

# First direct measurement of the Higgs-tau Yukawa coupling

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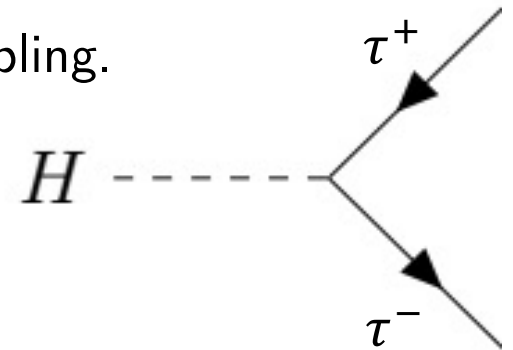
*15 June 2022*

IPM weekly seminars

- Concrete observations demand new physics, e.g. Dark Matter, matter-antimatter asymmetry, etc.
- 10 years after the Higgs discovery -> no new physics found in direct searches!
- Another approach -> precisely measuring the SM parameters.
  - Model-independent
  - interpretable in BSM
  - In line with the LHC plan: data (rather than energy) increase
- Measuring the Higgs charge conjugation-parity (CP)
  - Higgs unique in SM
  - Deviations predicted by BSM
  - matter-antimatter asymmetry

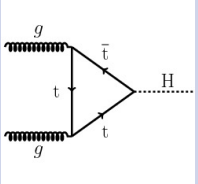
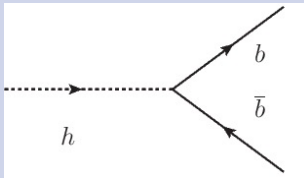
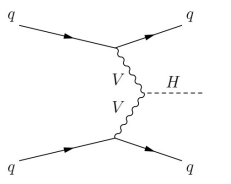
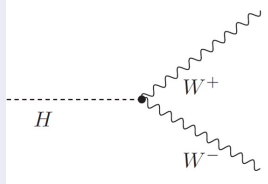
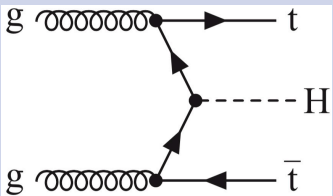
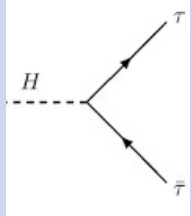


- CP:
  - C: particles to antiparticles
  - P:  $\vec{r} \rightarrow -\vec{r}$
- CP violation searches:
  - Quarks: observed in a few mesons ( $K^0$ ,  $B^0$ ,  $D^0$ )
  - Leptons: Not observed yet, but an evidence recently found in neutrino sector
  - Higgs: Not observed yet.
- SM predicts the Higgs boson to be *even* under CP operation.
- This study: first direct measurement of the CP structure of the  $H\tau\tau$  Yukawa coupling.



# How to measure the Higgs CP?



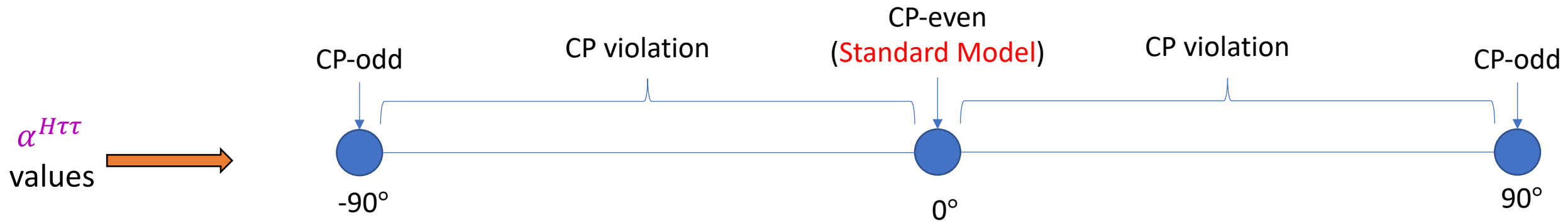
Production	Decay
<p>ggH: model dependent (loop)</p> 	<p>H-&gt;bb: Spin information washed out due to hadronization</p> 
<p>VBF: CP-odd is suppressed (CP-odd: non-renormalizable) V=Z/W</p> 	<p>H-&gt;VV (V=Z/W): CP-odd is suppressed (CP-odd: non-renormalizable)</p> 
<p>ttH: complementary to H-&gt;ττ (e.g. in C2HDM)</p> 	<p>H-&gt;ττ: model-independent, complementary to ttH</p> 
<p>bbH: Much harder than ttH to measure as the sensitivity of the kinematic shapes <math>\propto</math> mixing of the left- &amp; right-handed helicities <math>\propto</math> quark mass</p>	

Therefore  $H \rightarrow \tau\tau$  is an important channel to look at.

- The Lagrangian for  $H\tau\tau$  coupling can be decomposed into CP-even and CP-odd terms:

$$L_Y = -\frac{m_\tau}{v} h \left( \underbrace{\kappa_\tau \bar{\tau}\tau}_{\text{CP-even}} + \underbrace{\tilde{\kappa}_\tau \bar{\tau}i\gamma_5\tau}_{\text{CP-odd}} \right) , \quad m_\tau = \text{mass of } \tau, \quad v = \text{V.E.V.} = 246 \text{ GeV}$$

- Defining effective CP-mixing angle  $\alpha^{H\tau\tau} = \arctan\left(\frac{\tilde{\kappa}_\tau}{\kappa_\tau}\right)$



- The **final goal** is to measure  $\alpha^{H\tau\tau}$ .

- Calculating the partial decay width in the Higgs rest frame (and approximating  $\beta_\tau = \sqrt{1 - 4m_\tau^2/m_h^2} \approx 1$ ):

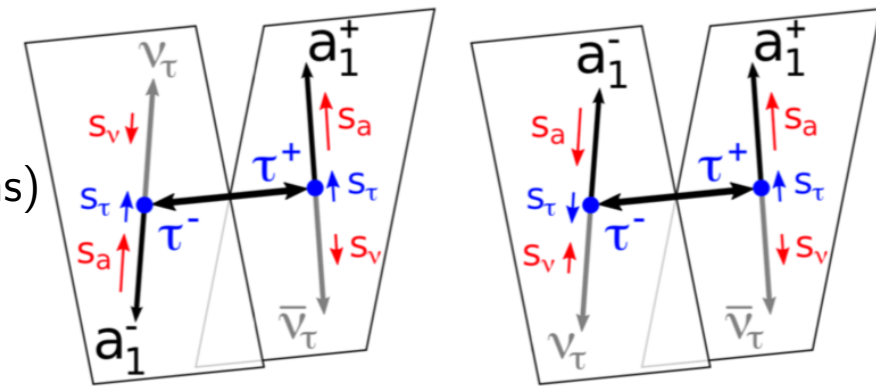
$$d\Gamma_{H \rightarrow \tau\tau} \propto 1 - s_z^- s_z^+ + \cos(2\alpha^{H\tau\tau}) (\mathbf{s}_T^- \cdot \mathbf{s}_T^+) + \sin(2\alpha^{H\tau\tau}) [(\mathbf{s}_T^+ \times \mathbf{s}_T^-) \cdot \hat{\mathbf{k}}^-]$$

in which  $s_T^\pm$  and  $s_z^\pm$  are the transverse and longitudinal component of the  $\tau^\pm$  spin with respect to  $\hat{\mathbf{k}}^-$ , the unit vector in the  $\tau^-$  direction. This can be shown to be equal to:

$$d\Gamma_{H \rightarrow \tau\tau} \propto 1 - s_z^- s_z^+ + |\mathbf{s}_T^-| |\mathbf{s}_T^+| \cos(\phi_s - 2\alpha^{H\tau\tau})$$

with  $\phi_s$  showing the angle between  $\mathbf{s}_T^+$  and  $\mathbf{s}_T^-$  in the right-handed coordinate system.

- Therefore, the CP of the Higgs affects the angle between  $\mathbf{s}_T^+$  and  $\mathbf{s}_T^-$ .
  - CP-even Higgs:  $\alpha^{H\tau\tau} = 0^\circ \rightarrow d\Gamma$  peaks at  $\phi_s = 0^\circ$  (parallel spins)
  - CP-odd Higgs:  $\alpha^{H\tau\tau} = 90^\circ \rightarrow d\Gamma$  peaks at  $\phi_s = 180^\circ$  (antiparallel spins)



- Neutrinos left handed  $\rightarrow$  spin correlates with decay planes

- Theory parameter ( $\alpha^{H\tau\tau}$ )  $\rightarrow$  angle between transverse spins ( $\phi_s$ )  $\rightarrow$  angle between decay planes ( $\phi_{CP}$ )

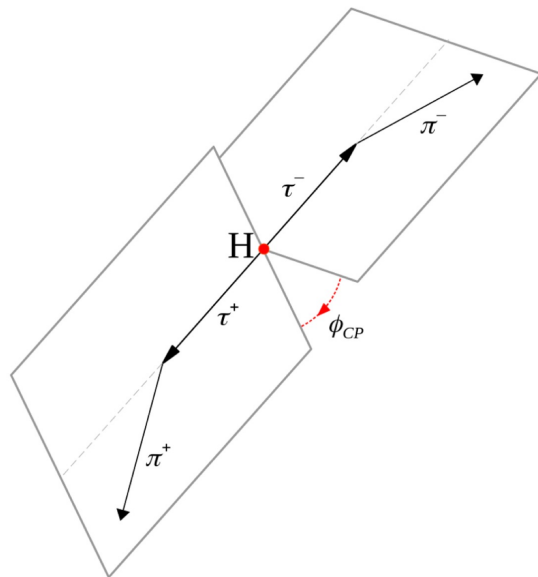
# Measurement strategy

$\rightarrow \alpha^{H\tau\tau}$  determines the tau spin correlation.  
 $\rightarrow$  tau spin is correlated with decay plane.

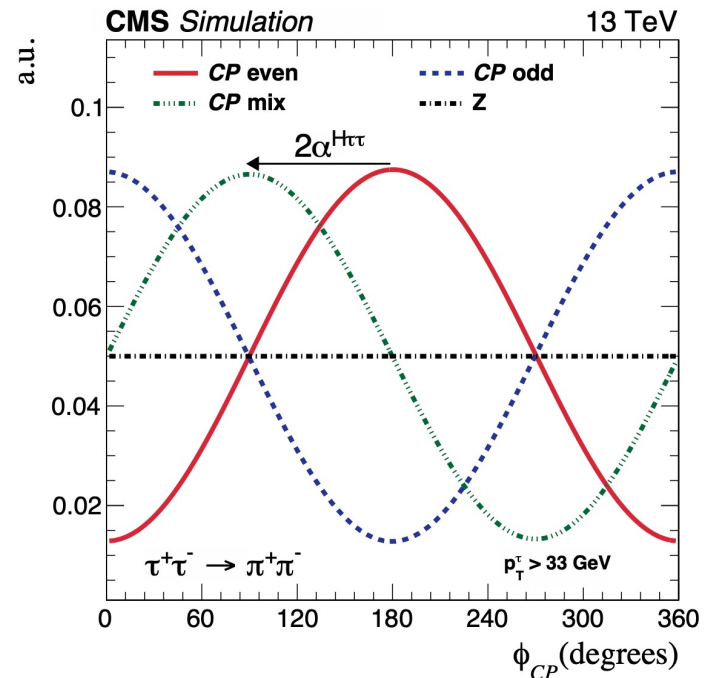
$\Rightarrow$  decay planes correlated based on  $\alpha^{H\tau\tau}$

$\triangleright$  We define an observable,  $\phi_{CP}$ , as the angle between  $\tau$  decay planes in the H rest frame (left fig.)

