Measuring the CP nature of the Yukawa coupling between the Higgs and tau leptons

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Motivation and theory

- The Standard Model Higgs boson is *even* under charge-parity (CP) inversion. However, some of the extensions of the SM predict the existence of a CP-odd component of the Higgs.

- This study is the **first direct measurement** of the CP nature of the Yukawa coupling between the Higgs and τ leptons. The measurement is performed on the $H \to \tau^+ \tau^-$ events recorded by the CMS experiment at CERN.

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

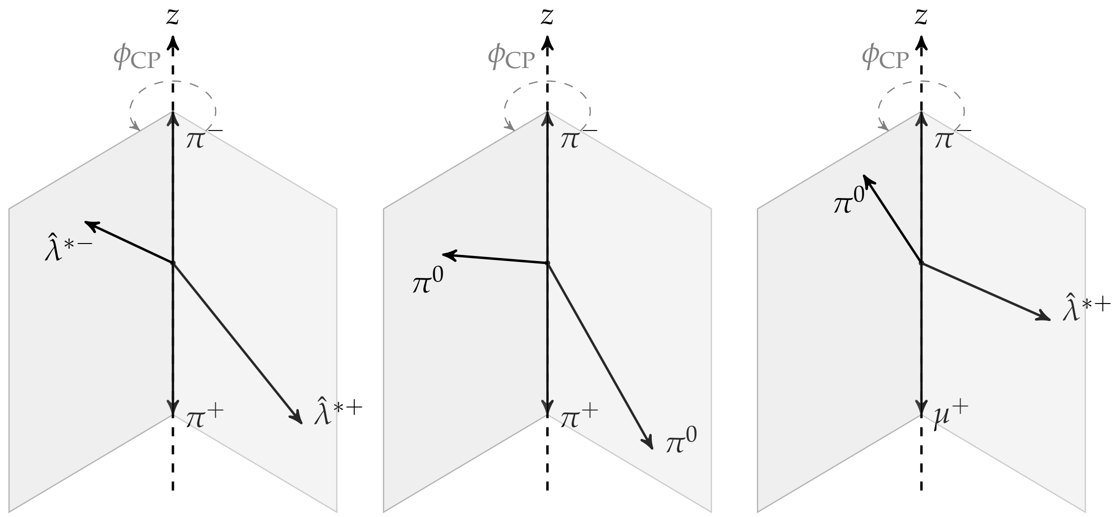
$$L_Y = -\frac{m_\tau}{v} H(\underbrace{\kappa_\tau \bar{\tau}\tau}_{\text{CP-even}} + \underbrace{\tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau}_{\text{CP-odd}}) \quad , m_\tau = \text{mass of } \tau, \;\; \text{v= V.E.V.} = 246 \text{ GeV}$$

- Defining the CP mixing angle as $\phi_{\tau\tau} = \arctan(\frac{\tilde{\kappa}_\tau}{\kappa_\tau})$
  - $\phi_{\tau\tau} = 0°$: CP-even coupling
  - $\phi_{\tau\tau} = 90°$: CP-odd coupling
  - Other values: mixed CP coupling (CP violating)

- **The goal is to measure $\phi_{\tau\tau}$.**

ϕ_{CP} observable

- $\phi_{\tau\tau}$ can be measured using the observable ϕ_{CP} which is defined as the angle between the planes produced by τ^+ and τ^- decay products.



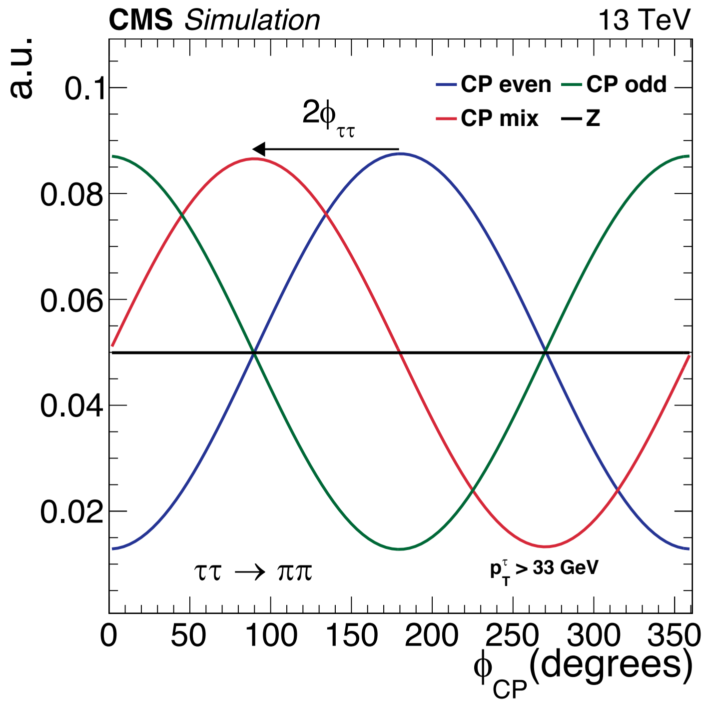
$\tau^- \to \pi^-$
$\tau^+ \to \pi^+$

$\tau^- \to \pi^-\pi^0$
$\tau^+ \to \pi^+\pi^0$

$\tau^- \to \pi^-\pi^0$
$\tau^+ \to \mu^+$

- It can be shown that:

$$\frac{d\sigma}{d\phi_{CP}} \propto \cos(\phi_{CP} - 2\phi_{\tau\tau}),$$ [arXiv: 1308.2674]



