Measurement of the CP properties of the Higgs boson

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Who I am

→ 2^{nd} year PhD student from Strasbourg

→ Working at the Institut Pluridisciplinaire Hubert Curien as part of the CMS collaboration

→ My thesis is entitled ***"Study of the CP properties of the Higgs boson in the tau-tau channel in the CMS experiment at the LHC"***

→ Quick overview : Introduction to Higgs boson properties, examples of CP studies, CP study in the $H \to \tau\tau$ channel

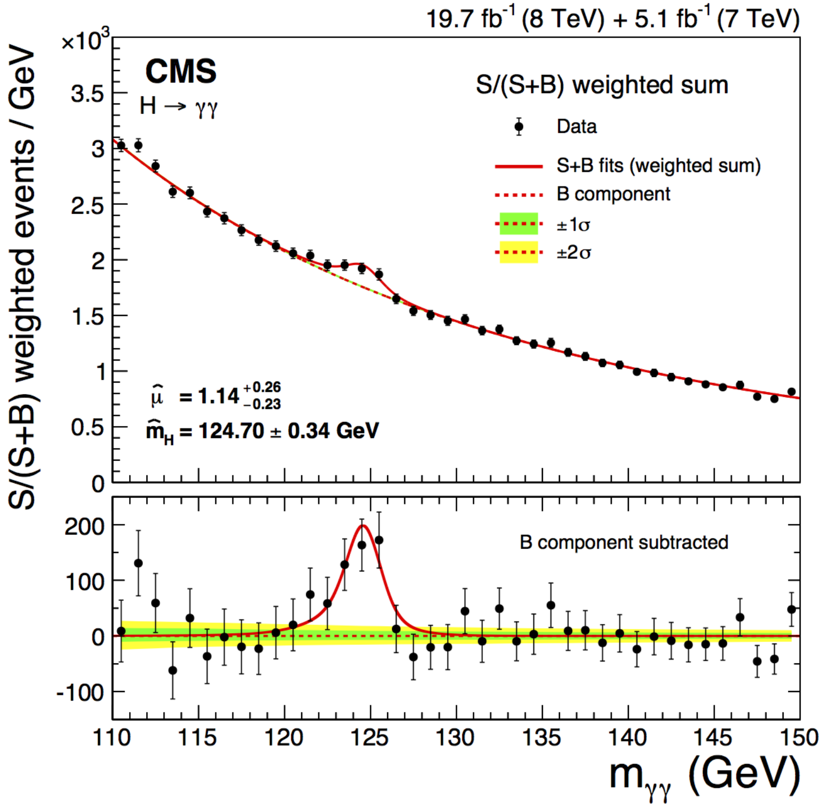
Introduction

→ Discovery of a new boson announced in 2012 by ATLAS and CMS collaborations with properties similar to standard Higgs boson

→ Last undiscovered particle of the standard model

→ Many properties already well known : neutral and spin 0 boson with a mass of 125,38 ± 0,14 GeV (CMS 2020)

→ The Higgs boson is described as a purely scalar particle in the standard model but CP violations could be occuring in its couplings

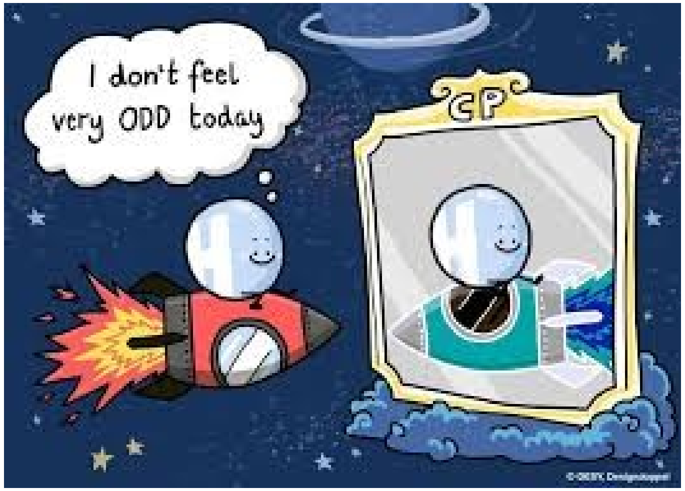


CP properties of the Higgs boson

CP is a combination of two operators standing for **C**harge and **P**arity

→ **C** transforms a particle into its anti-particle : **H is its own anti-particle**

→ **P** transforms the spatial coordinates of a particle into its mirror image : **would H decay the same way in a mirror ?**