$\triangleright$  It can be shown that ([S.Berge et al](#)):  $d\Gamma(H \rightarrow \tau^+\tau^-) \approx 1 - b(E_+)b(E_-) \cdot \frac{\pi^2}{16} \cos(\phi_{CP} - 2\alpha^{H\tau\tau})$ .

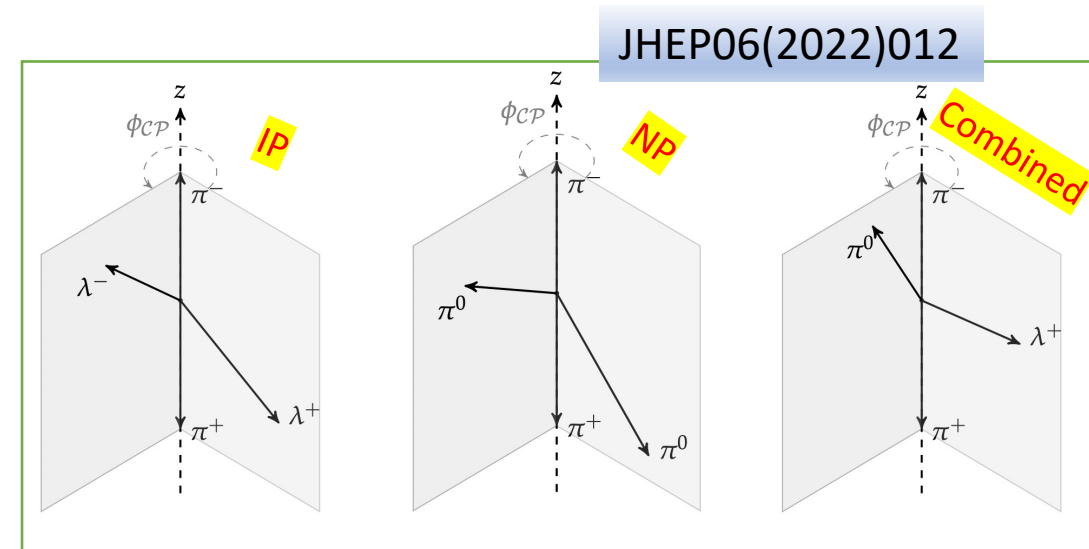
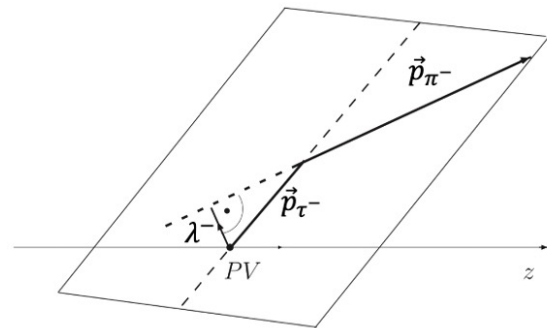


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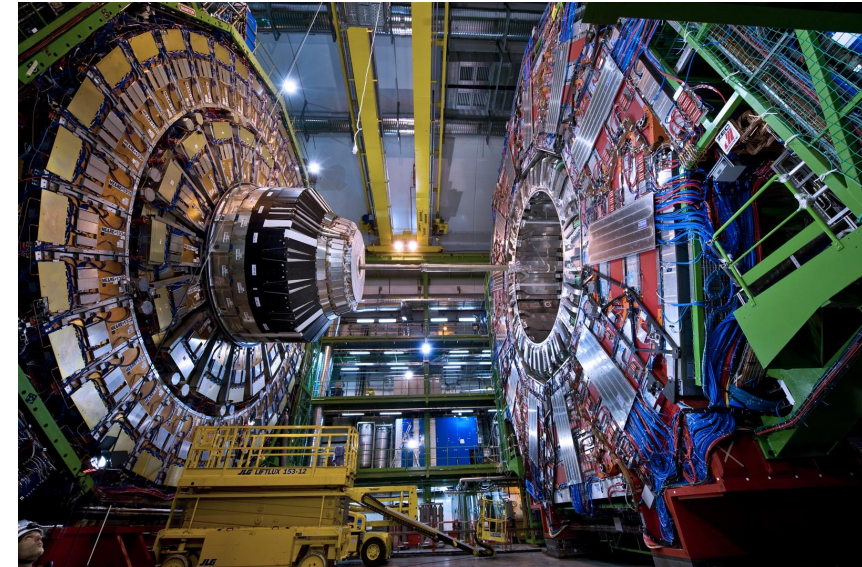
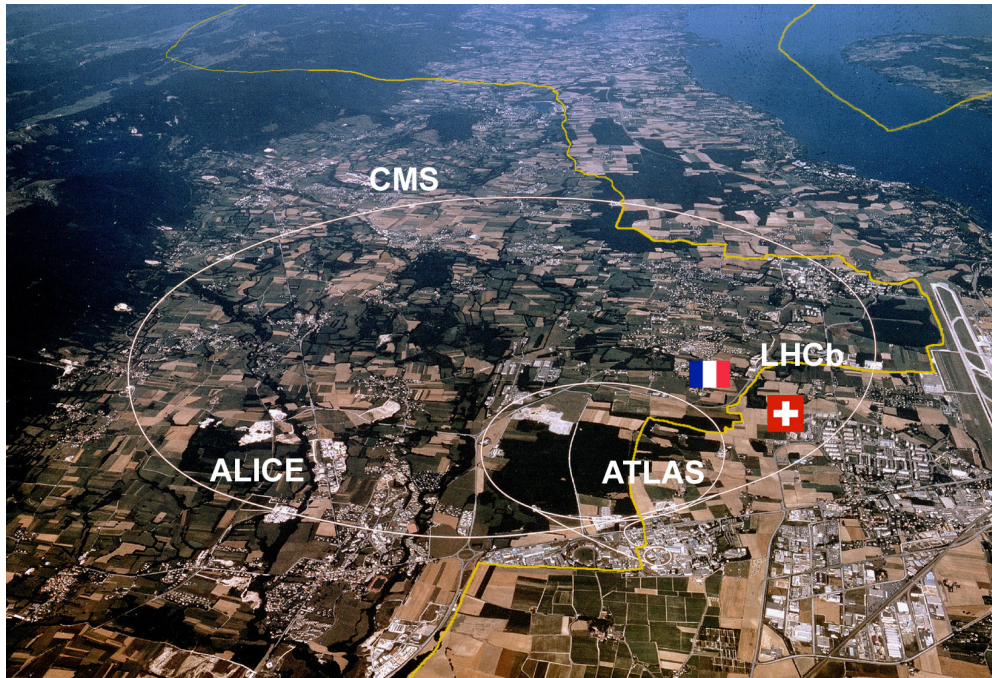


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- $\tau$  decays include neutrinos  $\rightarrow$  Not experimentally easy to reconstruct the H rest frame.
- But we can construct a zero-momentum-frame, correlated with the H rest frame.
- Several methods to define planes in this frame:
  - Impact parameter (IP) method
    - spanned by momentum of charged particle and its IP wrt PV
  - Neutral-pion (NP) method
    - spanned by momenta of charged particle and  $\pi^0$
  - Combined method
  - Polarimetric vector method
    - spanned by momentum of  $\tau$  and polarimetric vector



# The CMS experiment

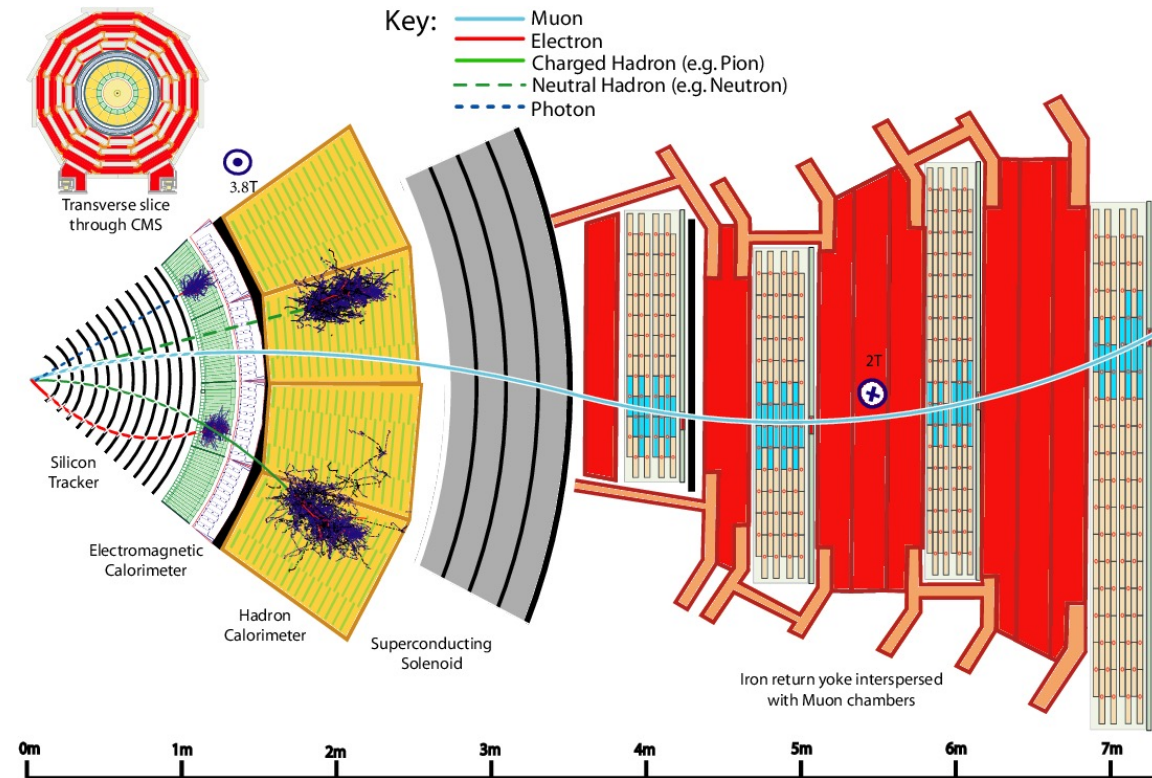


## The CMS experiment

- Weighs 14000 tonnes
- 15 meters high, 21 meters long
- 5k scientists, engineers, etc.
- 200 institutes from 50 countries