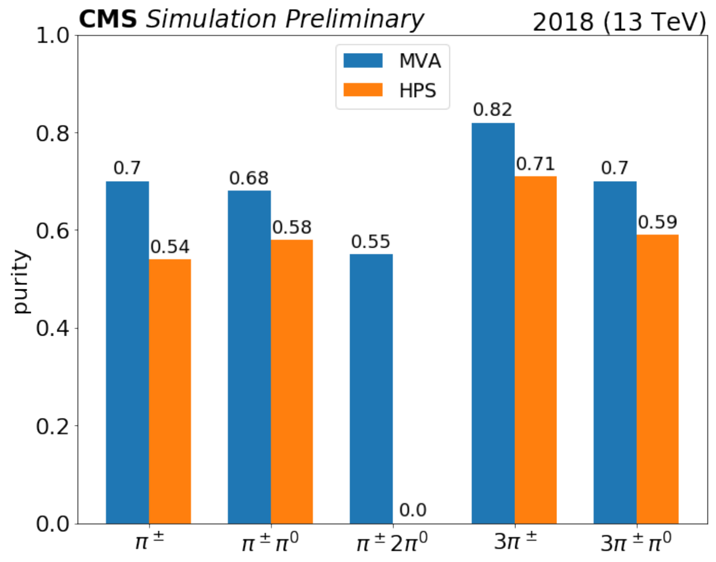
Measurement optimizations

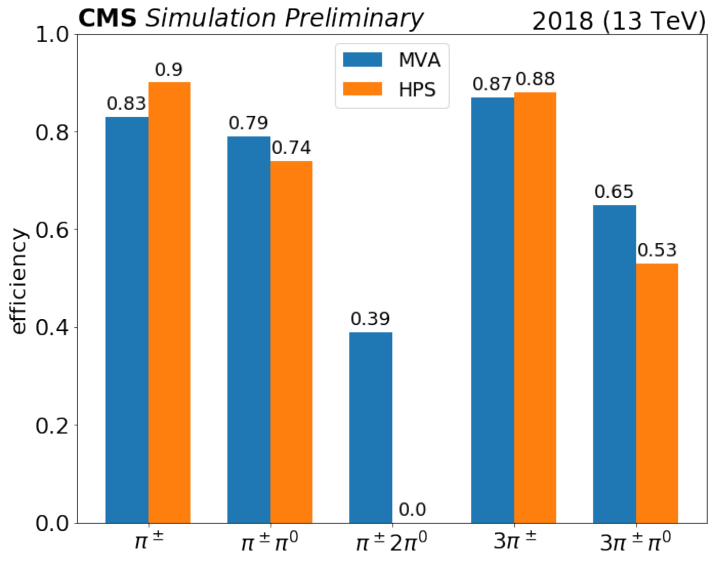
- Machine learning techniques (BDT/NN) used to separate signal ($H \rightarrow \tau\tau$) from background ($Z \rightarrow \tau\tau$, QCD faking $\tau\tau$, etc.)

- A separate classifier (BDT) to identify hadronic τ decay channels:
  - The **purity** of all hadronic τ decay channels by 10 to 55 %-points.
  - The **efficiency** of the decays with at least one π^0 by 5 to 40 %-points.
  - Separately published in a Detector Performance Summary (DPS) note [CERN-CMS-DP-2020-041].
  - $\approx$ 20% improvement in CP sensitivity

- Improved impact parameter reconstruction

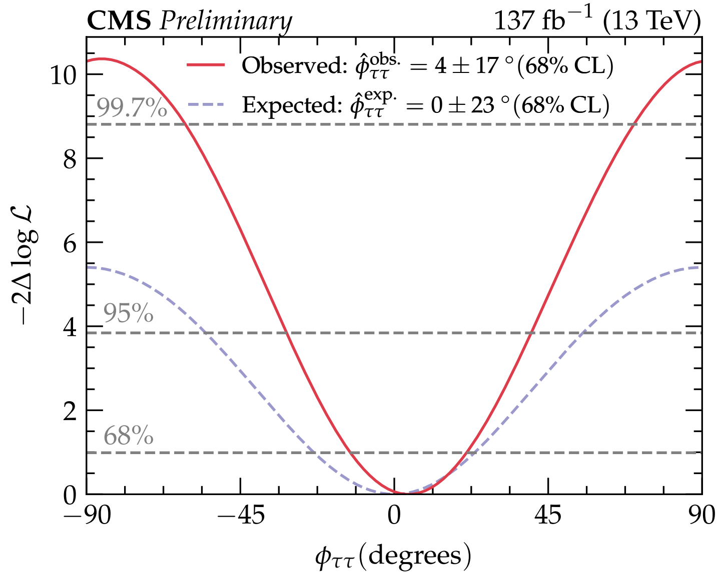
- Improved primary vertex (Higgs production position) reconstruction





Result

- The figure shows the negative log-likelihood scan of $\phi_{\tau\tau}$. The observed $\phi_{\tau\tau}$ is found to be $4^{\circ} \pm 17^{\circ}$ at 68% CL.
- This excludes the pure CP-odd scenario at $3.2\,\sigma$ significance.
- The result is compatible with the SM prediction within uncertainties.
- The next-to-minimal supersymmetric model (NMSSM) allows up to $\pm 27^{\circ}$ CP violation [arXiv: 1508.03255]. Our result exclude a part of the phase space of this model at 68% CL.
- $\phi_{\tau\tau} = (4 \pm 17\,(\text{stat}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{syst}) \pm 1\,(\text{theory}))^{\circ}$
  - Result fully statistically dominated → More data to come in the next couple of years. Stay tuned!



