PHYSICS AT THE TERASCALE
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Analysis of the CP structure of the Yukawa coupling in $H \rightarrow \tau\tau$ decays

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on behalf of the CMS collaboration

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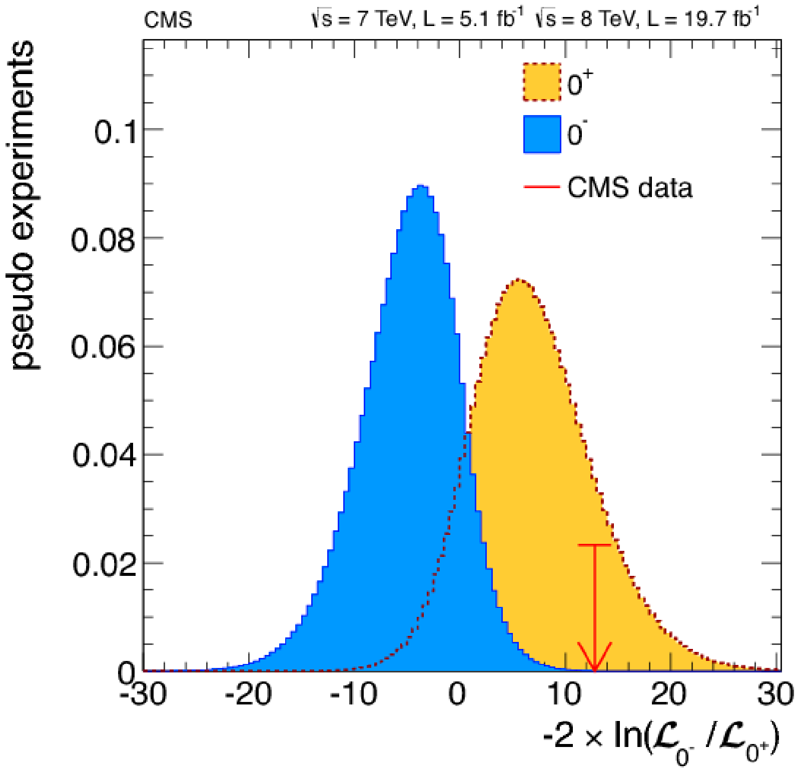
CP violation in the Higgs sector

- Higgs boson predicted to have spin-parity 0^+ → direct coupling to Z and W bosons

- Investigating CP violation in the Higgs sector
  - HVV couplings (V= Z,W bosons)
    - studied in 4 lepton final state / VBF production

Pure CP odd excluded
Mixing still possible

  - Yukawa coupling of Higgs to fermions
    - gg → H +jets (through top quark loop)
    - gg → ttH
    - **H → ττ decays**
      - Spin correlation between tau leptons and their decay products



doi:10.1103/PhysRevD.89.092007

- H → ττ Yukawa interaction can be parametrized as follows:
  - $\mathscr{L}_{Y,\tau} = -\frac{m_\tau}{v}\,\bar{\tau}(\kappa_\tau + i\gamma^5\tilde{\kappa}_\tau)H\tau$
  - CP mixing encoded in $\alpha^{H\tau\tau}$:
    - $\kappa_\tau = \sqrt{\mu^{\tau\tau}}\cos\left(\alpha^{H\tau\tau}\right)$
    - $\tilde{\kappa}_\tau = \sqrt{\mu^{\tau\tau}}\sin\left(\alpha^{H\tau\tau}\right)$
- CP mixing alters transverse-spin correlation between τ leptons
  - $\Gamma(H_{mix} \to \tau\tau) = \Gamma^{unpol}(1 - s^-_{//}s^+_{//} + s^-_\perp R(2\alpha^{H\tau\tau})s^+_\perp)$
  - The correlation carries over to the τ decay products

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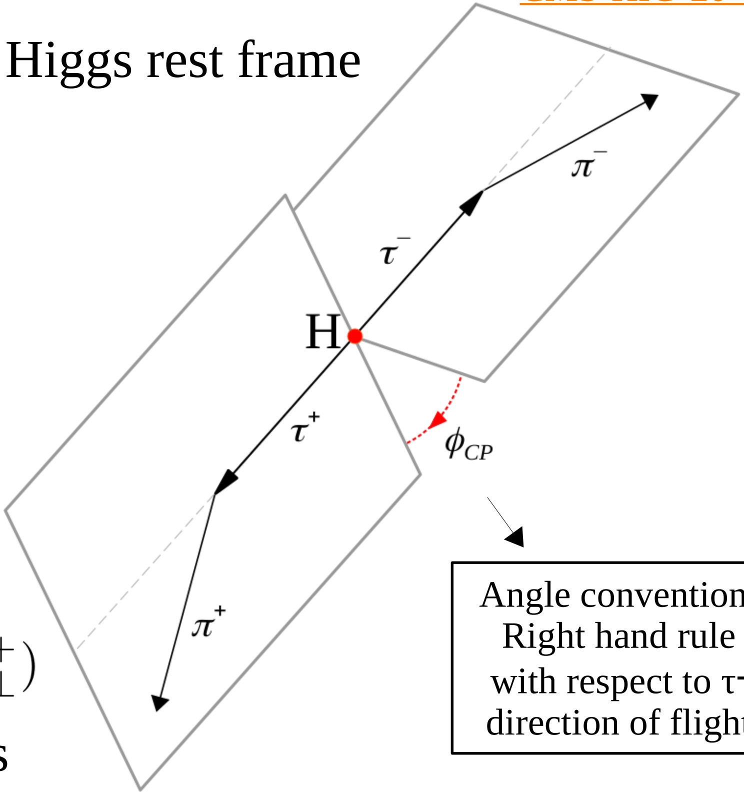
Higgs rest frame



Angle convention:
Right hand rule
with respect to τ⁻
direction of flight

CP measurement in $H \to \tau\tau$

- Transverse spin correlation can be accessed via the angle between the τ decay planes: **the acoplanarity angle, φ_{CP}**
- Spin correlation between τ leptons leads to sinusoidal dependence on φ_{CP} for the $H \to \tau\tau$ cross-section

$$\boxed{\frac{d\sigma}{d\varphi_{CP}} \propto const - \cos(\varphi_{CP} - 2\alpha^{H\tau\tau})}$$

- CP mixing appears as a **phase-shift** in the φ_{CP} distribution
- Acoplanarity angle reconstructed based on available visible decay products

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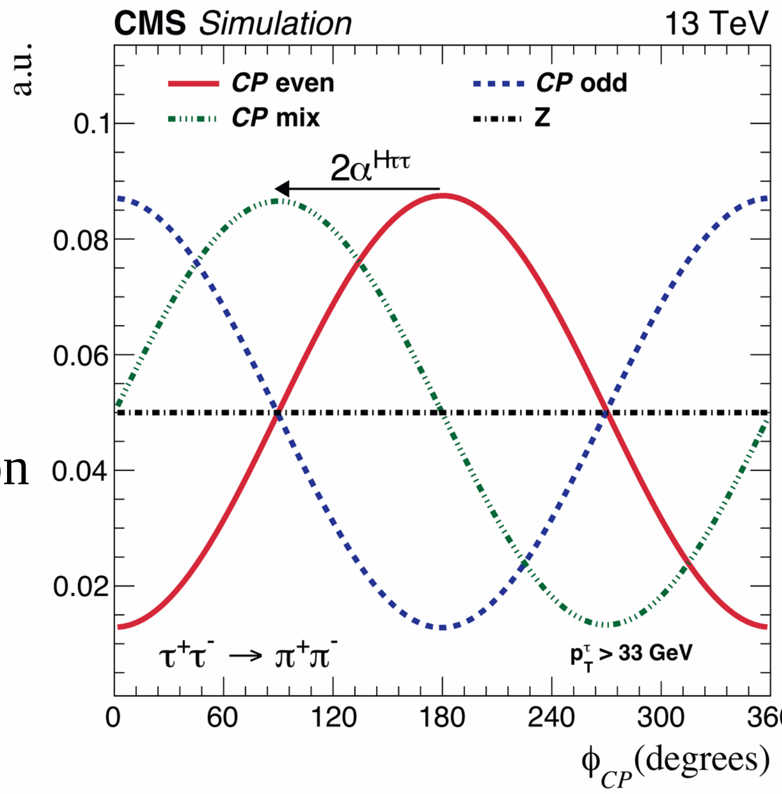

The acoplanarity angle

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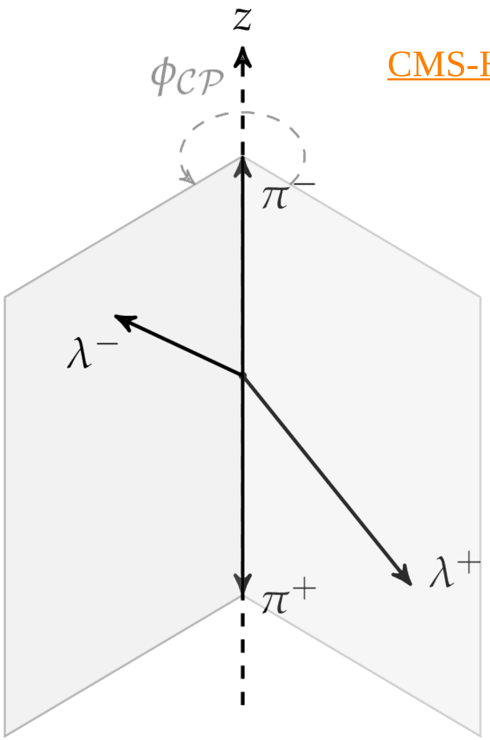
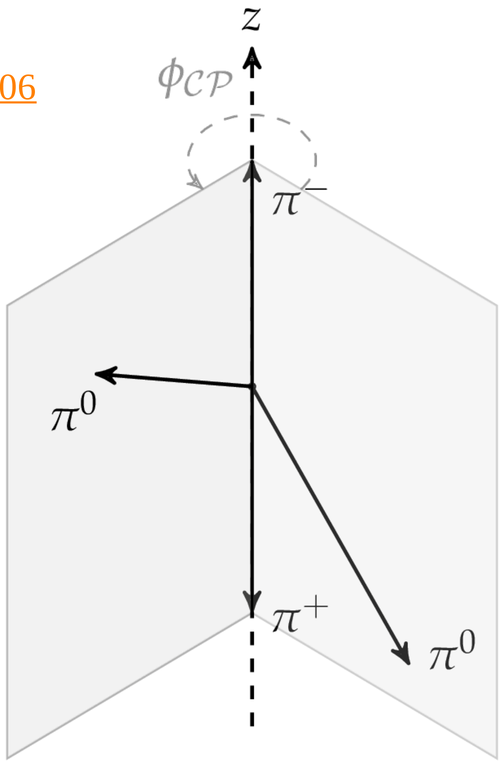
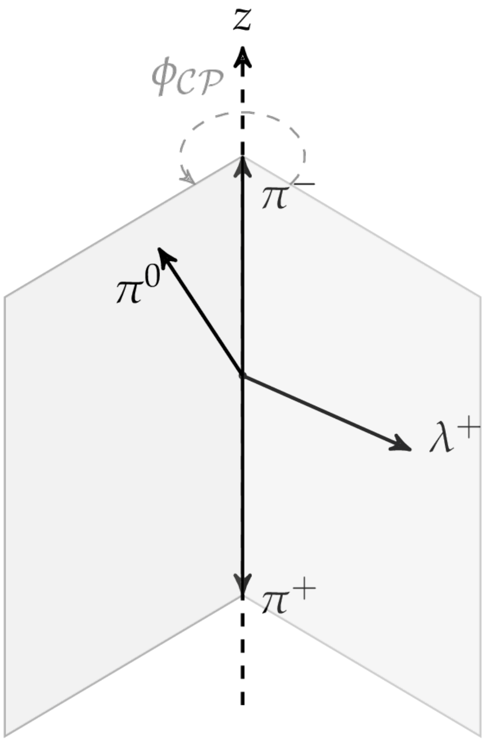


IP method:
2 momenta available
Channels: (π,l) x π



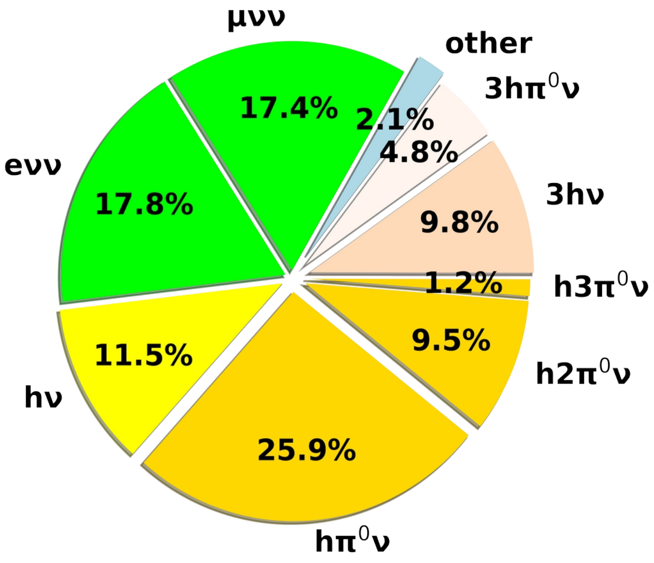
Neutral pion method:
4 momenta available
Channels: (ρ,a_1) x (ρ,a_1)



Mixed method:
Channels: (ρ,a_1) x (π,l)

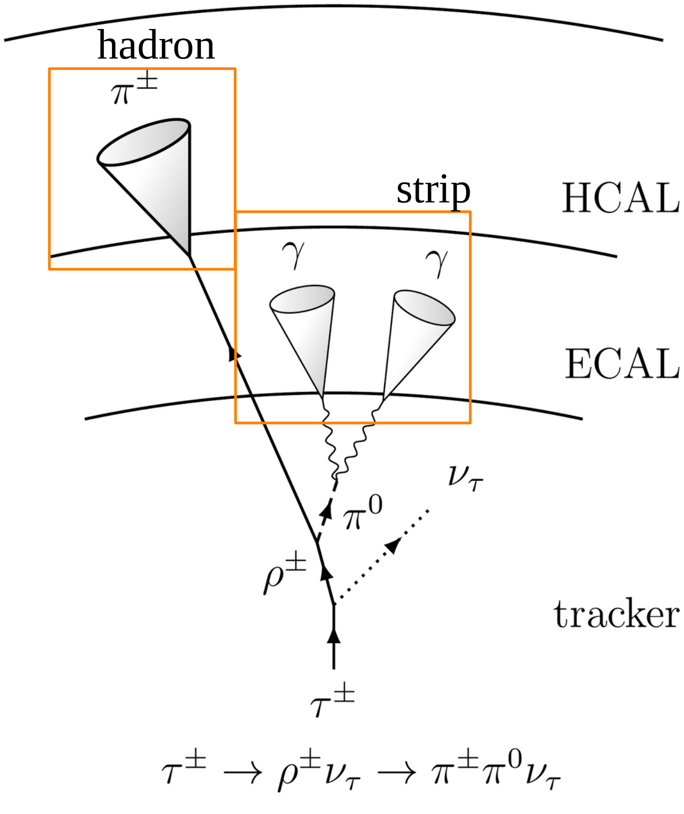
Studied channels

doi:10.3204/PUBDB-2021-03550



- Channels were chosen based on their spin analyzing power
- Their distinction is crucial in this study → requires precise τ identification

