The Higgs boson in the mirror

Measurement of the CP structure of the tau lepton Yukawa coupling with the CMS experiment

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Introduction

- The Higgs boson thoroughly studied after its discovery
  - Deviations from Standard Model exceptions looked for => window for New Physics (NP)

Standard Model predicts the Higgs boson with spin-parity 0^+, i.e. CP even scalar particle – it is the case?
Have to be checked in a CP mirror (in experiment) => swap particles with anti-particles (C) and invert spacial coordinates (P)

- CP-violation in the Higgs couplings can occur (and be accessed experimentally) in:
  - **HVV couplings**

    $H \rightarrow ZZ$ / WW decays, W/Z H production
  - **Yukawa (to fermion) couplings**

    $H \rightarrow \tau\tau$ decays

    ttH production (and $gg \rightarrow H$ production occurring via t-quark loop)

Tau Yukawa coupling (Y_τ)

- Yukawa coupling: CP-odd term can occur at tree level
  (no suppression by NP scale!)

$$\mathcal{L}_Y = -\frac{m_\tau H}{v}\left(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau\right)$$

CP even (scalar)

CP odd (pseudoscalar)

$$0 \leqslant \kappa_\tau, \tilde{\kappa}_\tau \leqslant 1, \sqrt{\kappa_\tau^2 + \tilde{\kappa}_\tau^2} = 1$$

- Parametrisation: effective **CP mixing angle ($\alpha^{H\tau\tau}$)**:

$$\tan\left(\alpha^{H\tau\tau}\right) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

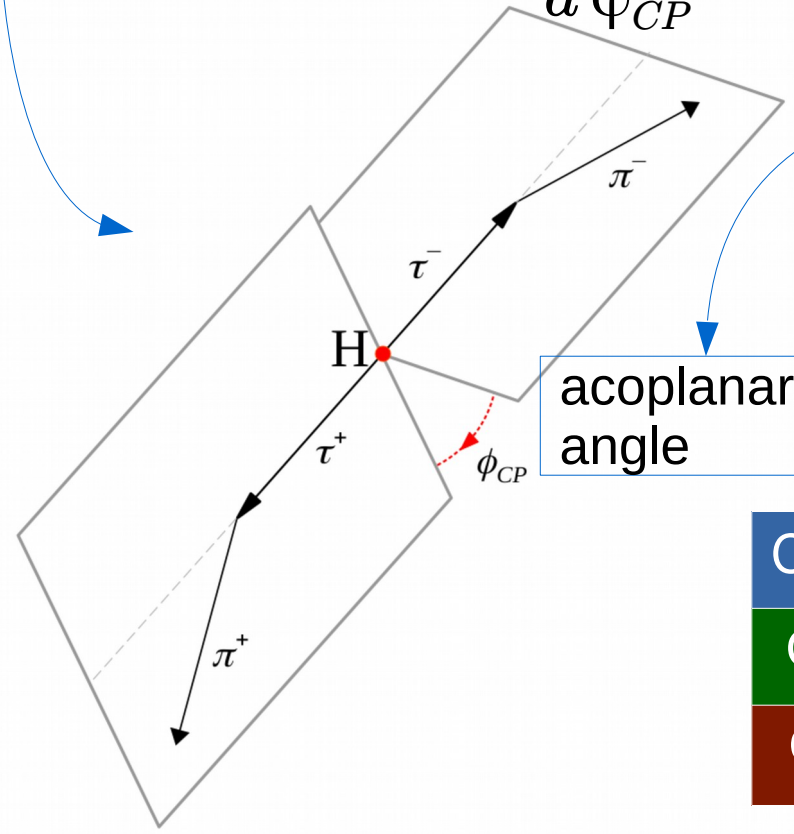
CP even	$\alpha^{H\tau\tau} = 0°$
CP odd	$\alpha^{H\tau\tau} = 90°$
CP mix	$\alpha^{H\tau\tau} = 45°$

Acoplanarity angle

CP encoded in correlations between transversal components τ spins
=> correlation between τ-decay planes (acoplanarity angle φ_{CP})

Cross-section of the H→ττ decay has a sinusoidal shape in acoplanarity angle (φ_{CP}) with phase given by CP mixing angle ($\alpha^{H\tau\tau}$)