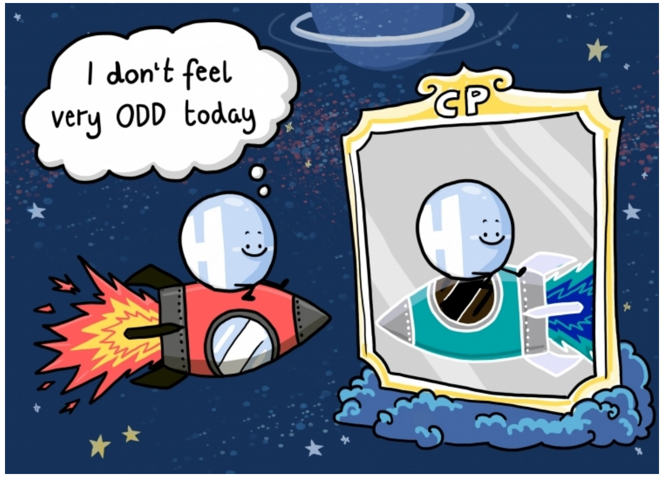
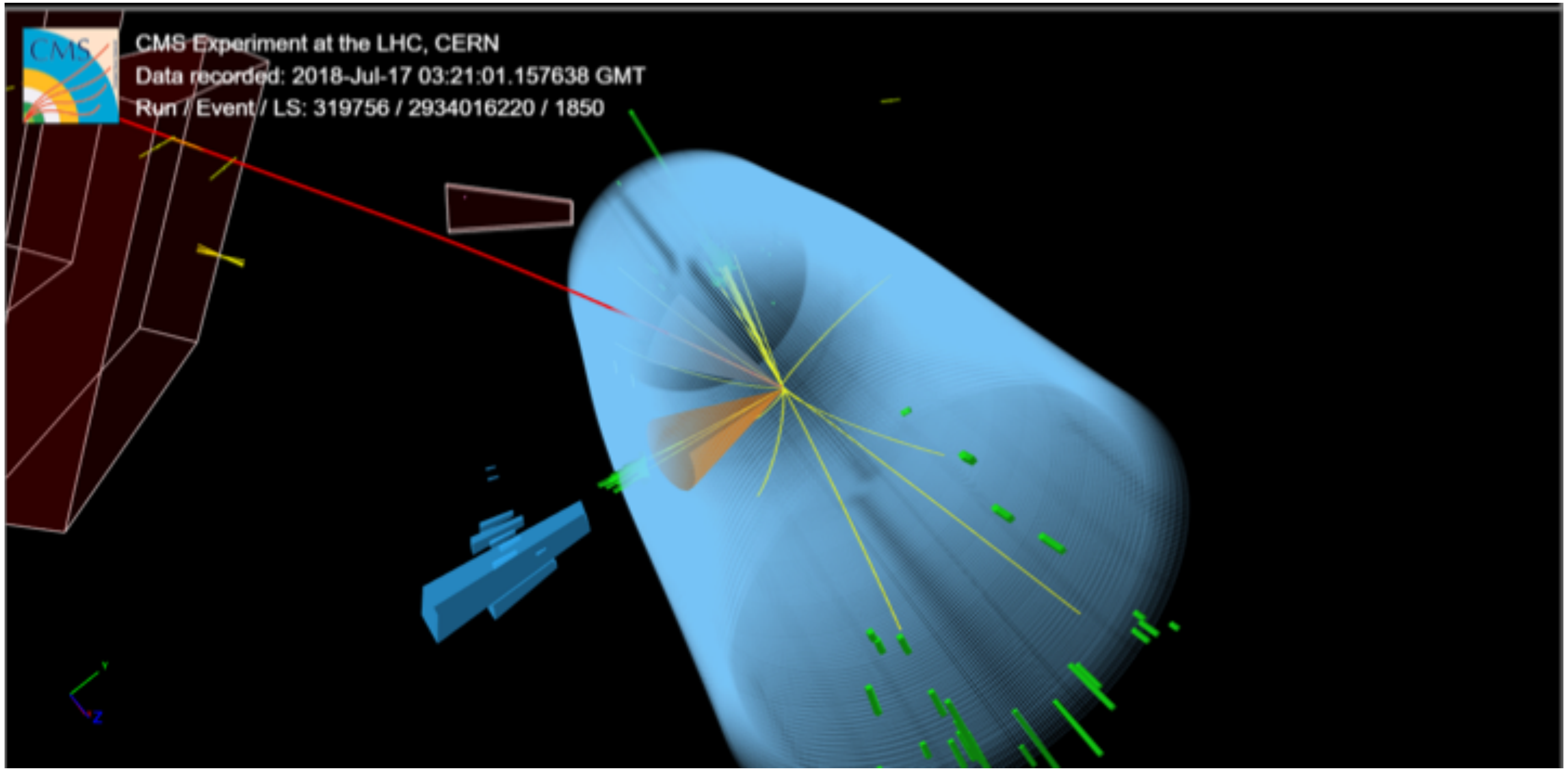


image: DESY/designdoppel

Backup

Event display

$$H \to \tau^+ \to \pi^+ + \text{possible more pions} + \bar{\nu}_\tau$$
$$H \to \tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$$



Event display

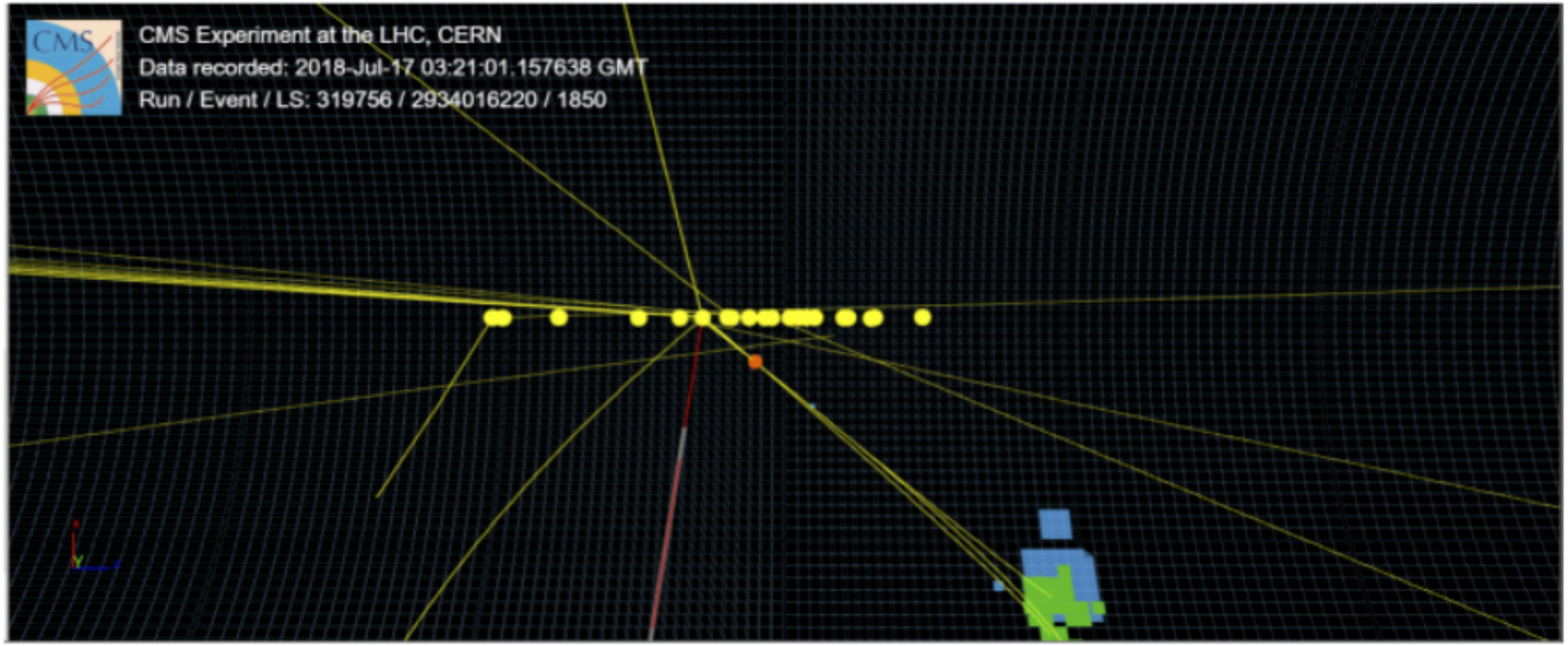
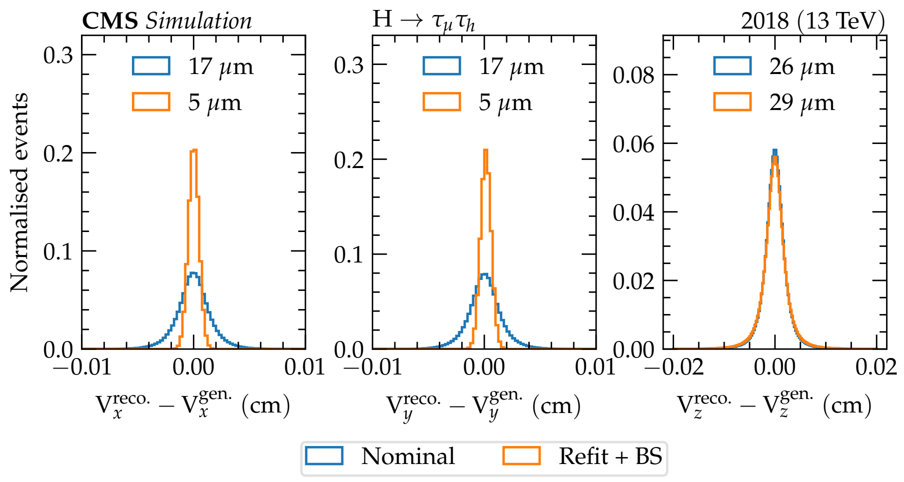