$\tau_\mu\tau_h$ channels:	$\tau_h\tau_h$ channels:
1 = $\mu\rho \rightarrow$ mixed method	9 = $\rho\rho \rightarrow$ neutral pion
2 = $\mu\pi \rightarrow$ IP method	10 = $\pi\rho \rightarrow$ mixed method
3 = $\mu a_1^{3pr} \rightarrow$ mixed method	11 = $\rho a_1^{3pr} \rightarrow$ neutral pion
4 = $\mu a_1^{1pr} \rightarrow$ mixed method	12 = $\rho a_1^{1pr} \rightarrow$ neutral pion
$\tau_e\tau_h$ channels:	13 = $\pi\pi \rightarrow$ IP method
5 = $e\rho \rightarrow$ mixed method	14 = $\pi a_1^{3pr} \rightarrow$ mixed method
6 = $e\pi \rightarrow$ IP method	15 = $\pi a_1^{1pr} \rightarrow$ mixed method
7 = $e a_1^{3pr} \rightarrow$ mixed method	16 = $a_1^{3pr} a_1^{3pr} \rightarrow$ neutral pion
8 = $e a_1^{1pr} \rightarrow$ mixed method	17 = $a_1^{3pr} a_1^{1pr} \rightarrow$ neutral pion

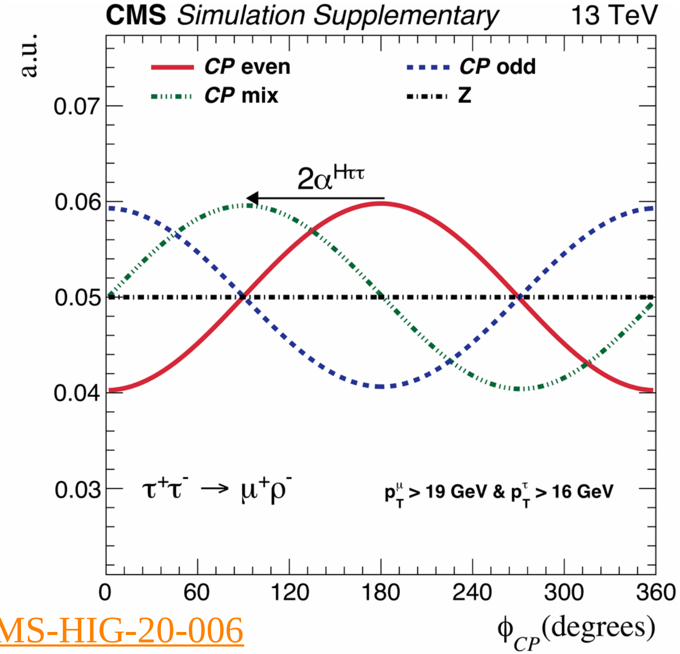


doi:10.3204/PUBDB-2021-03550

- Hadronic tau decays are identified as highly collimated jets (hadrons) + electromagnetic clusters (strips): **Hadron-plus-strip** algorithm
  - Dedicated algorithm to identify tau hadronic decay modes: **MVA-DM:** CMS-DP-2020-041
    - DM identified:
      0) $\tau \to \pi$
      1) $\tau \to \pi + \pi^0$
      2) $\tau \to \pi + 2\pi^0$
      10) $\tau \to 3\pi$
      11) $\tau \to 3\pi + \pi^0$
  - Rejection of jets and leptons mimicking τ_h performed with **DeepTau** neural network-based identification: CMS-DP-19-033

- Background modeling:
  - ~90% of bkg estimated with data-driven methods:
    - Embedded samples for events with two genuine τ leptons
    - "Fake Factor" method for $j \rightarrow \tau_h$ fakes
  - Other processes are estimated from MC
- $H \rightarrow \tau\tau$ process simulated with Powheg+Pythia8 MC generators
- CP correlation between tau decay products encoded with TauSpinner tool: signal template as weighted combination of **CP-even**, **CP-odd** and **Maximal Mixing** cases

$$\frac{d\sigma}{d\varphi_{CP}} = const + (\cos^2(\varphi_{\tau\tau}) - \sin(\varphi_{\tau\tau})\cos(\varphi_{\tau\tau}))\boxed{\frac{d\sigma^{CP-even}}{d\varphi_{CP}}}$$
$$+ (\sin^2(\varphi_{\tau\tau}) - \sin(\varphi_{\tau\tau})\cos(\varphi_{\tau\tau}))\boxed{\frac{d\sigma^{CP-odd}}{d\varphi_{CP}}}$$
$$+ 2\sin(\varphi_{\tau\tau})\cos(\varphi_{\tau\tau})\boxed{\frac{d\sigma^{CP-mix}}{d\varphi_{CP}}}$$



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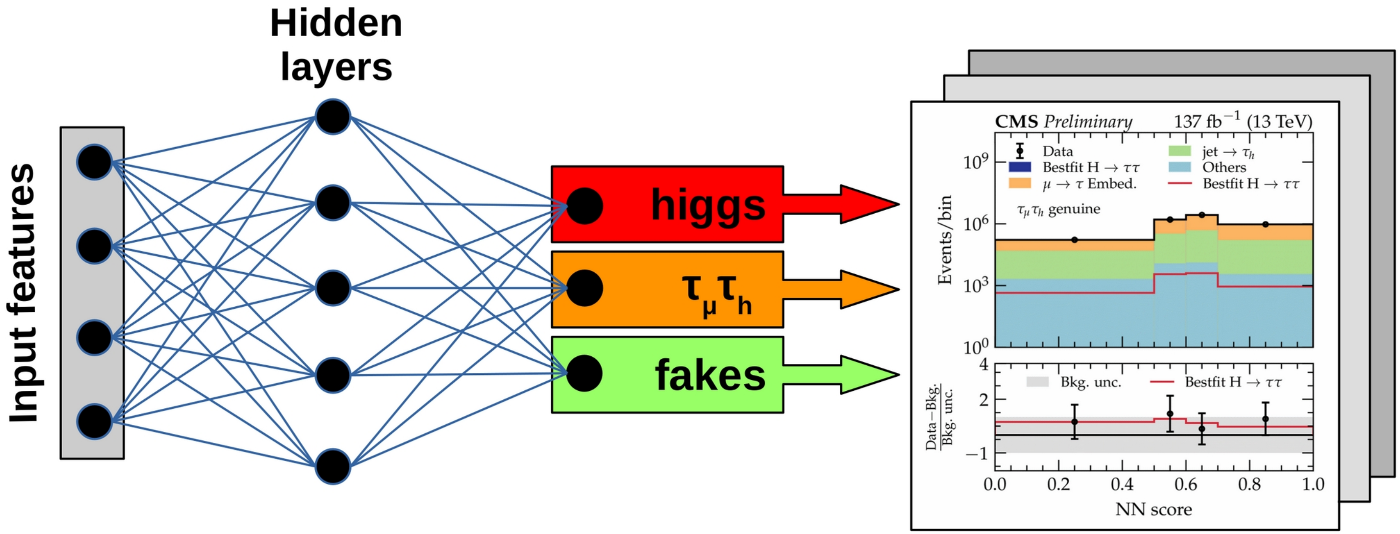
Event categorization

- $\tau_l\tau_h$ channel: fully connected, feed-forward multi-class neural network
- $\tau_h\tau_h$ channel: multi-class BDT with XGBoost algorithm
- 3 output categories for both channels: higgs, taus and fakes



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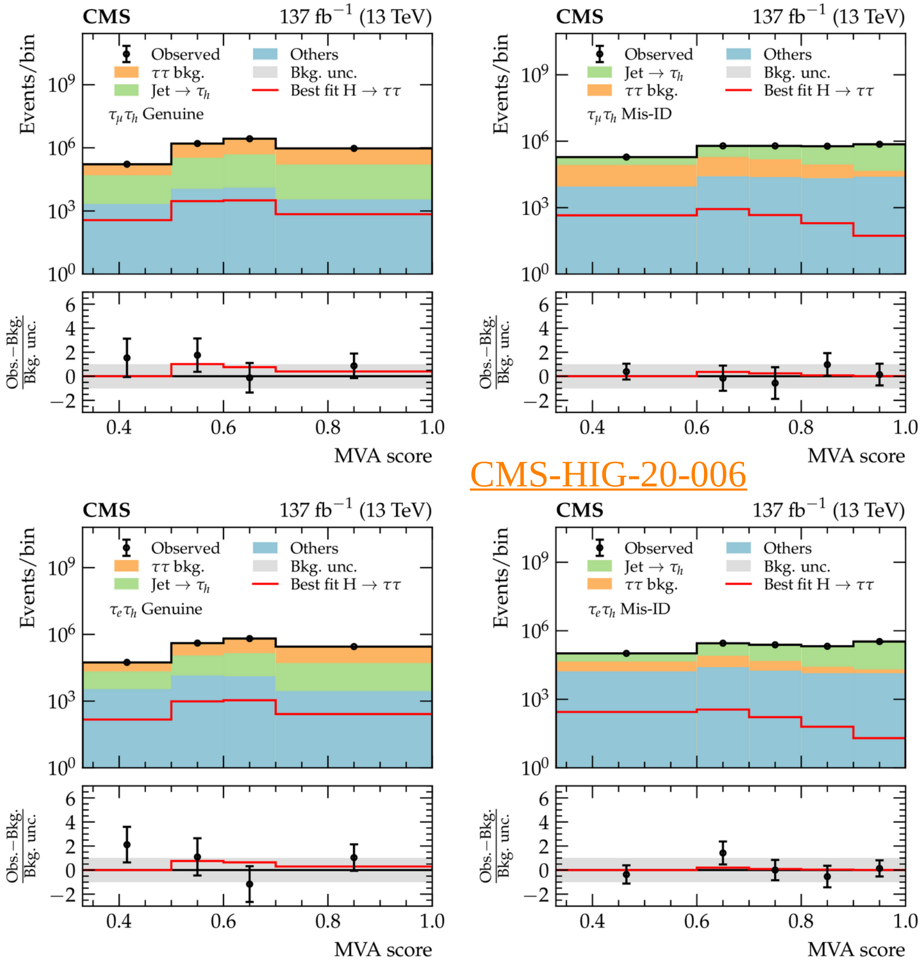
Observable	$\tau_\ell\tau_h$	$\tau_h\tau_h$
p_T of leading τ_h	✓	✓
p_T of trailing τ_h	—	✓
p_T of τ_ℓ	✓	—
p_T of visible di-τ	✓	✓
p_T of di-τ_h + p_T^{miss}	—	✓
p_T of $\tau_\ell\tau_h$ + p_T^{miss}	✓	—
Visible di-τ mass	✓	✓
Di-τ mass (using SVFIT)	✓	✓
Leading jet p_T	✓	✓
Trailing jet p_T	✓	
Jet multiplicity	✓	✓
Dijet invariant mass	✓	✓
Dijet p_T	✓	
Dijet $\lvert\Delta\eta\rvert$	✓	
p_T^{miss}	✓	✓

Measurement in recorded data

- Multicategory fit for the signal extraction:
  - > Bkg categories defined by BDT/NN: MVA score is used in the fit
    - **taus** and **fakes**
  - > Signal category split by decay channel: 17 channels with unrolled distribution of acoplanarity angle in bins of MVA score
- Fit performed on full Run 2 statistics: 137 fb^{-1}



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Most significant categories

ρρ - channel

μρ - channel

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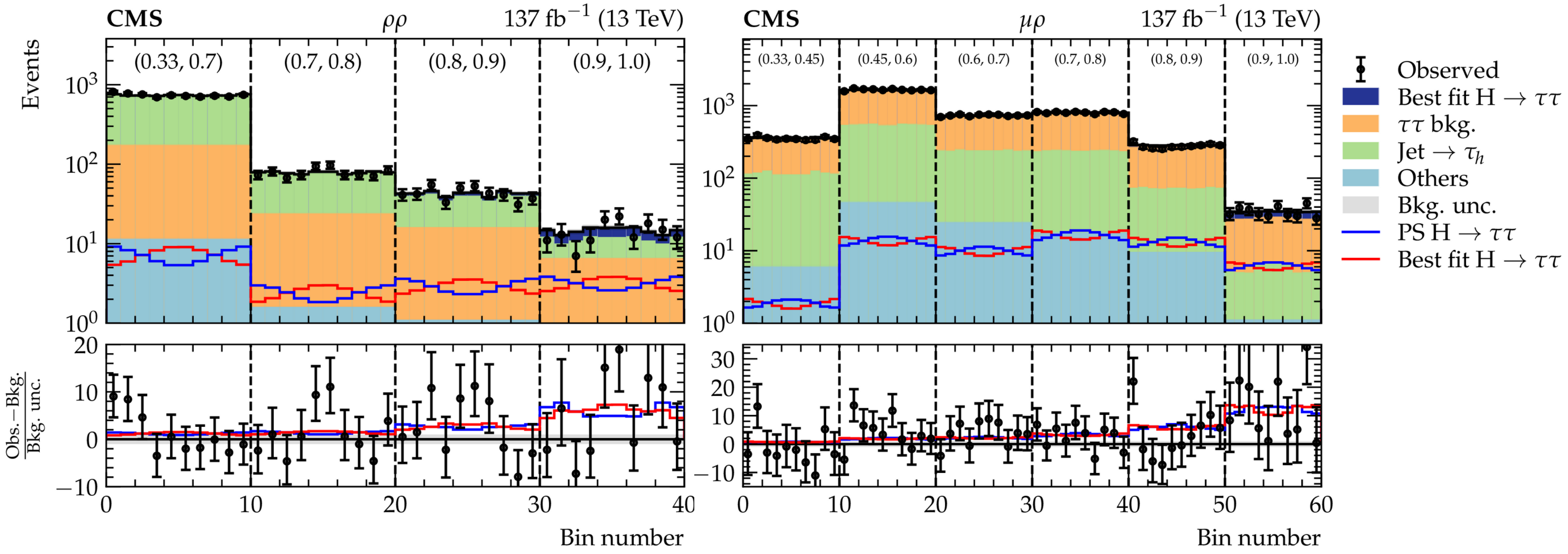
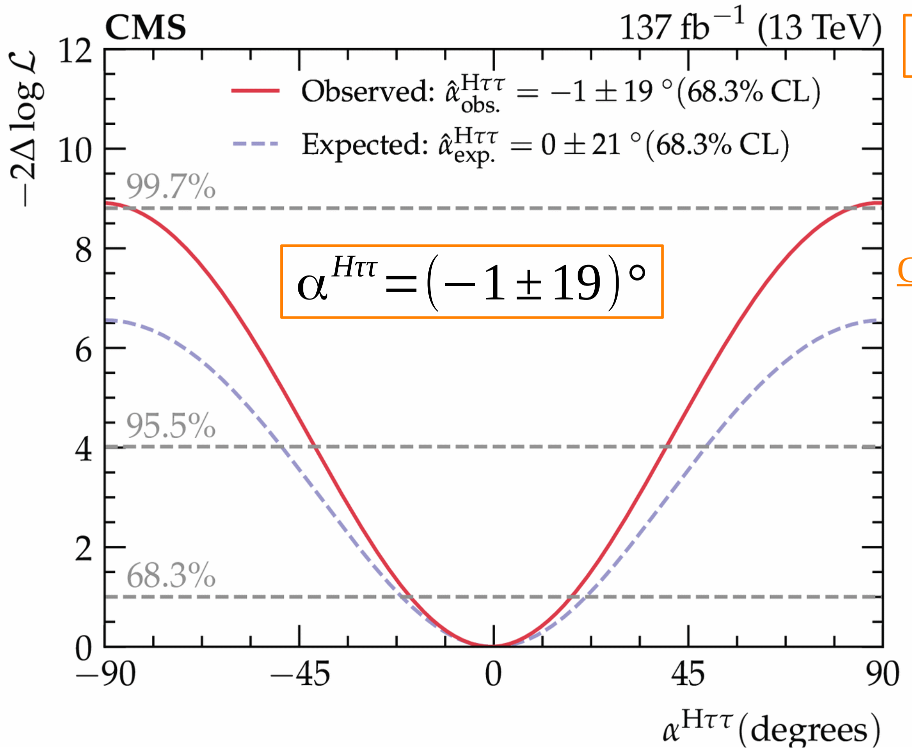


