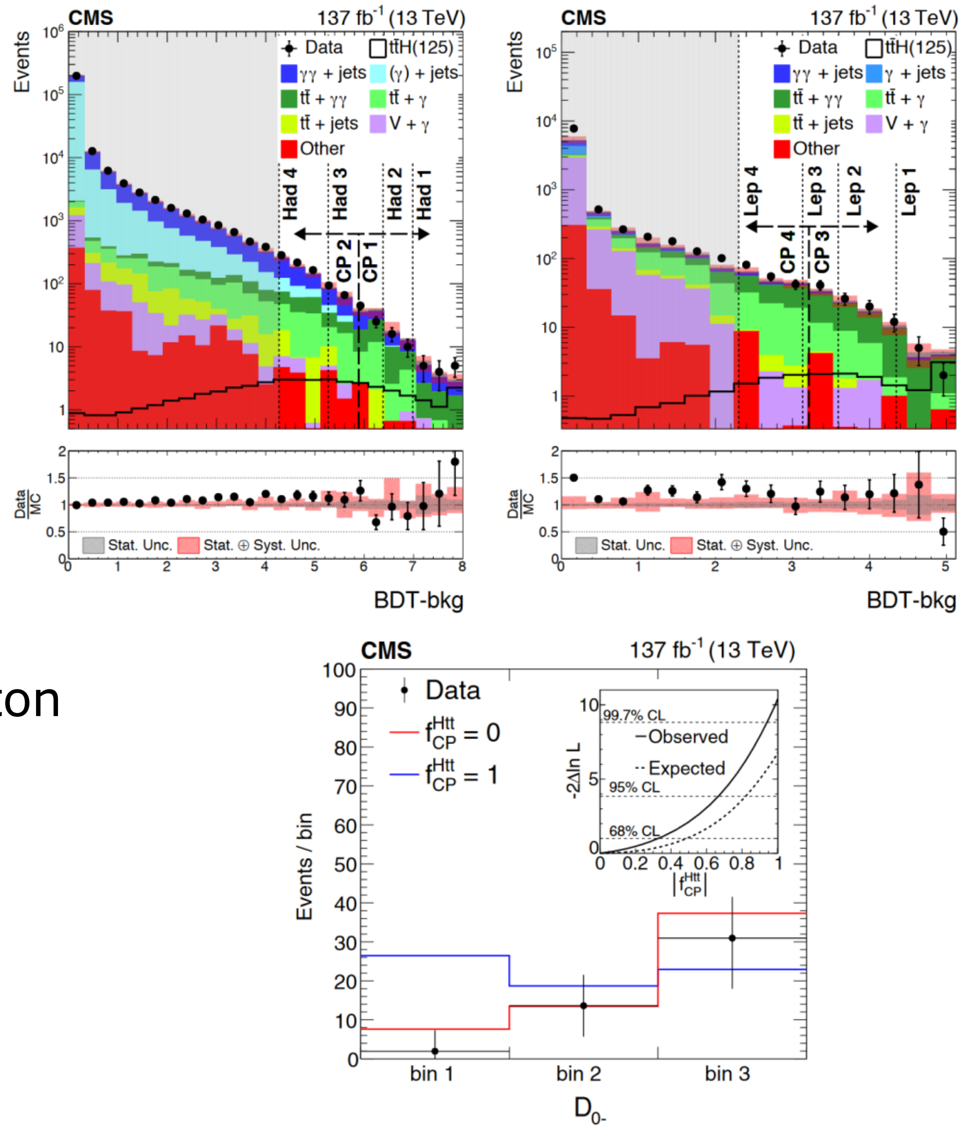
2 high pT γ+additional jets and leptons.
Two categories:

- Hadronic: 0 Leptons & ≥ 3 Jet & ≥ 1 btag
- Leptonic: ≥ 1 Lepton & ≥ 1 Jet

❑ MVA (BDT-bkg) in each category to separate signal from bkg.

❑ MVA to discriminate CP scenarios using:

- kinematic variables of jets, leptons and diphoton system (but not $m_{\gamma\gamma}$)
- the b-tagging scores of jets
- lepton multiplicity



Htt: ttH→ $\gamma\gamma$ II

Phys. Rev. Lett. 125, 061801

Results

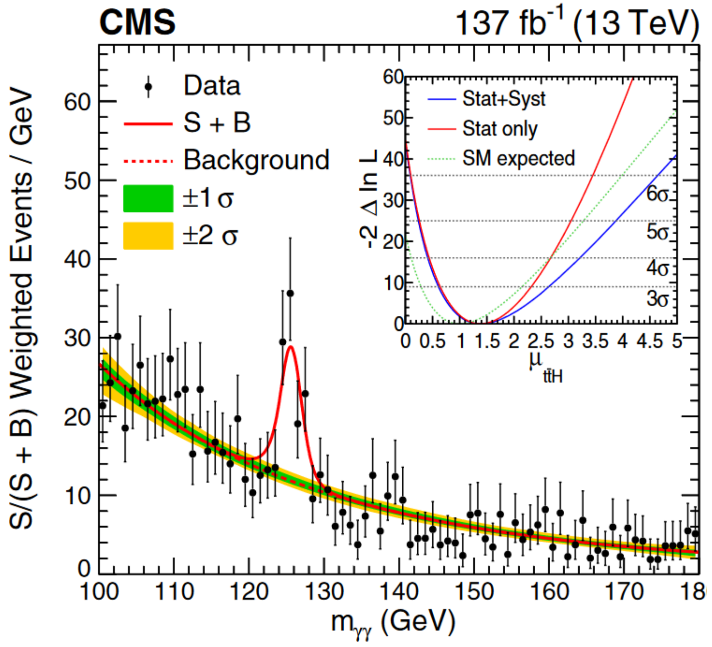
12 categories: 2 (BDT-bkg) x 3 (D_{0-}) x 2 (final state)

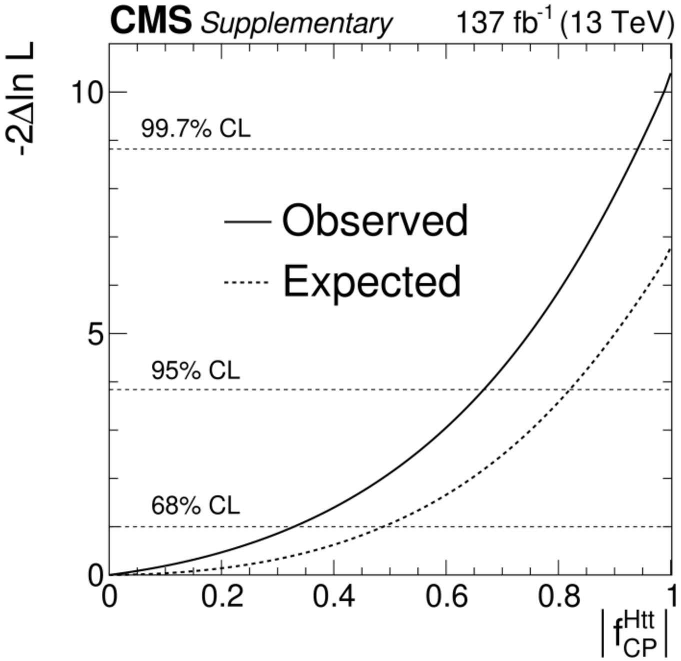
Simultaneous ML fit performed using the $m_{\gamma\gamma}$ distribution in the 12 categories to measure f_{CP}^{Htt}

$$f_{CP}^{Htt} = 0.00 \pm 0.33$$
$$|f_{CP}^{Htt}| < 0.67 @ \ 95\%\text{CL}$$

$$f_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2}$$

- Pure Pseudo Scalar model excluded at 3.2σ
- Cross section in good agreement with SM $\sigma_{t\bar{t}H}\mathcal{B}_{\gamma\gamma} = 1.56^{+0.34}_{-0.32}$ fb