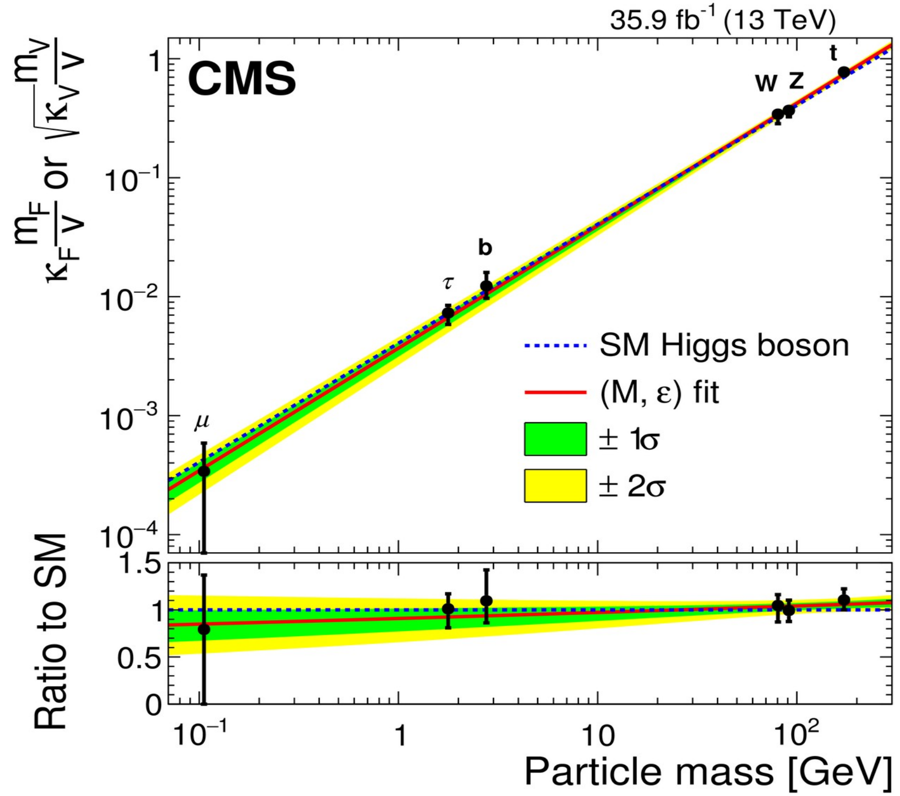
(image:DESY/designdoppel)

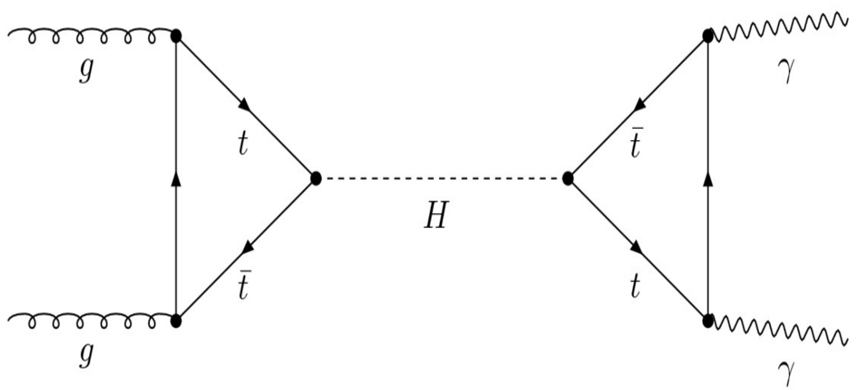
Looking at Higgs boson decay products in detectors such as CMS gives important information about the nature of its couplings

Couplings of the Higgs boson

Higgs boson coupling strength to other SM particles is proportional to their mass

No mass = no coupling ?





Higgs boson can still couple to gluons and photons through virtual particles

Couplings of the Higgs boson

Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

CP violating effects may occur at tree level in couplings to fermions but not to bosons

→ Decay to $t\bar{t}$: impossible due to large top mass

→ Decay to $c\bar{c}$: not observed yet

→ Decay to $\mu\mu$: very rare

→ Decay to $b\bar{b}$: spin information washed out

Tau decay channel and top production mode are therefore the best options for CP studies at the LHC

CP study in Z boson pair decay

→ CP studies are also performed in couplings to bosons

→ Pseudo-scalar hypothesis is tested in $H \to ZZ \to 4l$ decays

→ No neutrinos : event kinematic is fully described

→ Study is based on kinematic discriminants

→ Events are categorized according to their properties

→ Allows to discriminate background from signal but also to test several spin-parity hypothesis