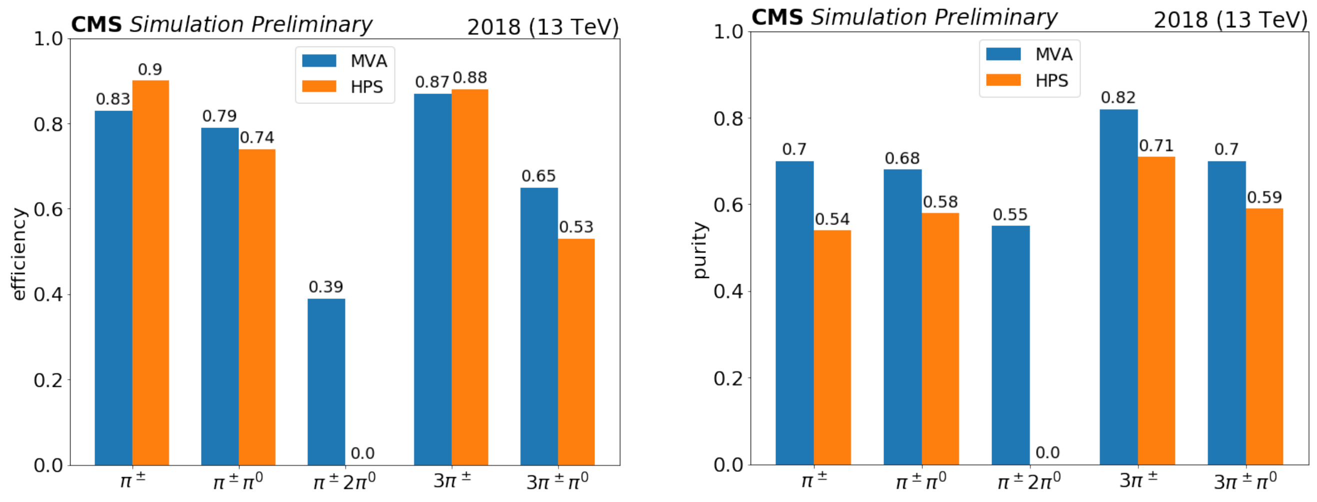
Figure 3: Zoomed event display of a proton-proton collision recorded at CMS with a candidate Higgs boson decaying into two tau leptons. The decay location of the tau, which decays into three charged hadrons, is clearly visible and indicated with an orange dot, as well as concurrent proton-proton collisions.

https://cms.cern/news/Mirror-mirror-on-the-wall-who-is-the-most-CP-even-of-them-all