- CP constrain dominated by statistic uncertainty
- Full run 3 lumi will increase sensitivity

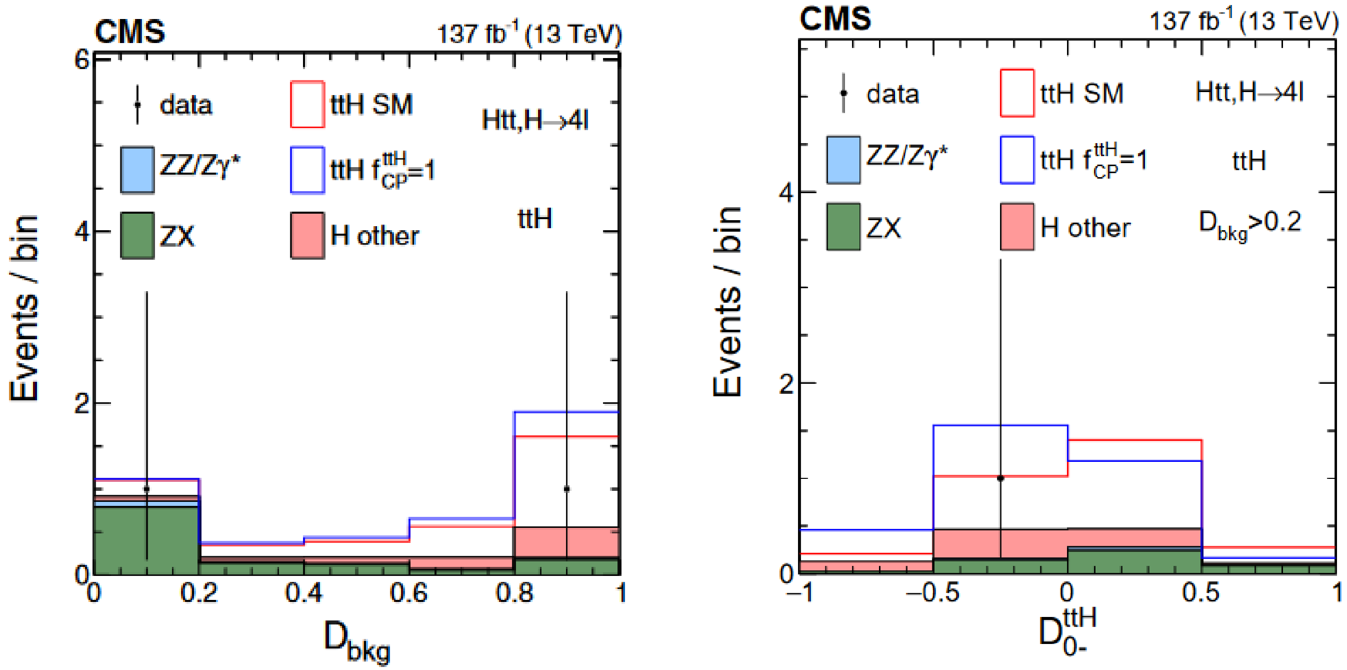
Htt: ttH→ 4 ℓ

Phys. Rev. D 104 (2021) 052004

- Anomalous couplings studies in final states with 4ℓ
- Targets several channels, in this talk we **focus on ttH:**

- **Selection:**
  a) ttH hadronic: ≥ 4 jets, a b-tagged jet, and no additional leptons
  b) ttH leptonic: At least 1 additional lepton

- BDT to discriminate signal form background
- **BDT (D_{0-}^{ttH})** used to exploit the kinematic information and discriminate CP-even vs CP-odd scenarios.



Htt: ttH→ $\gamma\gamma$+4l

Combined with Phys. Rev. D 104 (2021) 052004: Anomalous couplings in final state with 4l

- Production modes: ggF, VBF, VH, **ttH, tH**

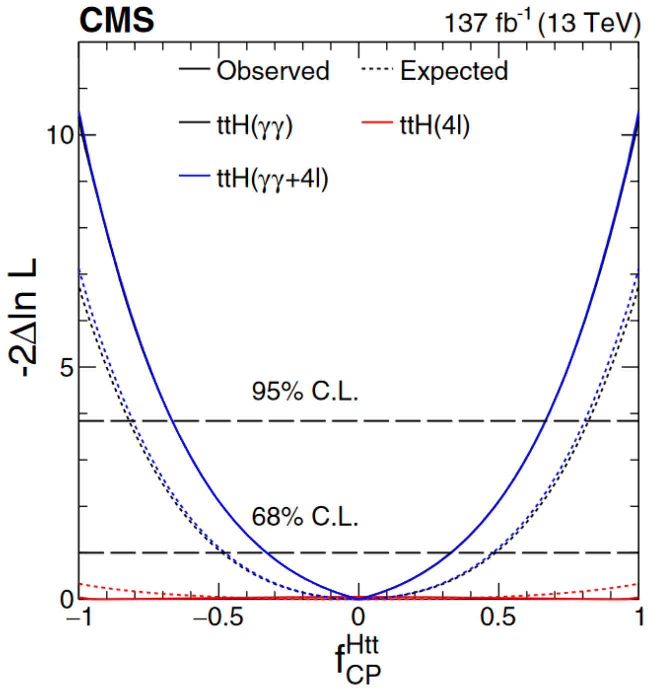
  Very limited statistics

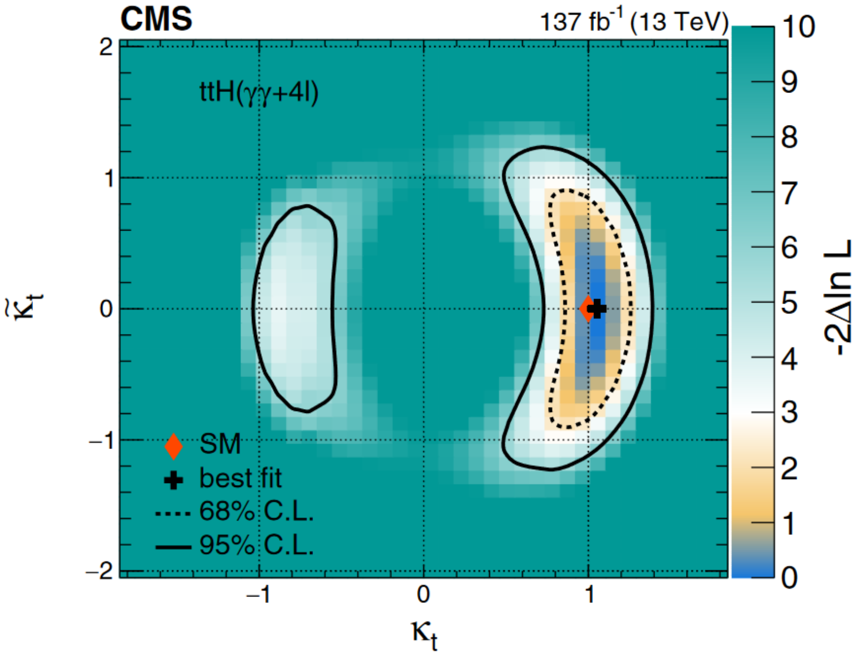
  - f_{cp} measured profiling:

    $\mu_{ttH}, \mu_{ttH}^{\gamma\gamma}$
    μ_{VH}, μ_{ggH} and their CP properties

- Parametrization using: κ_t $\tilde{\kappa}_t$
  - Fixing κ_b $\tilde{\kappa}_b$ to SM
  - μ_{ggH}, f_{a3}^{ggH}, profiled
  - HVV anomalous couplings not allowed

CP-odd Yukawa interaction excluded at 3.2σ





Htt: ttH→multileptons I

CMS-PAS-HIG-21-006

Selection

- 2lss +0 tau
- 2lss +1 tau
- 3l + 0 tau

} H→WW, $\tau\tau$

Dedicated selection in each category using **# Jets** and **b-tag** to targe ttH decays

- Extend selection with forward jets to **include tH**

Main Backgrounds

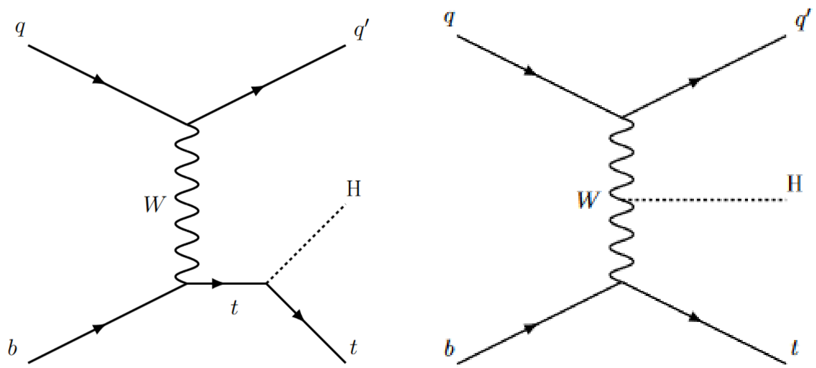
- Non prompt leptons and misidentified taus
- ttZ, ttW

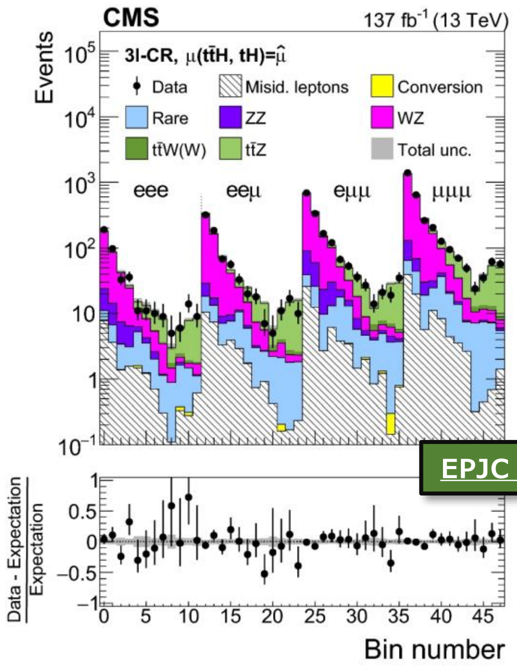
Simulation

- ttH and tH kinematic variations computed with MADGRAPH5 aMC@NLO

Main uncertainties

- Estimation of the misidentified leptons background
- Differences in signal modelling LO vs NLO





EPJC 81, 378 (2021)

Htt: ttH→multileptons II

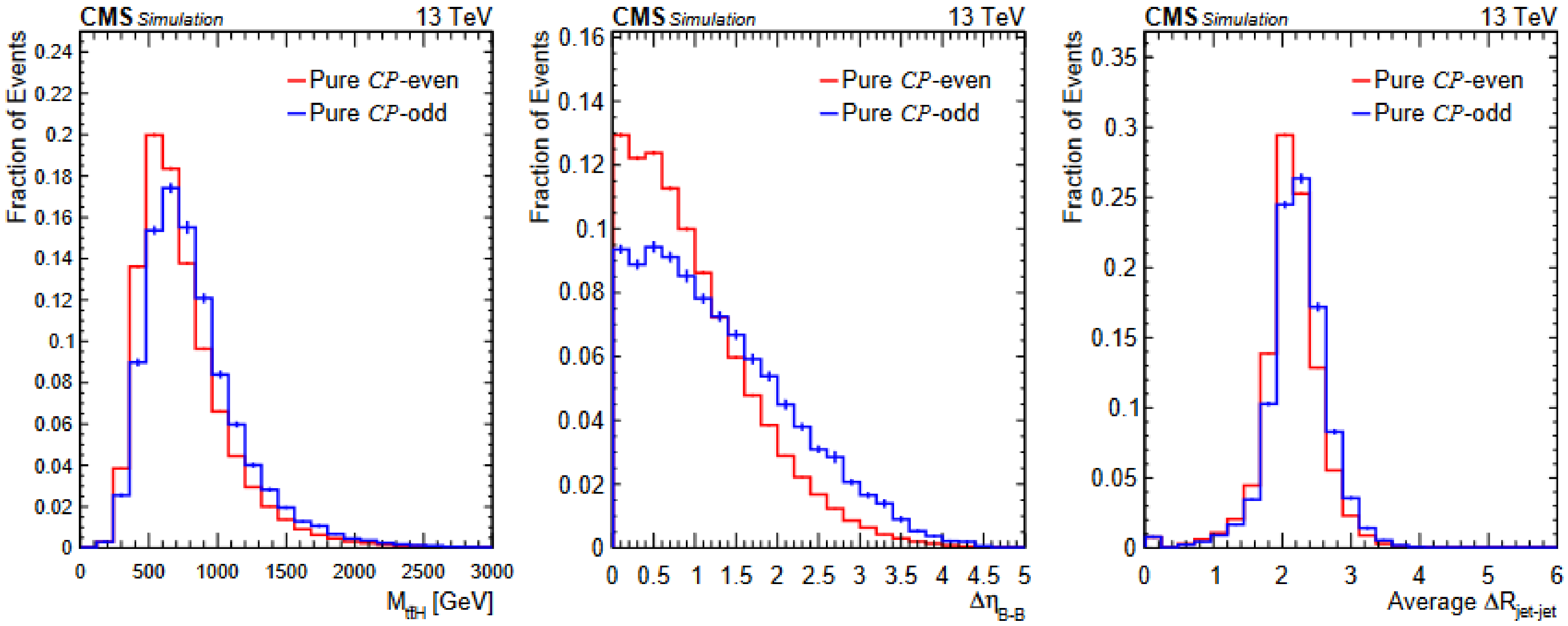
Dedicated multiclass **NN** in each category to discriminate
Signal and Background

CMS-PAS-HIG-21-006

CP discrimination:
BDT used in each category exploiting kinematical differences

Inputs: momentum of leptons and jets, angular variables, mases, object multiplicities and a specific tagger targeting hadronic top quark decays.