J^P model	J^P production	Expected ($\mu = 1$)	Obs. 0^+	Obs. J^P	$\mathrm{CL_s}$
0^-	any	2.4σ (2.7σ)	-1.0σ	$+3.8\sigma$	0.05%
0_h^+	any	1.7σ (1.9σ)	-0.3σ	$+2.1\sigma$	4.5%
1^-	$q\bar{q} \to X$	2.7σ (2.7σ)	-1.4σ	$+4.7\sigma$	0.002%
1^-	any	2.5σ (2.6σ)	-1.8σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \to X$	2.1σ (2.3σ)	-1.5σ	$+4.1\sigma$	0.02%
1^+	any	2.0σ (2.1σ)	-2.1σ	$+4.8\sigma$	0.004%
2_m^+	$gg \to X$	1.9σ (1.8σ)	-1.1σ	$+3.0\sigma$	0.9%
2_m^+	$q\bar{q} \to X$	1.7σ (1.7σ)	-1.7σ	$+3.8\sigma$	0.2%
2_m^+	any	1.5σ (1.5σ)	-1.6σ	$+3.4\sigma$	0.7%
2_b^+	$gg \to X$	1.6σ (1.8σ)	-1.4σ	$+3.4\sigma$	0.5%
2_h^+	$gg \to X$	3.8σ (4.0σ)	$+1.8\sigma$	$+2.0\sigma$	2.3%
2_h^-	$gg \to X$	4.2σ (4.5σ)	$+1.0\sigma$	$+3.2\sigma$	0.09%

→ Pseudo-scalar hypothesis is excluded with 3.8σ

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Yukawa coupling to fermions

Each fermionic interaction with the Higgs boson can be decomposed into a CP-even κ_l and a CP-odd $\tilde{\kappa}_l$ coupling :

$$L_Y = -\frac{m_l \phi}{v}(\kappa_l \overline{\psi_l}\psi_l + \tilde{\kappa}_l \overline{\psi_l} i\gamma_5 \psi_l)$$

The CP-odd fraction of the coupling is related to an effective mixing angle α^{Hll} :

$$f_{cp}^{Hll} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2} = \sin^2(\alpha^{Hll})$$