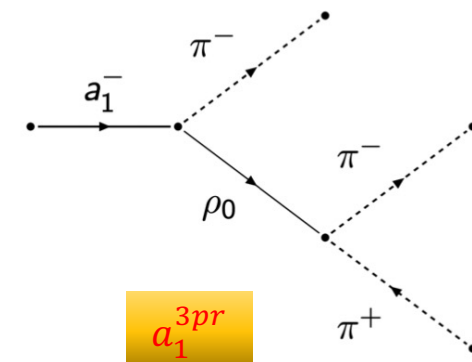
➤ The CMS includes:

- Tracker with strong 4T magnets: momentum of charged particles
- Electromagnetic calorimeter: energy of  $e, \gamma, \dots$
- Hadronic calorimeter: energy of  $\pi^\pm, K^\pm, \pi^0, \dots$
- Muon system: momentum of  $\mu$

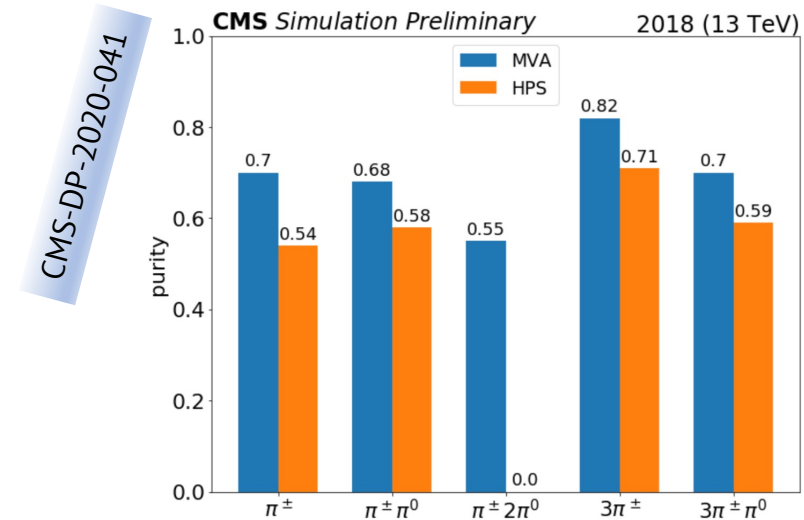
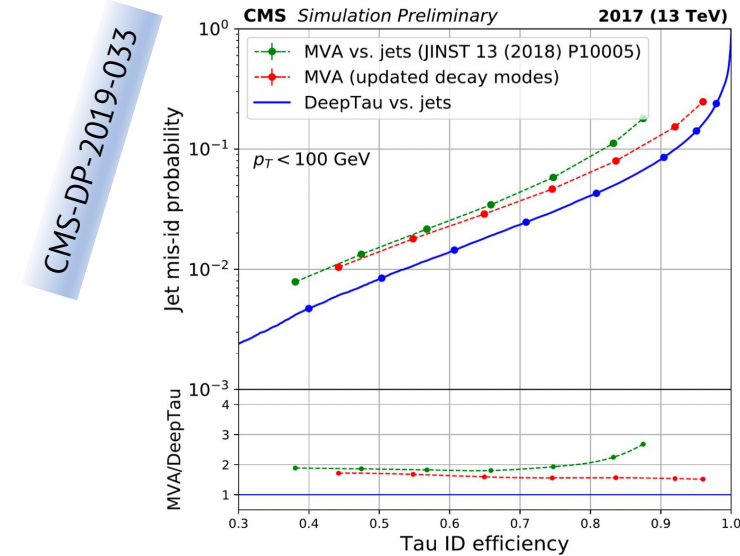


- Full Run II dataset,  $137.1 \text{ fb}^{-1}$ ,  $\sqrt{s} = 13 \text{ TeV}$
- $\tau_e \tau_h, \tau_\mu \tau_h, \tau_h \tau_h$  final states included ( $\approx 70\%$  of all  $H \rightarrow \tau\tau$  events)
- Methods used:
  - $e, \mu, \pi$ : Impact parameter method
  - $\rho, a_1^{1pr}, a_1^{3pr}$  (except  $\tau\tau \rightarrow a_1^{3p} a_1^{3p}$ ): Neutral-pion method
  - $\tau\tau \rightarrow a_1^{3pr} a_1^{3pr}$ : Polarimetric vector method

Dominant $\tau^-$ decays (neutrinos not shown)	Symbol	BR(%)
$e^-$	e	17.82
$\mu^-$	$\mu$	17.39
$\pi^-$	$\pi$	10.82
$\rho^- \rightarrow \pi^- \pi^0$	$\rho$	25.49
$a_1^- \rightarrow \rho^- \pi^0 \rightarrow \pi^- 2\pi^0$	$a_1^{1pr}$	9.26
$a_1^- \rightarrow \rho^0 \pi^- \rightarrow \pi^- \pi^+ \pi^-$	$a_1^{3pr}$	8.99
$\pi^- \pi^+ \pi^- \pi^0$	-	2.74



- We performed various optimizations in this analysis
- DNN used for hadronic  $\tau$  identification: DeepTau
  - vs jets
  - vs electrons
  - vs muons
- Signal (Higgs) identification performed with BDT/NN.
- BDT trained to identify hadronic  $\tau$  decay modes
  - $\approx 20\%$  CP sensitivity improvement
  - Published as a Detector Performance Note (DPS) ([CMS-DP-2020-041](#))
  - Useful for some other analysis, e.g. Z polarization measurement
- Primary vertex reco.
  - Refit after removing taus
  - Using beamspot constraints
  - a factor of  $\approx 3$  reduction in PV resolution in transverse plane
- Impact parameter reco.
  - Fit 3D helical curve to charged tracks
  - Provides IP + its uncertainty

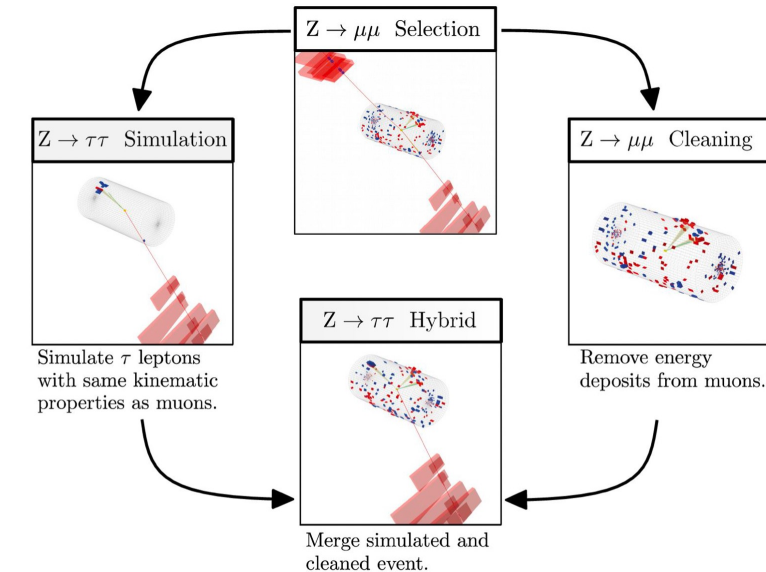
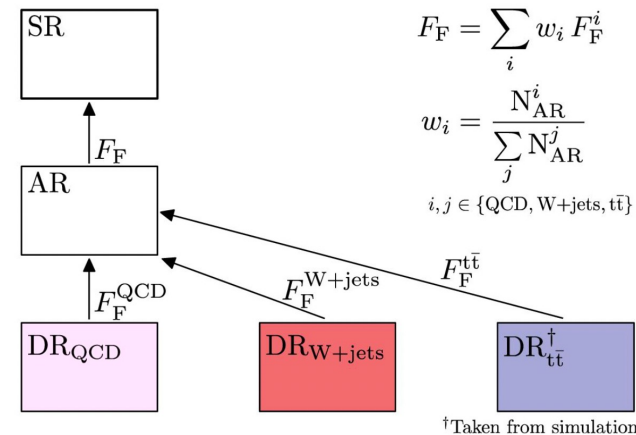


# Background estimation

- Where possible, data-driven techniques used to estimate the background
- Events with two genuine taus not from Higgs (mainly  $Z \rightarrow \tau^- \tau^+$ ) constitute a major bkg.
  - They are estimated using  $\mu \rightarrow \tau$  embedding method
  - Exploiting lepton universality
- Another major bkg are hadronic jets faking  $\tau$  (e.g. QCD)
  - “Fake factor” method is used.
  - estimating bkg from a determination region orthogonal to the signal region.

➤ All other bkg from MC.

➤ In total,  $\approx 90\%$  of bkg from data-driven techniques.

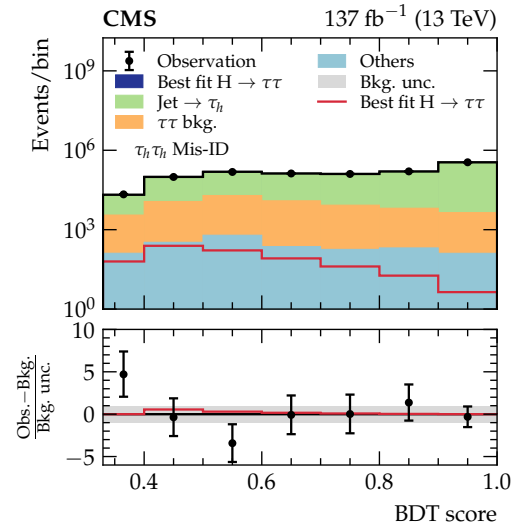


[JINST 14 \(2019\) P06032](#)

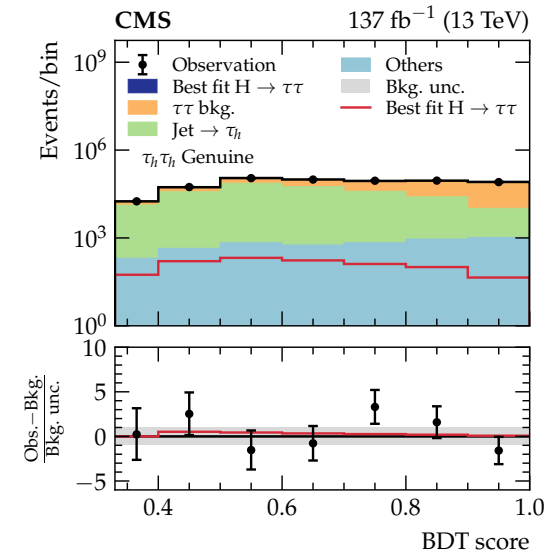
[Eur. Phys. J. C 78, 708 \(2018\)](#)

- As mentioned, BDT/NN (MVA) is used to separate signal from bkg
  - 3 output categories:
    - “Higgs” (ggH, VBF, VH combined)
    - “Genuine” (all bkg processes involving two genuine taus)
    - “mis-ID” (mainly jet/lepton faking a  $\tau$ )
  - Input to the MVA: kinematic and angular variables:  $p_T$ ,  $m_{\tau\tau}$ ,  $m_{jj}$ ,  $N_{jet}$ ,  $\Delta\eta_{jj}$ , ...