2lss 0 tau



Htt: ttH→multileptons III

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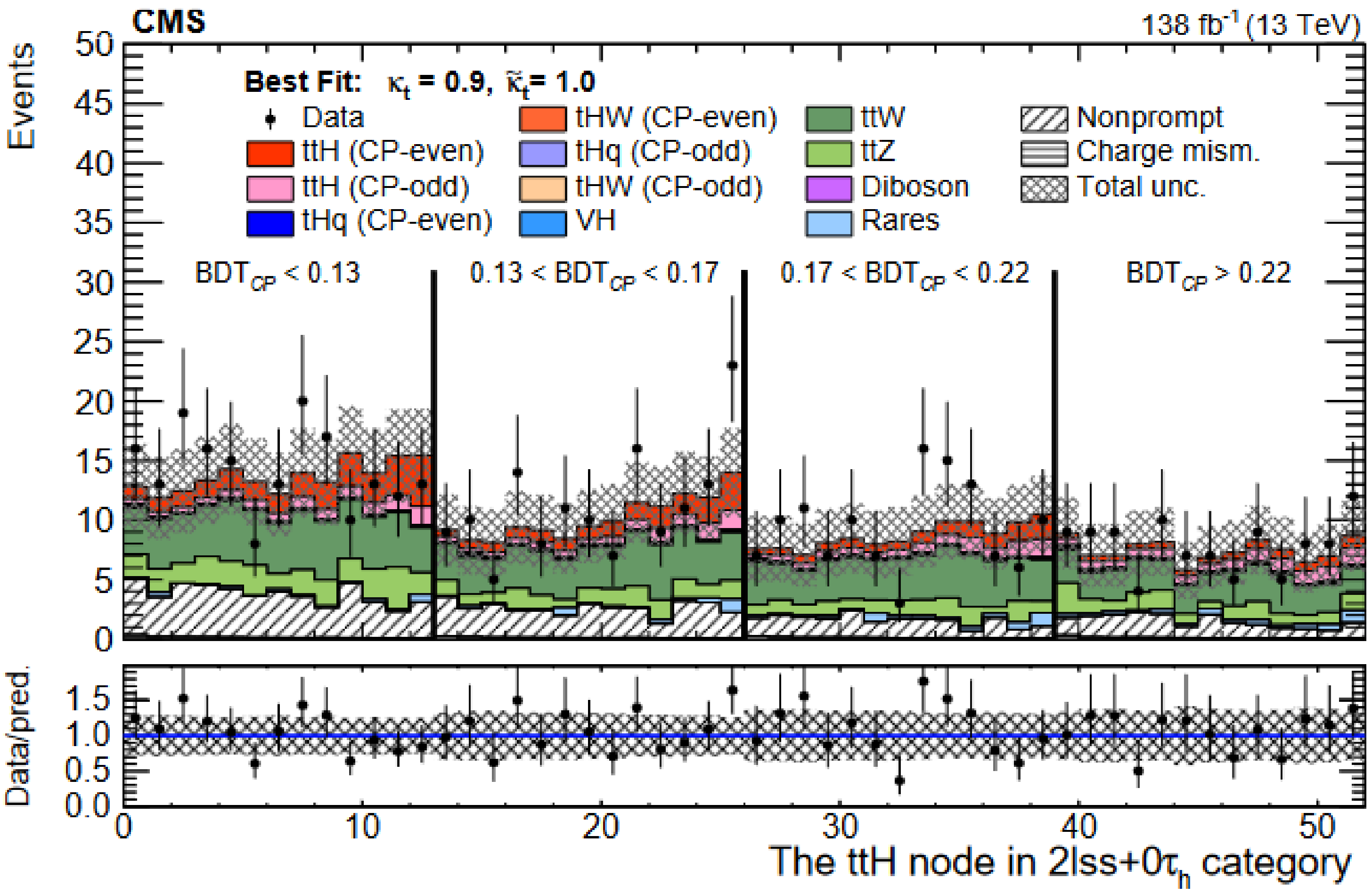
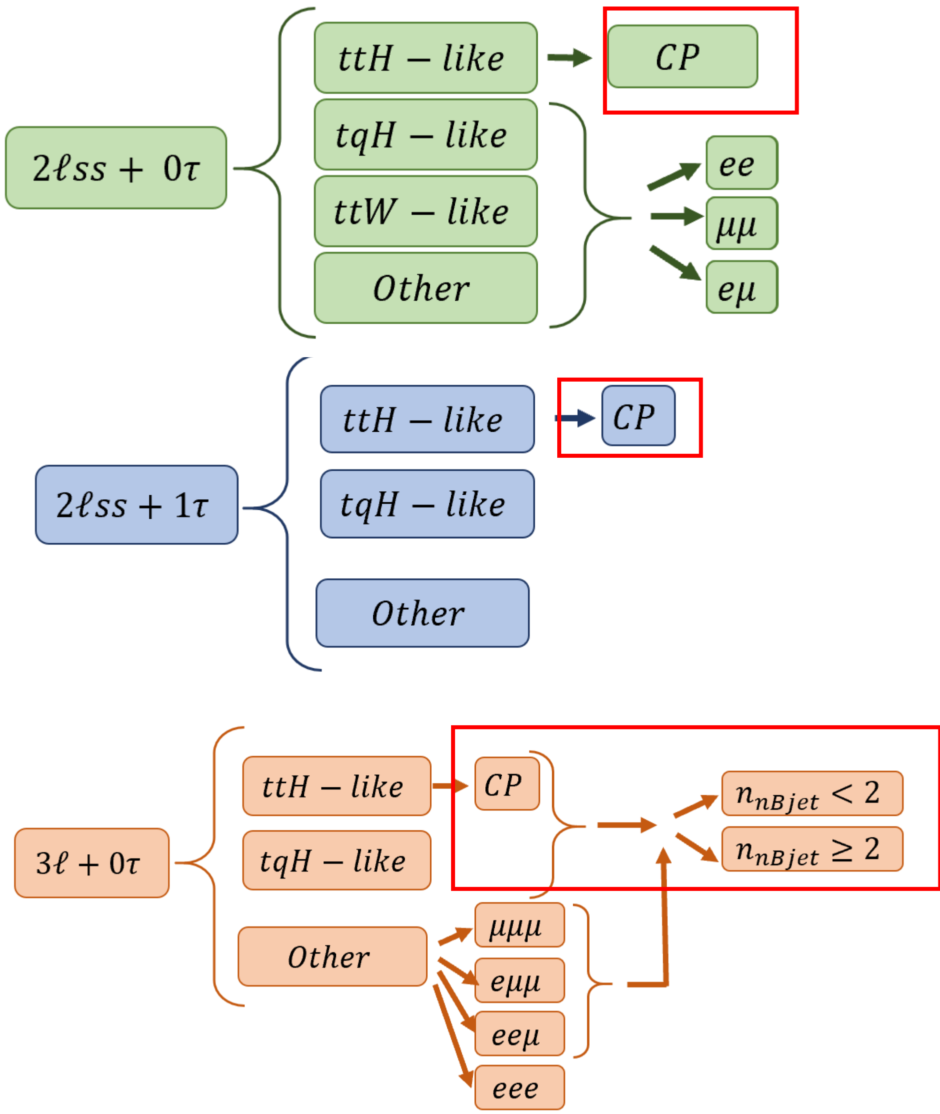
For the ttH-like category events are classified according to their score in CP-discriminant





Htt: ttH→ multileptons IV

Results:

Perform a **maximum likelihood fit** using:

- the three signal regions
  2lss + 0 τ_h,2lss + 1 τ_h and 3l + 0 τ_h
- Control regions