→ m_l is the mass of the interacting fermion

→ v = 246 GeV is the vacuum expectation value

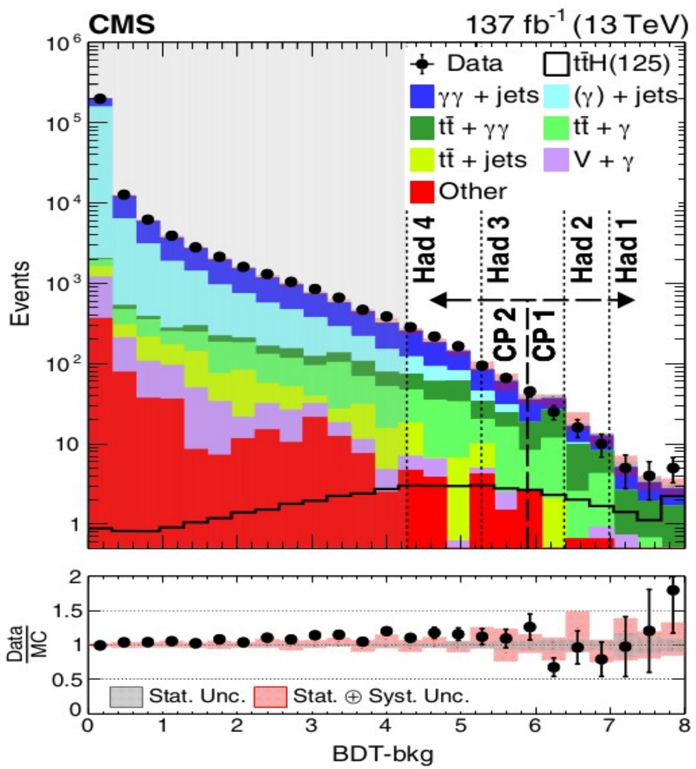
→ ϕ represents the Higgs scalar field

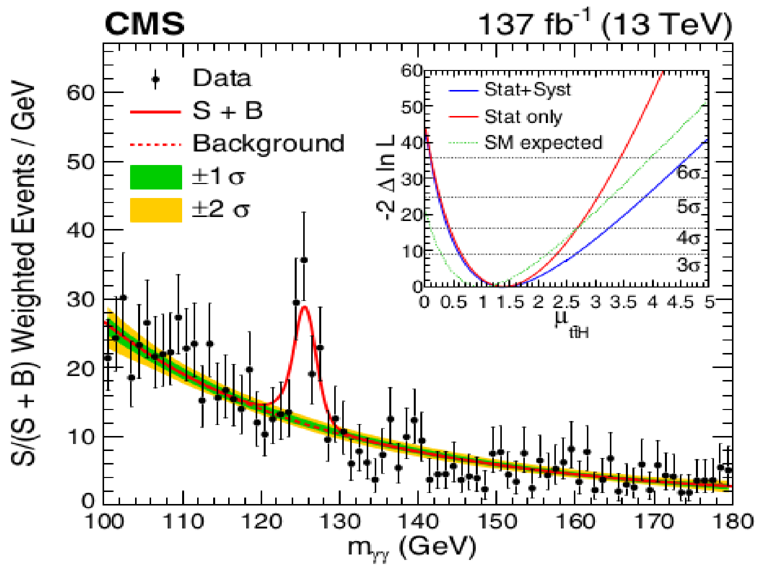
→ ψ_l represents the interacting fermionic field

For a mixing angle of 0° (90°) the coupling is purely scalar (pseudo-scalar) and is a mixed state for any other value

CP study in top quark production mode

This analysis looks at the top coupling in the $t\bar{t}H$ process with H decaying to $\gamma\gamma$





→ A BDT is trained to extract signal events from background events

→ Events are categorized according to their BDT score

→ Data are fitted to measure the signal strength of the process

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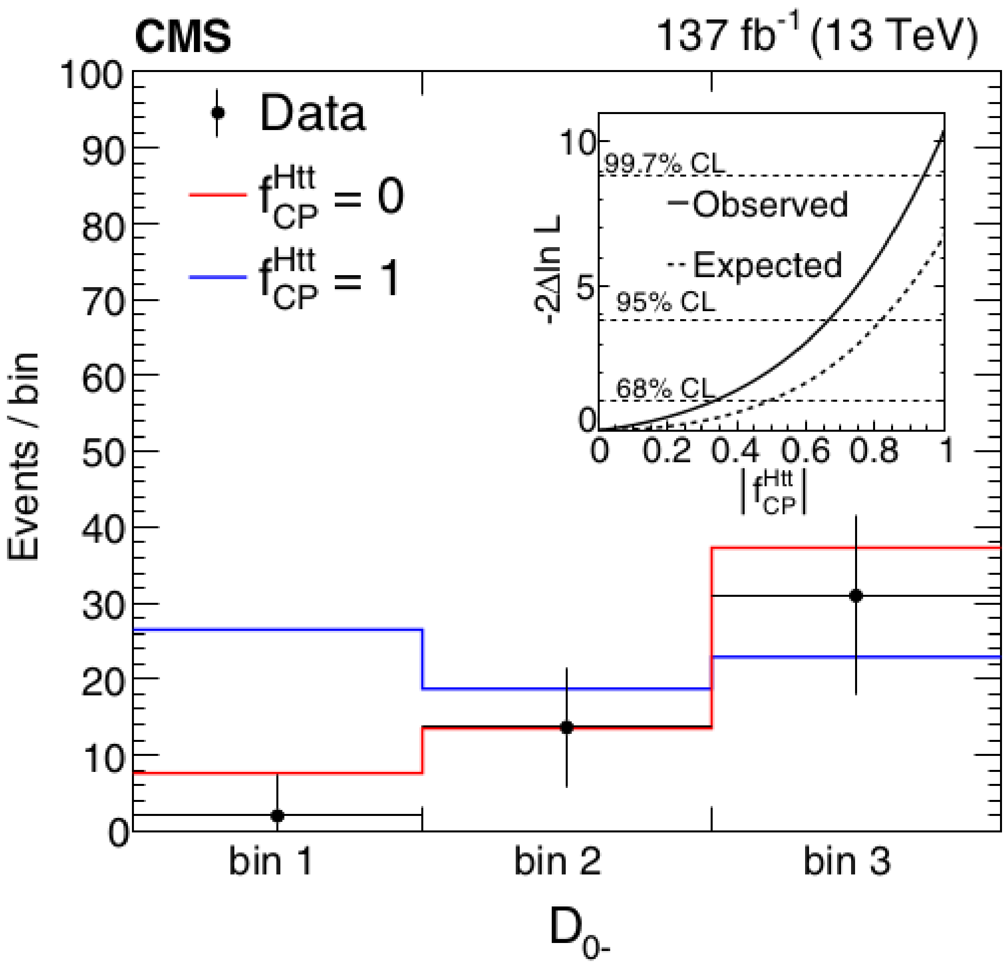
CP study in top quark production mode



