Measurement of the Higgs CP State in H → ττ Decays

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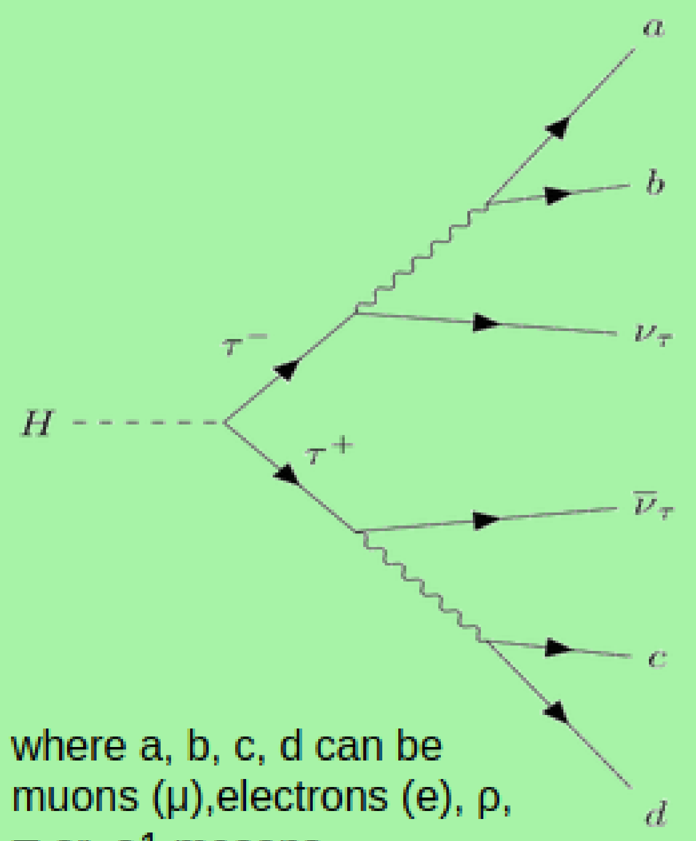
The Higgs Boson

The Higgs boson, is the quantum of the Higgs field, a key component of Standard Model (SM) theory and the only scalar boson the SM contains. The Higgs mechanism explains why the weak force bosons of the SM have mass. This in turn causes the weak force to be a short range interaction, in contrast to the electromagnetic interaction which has infinite range.

C and P are discrete spacetime symmetries. Charge (C) conjugation is the replacement of every particle by its antiparticle. Parity (P), is the reflection of every particle's position through the origin. A symmetry is violated if the laws of physics do not perform the same after conjugation is applied [1]. A large CP violation is required to explain the observed matter antimatter imbalance in the universe, this could be present in the Higgs sector.



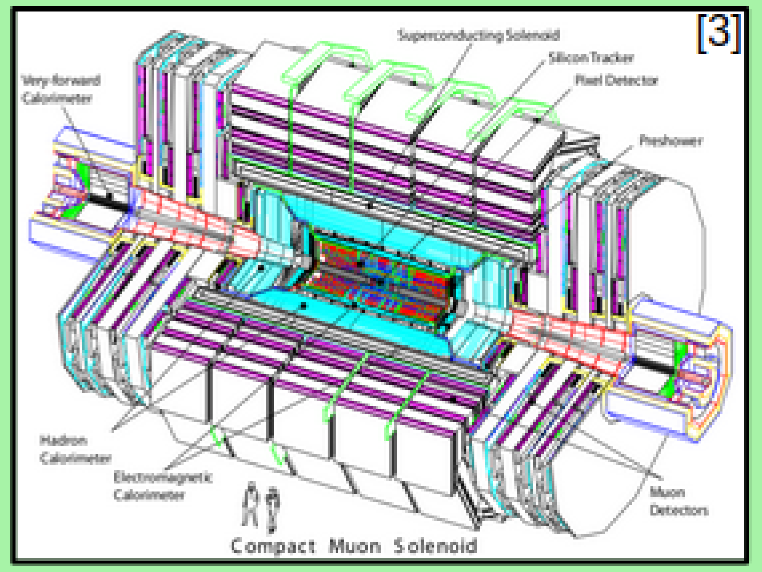
where a, b, c, d can be muons (μ), electrons (e), ρ, π or a1 mesons.

Decay mode	Branching Ratio (%)
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.39
$e^-\bar{\nu}_e\nu_\tau$	17.82
$\pi^-\nu_\tau$	10.82
$\pi^-\pi^0\nu_\tau$	25.49
$\pi^-2\pi^0\nu_\tau$	9.26
$2\pi^-\pi^+\nu_\tau$	8.99
$2\pi^-\pi^+\pi^0\nu_\tau$	2.74
$\pi^-\omega\nu_\tau$	1.95
$\pi^-3\pi^0\nu_\tau$	1.04

[2]

Our aim is to make a measurement of CP violation in Higgs decays to tau leptons. An example of such a decay is shown in the Feynman diagram.