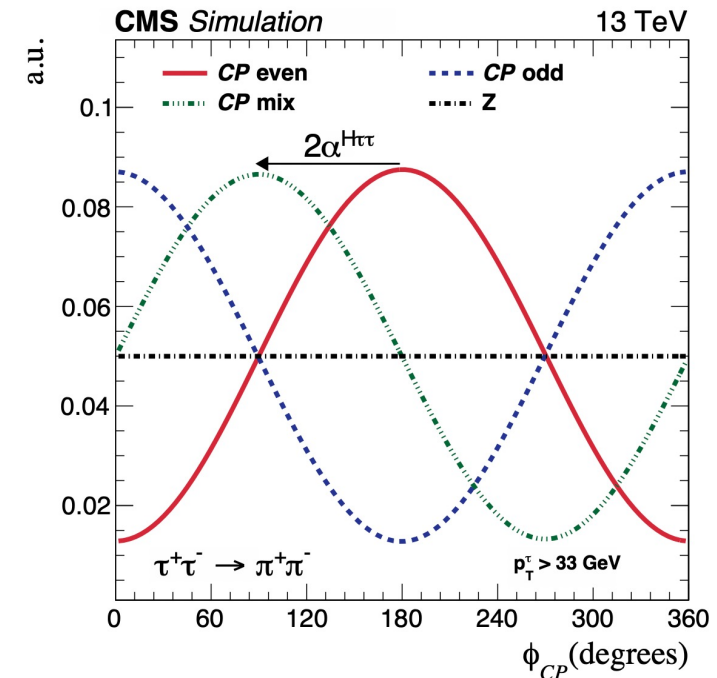
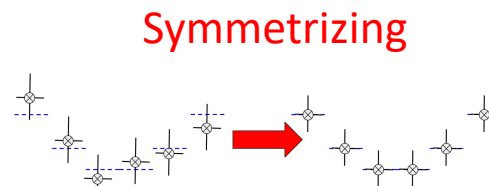
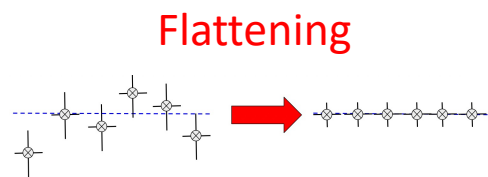
mis-ID ( $\tau_h\tau_h$ )



Genuine ( $\tau_h\tau_h$ )



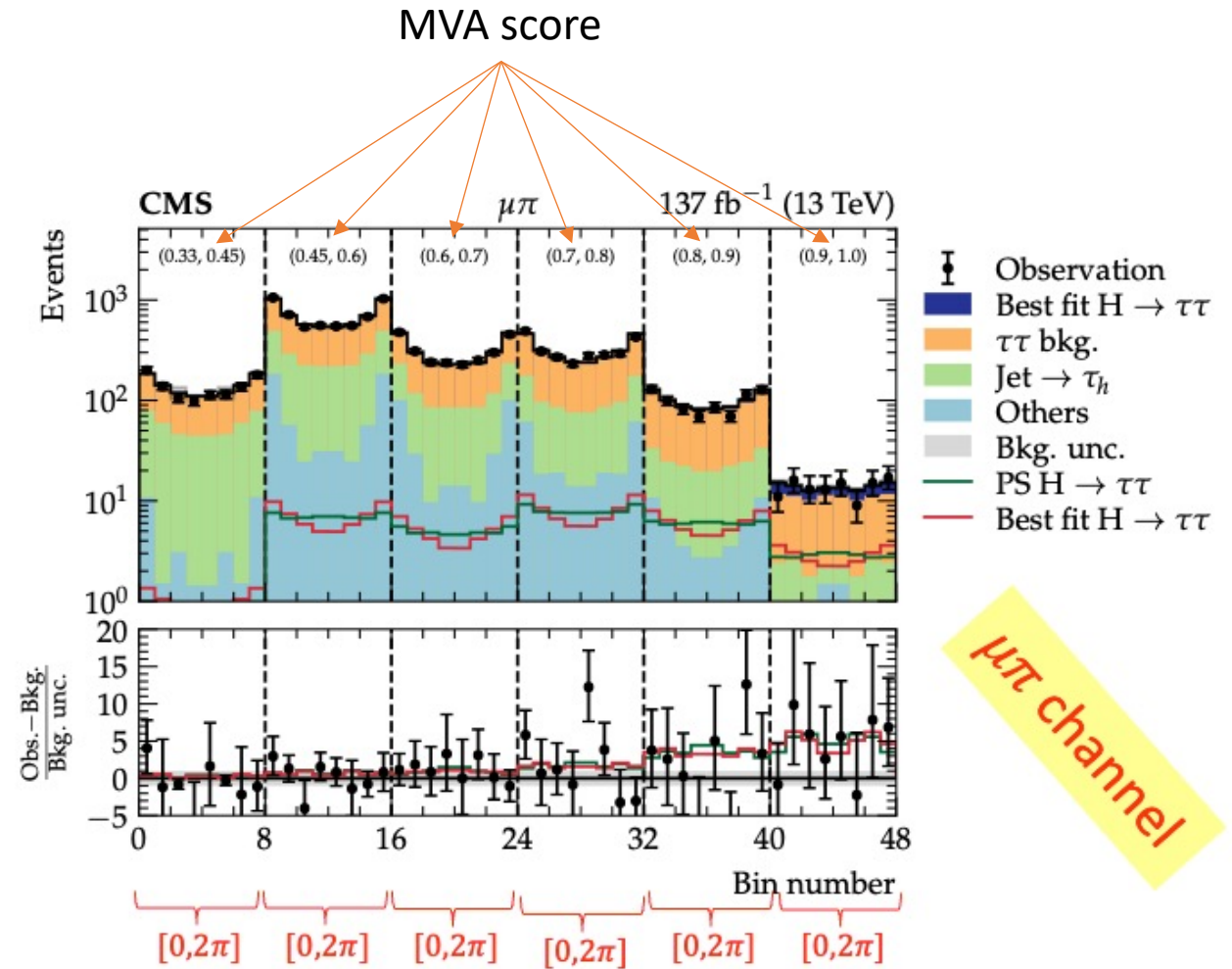
- The shape of  $\phi_{CP}$  for bkg well-known
  - Most bkg must be flat (no sinusoidal shape is expected)
  - In the impact parameter method bkg's are distorted because of the cutoff on IP. But still symmetric around  $\phi_{CP} = 180^\circ$
  - jets faking  $\tau$  also symmetric around  $\phi_{CP} = 180^\circ$ , but not flat (kinematic reasons)
  - signal is also symmetric around  $\phi_{CP} = 180^\circ$
- We merged  $\phi_{CP}$  bins to reduce the statistical uncertainty of the templates.
  - Checked with toy model and control region in data



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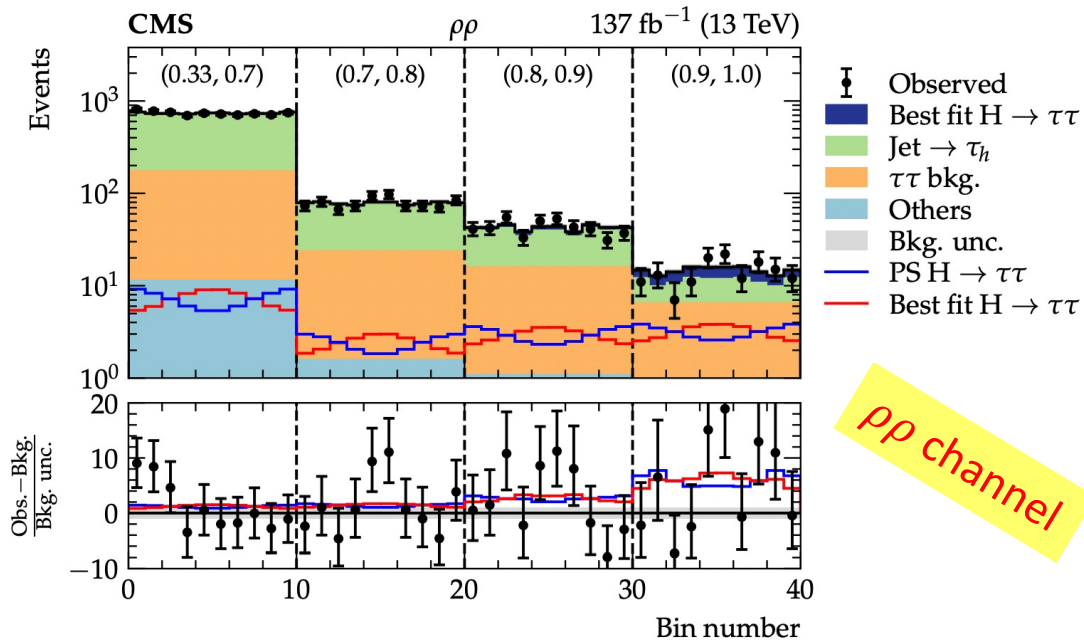
# $\phi_{CP}$ in windows of MVA

- Events identified as “Higgs” by the MVA are split in windows of the MVA score.
- In each window, the  $\phi_{CP}$  distribution is shown for data and simulated events (background and signal).
- These histograms used to extract  $\alpha^{H\tau\tau}$ .