→ A 2nd BDT is trained to separate CP-odd events from CP-even events

→ Background is removed from data using previous results

→ Events are categorized according to their BDT score called D_{0-}

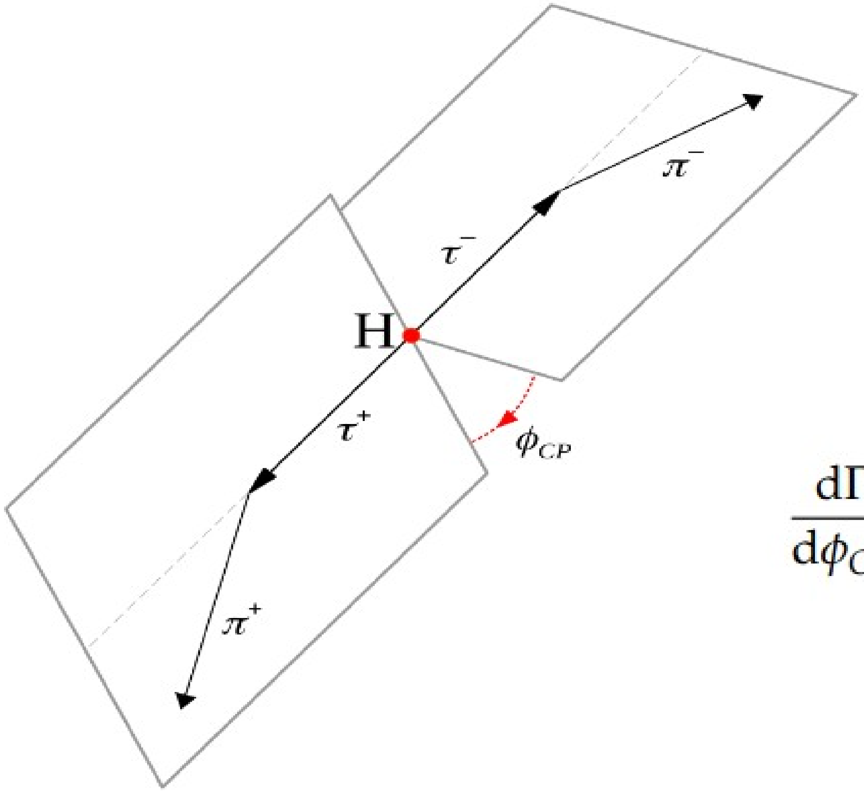
→ Data are fitted to measure the CP-odd fraction

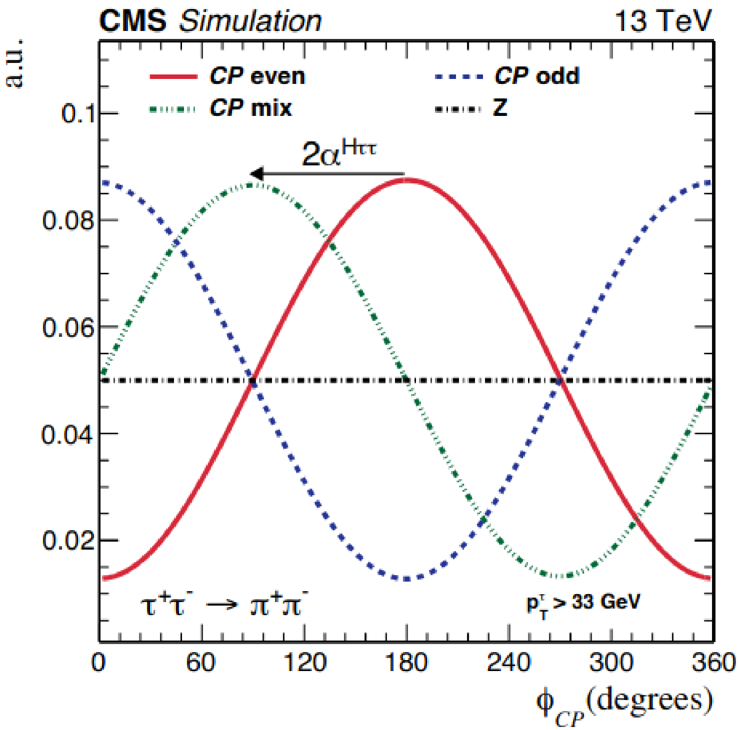
$f_{CP}^{Htt}=0.00\pm0.33$ at 68% CL

$f_{CP}^{Htt}=1$ excluded with 3.2σ

CP sensitive observable in the tau decay channel

ϕ_{cp} is defined as the angle between the taus decay planes in the Higgs boson rest frame