Our results will be derived from data taken at the CMS detector at the LHC. Before we calculate these results, we optimise our analysis on randomly generated Higgs decay events which have been passed through a full simulation of the CMS detector. This allows us to determine a method to extract as much information about the CP couplings to taus as possible from real data.

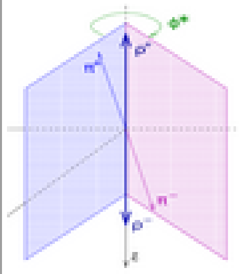


[3]

CP Sensitive Observables

In order to get a final result, we must search for the combinations of decay modes and observables that have the most information on the CP state.

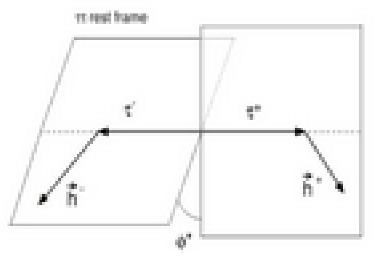
Acoplanary angles



The a1 and ρ originating from the taus' decay to multiple pions.

The acoplanary angles, are the angles between the different pions. These angles carry some information about the CP state of the Higgs.

Polarimetric vector angle



The polarimetric vectors $\vec{h}$ are defined as a weighted combination of the directions of the tau decay products in the Higgs' rest frame.

Φ_{tt}

All τ decay products are passed to the Tauola software. For each event it calculates the pseudo scalar, standard model and maximal mixing weights. Φ_{tt} is defined as the angle minimising the expression[4]:

$$\cos^2(\phi_{tt})w_{sm} + \sin^2(\phi_{tt})w_{ps} + 2\cos(\phi_{tt})\sin(\phi_{tt})(w_{mm} - \frac{w_{sm}}{2} - \frac{w_{ps}}{2})$$

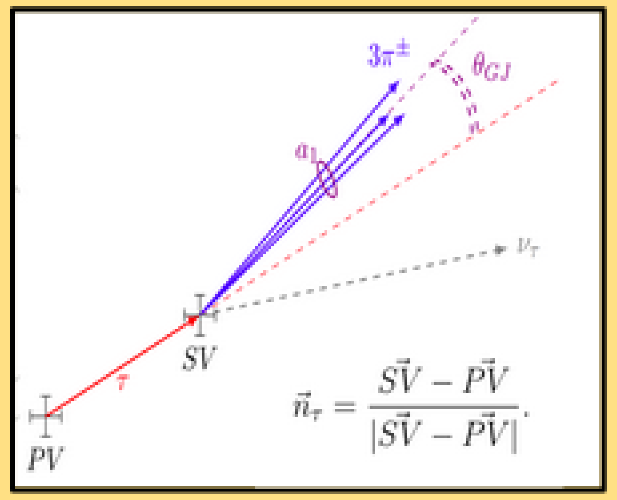
The distribution of each of these angles depend on the CP state of the Higgs with more or less separation for different tau decay modes.

Neutrino Reconstruction

To obtain CP-sensitive angles, we need to accurately reconstruct the original tau particle and therefore the tau neutrino, which is not directly detected. This project is looking at different ways to produce accurate reconstruction of the neutrinos.

Polarimetric vector approximation

For a tau decaying to a1, the tau direction $\vec{n}_\tau$ can be found from reconstructed Primary and Secondary vertices, PV and SV respectively, the points where the Higgs and tau decayed.