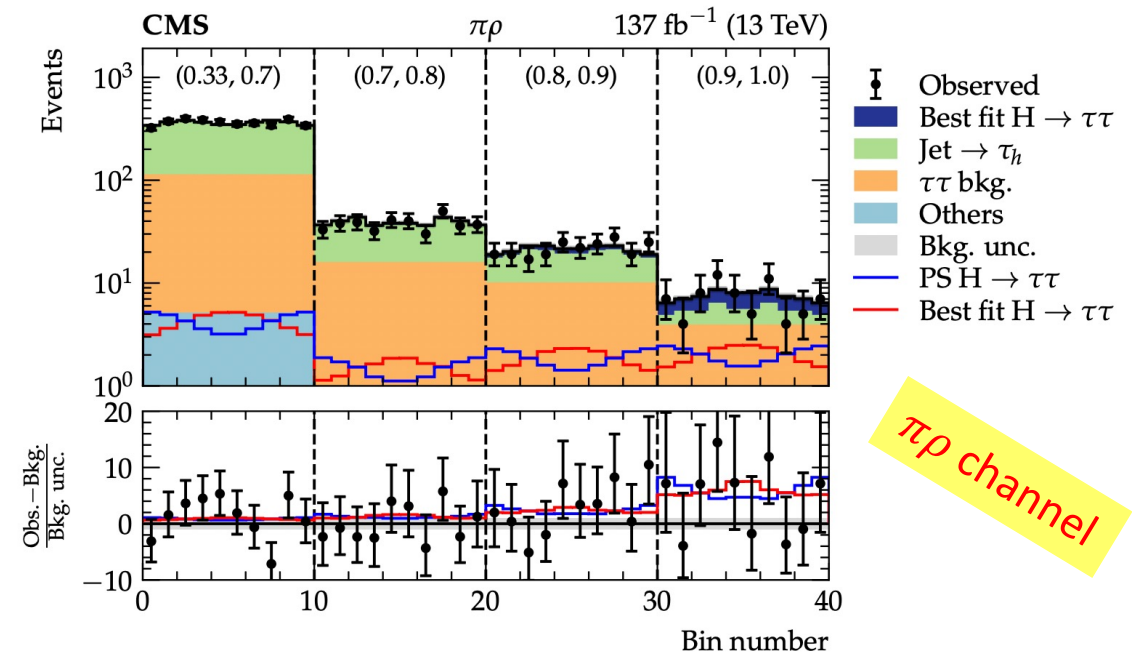
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# Other decay channel examples



$\rho\rho$  channel

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$\pi\rho$  channel

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➤ The likelihood function used to extract  $\alpha^{H\tau\tau}$  is:

$$L(\mathcal{L}, \vec{\mu}, \alpha^{H\tau\tau}, \vec{\theta}) = \prod_j^{N_{\text{categories}}} \prod_i^{N_{\text{bin}}} P(n_{i,j} | \mathcal{L} \vec{\mu} \vec{A}_{i,j}(\vec{\theta}, \alpha^{H\tau\tau}) + B_{i,j}(\vec{\theta})) \prod_m^{N_{\text{nuisance}}} C_m(\vec{\theta}).$$

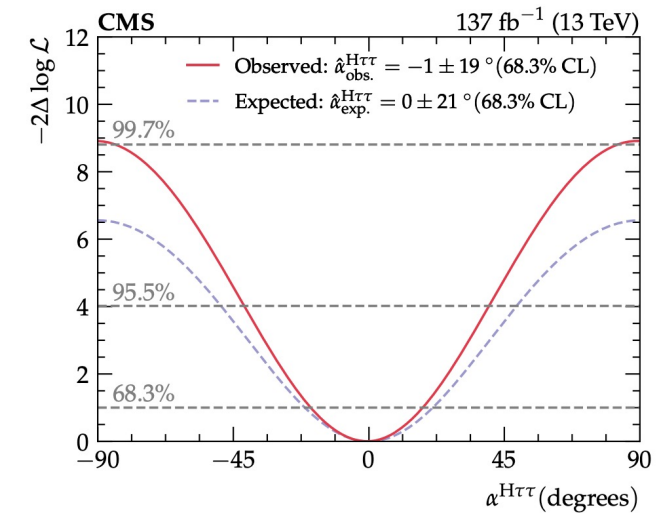
➤ The observed (expected) value for  $\alpha^{H\tau\tau}$  is found to be  $-1^\circ \pm 19^\circ$  ( $0^\circ \pm 21^\circ$ ) at 68% CL.

- CP-even and CP-odd are distinguishable with an observed (expected) sensitivity of  $3.0 \sigma$  ( $2.6 \sigma$ ).
- Compatible with the SM predictions within uncertainties.

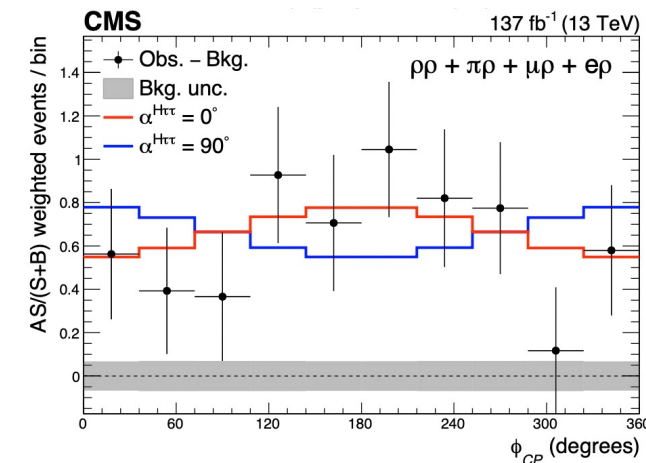
➤ Breakdown of uncertainties:

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

- statistically dominated
- followed by bin-by-bin, hadronic  $\tau$  trigger efficiency, theory, etc.



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- CMS projection for the  $\alpha^{H\tau\tau}$  uncertainty shown in the table.

- Will reach  $\pm 5^\circ$  in the HL-LHC

	Run II LHC	Run III LHC	HL-LHC
Prospective sensitivity	$0^\circ \pm 21^\circ$	$0 \pm 13^\circ$	$0 \pm 5^\circ$

- But several optimizations are planned!

- improving  $\tau$  identification and reco.
- Improving plane reco. methods (e.g. Global Event Fit method arXiv:1805.06988).
- Using regression with ML techniques to measure  $\alpha^{H\tau\tau}$ .
- Enhancing signal/background differentiation using a more complex ML technique.
- improving angular resolution of  $\pi^0$  using ML techniques
- Using “BDT reweighting” method (arXiv:1608.05806) to determine fake factor weights with BDT

- Target is to reach  $\sim 10^\circ$  (and less) uncertainty after Run III with the above optimizations.

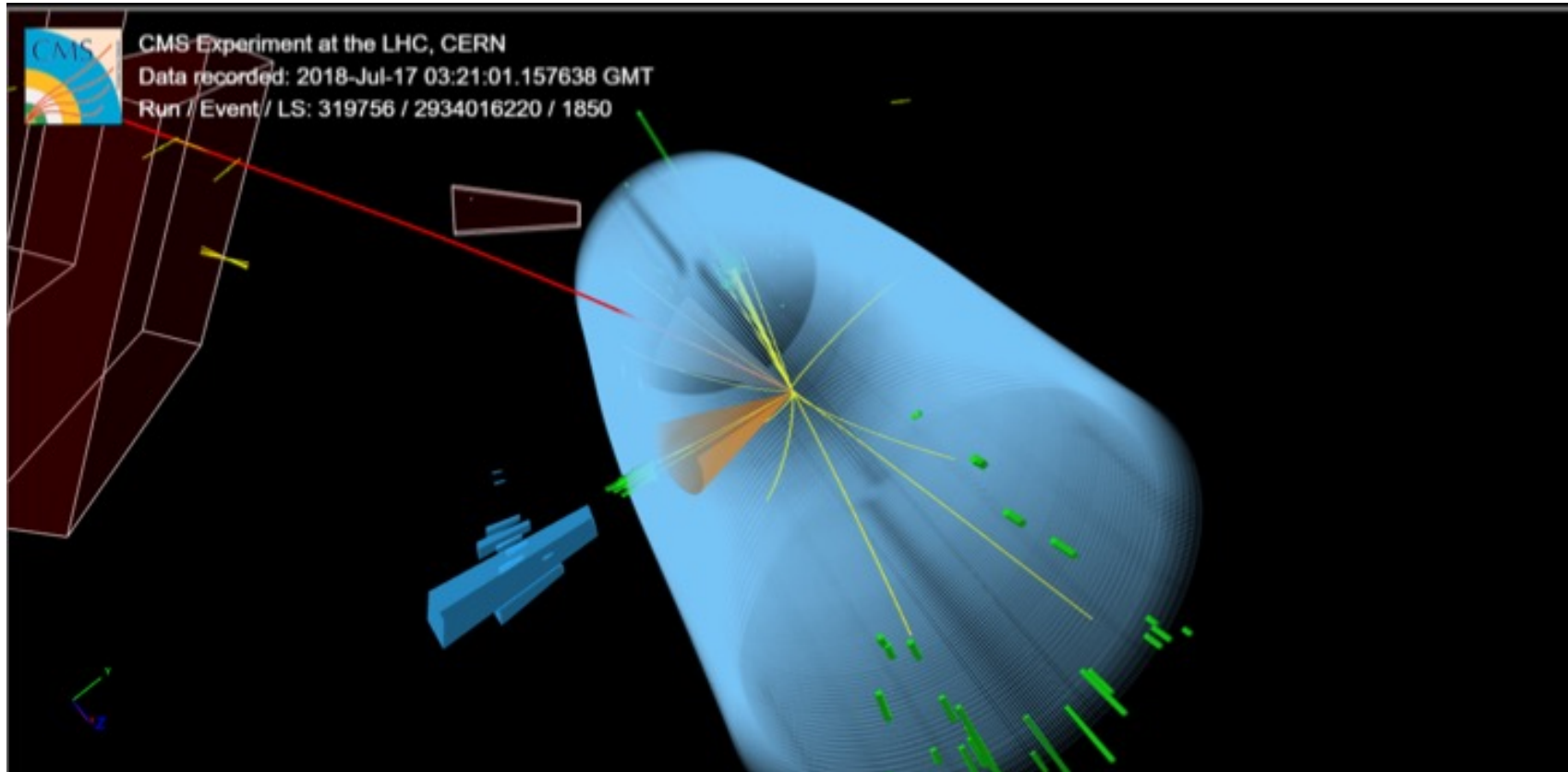
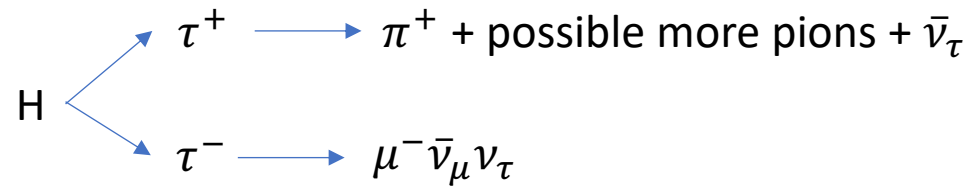
- With the LHC accumulating data, we search for new physics by precisely measuring the SM parameters.
- The CP structure of the Higgs-to-tau Yukawa coupling measured. This analysis has several benefits compared to the other Higgs CP analyses.
- The observed (expected) value for the CP-mixing angle,  $\alpha^{H\tau\tau}$ , is found  $-1^\circ \pm 19^\circ$  ( $0^\circ \pm 21^\circ$ ). The result is compatible with the SM prediction. The observed (expected) sensitivity to differentiate between CP-even and CP-odd is  $3.0 \sigma$  ( $2.6 \sigma$ ).
- The result is statistically limited. Future LHC data will pinpoint the value of  $\alpha^{H\tau\tau}$ .
- The projection of uncertainty for Run III is  $\pm 13^\circ$  but we can target to improve it to  $\sim 10^\circ$  and below.