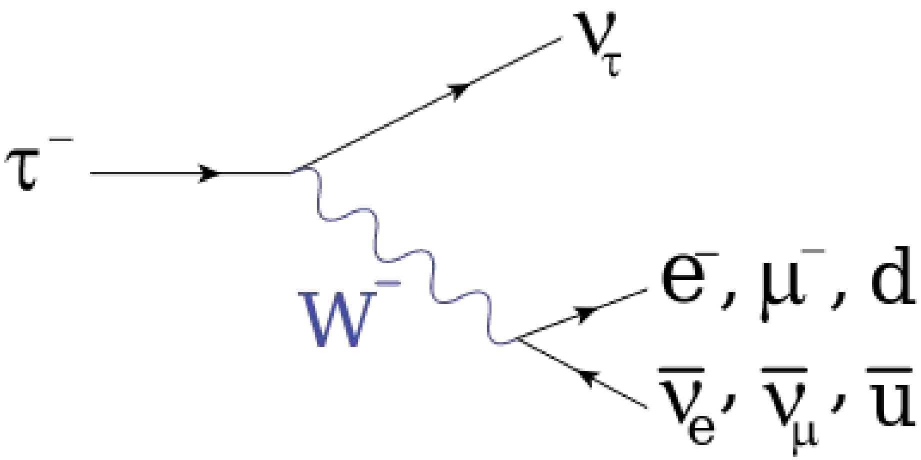
$$\frac{d\Gamma}{d\phi_{CP}}(H \rightarrow \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau}).$$

The differential cross section of H is related to ϕ_{cp} and α^{Hll}

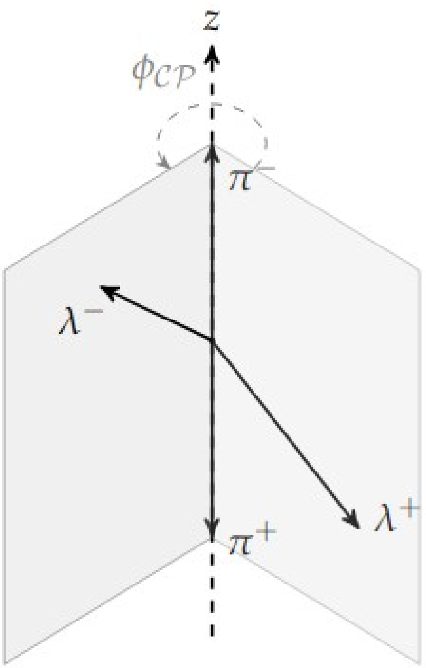
Tau lepton decay modes

Reconstructing the Higgs rest frame can be a tough task in a proton collider like the LHC : optimized methods are needed

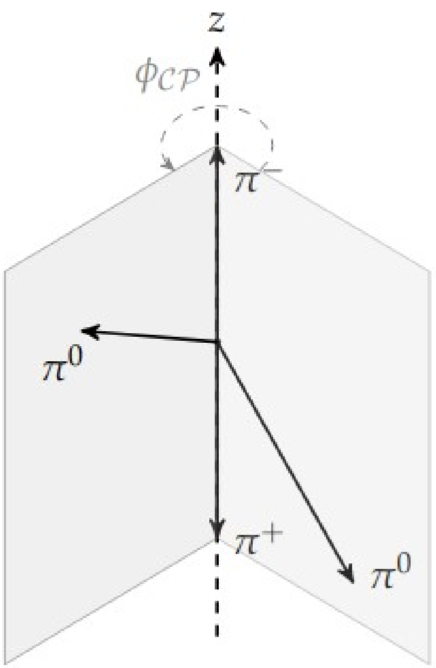
Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8