Measured CP mixing angle



$\boxed{\alpha^{H\tau\tau} = (-1 \pm 19)°}$

$\boxed{\alpha^{H\tau\tau} = -1 \pm 19\,(\text{stat}) \pm 1\,(\text{syst}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{theo})°}$

- Comparison between CP-even and CP-odd
  → weighted distribution for the φ_{CP} angle

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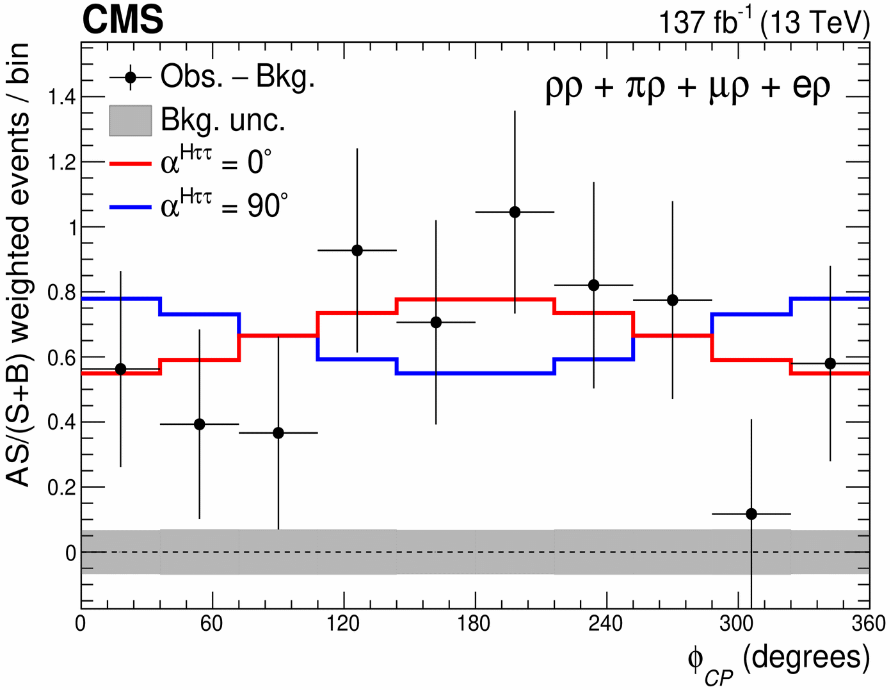

- Exclusion for CP-odd hypothesis:
  - Observed (exp.) significance = **3.0σ** (2.6σ)

- Extraction of $\alpha^{H\tau\tau}$ using 2 parameters to scale the Higgs production signal strength:
  - μ_g for ggH
  - μ_V for VBF and VH
- Dedicated 2D scan performed with inclusiv signal strength and $\alpha^{H\tau\tau}$

$$\boxed{\mu^{\tau\tau} = 0.87 \pm 0.14\ (1.0 \pm 0.16)}$$

All measurements consistent with SM prediction within 68% CL

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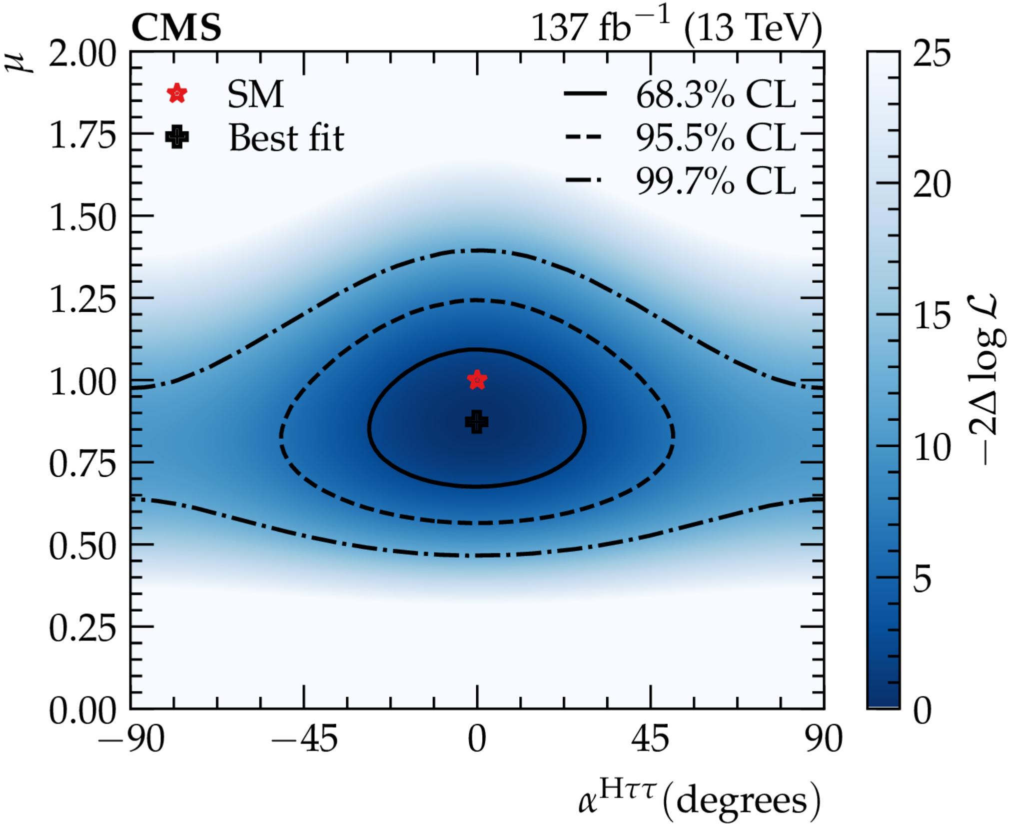
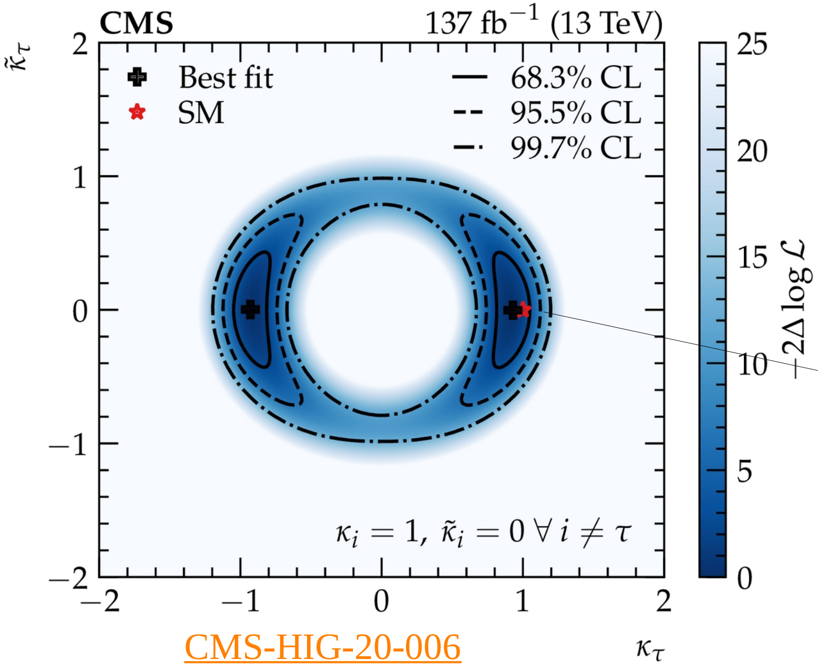


CP-even/odd couplings



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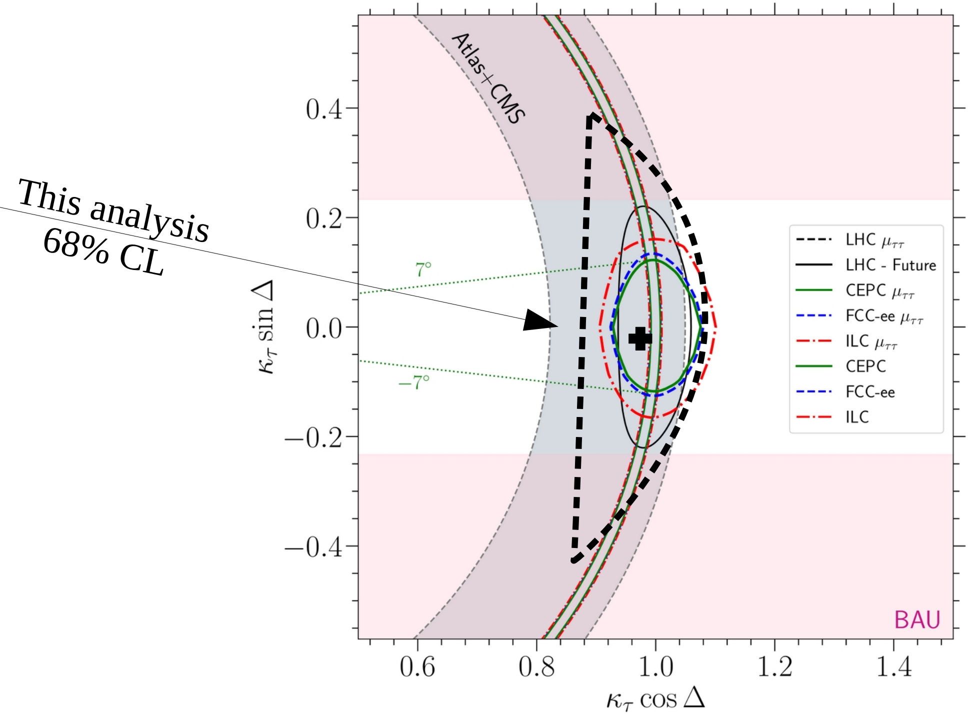
- More statistics is needed in order to probe the available parameter phase space for baryon asymmetry (BAU) in MSSM model

arXiv:2012.13922



- 2D scan performed with CP-even and CP-odd Yukawa couplings

All measurements consistent with SM prediction within 68% CL

- More details in talk from Elina Fuchs yesterday

Conclusions

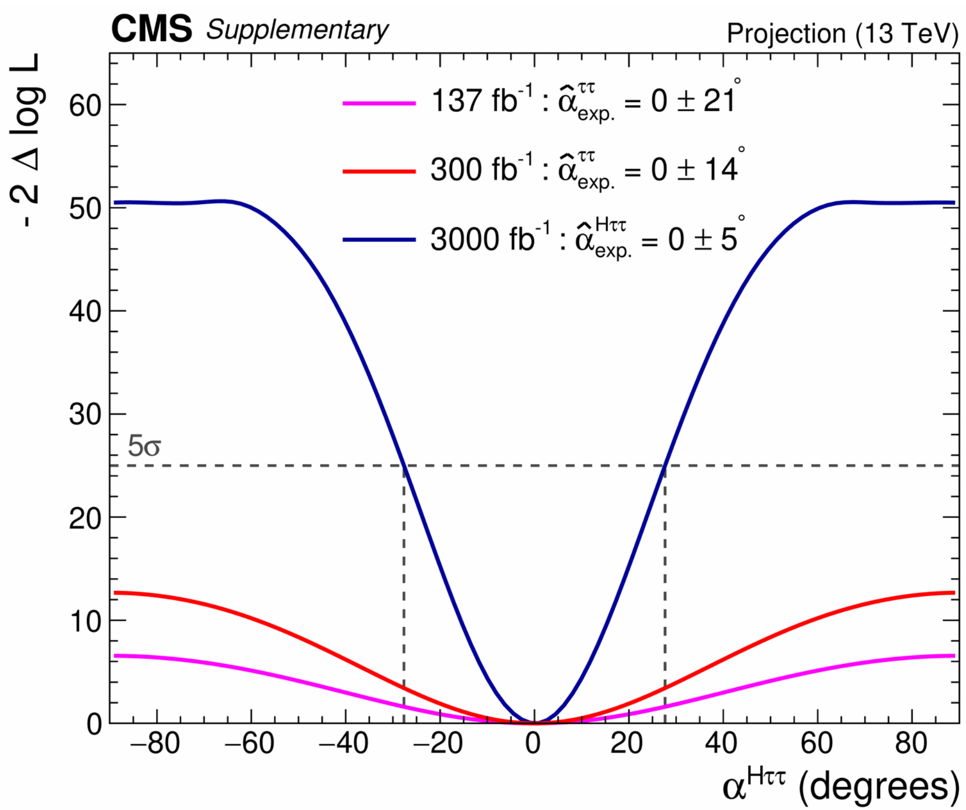
- The measurement of the CP structure of the Yukawa coupling was performed in the $\tau_\mu\tau_h$, $\tau_e\tau_h$ and $\tau_h\tau_h$ channels using the data collected by CMS during Run 2

CMS-HIG-20-006

- CP-odd contribution to Yukawa coupling is constrained at 95% confidence level to be:

$$\left|\frac{\tilde{\kappa}_\tau}{\kappa_\tau}\right| \lesssim 0.84$$

- The Higgs boson appears to be mostly CP-even
- Analysis to be repeated during Run 3 and HL-LHC to better constrain anomalous CP-odd couplings
- Expected sensitivity of the order of 5° at the HL-LHC with 3000 fb^{-1} using same analysis techniques



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Thanks for the attention.