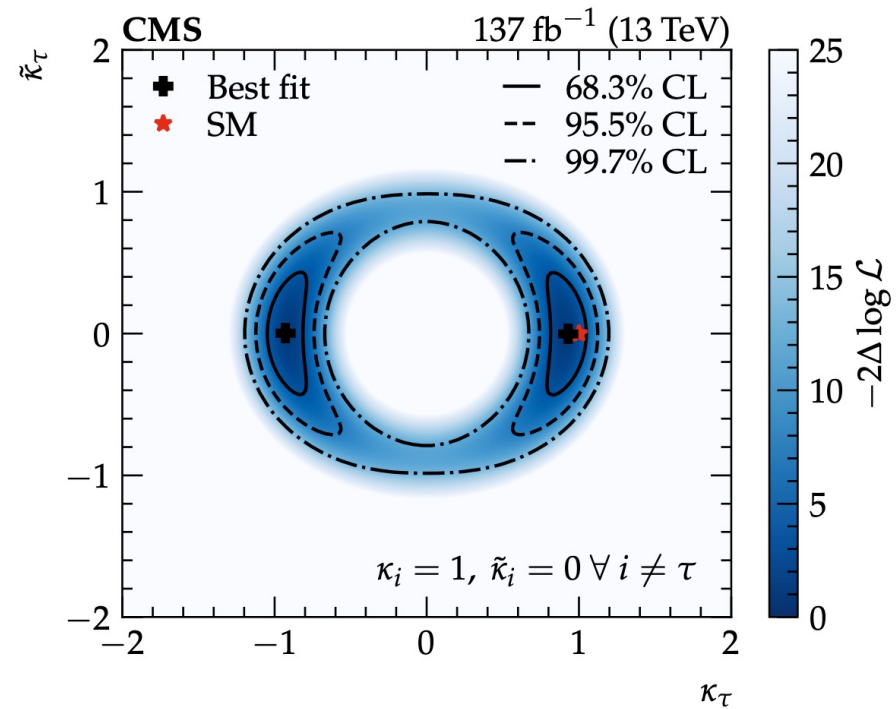
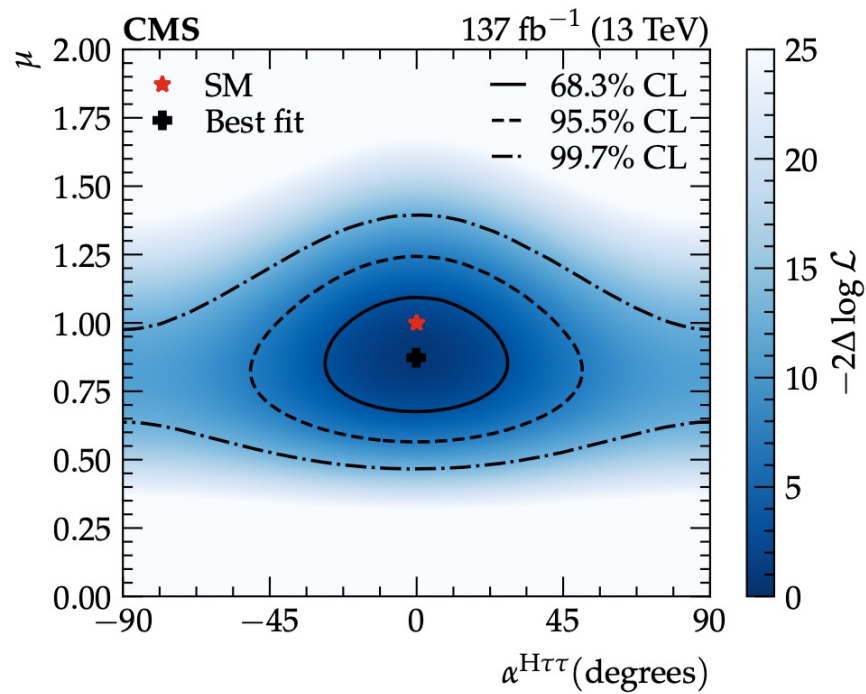
# Backup

# Projection of uncertainty



	Run II LHC (this result)	Run III LHC	HL-LHC
Prospective sensitivity at 68% CL	$0^\circ \pm 21^\circ$	$0 \pm 14^\circ$	$0 \pm 5^\circ$

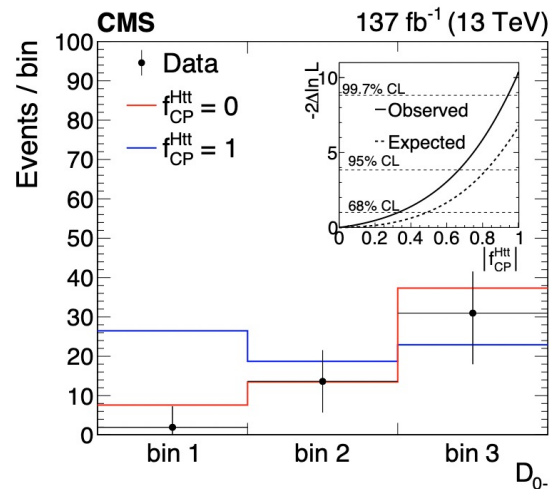




# ttH ( $H \rightarrow \gamma\gamma$ ) CP measurement (top quark)



CMS: pure CP odd excluded by  $3.2 \sigma$



ATLAS: pure CP odd excluded by  $3.9 \sigma$

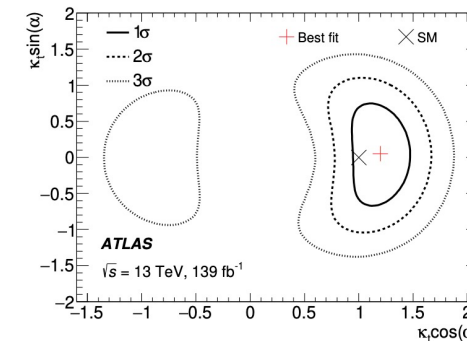
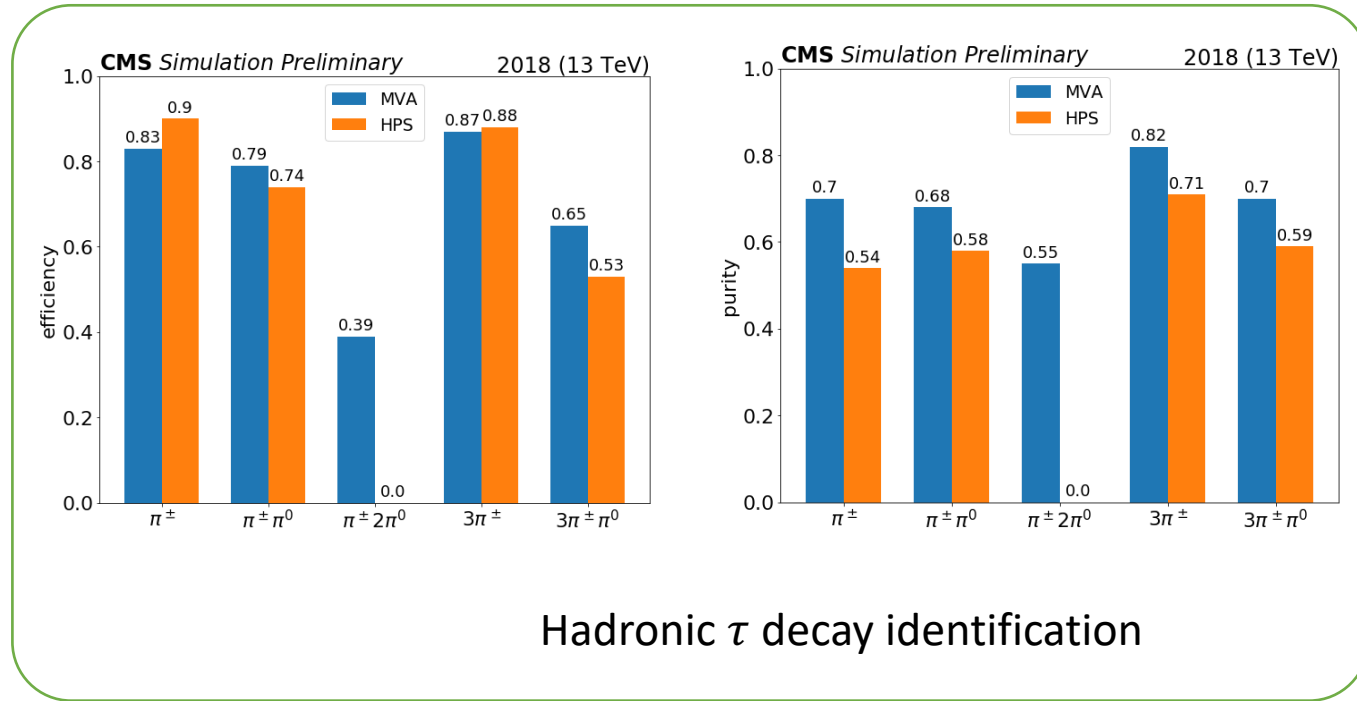
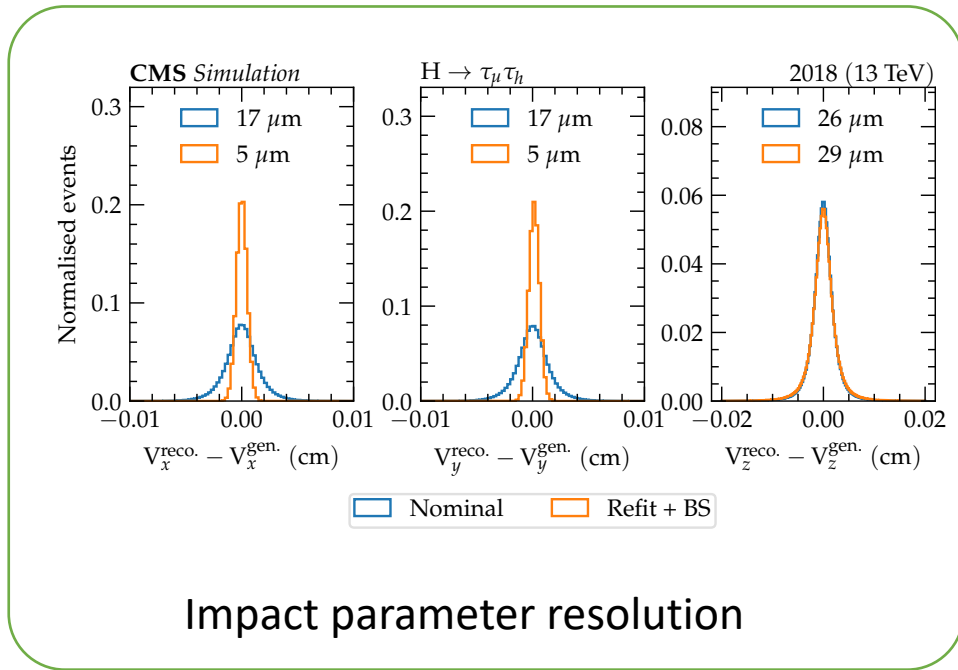


Figure 3: The distribution of events weighted by  $S/(S+B)$ , as in Fig. 2, in three bins of the  $\mathcal{D}_0$ -discriminant. In this display, leptonic/hadronic channels and BDT-bkg categories are combined in the mass range  $115 < m_{\gamma\gamma} < 135$  GeV and the background contribution, as determined in the fit to data, is subtracted. The inner panel shows the likelihood scan for  $|f_{CP}^{Htt}|$ .