Measurement optimizations



Impact parameter resolution

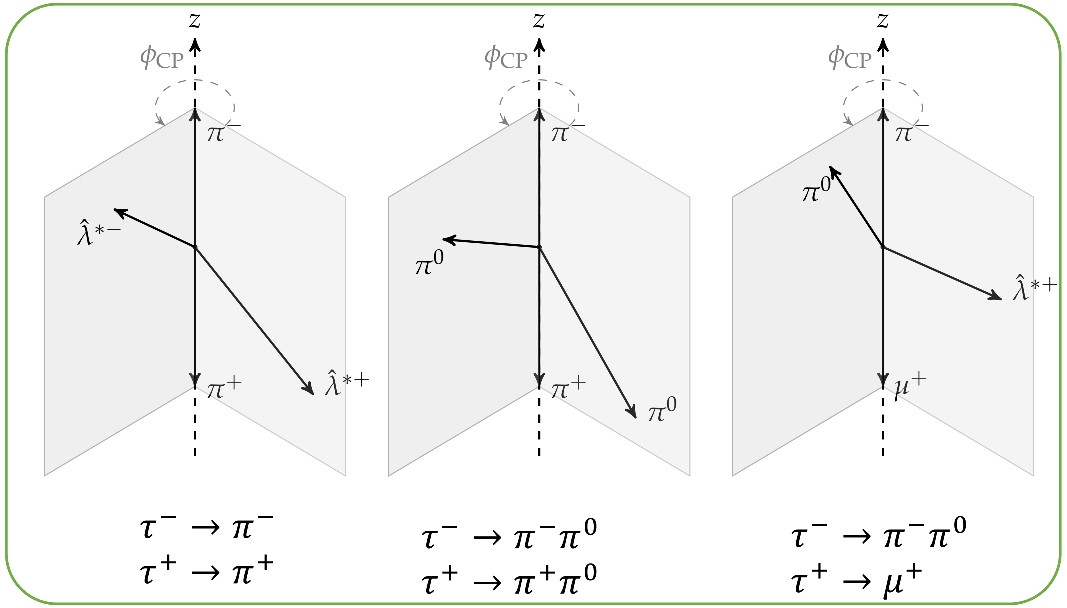


Hadronic τ decay identification

Decay plane methods

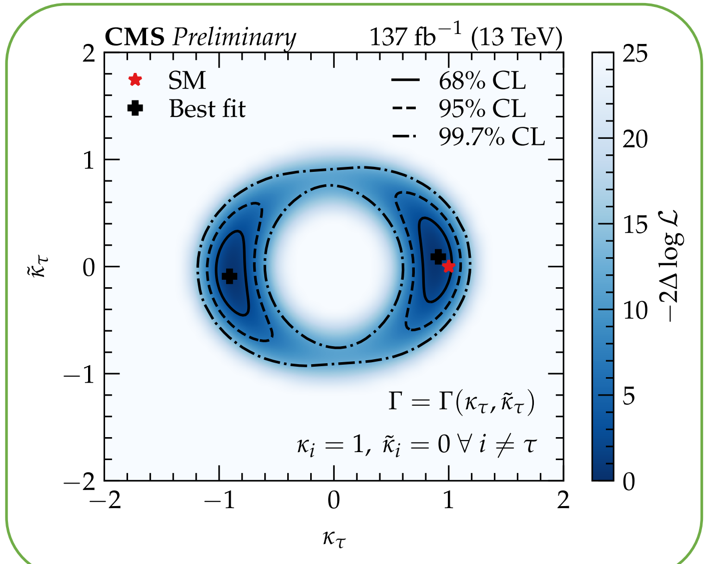
- In the figure:
  - Left: Impact parameter method
  - Middle: ρ-decay plane method
  - Right: Combined method

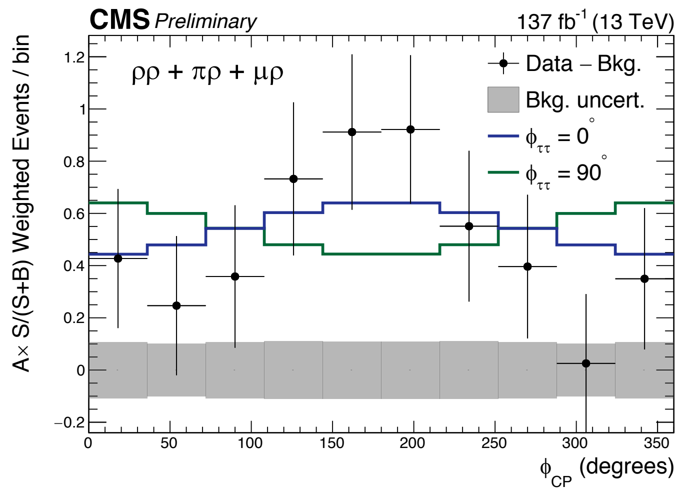
Main visible τ^- decay products
e^-
μ^-
π^-
$\pi^-\pi^0$
$\pi^-2\pi^0$
$\pi^-\pi^+\pi^-$
$\pi^-\pi^+\pi^-\pi^0$



More results

- Left: 2D negative log-likelihood scan of κ_τ and $\tilde{\kappa}_\tau$.
- Right: ϕ_{CP} distribution for the most sensitive channels.





NMSSM

7 Higgs bosons: $H_1, H_2, H_3, A_1, A_2, H^+, H^-$

5 neutralinos: $\tilde{\chi}_i^0\ (i = 1, ..., 5)$

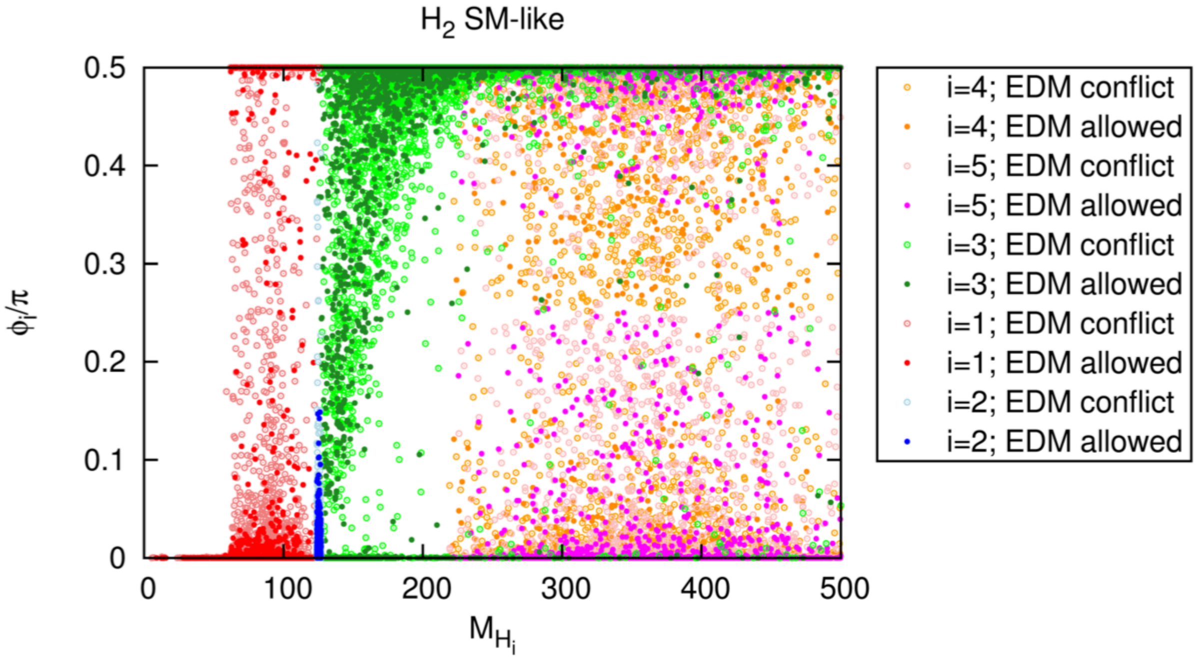
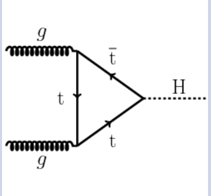
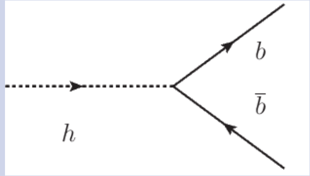
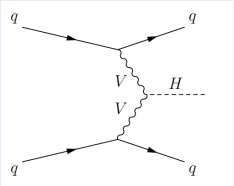
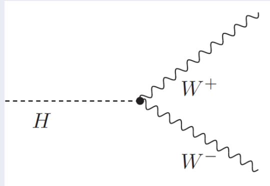
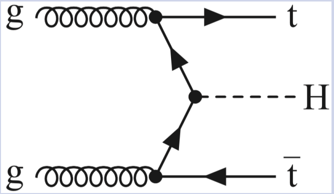
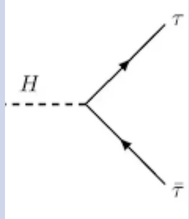