Impact parameter and decay plane methods



Planes spanned by the charged particle momentum and its impact parameter



Planes spanned by the visible particles momenta from the hadronic decay

Impact parameter

$\tau \to \pi, \mu$

Decay plane

$\tau \to \pi + \pi^0, \rho, a_1 \ldots$

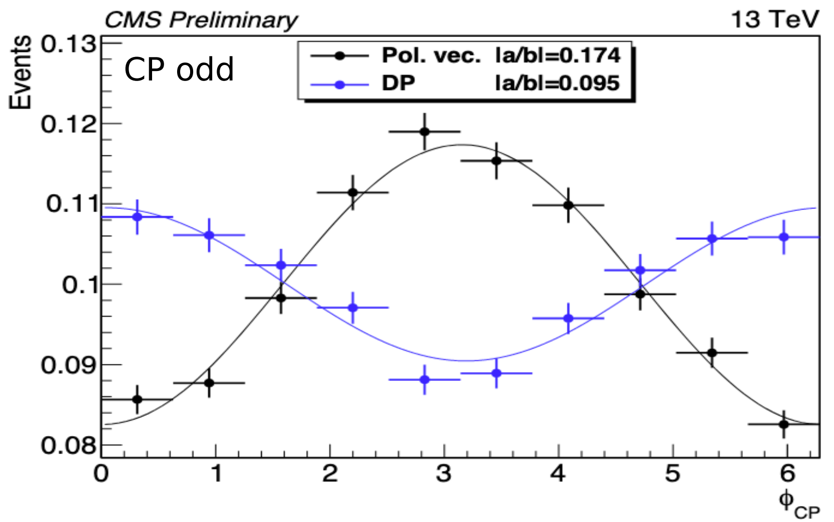
Angle calculation is performed in the Zero Momentun Frame (ZMF)

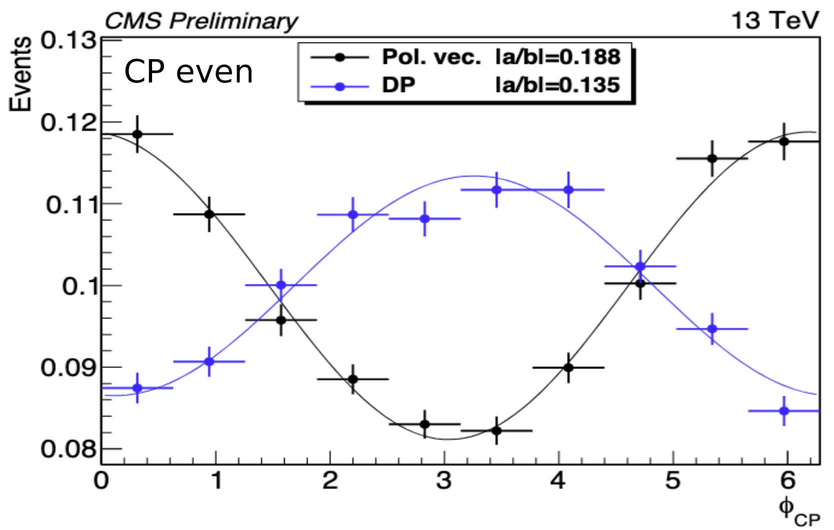
Polarimetric vector method

This method relies on the estimation of the most probable tau spin direction and could be used in any hadronic channel

Planes are spanned by the polarimetric vector and the tau momentum :

Tau reconstruction is needed





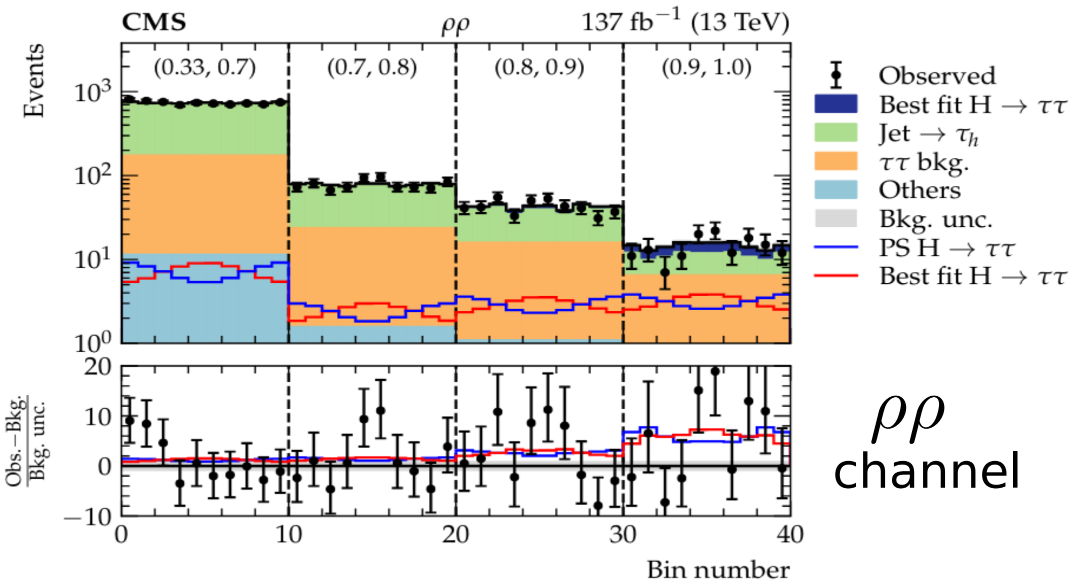
Improvement of the sensibility in the a1a1 channel w.r.t decay plane method, possible due to secondary vertices, **done in Strasbourg**