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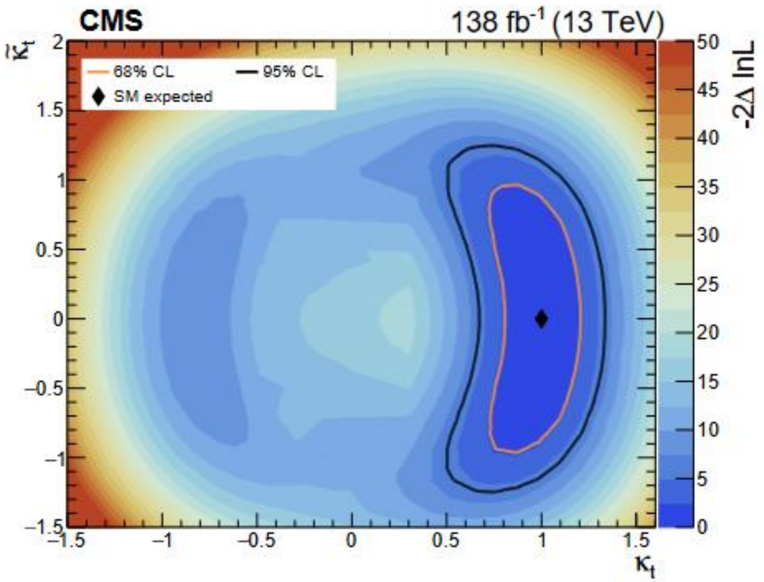
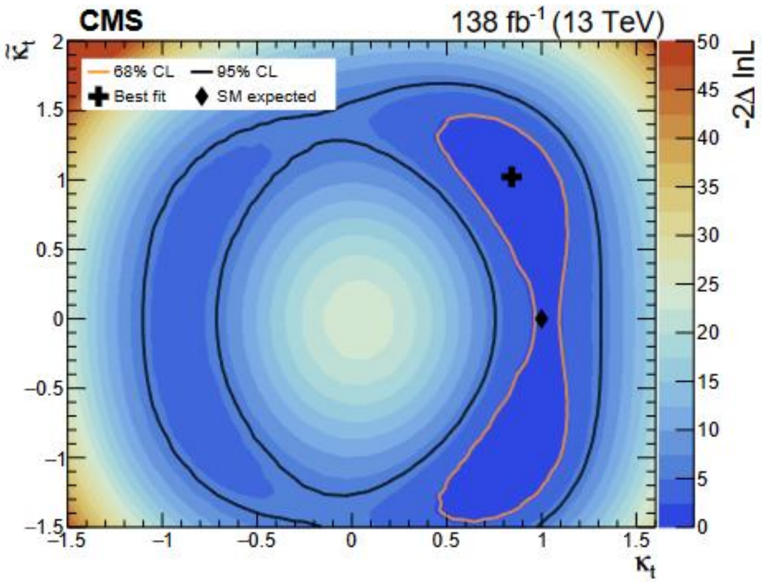
Expected

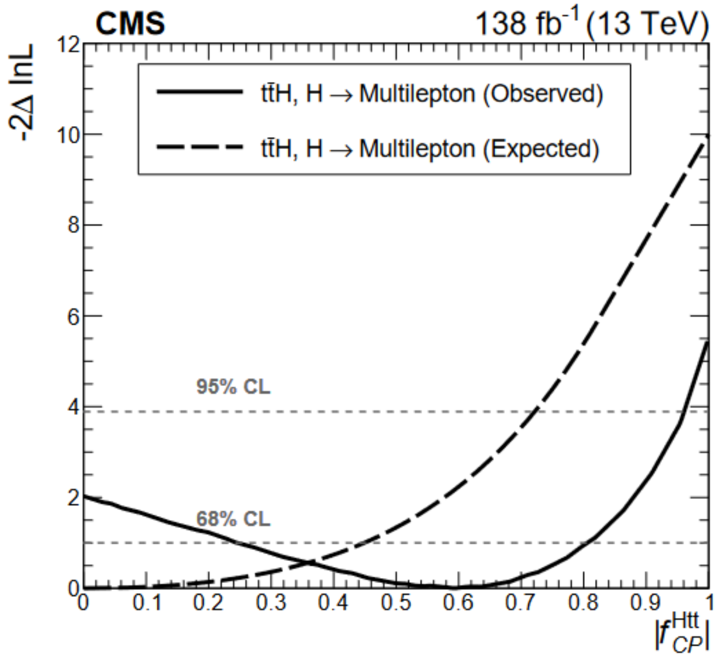


Observed



Best fit value:
κ_t = 0.9 & $\tilde{\kappa}_t$ =1.0   in good agreement with SM

f_{CP}(Profiling μ_{ttH})

