The Higgs through the looking glass.

Measurement of the CP structure of the Yukawa interaction in Higgs boson decays to $\tau$ leptons in CMS
Introduction

**CP-violation** in the Higgs couplings can occur in:

- HVV couplings
- Yukawa coupling:
  - Production via $t\bar{t}H$ and $ggH$
  - **Decays into \( \tau \) leptons**

The **Standard Model** predicts that I have spin-parity $0^+$.

But do I? Better check with a **CP mirror**

We invert spatial coordinates and swap particles with anti-particles.
If I **decay to τ leptons**
the angle between the decay planes depends on the **CP mixing angle**

The acoplanarity angle

\[
\frac{d\sigma}{d\varphi_{CP}} \propto \text{const} - \cos (\varphi_{CP} - 2\varphi_{\tau\tau})
\]

The cross-section of the H→ττ process has a **sinusoidal shape**

**CP even** \(\varphi_{\tau\tau} = 0^\circ\)

**CP mix** \(\varphi_{\tau\tau} = 45^\circ\)

**CP odd** \(\varphi_{\tau\tau} = 90^\circ\)

**CP mixing angle**

\[
\mathcal{L}_{Y,\tau} = -\frac{m_\tau}{v} \bar{\tau}(\kappa_\tau + i\gamma^5\bar{\kappa}_\tau)H\tau
\]

\[
\kappa_\tau = \sqrt{\mu_{\tau\tau}} \cos (\varphi_{\tau\tau})
\]

\[
\bar{\kappa}_\tau = \sqrt{\mu_{\tau\tau}} \sin (\varphi_{\tau\tau})
\]
Channels studied

Investigated $\tau$ decay channels

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mu^\pm$</th>
<th>$\pi^\pm$</th>
<th>$\rho^\pm \rightarrow \pi^\pm \pi^0$</th>
<th>$a_1^\perp \rightarrow \pi^\perp \pi^0 \pi^0$</th>
<th>$a_1^{1\text{pr}} \rightarrow \pi^\perp \pi^\perp \pi^\perp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(%)$</td>
<td>17.4</td>
<td>11.5</td>
<td>25.9</td>
<td>9.5</td>
<td>9.8</td>
</tr>
<tr>
<td>Symbol</td>
<td>$\mu$</td>
<td>$\pi$</td>
<td>$\rho$</td>
<td>$a_1^{1\text{pr}}$</td>
<td>$a_1^{3\text{pr}}$</td>
</tr>
</tbody>
</table>

Decay planes are reconstructed with the $\tau$ decay products momenta.

Impact parameters are used if only one charged particle is present.

The $\tau_h$ are identified with the **DeepTau** NN-based ID\(^2\)
MVA-based identification of the decay modes\(^3\)
**Event classification**

**Machine learning** tools\(^1\) can be used to identify the Higgs decays from dominant backgrounds:

- **Genuine di-tau** production
- **Lepton/jets** *faking* \(\tau_h\)

At the LHC many processes can produce similar signatures to my decays to \(\tau\) leptons:

- BDT and **neural network** can help in identifying me

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\(^1\) Excluding the use of heavy machines for optical lensing.
Simultaneous fit of signal and background models to data for 3 years of data-taking: **full Run 2**

**Signal category split by \( \tau \) decay channel**

**Genuine \( \tau^+ \tau^- / \tau^- \tau^+ \) categories**

**Leptons/jets faking \( \tau_h \) backgrounds**
Results-part 1

Likelihood profiled with respect to CP mixing angle

The CP mixing angle is consistent with 0 at 68% CL in agreement with the SM prediction! A pure CP-odd coupling is excluded at 99.7% CL (3.2σ)

If I look at myself in the CP mirror I just see myself!
Results-part 2

Likelihood profiled\(^1\) with respect to:

**Yukawa couplings**

\[ \Gamma = \Gamma(\kappa_\tau, \bar{\kappa}_\tau) \]

\[ \kappa_i = 1, \bar{\kappa}_i = 0 \forall i \neq \tau \]

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**CP mixing angle + signal strength**

\[ \mu_{\gamma\gamma H} = \mu_{V} = 1 \]

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Analysis **statistically** limited, to be continued in **Run 3**
Andrea Cardini
on behalf of the CMS collaboration

References.

1. CMS-PAS-HIG-20-006: “Analysis of the CP structure of the Yukawa coupling between the Higgs boson and \( \tau \) leptons in proton-proton collisions at \( \sqrt{s} = 13 \) TeV”
3. CMS-DP-2020-041: “Identification of hadronic tau decay channels using multivariate analysis (MVA decay mode)”