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References

- Andrea Cardini, Measurement of the CP properties of the Higgs boson in its decays to τ leptons with the CMS experiment, PUBDB-2021-03550, DESY-THESIS-2021-015, 10.3204/PUBDB-2021-03550.
- CMS Collaboration, “Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at s = √13 TeV”, CMS-HIG-20-006, arxiv.org/abs/2110.04836.
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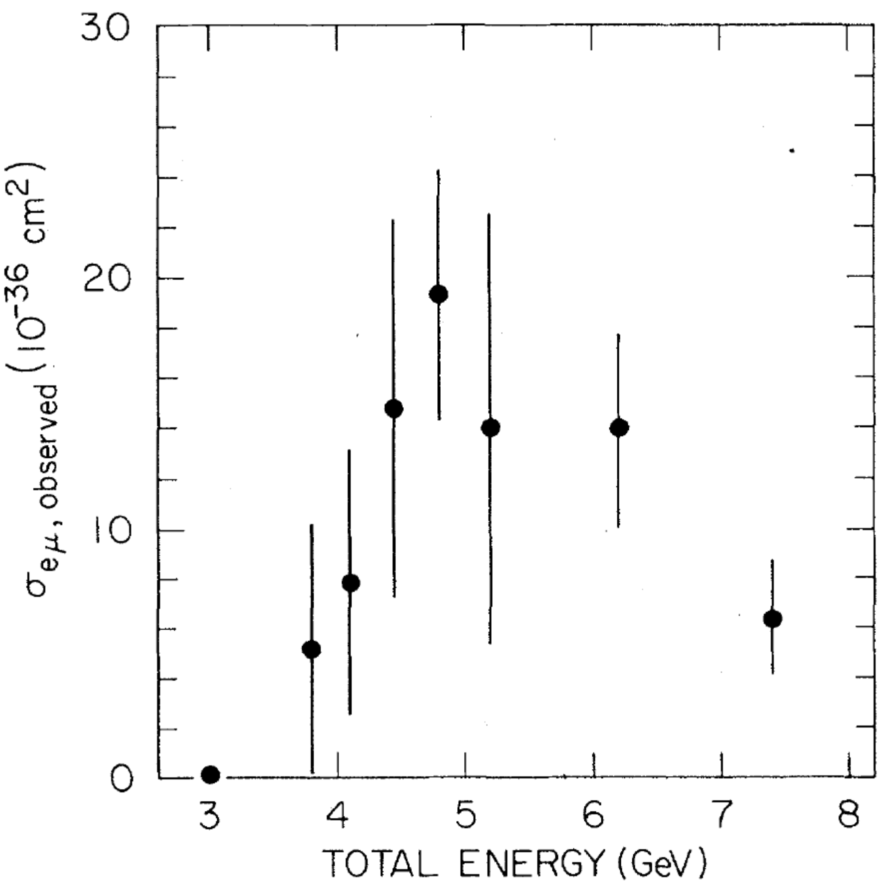
- CMS Collaboration, Identification of hadronic tau decay channels using multivariate analysis (MVA decay mode), CMS-DP-2020-041, cds.cern.ch/record/2727092.
- CMS Collaboration, “Measurement of the properties of a Higgs boson in the four-lepton final state”, doi:10.1103/PhysRevD.89.092007.
- S.-F. Ge, G. Li, P. Pasquini, and M. J. Ramsey-Musolf, CP-violating Higgs Di-tau Decays: Baryogenesis and Higgs Factories, arXiv:2012.13922.

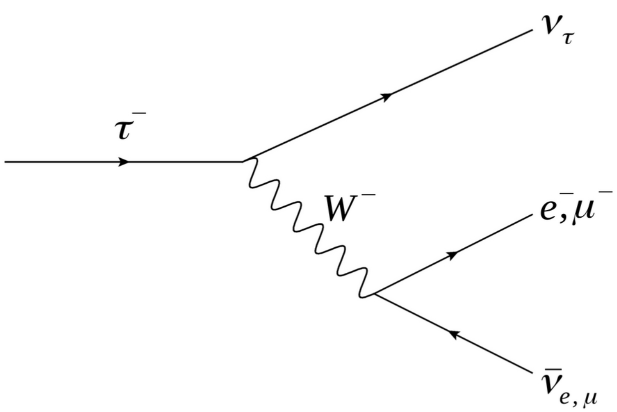
Tau lepton discovery

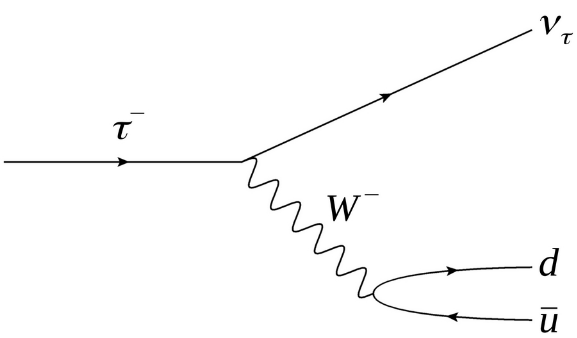


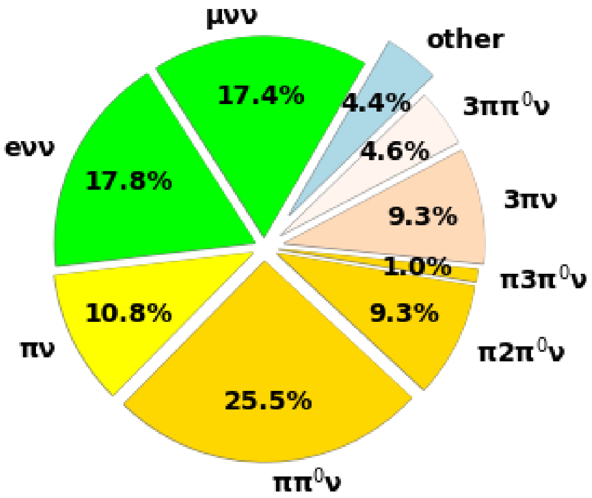
- Tau leptons discovered at SLAC (e+ e- collider) in 1975
- Events identified with:
  - e-μ pair with opposite charge
  - Total energy of e-μ system lower than center of mass energy → other non-reconstructed particles are required to explain the process
  - No decays of then know particles could explain the observed phenomena
  - Hypothesis of existence of heavy leptons

Tau properties

- Mass ~1.78 GeV
- Average lifetime ~3 x 10^{-13} s → decay length of 1.5 mm (E=30 GeV)
- Decays via charged current EW interaction







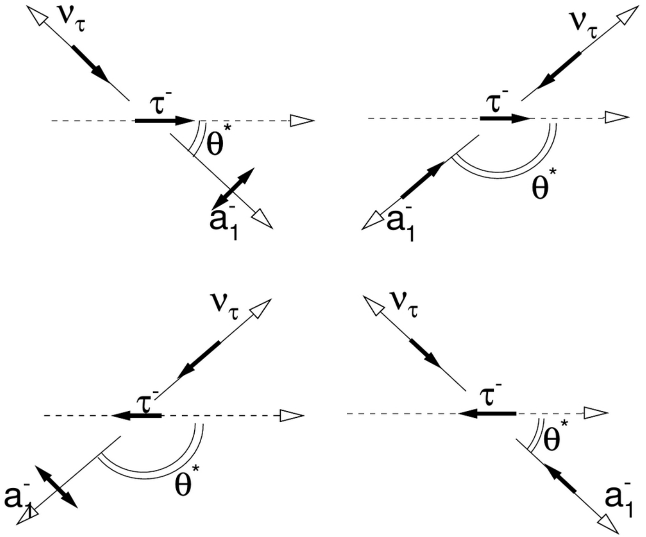
- Tau decays can be parametrized as:
  - Decay to charge particle + neutral system: $\tau \rightarrow a^{\pm} + X$

$$\Gamma\begin{pmatrix}\tau^- \rightarrow a^-(q) + X \\ \tau^+ \rightarrow a^+(q) + \bar{X}\end{pmatrix} = \int_0^1 dx \int \frac{d\Omega}{4\pi} A(x) \pm B(x)(\vec{w} \cdot \hat{q})$$

    - Spin correlation encoded into **charged particle momenta**
  - Decay to charged system + tauonic neutrino: $\tau \rightarrow \nu + X^{\pm}$

$$\mathrm{d}\Gamma_{\tau \rightarrow X+\nu_\tau} = \frac{1}{2m_\tau}|\mathscr{M}|^2(1 + h_\mu s^\mu)\mathrm{d}Lips$$

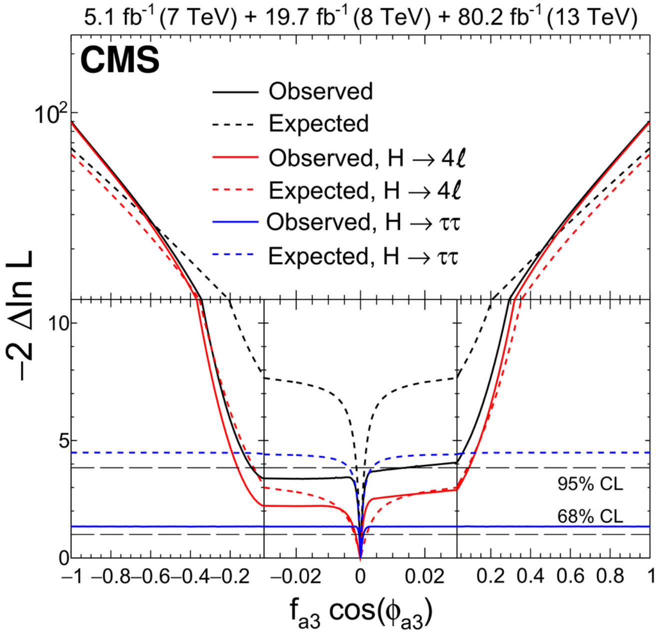
    - Spin correlation encoded into **polarimetric vector**



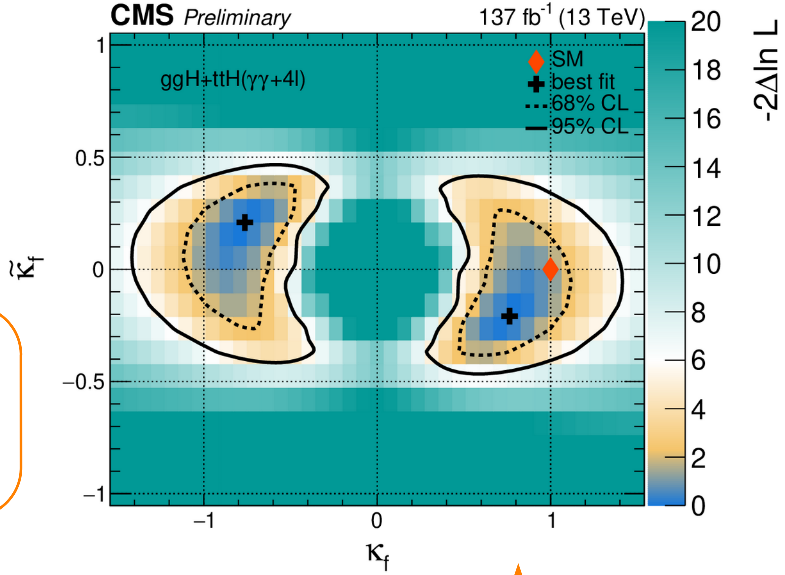
- General feature: the spin correlation is introduced via a scalar product between tau spin/polarization and a vector which depends on the decay products momenta → possibility to coherently define tau decay planes for different decay channels

- Higgs boson predicted to have spin-parity 0^+ → direct coupling to Z and W bosons
- Investigating CP violation in the Higgs sector
  - HVV couplings (V= Z,W bosons)

    studied in 4 lepton final state / VBF production



Pure CP odd excluded
Mixing still possible



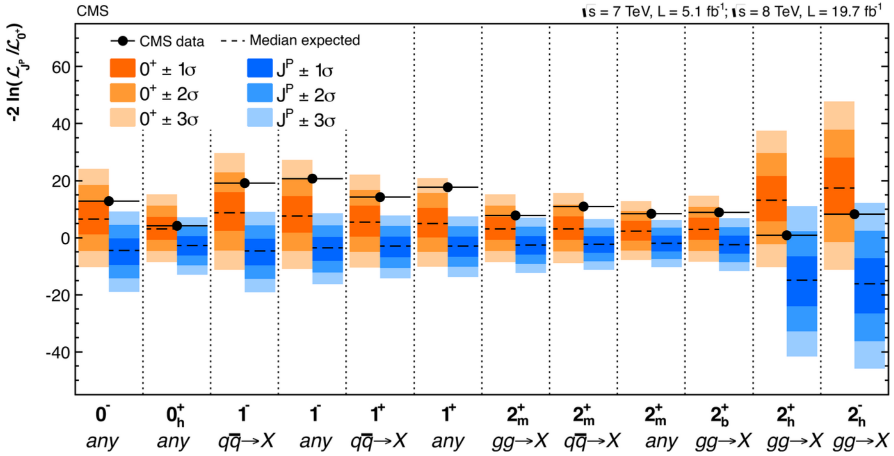
  - Yukawa coupling of Higgs to fermions
    - gg→H +jets (effective coupling to gluons)
    - gg→ttH
    - **H→ττ decays**
      - Spin correlation between tau leptons and their decay products

- Investigating CP violation in HVV with an EFT approach:
  - Additional terms are added to the Lagrangian related to an energy scale

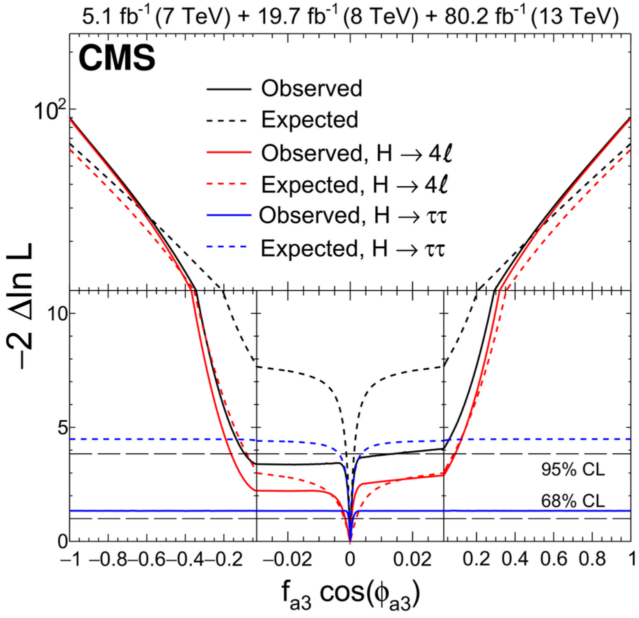
$$\mathscr{A}(HVV) \simeq \left[a_1^{VV} + \frac{k_1^{VV} q_1^2 + k_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} + \frac{k_3^{VV} (q_1+q_2)^2}{(\Lambda_Q^{VV})^2} \right] m_V^2 \varepsilon_{V1}^* \varepsilon_{V2}^*$$

$$+ a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

  - The effect on the cross-section is then parametrized as the fractional contribution of the anomalous coupling to the total cross-section