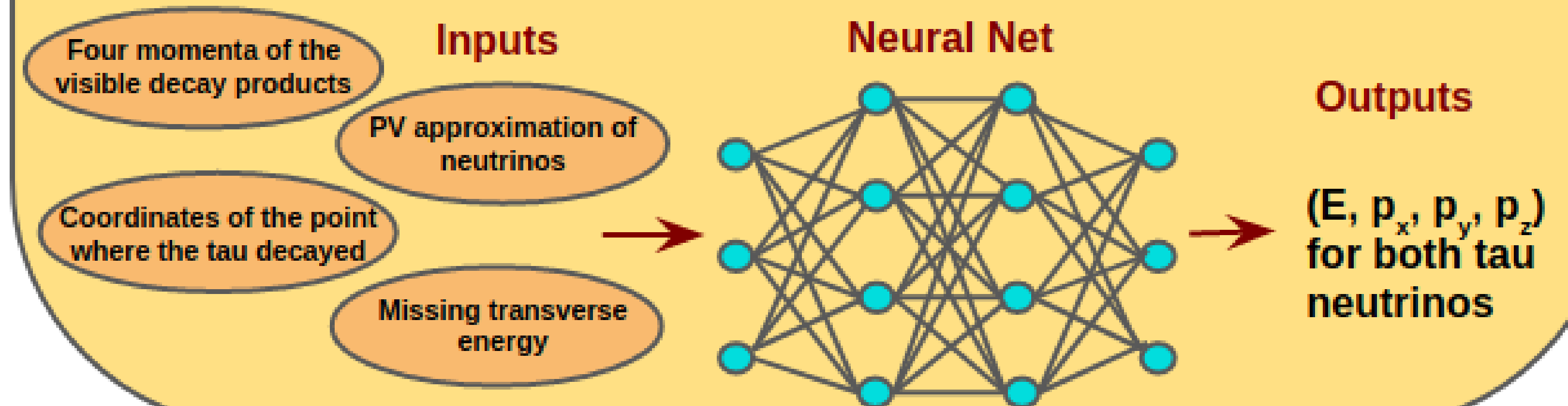


The tau momentum can also be calculated from [5]:

$$|\vec{p}_\tau| = \frac{(m_{a_1}^2 + m_\tau^2)|\vec{p}_{a_1}|\cos\theta_{GJ} \pm \sqrt{(m_{a_1}^2 + \vec{p}_{a_1}^2)[(m_{a_1}^2 - m_\tau^2)^2 - 4m_\tau^2\vec{p}_{a_1}^2\sin^2\theta_{GJ}]}}{2(m_{a_1}^2 + \vec{p}_{a_1}^2\sin^2\theta_{GJ})}$$

And from there the neutrino can be reconstructed.