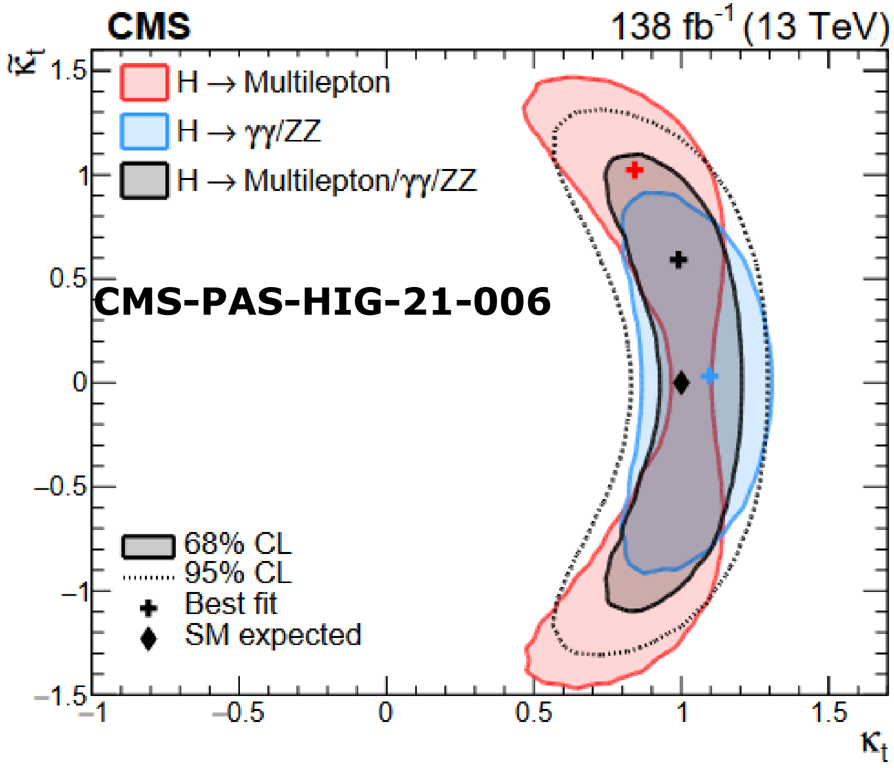


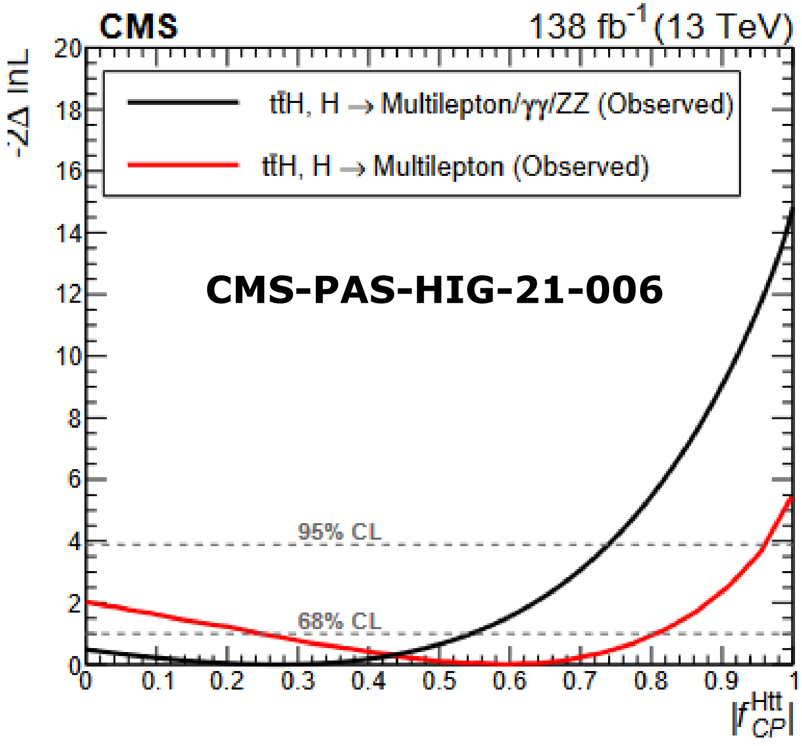
$f_{CP}^{Htt} = 0.59$ within (0.24, 0.81) at 68% CL

Htt: Combination

Combining ttH measurements:

- ZZ: Phys. Rev. D 104, 052004
- $\gamma\gamma$: Phys. Rev. Lett. 125, 061801
- multilepton (WW,$\tau\tau$): CMS-PAS-HIG-21-006





- f_{CP}^{Htt} = **0.28** within (-0.55, 0.55) at 68% CL
- $|f_{CP}^{Htt}| = 1$ excluded with 3.7σ

Summary

- CP violation can be searched in the Higgs sector
- Study the coupling of the Higgs with high precision is necessary

- LHC data taken during Run 2 allow us to study CP violation in Higgs coupling to
  - Vector bosons
  - Fermions

- Machine learning techniques are used to improve the sensitivity and discriminating power

- Working on the way of improving the observables
- Improving object reconstruction would also help
- These measurements are **statistical dominated**, run 3 data will help

- Other (more general) approaches as SMEFT also used to check anomalous couplings

- Results with run 2 data still coming → **stay tuned!**

Back up

Hττ: CP I

- First measurement of the CP structure of the H-τ Yukawa coupling
- ggH dominant production mode
- Channels: $\tau_h\tau_h, \tau_e\tau_h$ and $\tau_\mu\tau_h$ (70% of decay modes)
- Leptons allow to investigate the **CP nature** of the Higgs due to the spin correlation with their **decay products**

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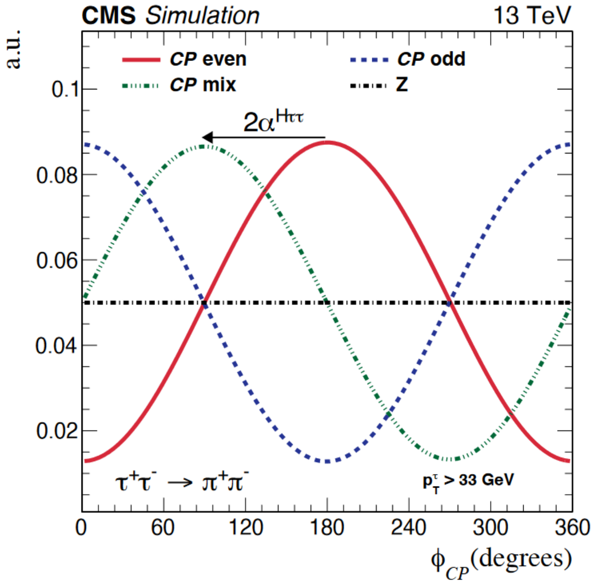
* Submitted to JHEP



Methodology

- Using the parametrization:

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

$\alpha^{H\tau\tau}$: effective mixing angle $\quad \tan(\alpha^{\mathrm{H}\tau\tau}) = \frac{\widetilde{\kappa}_\tau}{\kappa_\tau}$

ϕ_{CP} : angle between the τ decay plane, sensitive to $\alpha^{H\tau\tau}$

- Several methods to reconstruct the decay planes depending on the target decay:

$\tau_\mu \to \mu^\pm \nu\nu \quad \tau_e \to e^\pm \nu\nu$

$\tau_h \to \pi^\pm \nu$

Impact parameter method

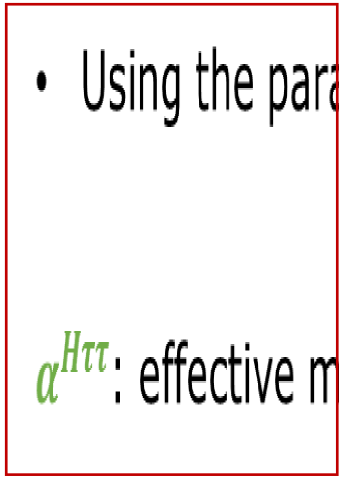
$\tau_h \to \rho^\pm \nu \to \pi^\pm \pi^0 \nu$

$\tau_h \to a_1^{1pr} \nu \to \pi^\pm \pi^0 \pi^0 \nu$

$\tau_h \to a_1^{3pr} \nu \to \pi^\pm \rho^0 \nu \to \pi^\pm \pi^\pm \pi^\pm \nu$