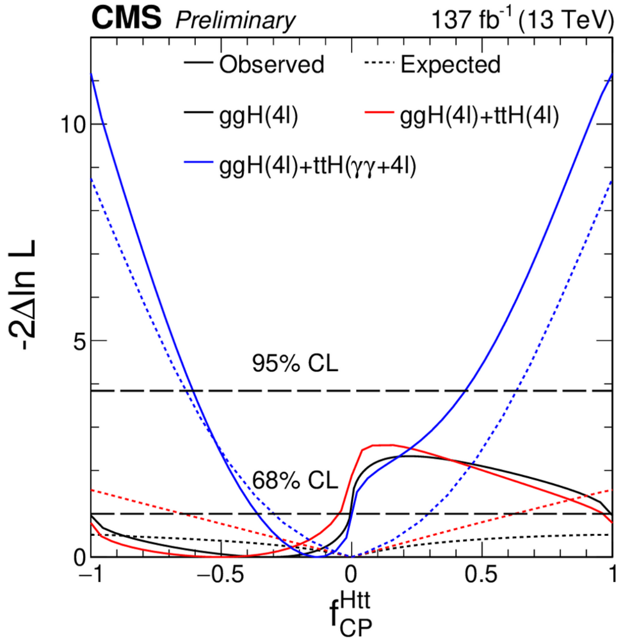
Run 1 study in $H \rightarrow 4l$

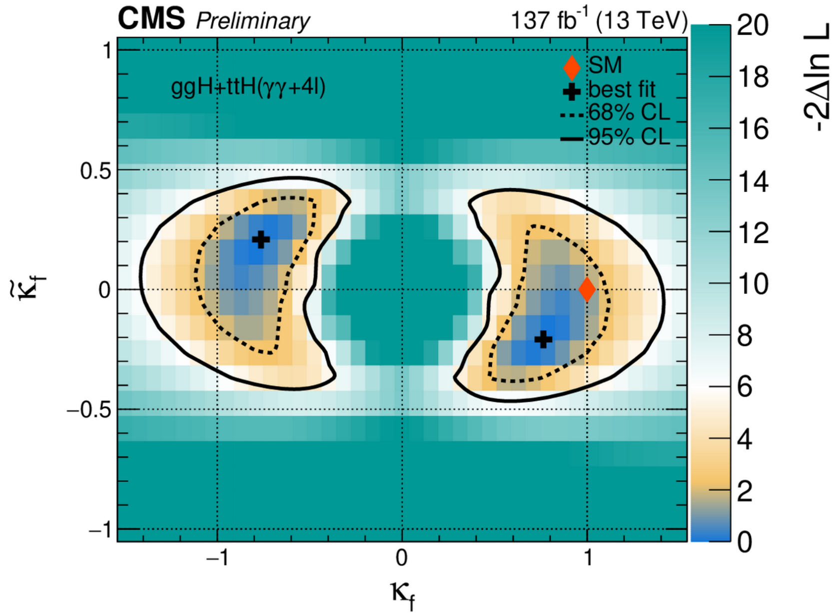


Run 1 + partial Run 2 study in $H \rightarrow 4l$ + VBF $H \rightarrow \tau\tau$

- CP violation in Yukawa coupling:
  - Effective coupling in ggH: studied as HVV coupling
  - Direct coupling to top quarks: studied in top-associated production

$$\mathscr{L}_{Y,f} = -\bar{\psi}_f(y_f + i\gamma^5\tilde{y}_f)H\psi_f$$





  - Combination performed under hypothesis that ggH loop is dominated by top quark

CP structure of Yukawa coupling

- Long history of measurements on HVV couplings in CMS e.g. [HIG-19-009]
- Yukawa coupling can easily be altered to account for a CP-odd component at leading order

$$L_Y = y_f \, h \, \bar{f} \, f + \tilde{y}_f \, h \, \bar{f} \, i \gamma_5 \, f$$

- Couplings to top quarks and τ leptons can be exploited for measuring possible CP-odd couplings
- Analysis strategy:
  - CP violation in production: ggH + 2 jets [HIG-20-007], and ttH [CMS-HIG-19-013]
  - CP structure in decays: H→ττ
    - **Spin correlation** between τ leptons allows to investigate the CP nature of the Higgs

CP mixing in H → ττ decays

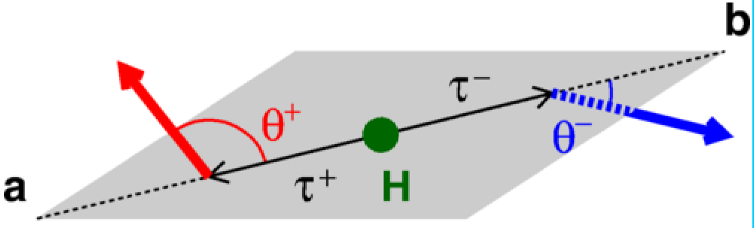
- Higgs Yukawa Lagrangian with CP mixing:
  - $\mathscr{L}_{Y,\tau} = -\frac{m_\tau}{v}\,\bar{\tau}(\kappa_\tau + i\gamma^5\tilde{\kappa}_\tau)H\tau$
- The Higgs decay width to τ leptons can be modified to account for CP mixing:
  - $\Gamma(H_{mix} \to \tau\tau) = \Gamma^{unpol}(1 - s^-_{/\!/} s^+_{/\!/} + s^-_\perp R(\varphi_{\tau\tau}) s^+_\perp)$
  - $R(\varphi_{\tau\tau}) = \begin{bmatrix} R_{11} & R_{12} & 0 \\ R_{21} & R_{22} & 0 \\ 0 & 0 & -1 \end{bmatrix}$ with $R_{11} = R_{22} = \frac{\cos^2(\varphi_{\tau\tau})\beta - \sin^2(\varphi_{\tau\tau})}{\cos^2(\varphi_{\tau\tau})\beta + \sin^2(\varphi_{\tau\tau})}$, $R_{12} = -R_{21} = \frac{2\sin(\varphi_{\tau\tau})\cos(\varphi_{\tau\tau})\beta}{\cos^2(\varphi_{\tau\tau})\beta + \sin^2(\varphi_{\tau\tau})}$
  - The decay width is written in the Higgs rest frame → the tau momenta can be assumed to be directed along the z axis → their transversal polarizations have non-zero x and y components only

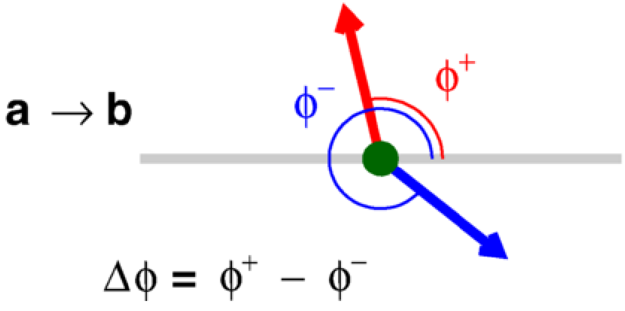
Spin correlation in τ decays

- Tau decays can be parametrized as:
  - Decay to charged system + tauonic neutrino: $\tau \to \nu + X^{\pm}$

$$d\Gamma_{\tau\to X+\nu_\tau} = \frac{1}{2m_\tau}|\mathscr{M}|^2(1+h_\mu s^\mu)dLips$$

  - Spin correlation encoded into **polarimetric vector**





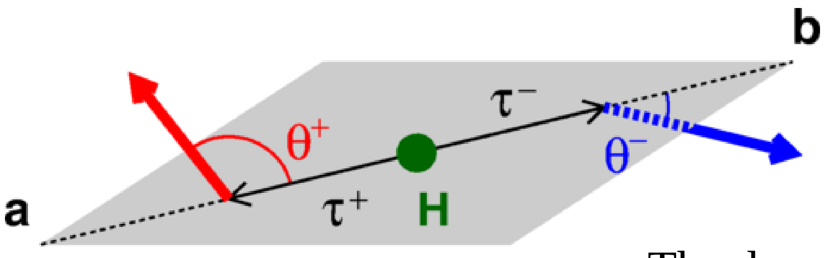
doi:10.1103/PhysRevD.98.013007

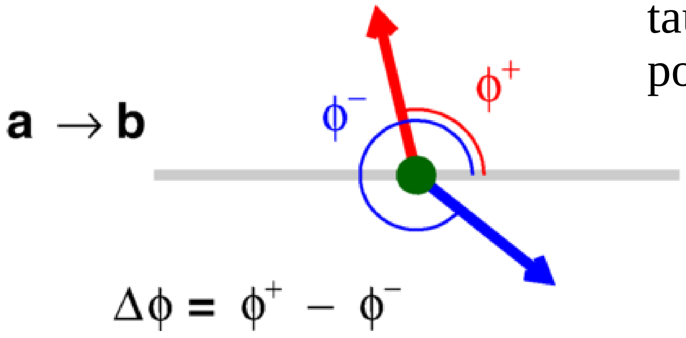
- The $H\to\tau\tau$ cross section has a sinusoidal dependence on the **azymuthal angle** spanned by the polarimetric vectors
  - $d\sigma_{H\to\tau\tau}/d\cos(\theta^+)\,d\cos(\theta^-)\,d\cos(\phi^+)\,d\cos(\phi^-) \propto$

$$\left(1+\cos(\theta^+)\cos(\theta^-) - \sin(\theta^+)\sin(\theta^-)\cos\left(\phi^+ - \phi^- - 2\varphi_{\tau\tau}\right)\right)$$

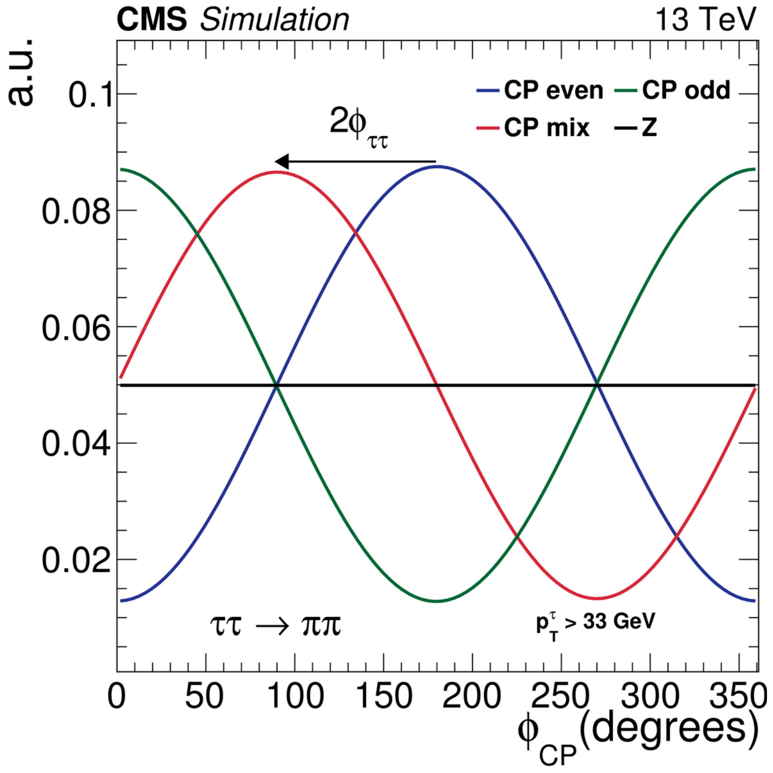
Spin correlation between tau decay planes

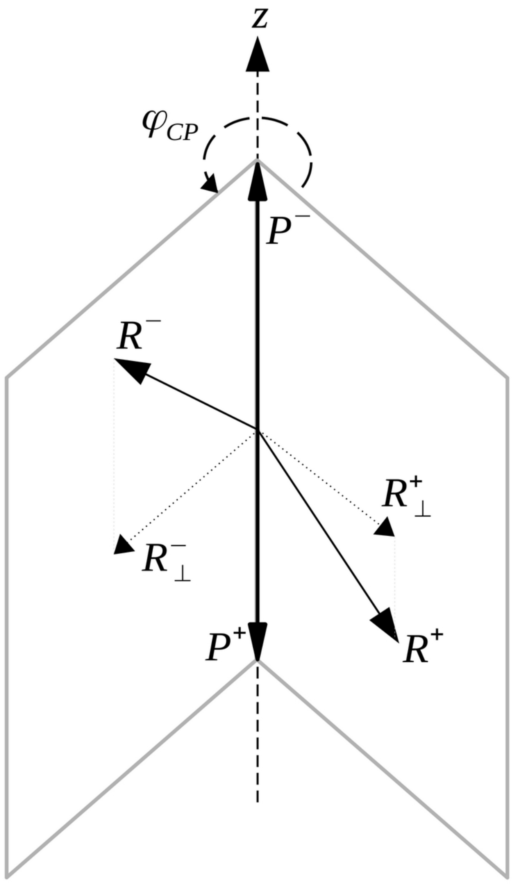
- $$\mathrm{d}\sigma_{H\to\tau\tau}/\mathrm{d}\cos\left(\theta^{+}\right)\,\mathrm{d}\cos\left(\theta^{-}\right)\,\mathrm{d}\cos\left(\phi^{+}\right)\,\mathrm{d}\cos\left(\phi^{-}\right)\propto$$
$$\left(1+\cos\left(\theta^{+}\right)\cos\left(\theta^{-}\right)-\sin\left(\theta^{+}\right)\sin\left(\theta^{-}\right)\cos\left(\phi^{+}-\phi^{-}-2\varphi_{\tau\tau}\right)\right)$$