Figure 3: Two-dimensional likelihood contours for  $\kappa_t \cos(\alpha)$  and  $\kappa_t \sin(\alpha)$  with ggF and  $H \rightarrow \gamma\gamma$  constrained by the Higgs boson coupling combination.

2003.10866

2004.04545



7 Higgs bosons:  $H_1, H_2, H_3, A_1, A_2, H^+, H^-$   
 5 neutralinos:  $\tilde{\chi}_i^0$  ( $i = 1, \dots, 5$ )

$\approx 27^\circ$  CP violation allowed for 125 GeV  
 Higgs (if  $H_2$  is SM-like)

1508.03255

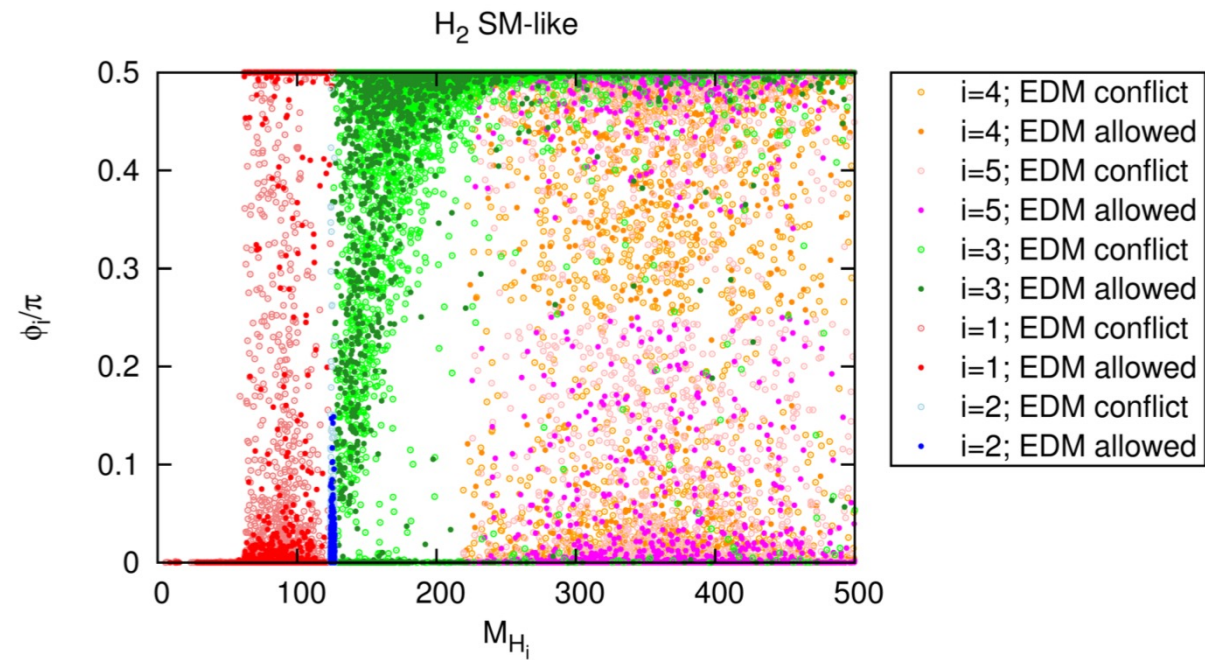
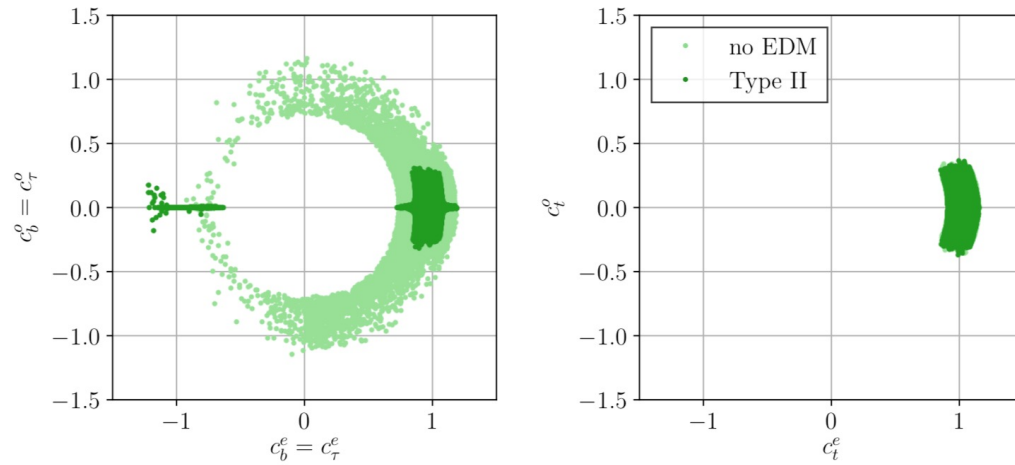
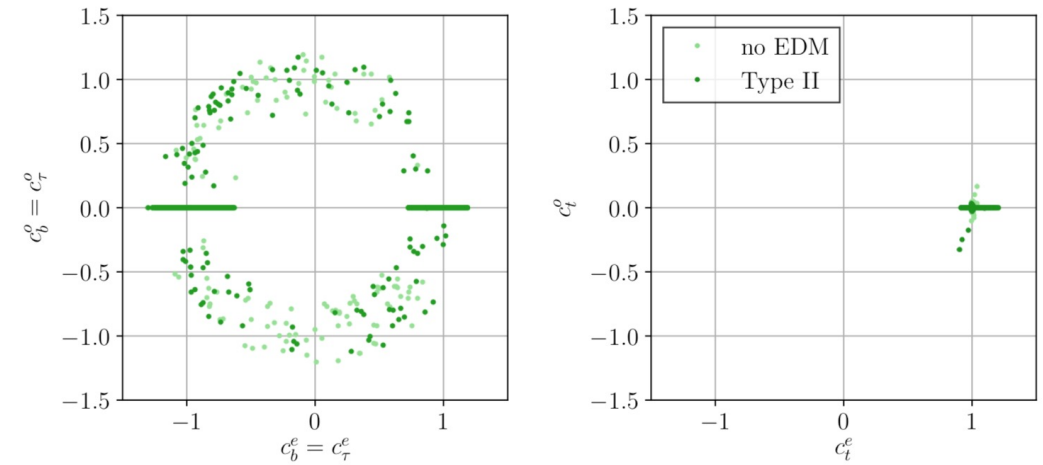


Figure 16: The phase  $\phi_i$ , which measures the CP violation in the  $H_i\tau^+\tau^-$  coupling, as a function of the mass of the Higgs boson  $H_i$ . Only scenarios that feature  $H_2$  as the SM-like Higgs boson with a mass of 125 GeV are included. Light colored open points are in conflict with the EDM bounds, whereas dark colored full points respect the bounds.

Right figure: a model in which pseudoscalar coupling is more allowed in  $\tau$  and bottom quark than in top quark.



**Figure 3:** C2HDM Type II,  $h_{125} = H_1$ : Yukawa couplings to bottom quarks and tau leptons (left) and top quarks (right) for sample 1 (dark) and sample 2 (light).



**Figure 4:** C2HDM Type II,  $h_{125} = H_2$ : Yukawa couplings to bottom quarks (left) and top quarks (right) for sample 1 (dark) and sample 2 (light).

arxiv: 1711.09419

➤ JHEP08(2020)026

Regular Article - Theoretical Physics | [Open Access](#) | [Published: 06 August 2020](#)

## Aligned CP-violating Higgs sector canceling the electric dipole moment

[Shinya Kanemura](#), [Mitsunori Kubota](#)  & [Kei Yagyu](#)

[Journal of High Energy Physics](#) **2020**, Article number: 26 (2020) | [Cite this article](#)

**243** Accesses | **13** Citations | [Metrics](#)

 A [preprint version](#) of the article is available at arXiv.

## By signal strength

This means that the  $h \rightarrow b\bar{b}$  branching ratio is now

$$\text{Br}(h \rightarrow b\bar{b}) = \frac{(\kappa_b^2 + \tilde{\kappa}_b^2) \text{Br}(h \rightarrow b\bar{b})_{\text{SM}}}{1 + (\kappa_b^2 + \tilde{\kappa}_b^2 - 1) \text{Br}(h \rightarrow b\bar{b})_{\text{SM}}}, \quad (5.6)$$

while all the other Higgs-decay modes get rescaled to

$$\text{Br}(h \rightarrow X) = \frac{\text{Br}(h \rightarrow X)_{\text{SM}}}{1 + (\kappa_b^2 + \tilde{\kappa}_b^2 - 1) \text{Br}(h \rightarrow b\bar{b})_{\text{SM}}}, \quad (5.7)$$

where  $X \neq b\bar{b}$ . As inputs we use the naive averages of the ATLAS [2] and CMS collaborations [1] in different Higgs-decay channels