Neutral pion method

Polarimetric method



Hττ: CP II

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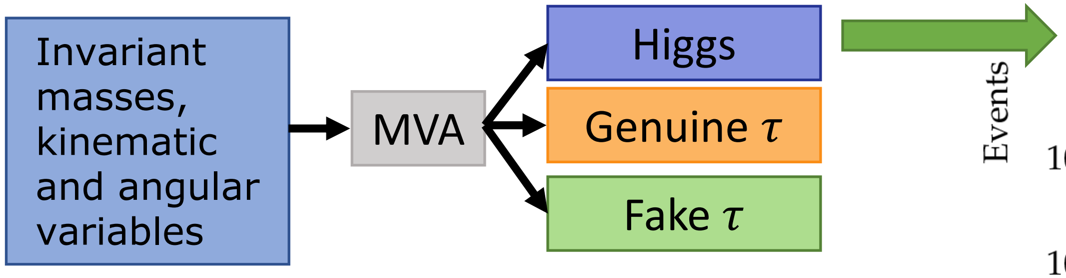
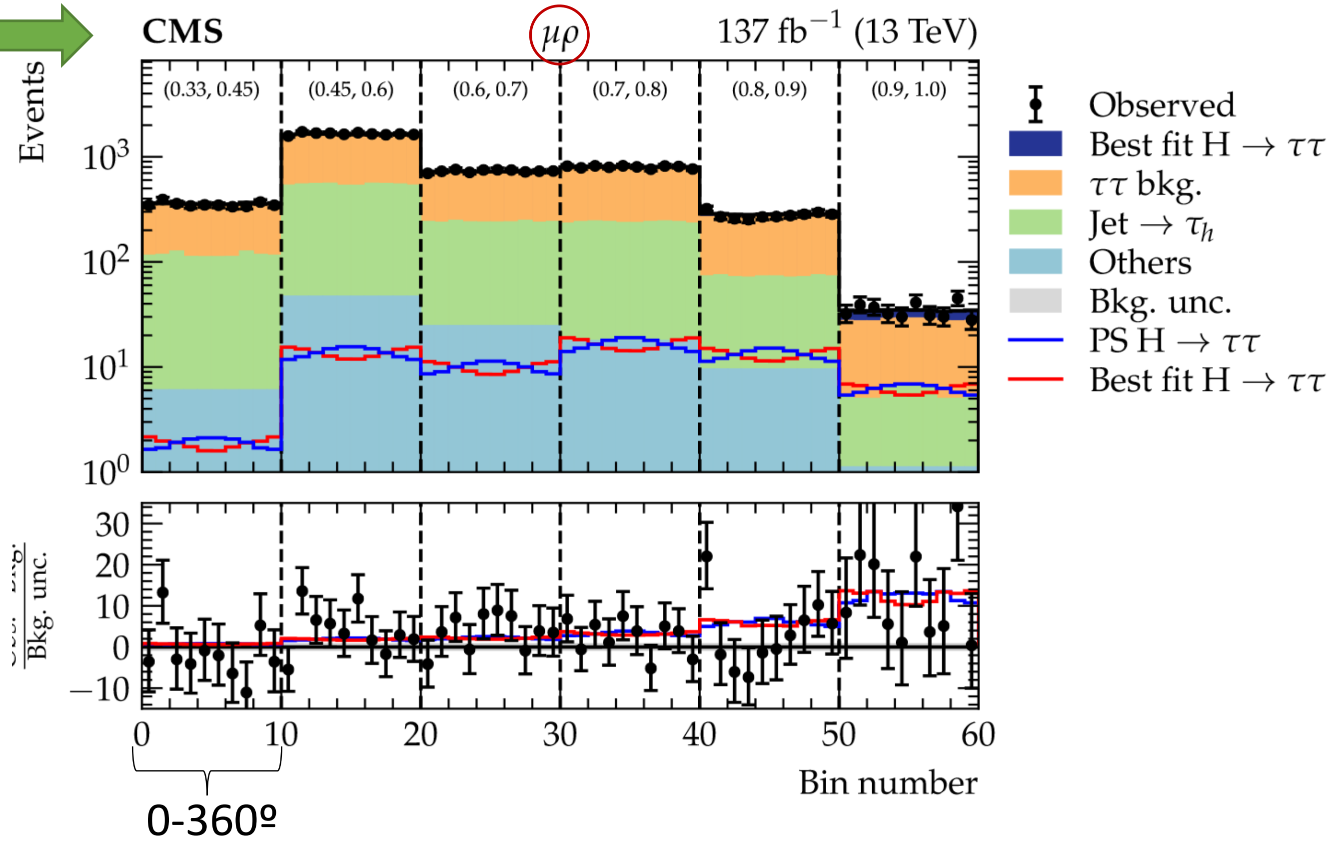
* Submitted to JHEP

Analysis strategy

- Baseline selection and bkg. estimation as in HIG-19-010
- Signal vs. Background discrimination using multiclass MVA in each channel.





- In order to extract CP information: For the signal (Higgs) category ϕ_{CP} distribution is used in windows of the MVA discriminant for each of the (13) decay modes.

$H\tau\tau$: CP III

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* Submitted to JHEP

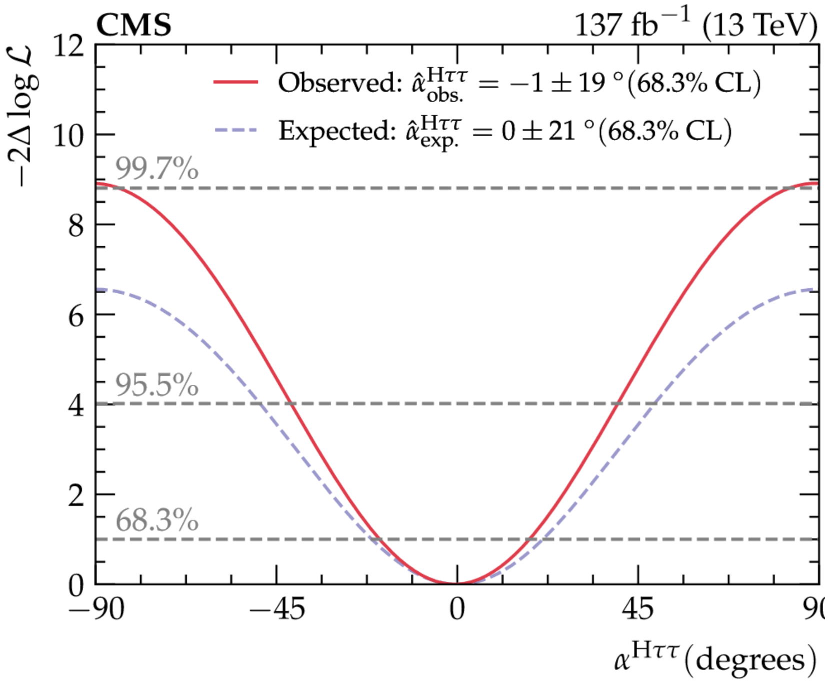
Results

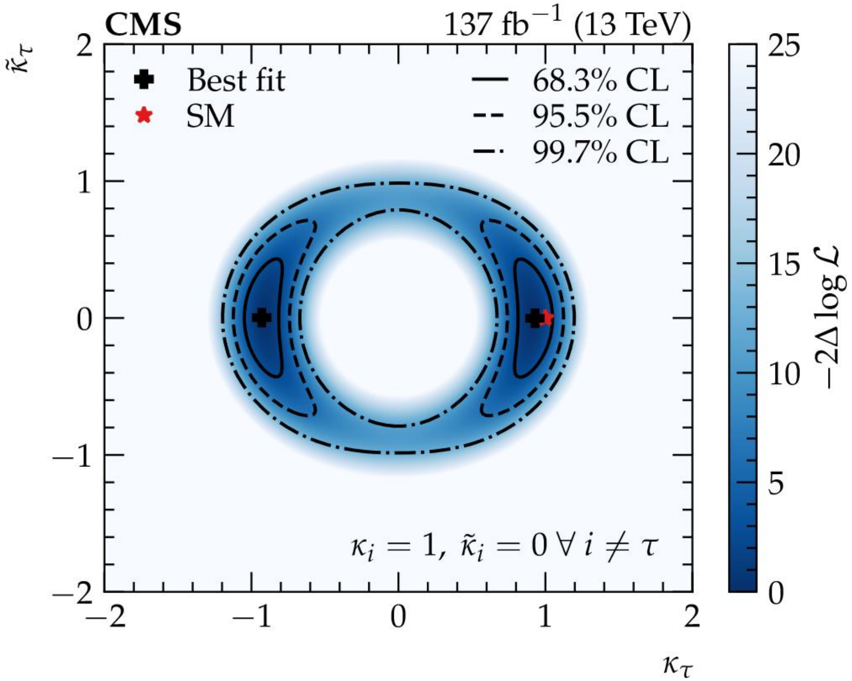
Maximum Likelihood fit to all Signal $\phi_{CP} - \mathrm{MVA}$ distributions and control regions:

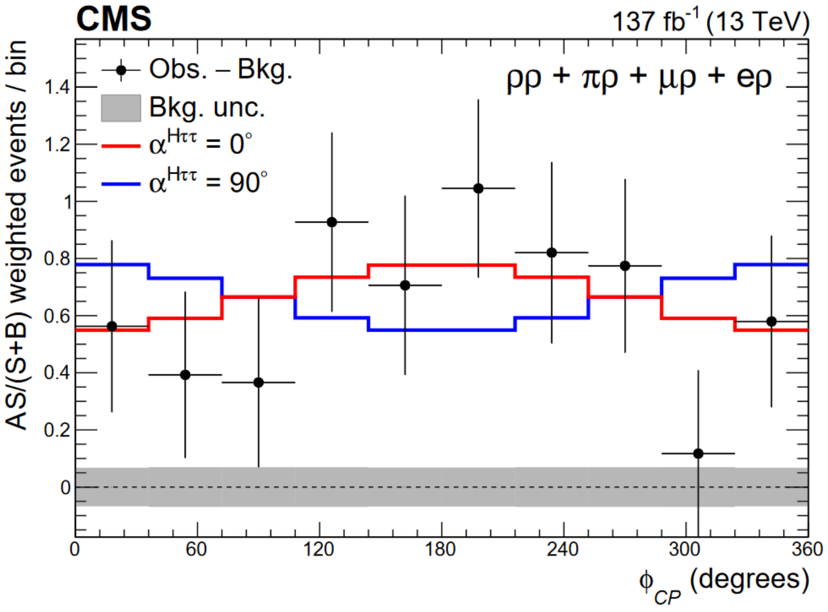
$$L(\mathcal{L}, \vec{\mu}, \alpha^{H\tau\tau}, \vec{\theta}) \quad \text{with} \quad \vec{\mu} = (\mu_{ggH}, \mu_{qqH})$$

Two dim limits parametrizing the L as a function of κ_τ and $\tilde{\kappa}_\tau$. Fixing other κ to the SM.

- $\alpha^{H\tau\tau}$ **=(-1±19)° @68%CL. Dominated by statistical uncertainties**.
- Pure CP odd **H$\tau\tau$** coupling excluded with **3.0σ** (2.6σ expected)







CP model ttH-> ml

- POIs: κ_t and $\tilde{\kappa}_t$
- Other κ also defined as POIs (fixed to SM the fit)
  $\kappa_V, \kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu, \kappa_\gamma, \kappa_g$
- Contribution from signal processes ttH and tH divided:
  ttH CP even → κ_t
  ttH CP odd → $\tilde{\kappa}_t$
  tH SM → κ_t and κ_V
  tH CP odd → $\tilde{\kappa}_t^2$
  tH_kv_0_kt_1 → $\kappa_t \cdot (\kappa_t - \kappa_V)$
  tH_kv_1_kt_0 → $\kappa_V \cdot (\kappa_V - \kappa_t)$
- For combination: tH process scaled with xsec only using the same parametrization as in HIG-19-013
- BR: fixed to SM in the fit

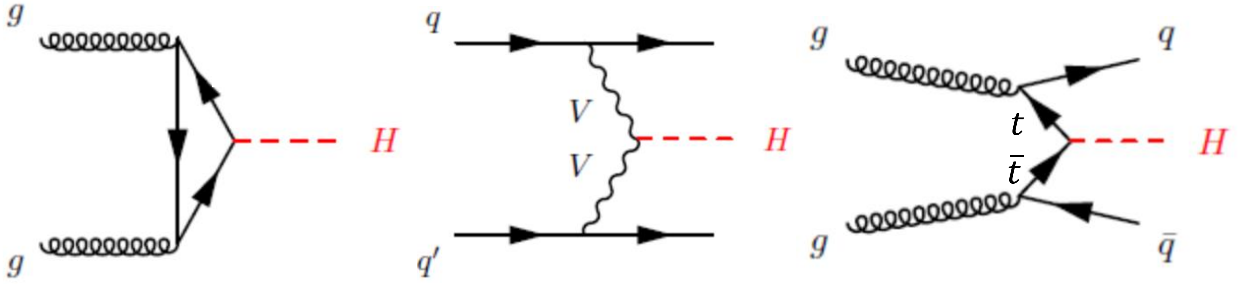
CP structure of Higgs coupling

In the SM Higgs boson is even under CP inversion.
Measure the CP structure of the Higgs coupling to:

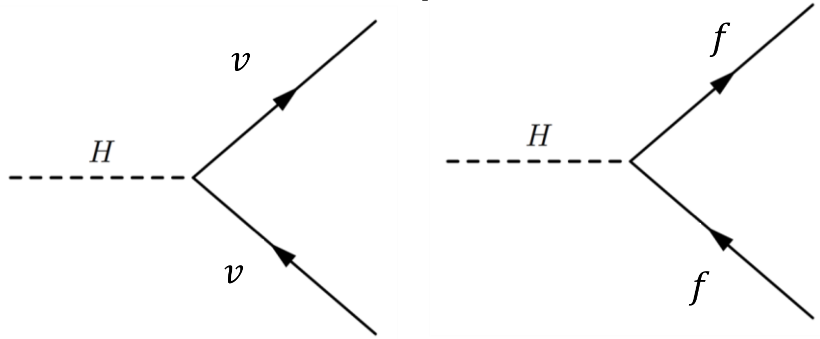
- Gauge bosons
- Fermions

Several strategies, using different:

Production modes



Decays



Generic spin-0 HVV scattering amplitude

tree-level SM-like

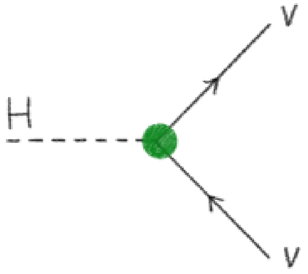
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}}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

$a_1^{ZZ} = a_1^{WW}$ (custodial symmetry)

Where VV = ZZ, WW, $Z\gamma$, $\gamma\gamma$ or gg

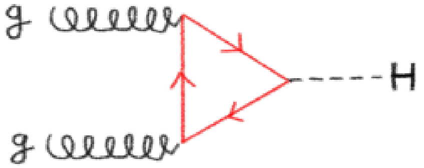
Considering gauge invariance

1) When VV = ZZ, WW, $Z\gamma$ — 4 couplings from each term



- a_1^{VV} (CP) : SM, where $a_1^{Z\gamma} = 0$
- a_2^{VV} (CP)
- Λ_1^{VV} (CP)
- a_3^{VV} ~~(CP)~~

2) When VV = $\gamma\gamma$, gg — 2 couplings from 3rd and 4th terms



- a_2^{VV} (CP) : SM
- a_3^{VV} ~~(CP)~~

In total, 15 couplings

- 4 constraint

  $a_i^{ZZ} = a_i^{WW}$, $\kappa_i^{ZZ}/(\Lambda_1^{ZZ})^2 = \kappa_i^{WW}/(\Lambda_1^{WW})^2$

  Hereafter WW and ZZ superscript will be omitted

- 4 uninteresting couplings

  Earlier measurement indicates substantially tighter limits on $a_2^{\gamma\gamma/Z\gamma}$, $a_3^{\gamma\gamma/Z\gamma}$

---

2 SM-like couplings :

→ a_1 and a_2^{ggH}

5 anomalous couplings are of our interest :

→ a_2 , a_3 , Λ_1 , $\Lambda_1^{Z\gamma}$ and a_3^{ggH}