The decay plane can be defined using the tau momenta and its polarimetric vector





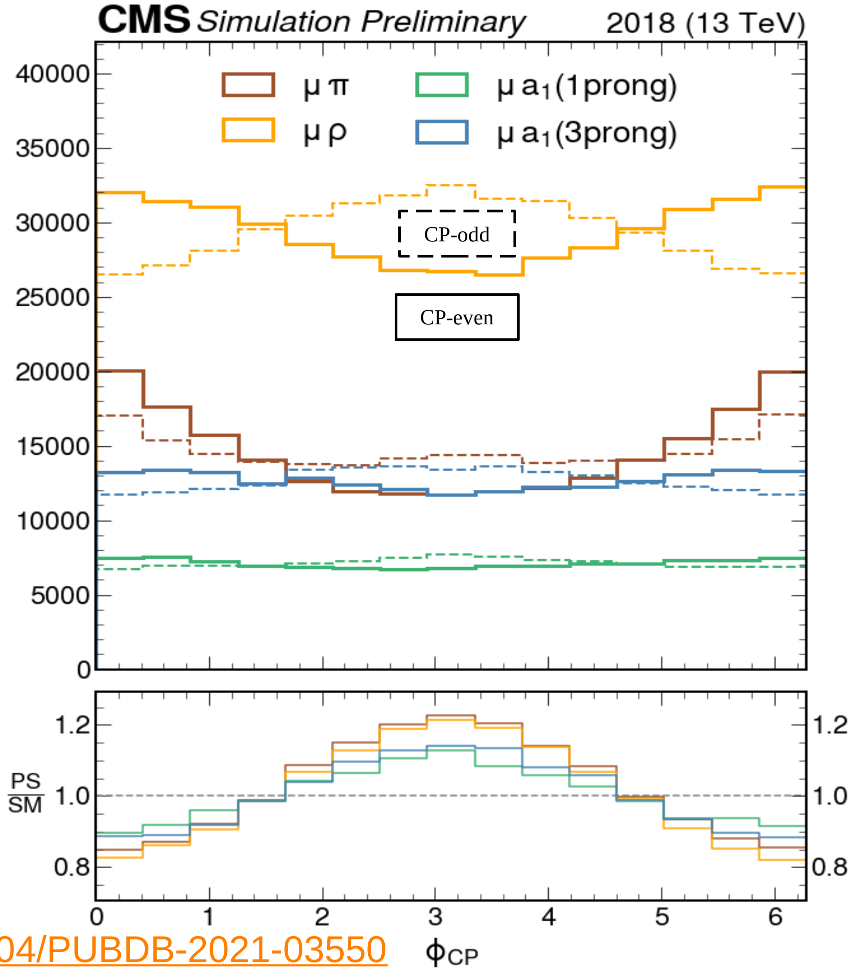
doi:10.3204/PUBDB-2021-03550

- Acoplanarity angle in the Higgs rest frame:
  - $\varphi^* = \arccos\left(\frac{\vec{h}^- \times \vec{p}_\tau^{\,-}}{\left|\vec{h}^- \times \vec{p}_\tau^{\,-}\right|} \cdot \frac{\vec{h}^+ \times \vec{p}_\tau^{\,+}}{\left|\vec{h}^+ \times \vec{p}_\tau^{\,+}\right|}\right)$
  - It is defined using the tau momentum and polarimetric vector
- Requirements for defining the decay plane:
  - Frame of reference where an axis lays on both decay planes → zero momentum frame for a pair of momenta
    - Momentum of a charged decay product can be used both in **defining the plane and for defining the frame of reference**
  - The pair of vectors have vector product ~ parallel to $(\vec{h} \times \vec{p}_\tau)$
    - IP of charged particle satisfies this property → estimates tau direction of flight and is // to charged particle momentum
    - Momenta of decay products of intermediate mesonic resonance

Acoplanarity angle reconstruction

- τ_h signatures considered:
  - > π, ρ, $a_1^{(1Pr.)}$, $a_1^{(3Pr.)}$
- One momentum per plane → Impact parameter (IP)
- 2 or 3 momenta → plane defined by particle momenta

	Vectors			
Channel	P1	R1	P2	R2
$\tau_{\mu,\pi} \times \tau_{\mu,\pi}$	$\vec{p}_{\mu,\pi}$	$\overrightarrow{IP}_{\mu,\pi}$	$\vec{p}_{\mu,\pi}$	$\overrightarrow{IP}_{\mu,\pi}$
$\tau_{\mu,\pi} \times \tau_{\rho,a_1^{1Pr}}$	$\vec{p}_{\mu,\pi}$	$\overrightarrow{IP}_{\mu,\pi}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^0}$
$\tau_{\mu,\pi} \times \tau^{\pm}_{a_1^{3Pr}}$	$\vec{p}_{\mu,\pi}$	$\overrightarrow{IP}_{\mu,\pi}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^\mp}$
$\tau_{\rho,a_1^{1Pr}} \times \tau^{\pm}_{a_1^{3Pr}}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^0}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^\mp}$
$\tau_{a_1^{3Pr}} \times \tau^{\pm}_{a_1^{3Pr}}$	$\vec{p}_{\tau}$	$\vec{h}$	$\vec{p}_{\tau}$	$\vec{h}$



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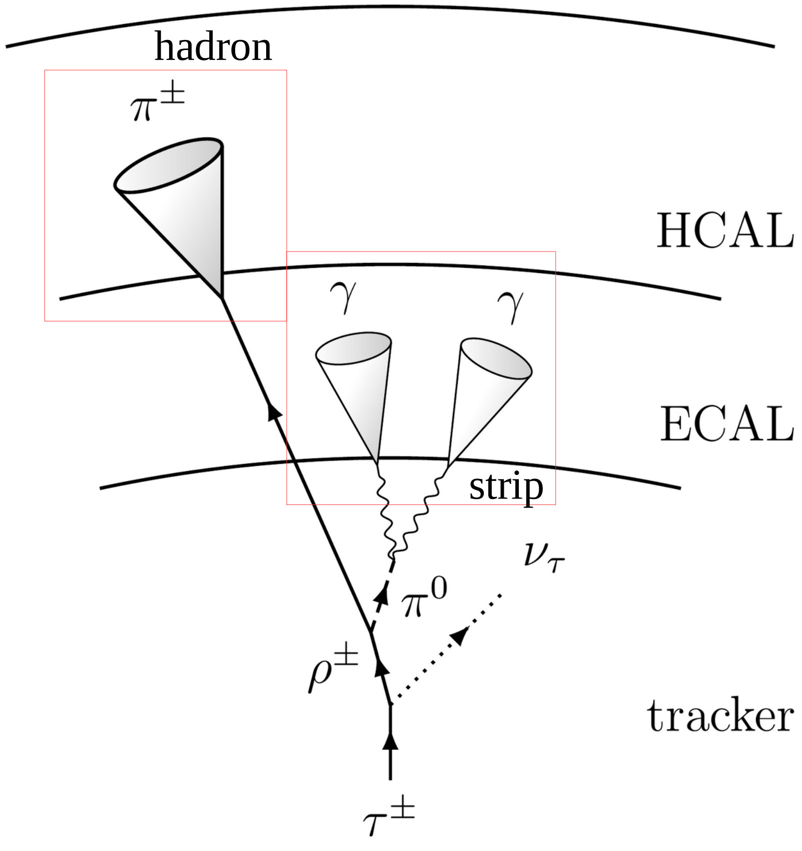
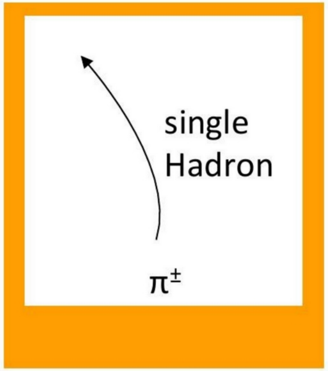
Treatment of mesonic resonances

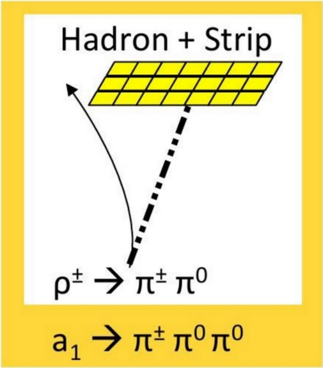
- 1 prong decays:
  - > $\tau \rightarrow \rho + \nu_\tau \rightarrow \pi + \pi^0 + \nu_\tau$
    - Tau polarimeter is defined as a combination of pion and neutrino momenta
      - $\vec{h} = \mathcal{N}(2(q \cdot N)\vec{q} - q^2\vec{N})$
    - In τ rest frame polarimetric vector coplanar to pion momenta and τ direction of flight orthogonal to decay plane → use pion momenta to define acoplanarity angle
      - $\frac{\vec{p}_{\pi^\pm} \times \vec{p}_{\pi^0}}{|\vec{p}_{\pi^\pm} \times \vec{p}_{\pi^0}|} \times \mathrm{sign}(E_{\pi^\pm} - E_{\pi^0}) \simeq \frac{\vec{h} \times \vec{p}_\tau}{|\vec{h} \times \vec{p}_\tau|}$
  - > $\tau \rightarrow a_1 + \nu_\tau \rightarrow \rho + \pi^0 + \nu_\tau \rightarrow \pi + 2\pi^0 + \nu_\tau$
    - Resolution of single π^0 direction of flight difficult experimentally → revert to method used for ρ resonance merging the π^0 momenta
- 3 prong decay:
  - > $\tau \rightarrow a_1 + \nu_\tau \rightarrow \rho + \pi + \nu_\tau \rightarrow 3\,\pi + \nu_\tau$
    - Use momenta of pions coming from intermediate ρ resonance, or the polarimetric vectors

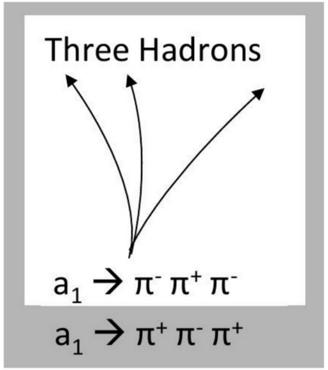


$$\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau$$

- All objects in CMS are reconstructed via the Particle Flow (PF) algorithm $\rightarrow$ PFCandidates
- The Hadron-plus-strip (HPS) algorithm combines:
  - PFCandidates for jets $\rightarrow$ hadronic jets
  - Electrons+photon clusters in ECAL which are elongated in φ $\rightarrow$ strips
- 3 reconstructed decay channels in older version $\rightarrow$ now 4 decay modes are identified



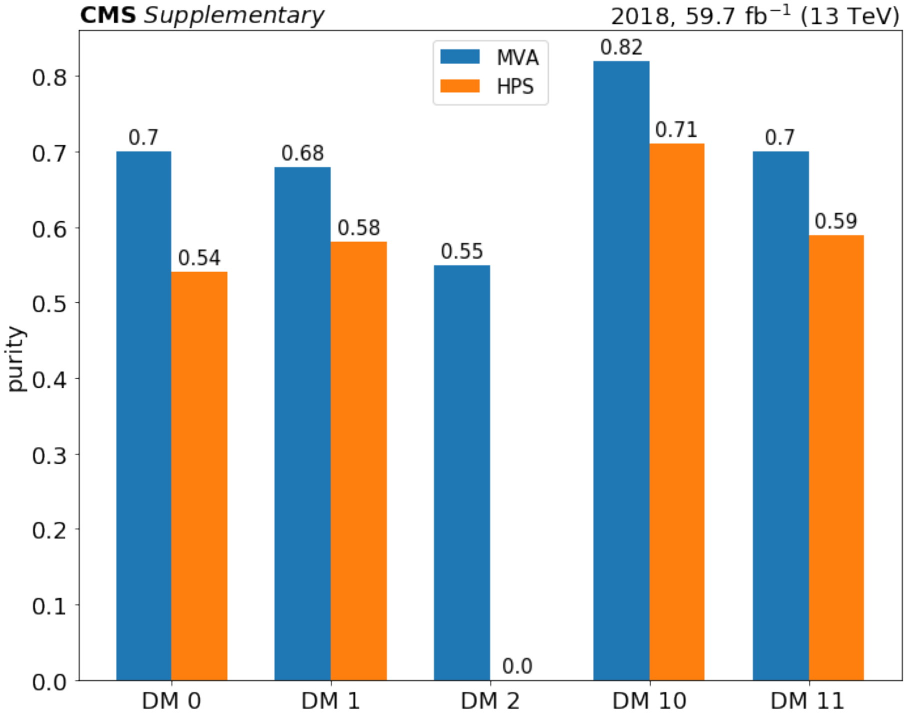




Decay mode identification

- φ_{CP} reconstruction depends heavily on DM identification
- In CMSSW τ hadronic DMs are identified with the Hadron-plu-strip (HPS) algorithm
- Here we use a BDT based decay mode, which adds one possible decay channel: the 1 prong + 2 π^0

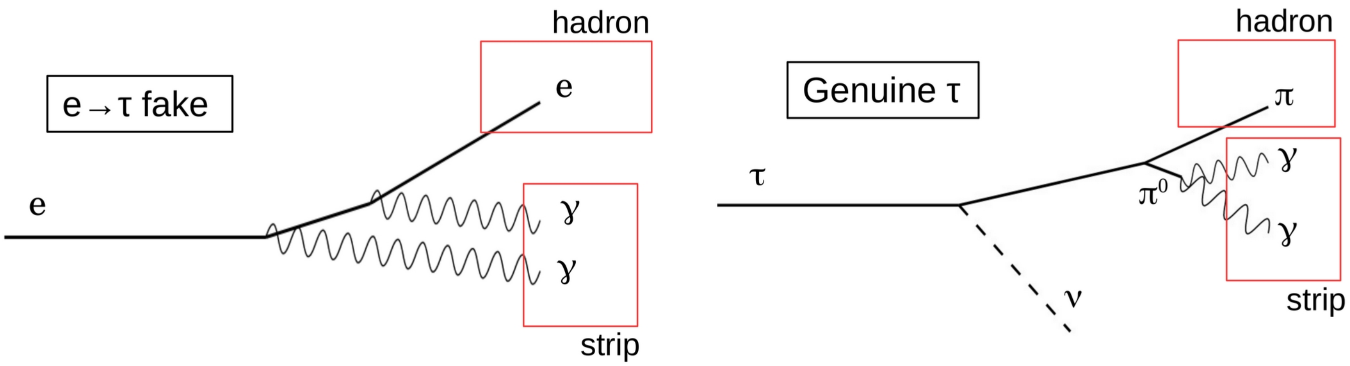
	π	ρ	a_1^{1pr}	a_1^{3pr}	$\pi^\pm\pi^\mp\pi^\pm\pi^0$
Purity	70%	68%	55%	82%	71%
Efficiency	83%	79%	39%	87%	65%



- It improves τ DM identification w.r.t. the HPS algorithm
- Increase in sensitivity of ~20%