Figure 16: The phase ϕ_i, which measures the CP violation in the $H_i\tau^+\tau^-$ coupling, as a function of the mass of the Higgs boson H_i. Only scenarios that feature H_2 as the SM-like Higgs boson with a mass of 125 GeV are included. Light colored open points are in conflict with the EDM bounds,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

Measuring CP nature of the couplings to the Higgs

Production		Decay	
ggH: model dependent (loop)		H->bb: Spin information washed out due to hadronization	
VBF: CP-odd could be suppressed (CP-odd: non-renormalizable) V=Z/W		H->VV (V=Z/W): CP-odd could be suppressed (CP-odd: non-renormalizable)	
ttH: less allowed CP-odd component in some models (e.g. C2HDM Type II)		H-> $\tau\tau$: model-independent, complementary to ttH	
bbH: Much harder than ttH to measure as the sensitivity of the kinematic shapes $\propto$ mixing of the left- & right-handed helicities $\propto$ quark mass			

Therefore $H \to \tau\tau$ is a good channel to look at.

Spin correlation

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

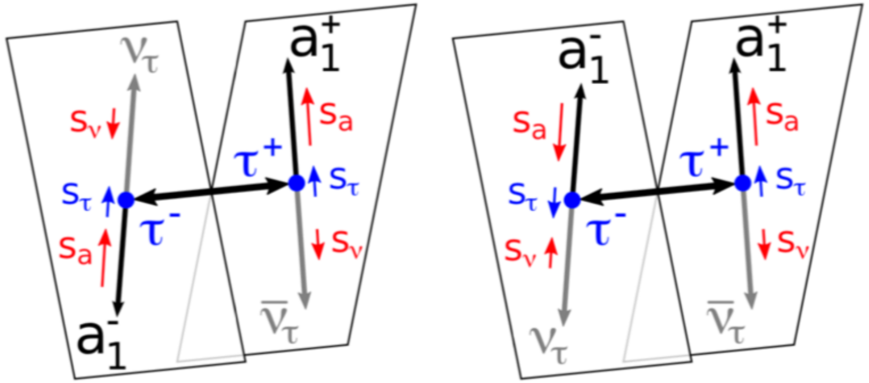
$$d\Gamma_{H\to\tau\tau} \propto 1 - s_z^- s_z^+ + \cos(2\phi_{\tau\tau})\,(\boldsymbol{s_T^-}.\boldsymbol{s_T^+}) + \sin(2\phi_{\tau\tau})\,[(\boldsymbol{s_T^+} \times \boldsymbol{s_T^-})\,.\,\widehat{\boldsymbol{k}}^-]$$

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

$$d\Gamma_{H\to\tau\tau} \propto 1 - s_z^- s_z^+ + |\boldsymbol{s_T^-}||\boldsymbol{s_T^+}|\cos(\phi_s - 2\phi_{\tau\tau})$$

with ϕ_s showing the angle between $\boldsymbol{s_T^+}$ and $\boldsymbol{s_T^-}$ in the right-handed coordinate system.

- Therefore, the CP of the coupling affects the angle between $\boldsymbol{s_T^+}$ and $\boldsymbol{s_T^-}$.
  - CP-even Higgs: $\phi_{\tau\tau} = 0°$ -> $d\Gamma$ peaks at $\phi_s = 0°$ (parallel spins)
  - CP-odd Higgs: $\phi_{\tau\tau} = 90°$ -> $d\Gamma$ peaks at $\phi_s = 180°$ (antiparallel spins)



- And the direction of the charged decay products of the two taus are also correlated (as neutrinos are left-handed)

- Likewise, the signed angle between the decay planes.

C2HDM

A complex 2HDM

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.)$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2) + h.c.\right]$$

and CP is explicitly and not spontaneously broken

$$<\Phi_1> = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

- m^2_{12} and λ_5 real **2HDM**
- m^2_{12} and λ_5 complex **C2HDM**

➡ $\boxed{\tan\beta = \frac{v_2}{v_1}}$ ratio of vacuum expectation values

➡ 2 charged, $H^\pm$, and 3 neutral CP-conserving - h, H and A

CP-violating - h_1, h_2 and h_3

➡ rotation angles in the neutral sector CP-conserving - α

CP-violating - α_1, α_2 and α_3

➡ soft breaking parameter

CP-conserving - m^2_{12}

CP-violating - $\mathrm{Re}(m^2_{12})$

C2HDM

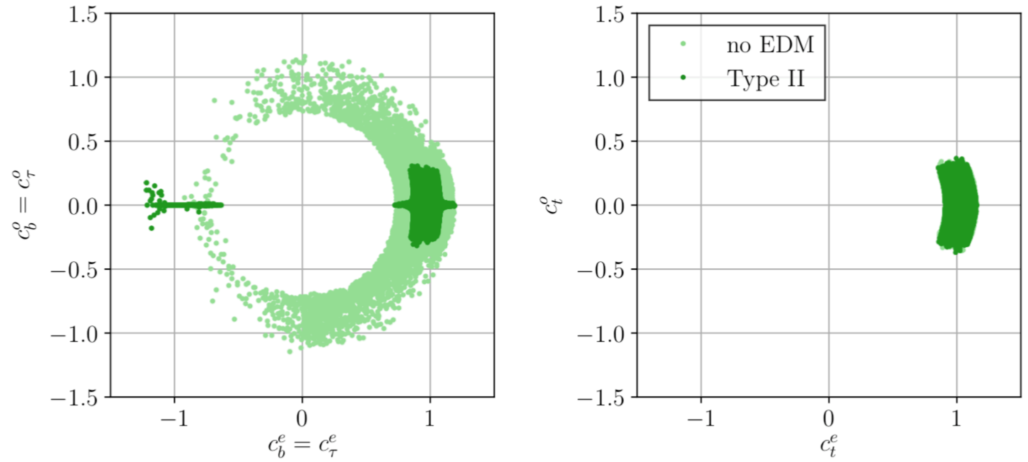


Figure 3: C2HDM Type II, $h_{125} = H_1$: Yukawa couplings to bottom quarks and tau leptons (left) and top quarks (right) for sample 1 (dark) and sample 2 (light).