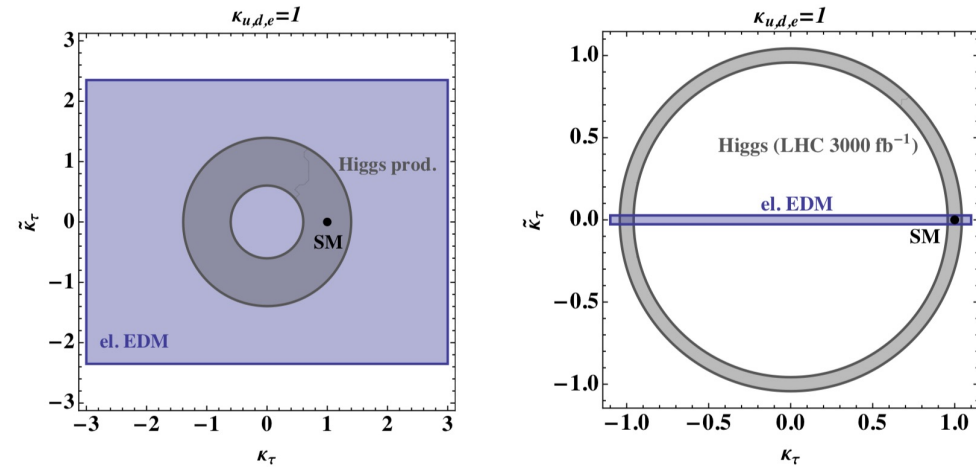
$$\begin{aligned} \hat{\mu}_{b\bar{b}} &= 0.72 \pm 0.53, & \hat{\mu}_{\tau\bar{\tau}} &= 1.02 \pm 0.35, & \hat{\mu}_{\gamma\gamma} &= 1.14 \pm 0.20, \\ \hat{\mu}_{WW} &= 0.78 \pm 0.17, & \hat{\mu}_{ZZ} &= 1.11 \pm 0.23, \end{aligned} \quad (5.8)$$

where  $\hat{\mu}_X \equiv [\sigma(pp \rightarrow h)\text{Br}(h \rightarrow X)]/[\sigma(pp \rightarrow h)\text{Br}(h \rightarrow X)]_{\text{SM}}$  denotes the signal strengths. We work in the limit where the Higgs couplings to the  $W$  and  $Z$  bosons are the SM ones. We keep the effect of  $\kappa_b, \tilde{\kappa}_b$  in the  $gg \rightarrow h$  and  $h \rightarrow \gamma\gamma$  vertices (cf. Eq. (5.4)), where the former interaction also modifies the Higgs production cross section. Up to these

$$\kappa_\gamma \simeq (0.004 - 0.003i) \kappa_\tau + 0.996 + 0.003i, \quad \tilde{\kappa}_\gamma \simeq (0.004 - 0.003i) \tilde{\kappa}_\tau. \quad (5.9)$$

arXiv:1310.1385

## By electron EDM (paper for 2013)



**Figure 6.** Left: Present constraints on  $\kappa_\tau$  and  $\tilde{\kappa}_\tau$  from the electron EDM (blue) and Higgs production (gray), assuming SM values for the remaining Higgs couplings. Right: Possible future constraints on  $\kappa_\tau$  and  $\tilde{\kappa}_\tau$ , see text for details.

arXiv:1310.1385

## Latest electron EDM:

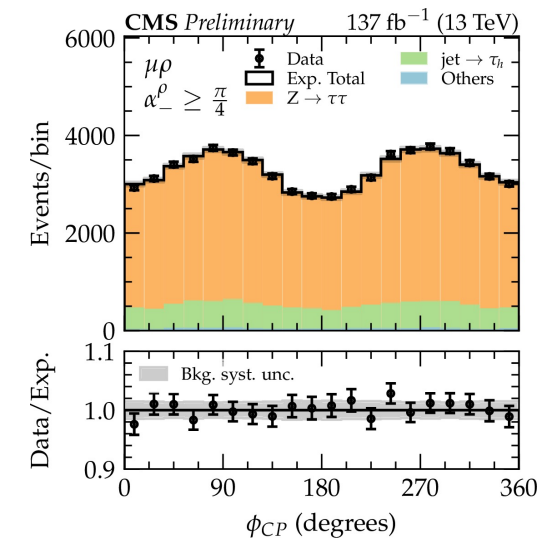
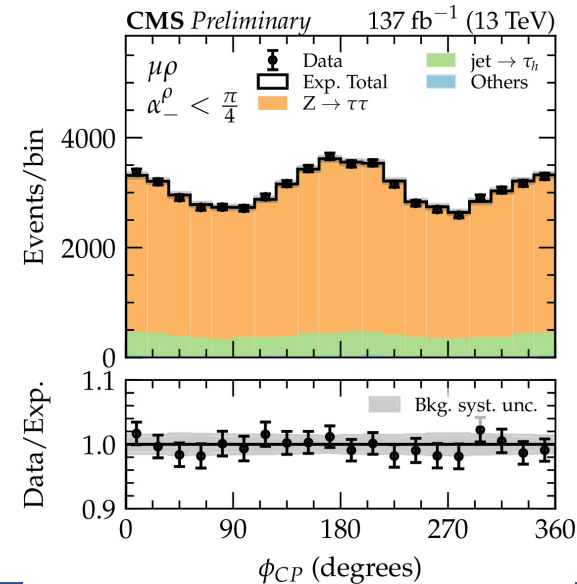
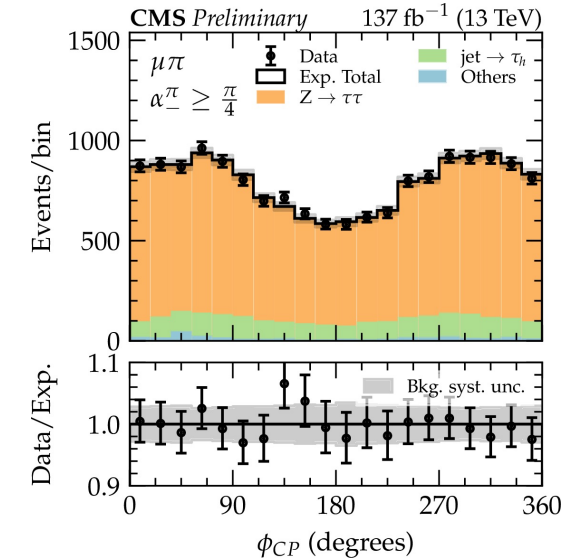
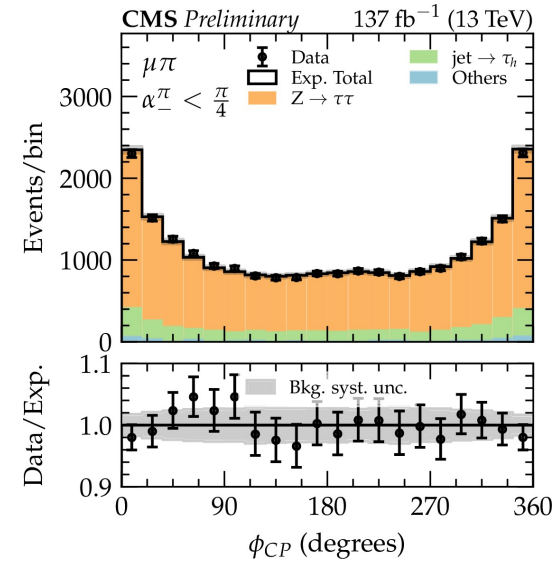
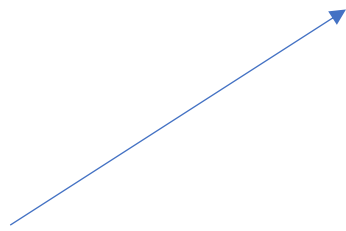
Latest electron EDM result:  $|d_e| < 1.1 \times 10^{-29}$  [1]. But models such as NMSSM, C2HDM, etc. still allows significant CP violation.

[1] ACME collaboration, Improved limit on the electric dipole moment of the electron, Nature 562 (2018) 355

# Validation with $Z \rightarrow \tau\tau$

- $Z \rightarrow \tau\tau$  is expected to have a  $\sim$ flat distribution.
- But using a variable called  $\alpha_-$ , this flat distribution splits into two sinusoidal contributions.
- $\alpha_-$  is defined in a paper by Stefan Berge, et al. (arxiv:1408.0798)

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-20-006/index.html>



➤ A good summary of Higgs CP studies at the LHC can be found in this talk by Maria Llacer:

<https://indico.cern.ch/event/905399/contributions/4282247/>

## LHC Run2 results testing the CP nature of the Higgs boson

Direct searches	ATLAS	CMS
<b>H→4l</b> (all prod. modes: H+2j, VH, ttH)	{HVV, Hgg, Htt} EFT coefficients (Warsaw basis) reinterpretation of cross-section measurements* <a href="#">EPJC(2020)80:957</a> , full Run2	HVV, Hgg, Htt anomalous couplings & EFT coefficients (Higgs and Warsaw basis) using MELA disc. <b>NEW</b> <a href="#">arXiv:2104.12152</a> (sub. to PRD), full Run2
<b>H→WW*→eνμν</b> (prod. mode: H+2j)	Hgg anomalous couplings <b>NEW</b> HC model (mass basis), using signed $\Delta\phi_{ij}$ <a href="#">ATLAS-CONF-2020-055</a> , 36 fb <sup>-1</sup>	---
<b>H→ττ</b>	HVV anomalous couplings using $O_{optimal}$ (CP-odd only, targets VBF) <a href="#">PLB805(2020)135426</a> , 36 fb <sup>-1</sup>  (Hττ <a href="#">ATL-PHYS-PUB-2019-008</a> , HL-LHC prospects)	HVV anomalous couplings using MELA disc. <a href="#">PRD100.112002(2019)</a> , 36 fb <sup>-1</sup>  Hττ <b>NEW</b> $ \phi  < 36^\circ$ @95%CL, using $\phi_{CP}$ , VBF+ggH+VH Pure CP-odd coupling excluded > 3σ <a href="#">CMS-PAS-HIG-20-006</a> , full Run2
<b>ttH (H→γγ)</b>	Htt Higgs Charact. model, $ \phi  < 43^\circ$ @95%CL Pure CP-odd coupling excluded > 3σ <a href="#">PRL125.061802(2020)</a> , full Run2	Htt using MELA disc., $ \phi  < 55^\circ$ @95%CL Pure CP-odd coupling excluded > 3σ <a href="#">PRL125.061801(2020)</a> , full Run2

\*ATLAS-CONF-2019-029:  
interpretations in H→γγ decay mode

→ This talk will focus on the **new results** (since LHCP2020)

07/06/21

María Moreno Llacer - Higgs CP studies at ATLAS+CMS

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arXiv:2205.07715

A very good summary of future Higgs CP measurements at photon, muon, hadron, and ee colliders as well as EDM.

## Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments

Editor: Andrei V. Gritsan,<sup>1</sup> Contributors: Rahool Kumar Barman,<sup>2</sup> Ivanka Božović-Jelisavčić,<sup>3</sup> Jeffrey Davis,<sup>1</sup> Wouter Dekens,<sup>4</sup> Yanyan Gao,<sup>5</sup> Dorival Gonçalves,<sup>2</sup> Lucas S. Mandacarú Guerra,<sup>1</sup> Daniel Jeans,<sup>6</sup> Kyoungchul Kong,<sup>7</sup> Savvas Kyriacou,<sup>1</sup> Ren-Qi Pan,<sup>8</sup> Jeffrey Roskes,<sup>1</sup> Nhan V. Tran,<sup>9</sup> Natasa Vukašinović,<sup>3</sup> and Meng Xiao<sup>8</sup>

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(Dated: May 16, 2022)

The search for  $CP$  violation in interactions of the Higgs boson with either fermions or bosons provides attractive reference measurements in the Particle Physics Community Planning Exercise (a.k.a. “Snowmass”). Benchmark measurements of  $CP$  violation provide a limited and well-defined set of parameters that could be tested at the proton, electron-positron, photon, and muon colliders, and compared to those achieved through study of virtual effects in electric dipole moment measurements. We review the current status of these  $CP$ -sensitive studies and provide projections to future measurements.