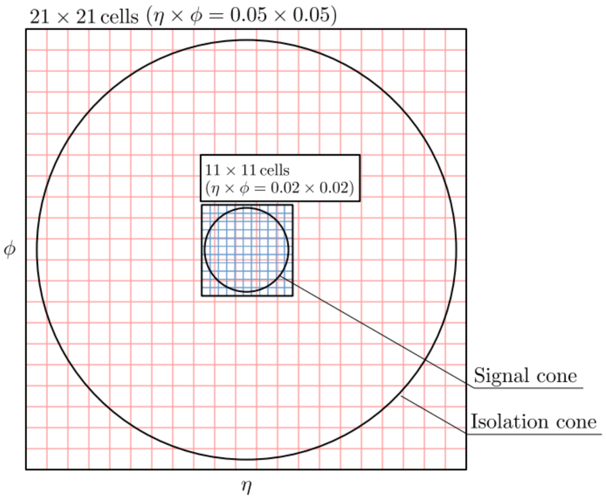
Tau identification in CMS

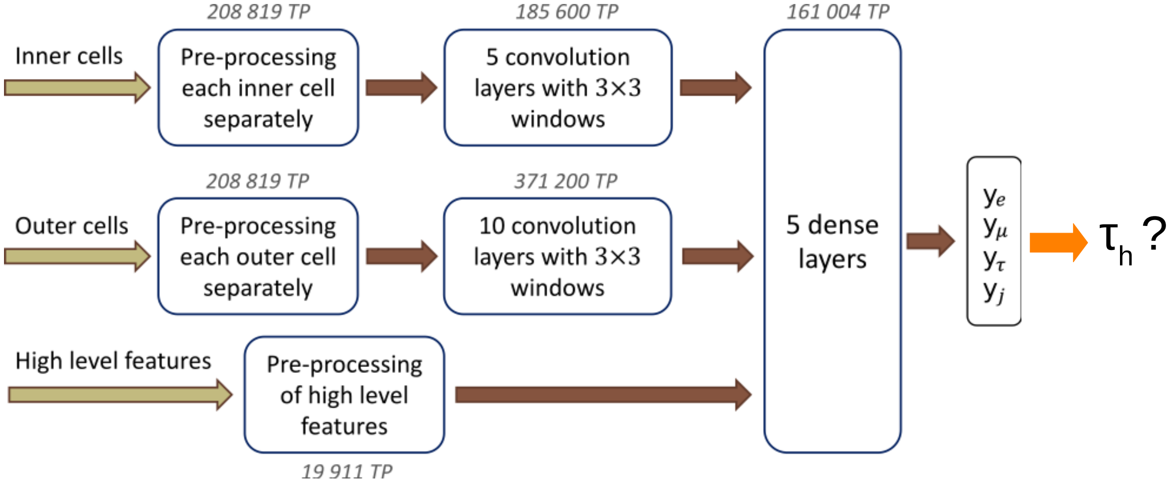
- Several objects can be misidentified as hadronic taus by the HPS algorithm:
  - Jets → a highly collimated quark or gluon jet can be mistaken for any tau decay
  - Muons → mainly affects the 1 prong channel
  - Electrons → can emit photons via bremsstrahlung radiation and mimic the ρ decay



- Rejection of jets and leptons mimicking τ_h performed with **DeepTau** NN-based identification

DeepTau Identification





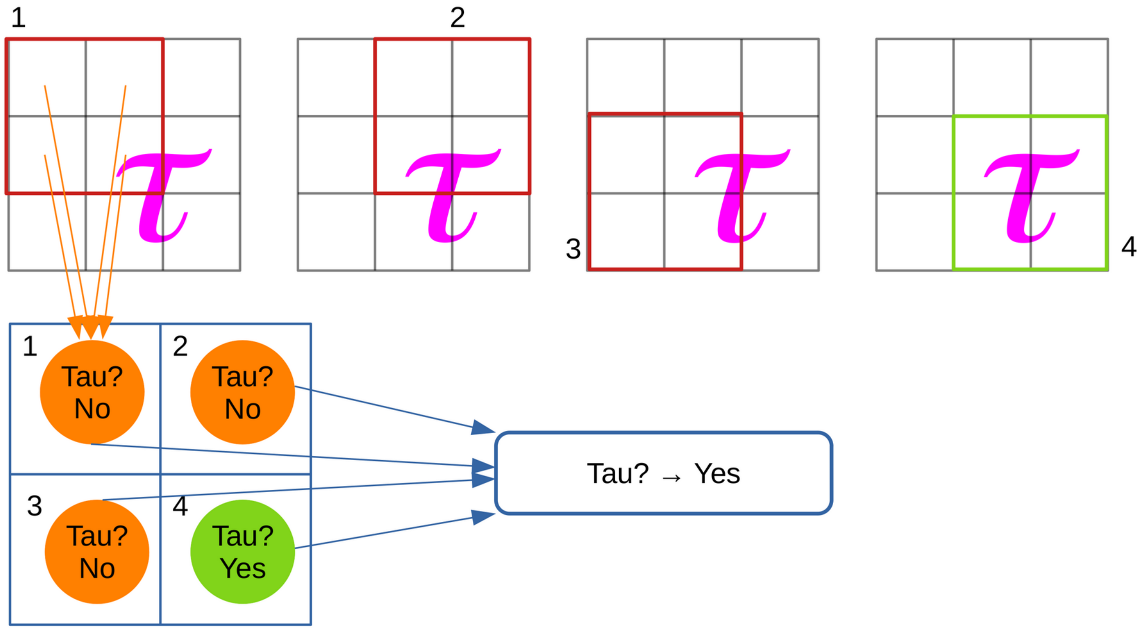
Inputs:

- Low-level
  - Tracks and energy deposits of PFCandidates
- High-level
  - Transverse momenta, decay mode, etc. of tau candidate + general event properties

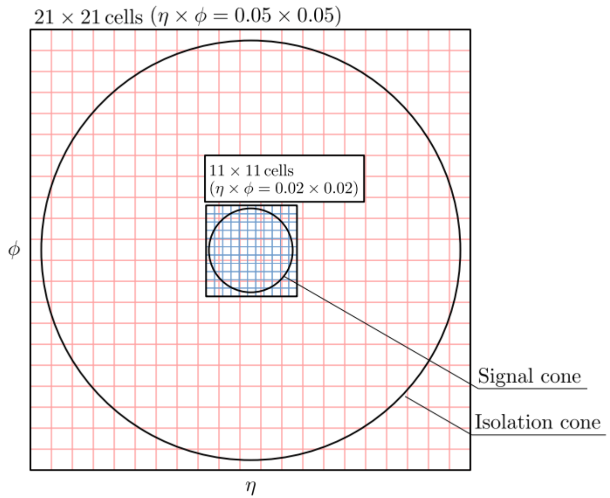
4 outputs → 3 classifiers used to reduce the miss-ID rate

$$P_{\tau\, vs\, obj.} = \frac{P_\tau}{P_\tau + P_{obj.}}$$

Convolutional NN

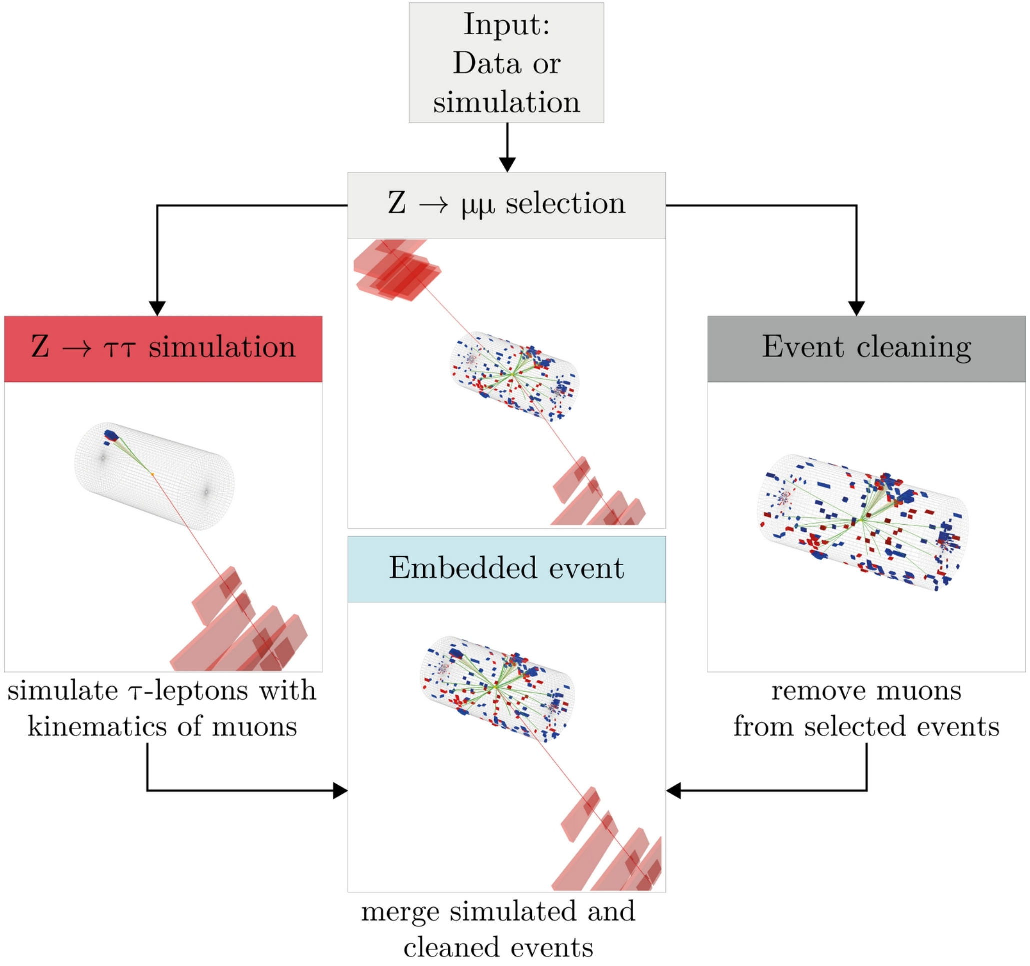


- Inputs features are collected within a grid and processed regardless of where they appear
- Only relative distance and angular correlation of the inputs count towards the classification



- In DeepTau two grids are used:
  - Signal cone: window size 0.02 x 0.02
  - Isolation cone: window size 0.05 x 0.05

Data-driven bkg estimation: embedding

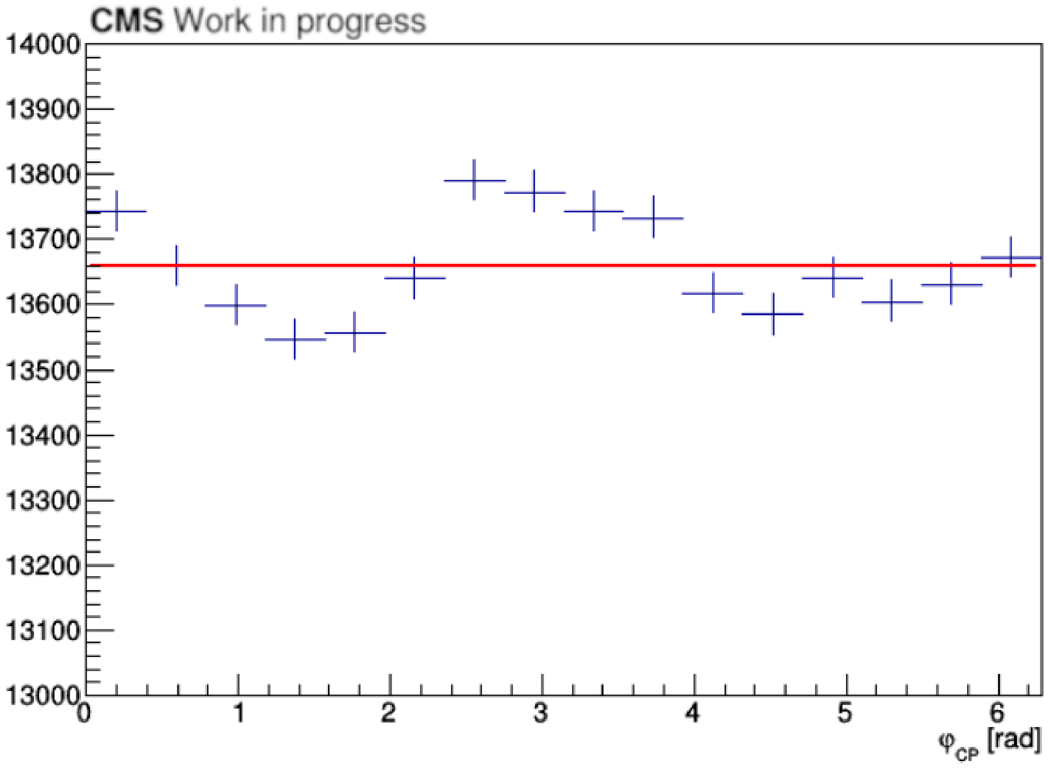


- Used to estimate $Z/\gamma^* \rightarrow \tau\tau$, and other processes with two genuine τ leptons
- It is derived based on the principle of lepton universality
- It combines $\mu^+\mu^-$ collected events with $Z \rightarrow \tau\tau$, tt-bar and VV simulation
- Increases the effective statistic for these processes and reduces number of systematics

Acoplanarity angle in embedded events

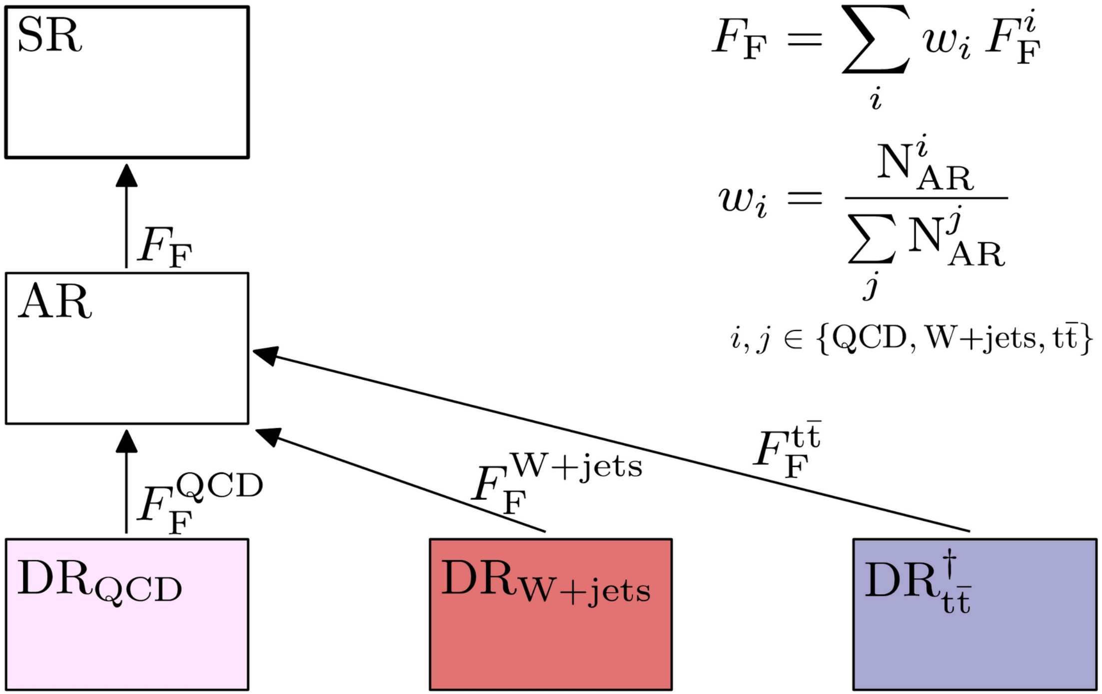
- Tau leptons are simulated in an **empty detector** and then embedded in the reconstructed di-muon event after the cleaning of muon tracks and energy deposits