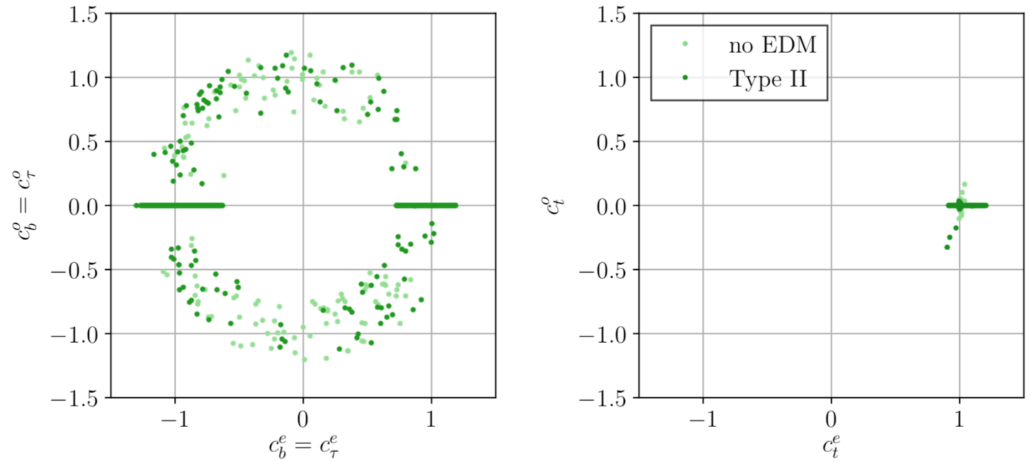


Figure 4: C2HDM Type II, $h_{125} = H_2$: Yukawa couplings to bottom quarks (left) and top quarks (right) for sample 1 (dark) and sample 2 (light).

C2HDM top vs tau

What if the 125 GeV reveals different CP behaviour in two decay channels?

The SM-like Higgs coupling to ZZ(WW) relative to the corresponding SM coupling is

$$\kappa_{C2HDM}^{h_{125}WW} = c_2 \sin(\beta - \alpha)$$

and c_2 cannot be far from 1. But α_2 is the CP-violating angle and therefore it should be small. However, the CP-odd component has an extra tanβ factor for down quarks and leptons, but not for the up quarks

$$Y_{C2HDM}^{TypeII} = c_2 Y_{2HDM}^{TypeII} - i\gamma_5 s_2 t_\beta \qquad \text{bottom, tau}$$

$$Y_{C2HDM}^{TypeII} = c_2 Y_{2HDM}^{TypeII} - i\gamma_5 \frac{s_2}{t_\beta} \qquad \text{top}$$

Thus, the SM-like Higgs couplings to the tops could be mainly CP-even while couplings to the bottoms and taus could be mainly CP-odd.

FONTES, MUHLLEITNER, ROMÃO, RS, SILVA, WITTBRODT, JHEP 1802 (2018) 073.

Indirect measurement

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

$$\mathrm{Br}(h \to b\bar{b}) = \frac{\left(\kappa_b^2 + \tilde{\kappa}_b^2\right) \mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right) \mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}\,, \tag{5.6}$$

while all the other Higgs-decay modes get rescaled to

$$\mathrm{Br}(h \to X) = \frac{\mathrm{Br}(h \to X)_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right) \mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}\,, \tag{5.7}$$

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

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

where $\hat{\mu}_X \equiv [\sigma(pp \to h)\,\mathrm{Br}(h \to X)]/[\sigma(pp \to h)\,\mathrm{Br}(h \to X)]_{\mathrm{SM}}$ 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 $gg \to h$ and $h \to \gamma\gamma$ vertices (cf. Eq. (5.4)), where the former interaction also modifies the Higgs production cross section. Up to these

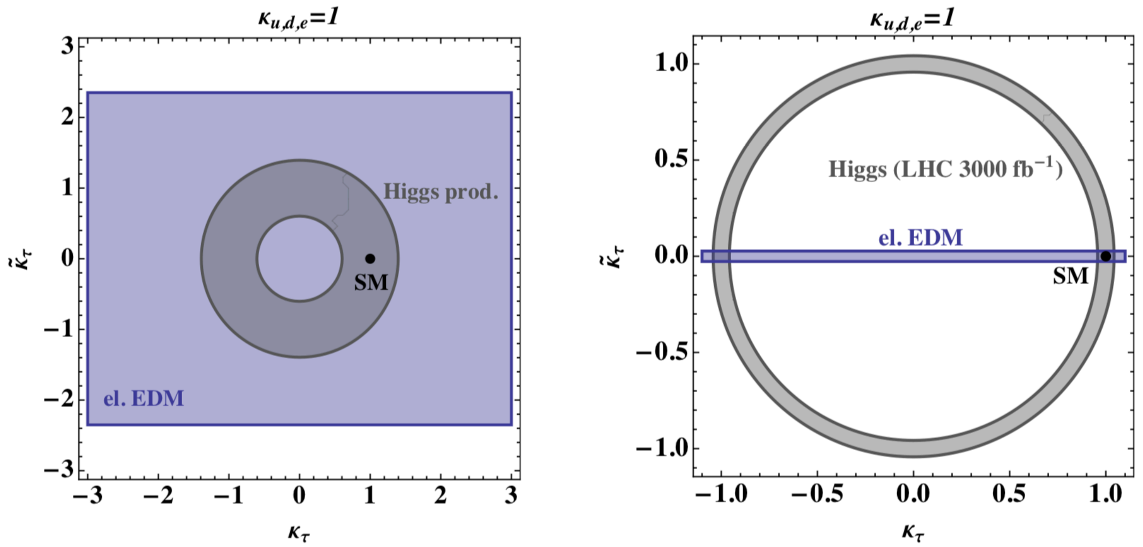


Figure 6. Left: Present constraints on κ_τ and $\tilde{\kappa}_\tau$ from the electron EDM (blue) and Higgs production (gray), assuming SM values for the remaining Higgs couplings. Right: Possible future constraints on κ_τ and $\tilde{\kappa}_\tau$, see text for details.