Event categorisation

→ Signal is separated from background with a MVA

→ MVA uses kinematic variables as input

→ 3 possible outputs categories :
- → Higgs (signal)
- → Genuine τ_h background (embedding)
- → Fake τ_h background (misidentified jet)



$\rho\rho$ channel

→ Unrolled plots are distributions of the CP angle for several MVA score ranges

→ Background estimation consistency checked in genuine and fake bkg categories

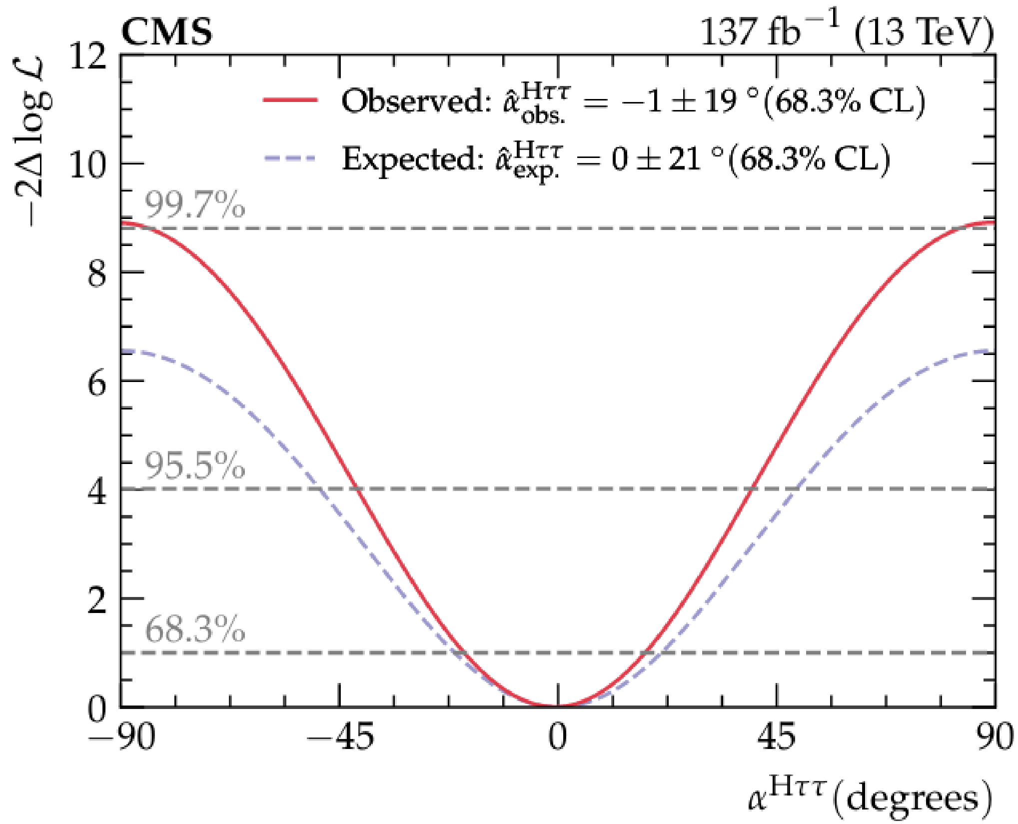
→ Signal category is "unblinded" lastly

→ "best fit" of data is extracted from a likelihood function

Results

→ Negative log-likelihood scan to extract CP properties

$$-2\Delta \ln L = -2\left(\ln(L\alpha^{H\tau\tau}) - \ln(L\alpha^{H\tau\tau}_{\text{best fit}})\right)$$



→ CP mixing angle is measured to be -1±19° at 68% CL

→ CP odd hypothesis is excluded with 3,2σ

Perspectives of improvement

→ Extend the usage of the polarimetric vector to new channels :

Tests performed in $\tau\tau \to a_1 + \pi, \mu$ channels :

→ Tau reconstruction with Global Event Fit (GEF)

→ Can reconstruct taus in any a1+ one charged particle channel

Some improvement already observed

→ Some channels can't be exploited with GEF : $\tau\tau \to \pi\pi, \rho\rho, a_1\rho, \pi\rho$

Need to have sufficient resolutions :

→ Develop machine learning techniques to reconstruct taus

On-going work !

Conclusion

→ CP properties of the Higgs boson have been studied in several channels

→ All measurements are consistent with the standard model so far

→ Study in the tau tau channel recently published with a contribution from Strasbourg : arXiv:2110.04836

→ First measurement of this kind in this channel

→ My thesis aims for improvements of the CP sensibility in hadronic or semi-leptonic channels with the polarimetric vector method

THANK YOU