- This leads to a misalignment effect for the tau decay products
  - The resulting acoplanarity angle has a non-physical modulation (not present in gen level/DY MC)
  - The modulation for smoothed



Data-driven bkg estimation: FF method

- The phase space is divided into:
  - SR: signal region
  - AR: application region
  - DRs: determination regions
    - These regions have no cuts relative to the variable which separates AR and SR
- Each region is orthogonal to the others
- The method:
  - Weights for each processes are determined in their respective DRs
  - The weights are combined and applied in the AR to determine the bkg contribution in the SR



$$F_{\mathrm{F}} = \sum_i w_i \, F_{\mathrm{F}}^i$$

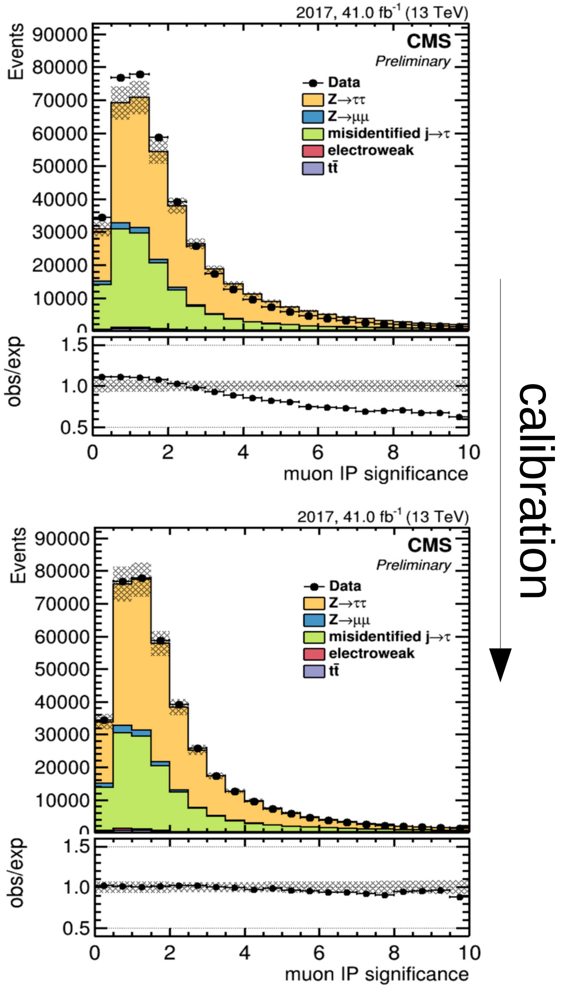
$$w_i = \frac{\mathrm{N}^i_{\mathrm{AR}}}{\sum_j \mathrm{N}^j_{\mathrm{AR}}}$$

$$i, j \in \{\mathrm{QCD}, \mathrm{W{+}jets}, \mathrm{t\bar{t}}\}$$

†Taken from simulation

IP method: 3D reconstruction and significance

- CMSSW IP are minimized in 2D $\rightarrow$ for our method we use 3D IP reconstruction
- The track is parametrized as a helix and the point of closest approach to the PV is used to compute the IP
- This parametrization allows to compute analytically the error on the IP
  - We can then define a significance as $IP_{sig} = |\vec{IP}| / \sigma_{IP}$
  - A cut on $IP_{sig} > 1.5$ is used to enhance the sensitivity
- The 3D minimization also improves IP_z reconstruction for tracks with high η
- Calibration on the IP significance for each tested vertex done using $Z \rightarrow \mu\mu$ sideband region was made to correct data/MC agreement

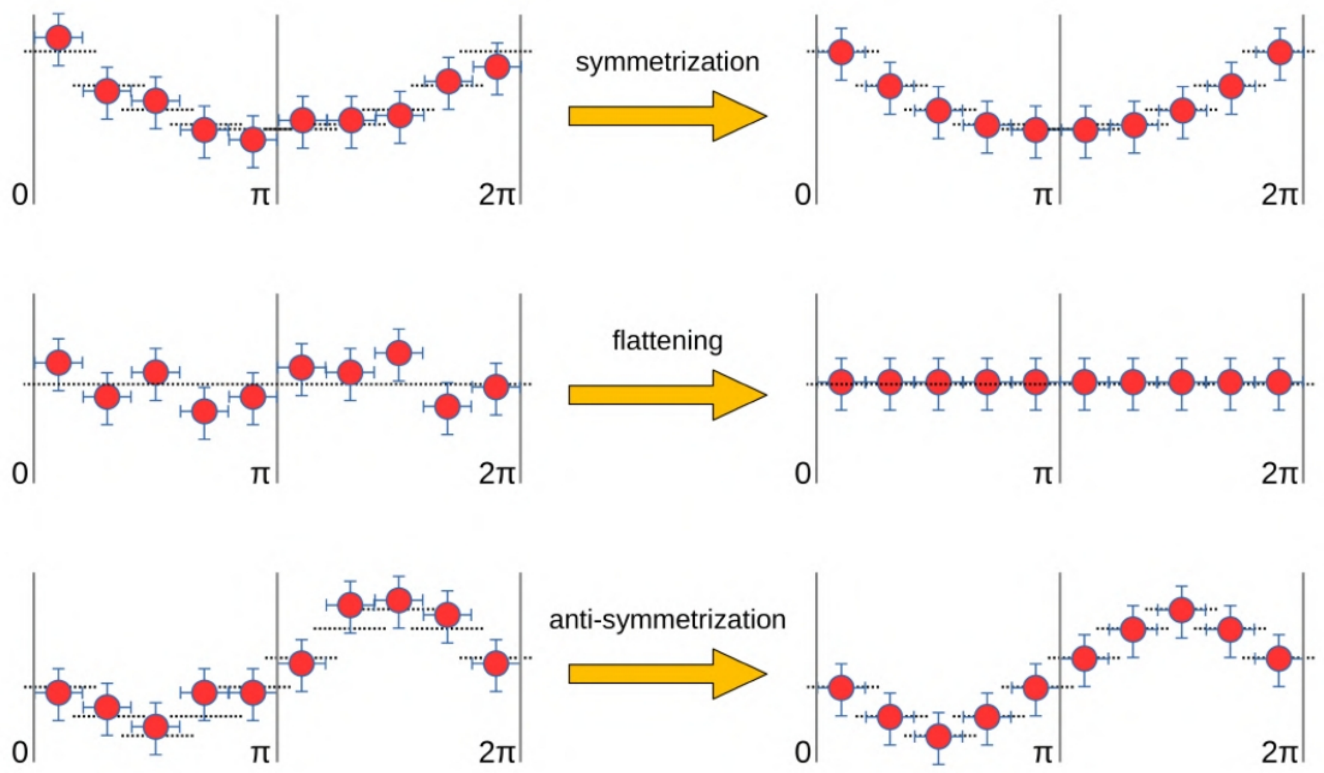


SVFit algorithm

- Algorithm developed to estimate $m_{\tau\tau}$ based on momenta of visible decay products and MET
- Inputs:
  - τ_μ τ_e : pT, η, φ of lepton
  - τ_h: p_T , η, φ, m_τ and HPS-DM of tau
  - MET
- The algorithm estimates the probability of obtaining the measured quantities based on the invariant mass of the di-tau system
- Mass points are tested using a Dynamical Likelihood Approach and the value of $m_{\tau\tau}$ most compatible with the observed event is chosen

Background smoothing

- Exploit symmetries in the bkg and signal processes to reduce statistical fluctuations in MC and data-driven models



Symmetrization

used for processes with $j \rightarrow \tau$ fakes or IP method

Flattening

used for processes with genuine taus or $l \rightarrow \tau$ fakes

Anti-symmetrization

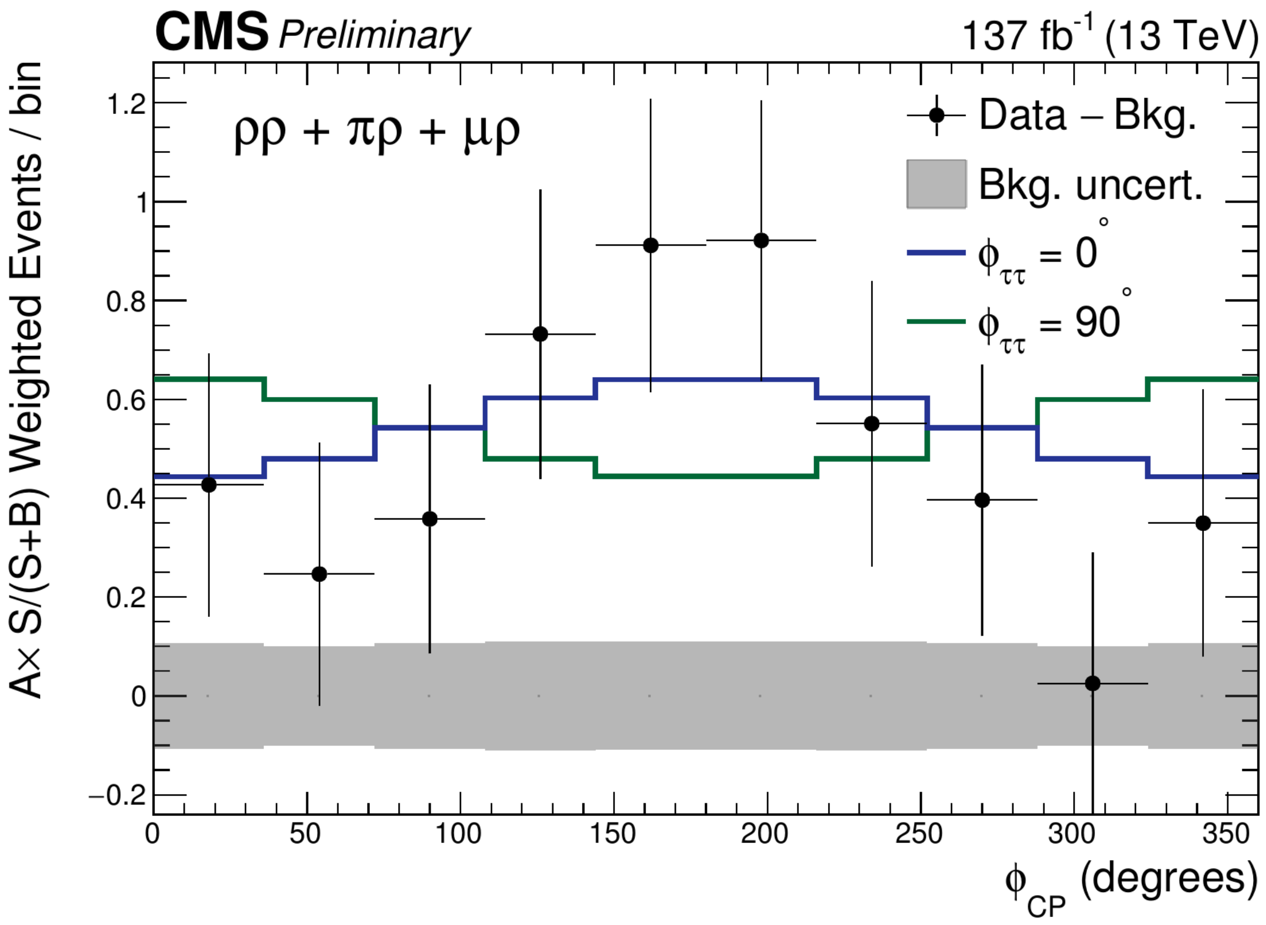
used for MM ($\varphi_{\tau\tau}$=45°) signal template

Uncertainties

- The uncertainty for this measurement is statistically dominated
- The main contribution to the systematics comes from **bin-by-bin statistical fluctuation** of bkg templates
- Other "relevant" systematics:
  - Theory uncertainties for signal models:
    - Factorization and renormalization scales + PS uncertainty for ISR and FSR
  - Energy Scale for muons/taus
  - Jet Energy Resolution
  - Uncertainty on IP calibration
  - Uncertainty of Fake Factors
  - Normalization uncertainty on bkg templates

Description	Value	Templates affected	Type
Luminosity uncertainty	2016: 2.5%	MC	lnN
	2017: 2.3%		
	2018: 2.5%		
μ identification	1%.	MC	lnN
μ trigger	2%	MC	lnN
τ_h trigger	p_T dep.	MC	shape
b-jet veto	1-9%	$t\bar{t}$, ST	lnN
$\mu \to \tau_h$ FR	η_{τ_h} dep. (20-40%)	MC with $l \to \tau_h$	shape
Muon and pion IP_{sig} calib.	25%	MC	lnN
τ_h identification	p_T/DM dep. (2-3%)	MC, embedded	shape
τ_h ES	1%	MC	shape
	1.5%	embedded	
μ ES	0.4–2.7%	MC, embedded	shape
$\mu \to \tau_h$ ES	1%	MC	shape
Jet ES	event-dep.	MC	shape
MET recoil corr.	event-dep.	MC	shape
MET unclustered ES	event-dep.	MC	shape
non-DY in embedded	10%	embedded	shape
top p_T reweighing	10%	$t\bar{t}$, ST	shape
Z p_T reweighing	10%	DY	shape
FF uncertainties	event-dep.	fakes	shape
Pre-firing	event-dep.	MC	lnN
Bin-by-bin stat. uncertainty	event-dep.	All	shape

CP-even vs CP-odd



- Comparison between CP-even and CP-odd $\rightarrow$ weighted distribution for the φ_{CP} angle

- Events are weighted by

$$A \times \frac{S}{S+B}$$

with S–signal, B–background and A separation between hypotesis:

$$A = \frac{|CP^{even} - CP^{odd}|}{CP^{even} + CP^{odd}}$$

- In nMSSM a total of 5 neutral Higgs bosons are considered
- Each $H_i(m_{Hi})$ is associated to a CP-mixing angle φ_i
- For m_{Hi}~125 GeV the phase space allowed is $\varphi_{\tau\tau} < 27°$
- Our measurement allows to probe and constrain nMSSM parameters within that phase space at 68% CL
- Performing the measurement assuming multiple values of m_H necessary to constrain other CP-mixing phases