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

Partial decay width in $H \to \tau^+\tau^-$

More generally, and to anticipate the discussions that we will have on the Higgs CP–properties, for a Φ boson with mixed CP–even and CP–odd couplings $g_{\Phi \bar{f} f} \propto a + ib\gamma_5$, the differential rate for the fermionic decay $\Phi(p_+) \to f(p,s)\bar{f}(\bar{p},\bar{s})$ where s and $\bar{s}$ denote the polarization vectors of the fermions and the four–momenta are such that $p_\pm = p \pm \bar{p}$, is given by [see Ref. [147] for instance]

$$\begin{aligned}\frac{d\Gamma}{d\Omega}(s,\bar{s}) \;=\; & \frac{\beta_f}{64\pi^2 M_\Phi}\Big[(|a|^2+|b|^2)\Big(\frac{1}{2}M_\Phi^2 - m_f^2 + m_f^2 s\cdot\bar{s}\Big) \\ & +(|a|^2-|b|^2)\Big(p_+\cdot s\, p_+\cdot\bar{s} - \frac{1}{2}M_\Phi^2 s\cdot\bar{s} + m_f^2 s\cdot\bar{s} - m_f^2\Big) \\ & -\mathrm{Re}(ab^*)\epsilon_{\mu\nu\rho\sigma}p_+^\mu p_-^\nu s^\rho \bar{s}^\sigma - 2\mathrm{Im}(ab^*) m_f p_+\cdot(s+\bar{s})\Big] \qquad (2.8)\end{aligned}$$

The terms proportional to $\mathrm{Re}(ab^*)$ and $\mathrm{Im}(ab^*)$ represent the CP–violating part of the couplings. Averaging over the polarizations of the two fermions, these two terms disappear and we are left with the two contributions $\propto \frac{1}{2}|a|^2(M_\Phi^2 - 2m_f^2 - 2m_f^2)$ and $\propto \frac{1}{2}|b|^2(M_\Phi^2 - 2m_f^2 + 2m_f^2)$ which reproduce the β_f^3 and β_f threshold behaviors of the pure CP–even ($b=0$) and CP–odd ($a=0$) states noted above.

Impact parameter

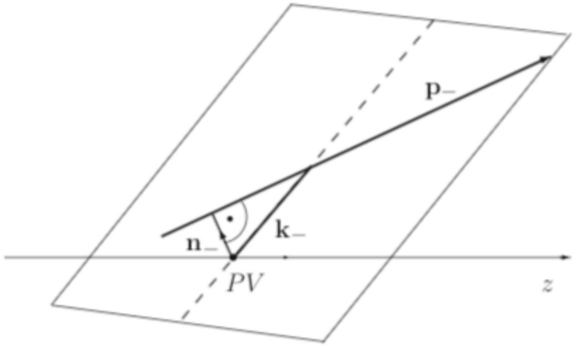


Figure 1: Definition of the impact parameter vector $\mathbf{n}_-$ in the plane of the decay $\phi \to \tau^- \to \pi^-$ in the laboratory frame. Here, $\mathbf{p}_-$ is the measured π^- momentum, PV is the τ^- production vertex, and $\mathbf{k}_-$ is the 3-momentum of the τ^-.

sensitivity can be achieved by determining the analogous correlations in the $\pi^-\pi^+$ ZMF. One can reconstruct this frame by a Lorentz boost from the laboratory frame with the measured pion 4-momenta $p^\mu_\mp = (E_\mp, \mathbf{p}_\mp)$. The resulting $\pi^\mp$ energies and momenta are $E^*_\mp$, $\mathbf{p}^*_\mp$ with $\mathbf{p}^*_+ = -\mathbf{p}^*_-$. (All quantities in this frame will be denoted by an asterisk.) However, the true decay planes in this frame can not be reconstructed, because the true impact parameter vectors in this frame can not be obtained from the measured laboratory-frame 3-vectors $\mathbf{n}_\mp$. Instead we proceed as follows. Denoting the normalized impact parameter vectors in the laboratory frame by $\hat{\mathbf{n}}_\mp$, we *define* the two space-like laboratory-frame 4-vectors $n^\mu_\mp = (0, \hat{\mathbf{n}}_\mp)$. These vectors are boosted to the $\pi^-\pi^+$ ZMF, and we obtain $n^{*\mu}_\mp = (n^*_{0\mp}, \mathbf{n}^*_\mp)$. Next we decompose the spatial parts $\mathbf{n}^*_\mp$ into components parallel and perpendicular to the respective pion momentum $\mathbf{p}^*_\mp$:

$$\mathbf{n}^*_\mp = r^\mp_\perp \hat{\mathbf{n}}^{*\mp}_\perp + r^\mp_\parallel \hat{\mathbf{n}}^{*\mp}_\parallel , \tag{7}$$

where $r^\mp_\perp, r^\mp_\parallel$ are constants. In this way we obtain the unit vectors $\hat{\mathbf{n}}^{*\mp}_\perp$, which are orthogonal to $\mathbf{p}^*_\mp$, respectively, for each event in a unique fashion. The angle, which takes the role of the true angle between the unsigned normal vectors of the decay planes , Eq. (6), is defined by

$$\varphi^* = \arccos(\hat{\mathbf{n}}^{*+}_\perp \cdot \hat{\mathbf{n}}^{*-}_\perp) , \tag{8}$$

where $0 \le \varphi^* < \pi$. In addition, the CP-odd and T-odd triple correlation $O^*_{CP} = \hat{\mathbf{p}}^*_- \cdot (\hat{\mathbf{n}}^{*+}_\perp \times \hat{\mathbf{n}}^{*-}_\perp)$ turns out to be an appropriate tool for distinguishing between CP invariance and CP violation in Higgs-boson decay. Here $\hat{\mathbf{p}}^*_-$ denotes the normalized π^- momentum. As $-1 \le O^*_{CP} \le 1$, it is convenient to consider, alternatively, the distribution of the angle

$$\psi^*_{CP} = \arccos(\hat{\mathbf{p}}^*_- \cdot (\hat{\mathbf{n}}^{*+}_\perp \times \hat{\mathbf{n}}^{*-}_\perp)) . \tag{9}$$

We shall show in the next section that (8) and (9) are sensitive and robust observables for determining the CP nature of a neutral Higgs boson.

Main visible τ^- decay products
e^-
μ^-
π^-
$\pi^-\pi^0$
$\pi^-2\pi^0$
$\pi^-\pi^+\pi^-$
$\pi^-\pi^+\pi^-\pi^0$

Unrolled ϕ_{CP}

- ϕ_{CP} distribution in bins of MVA for $\mu\ +\pi$ final state.
- Each window shows ϕ_{CP} in $[0,2\pi]$