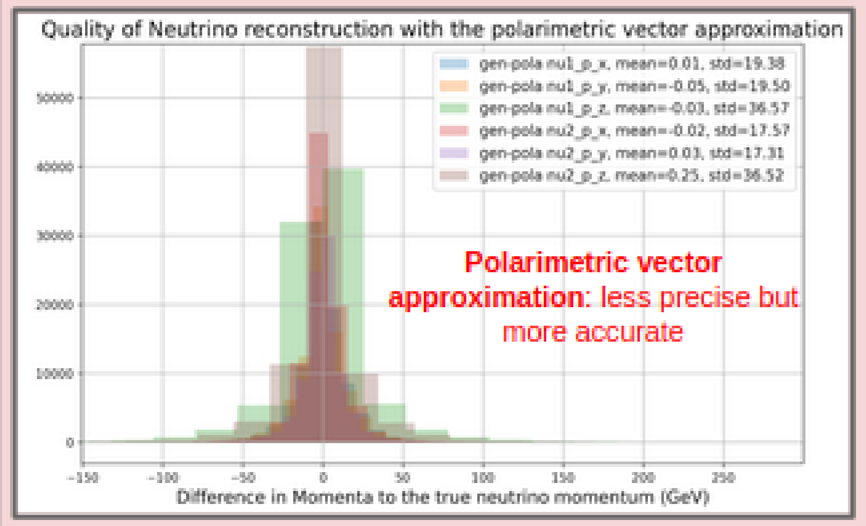
Neural Net Regression

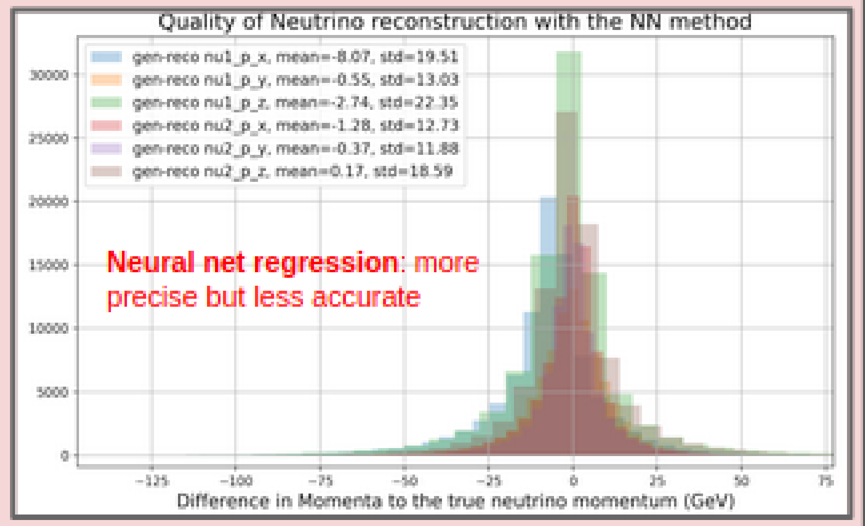


Results

Neutrino reconstruction

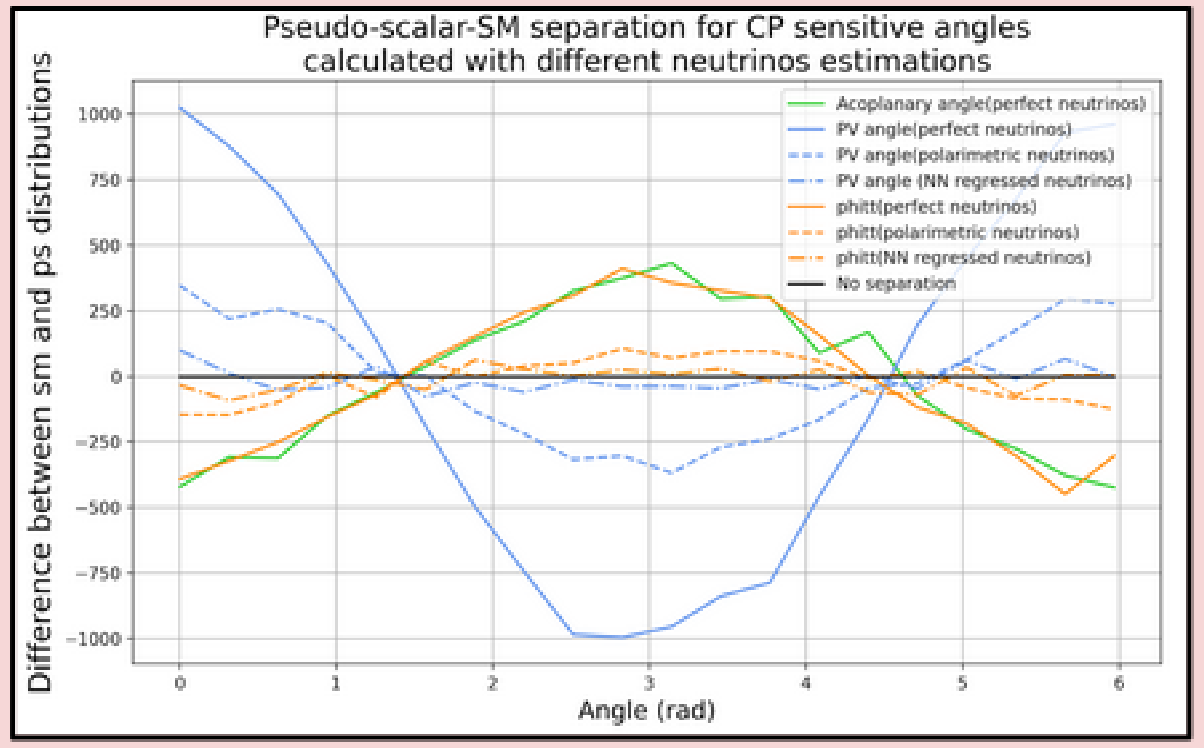
The quality of CMS's estimation of the Higgs CP state will entirely depend on the precision of the measurement of the different CP-sensitive angles which in turn depends on how well the neutrinos are reconstructed.





Separation between CP even and odd scenarios

The CP sensitivity of a variable is estimated by comparing its distributions in the CP even and odd cases. The larger the difference, the more information this variable contains about the Higgs' CP state.



Our work has showed that in the a1-a1 channel, the PV angle is strongly CP sensitive when calculated using polarimetric neutrinos.

We expect to extend this method to other decay channels to increase the amount of data available.

Our estimation of the Higgs CP violation will allow us to quantify any potential deviation from the Standard Model's prediction of 0±23°[3] and reduce the margin error on this measurement compared to the previous result of 4±17° [3].

References

[1] M. E. Peskin and D. V. Schroeder, An Introduction to quantum field theory. Reading, USA: Addison-Wesley, 1995.
[2] P. D. Group, "Review of Particle Physics", Progress of Theoretical and Experimental Physics, vol. 2020, no. 8, 08 2020, 083C01.
[3] Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at s = √13 TeV. Geneva: CERN; 2020.
[4] T. Przedzinski, E. Richter-Was, and Z. Was, "Documentation of Tauspinner algorithms: program for simulating spin effects in τ-lepton production at LHC, 2019.
[5] V. Cherepanov and A. Zotz, "Kinematic reconstruction of Z/H ττ decay in proton-proton collisions," 2018.