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



acoplanarity angle

CP mixing angle

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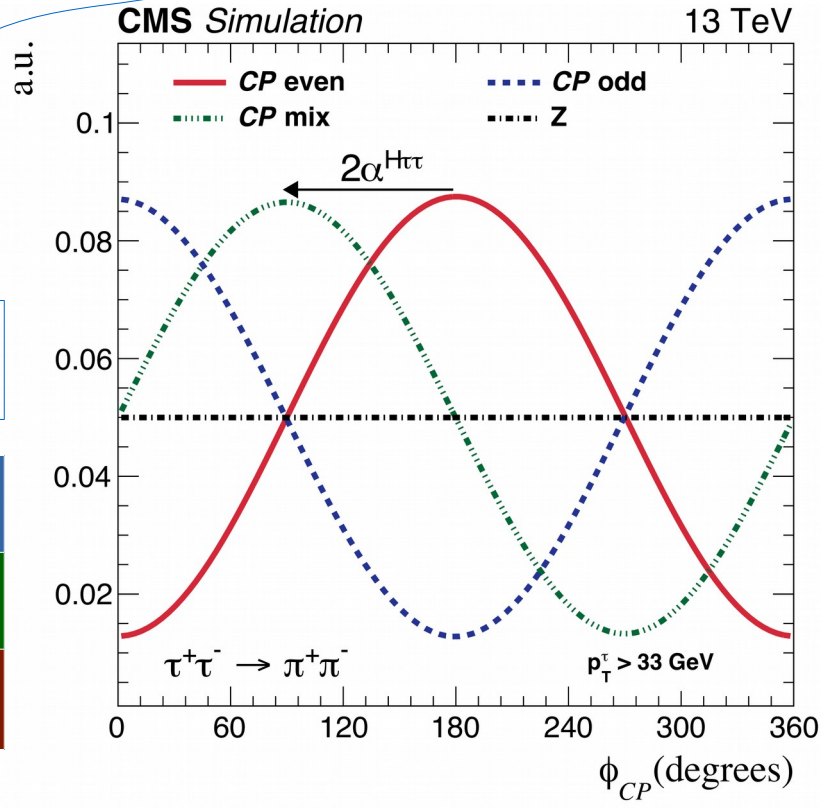


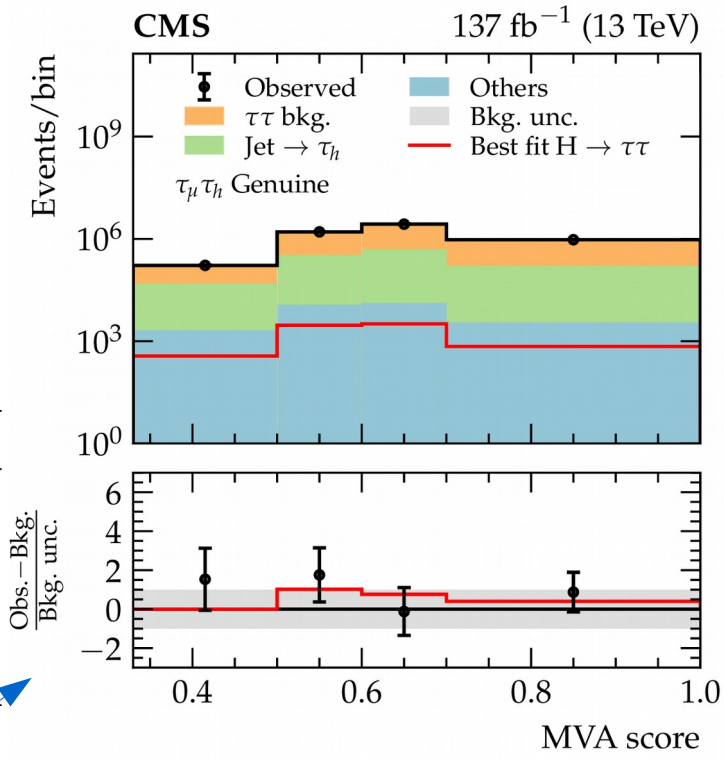
Strategy

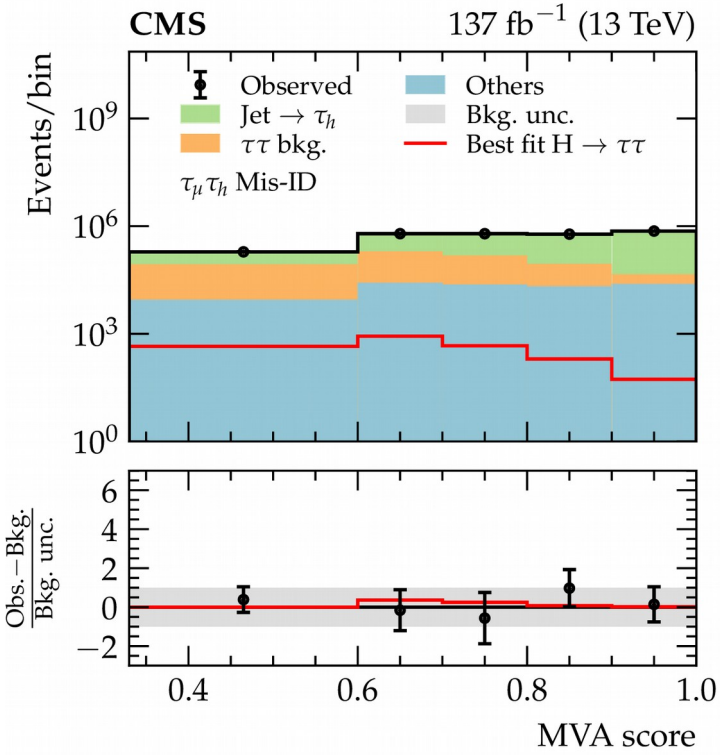
- Full Run-2 data of 137/fb at 13TeV (2016-2018)
- Most sensitive channels: $e\tau_h$ & $\mu\tau_h$ & $\tau_h\tau_h$
  (~85% of all ττ final states)

Mode	$e^{\pm}\nu\nu$	$\mu^{\pm}\nu\nu$	$h^{\pm}\nu$	$h^{\pm}\pi^0\nu$	$h^{\pm}\pi^0\pi^0\nu$	$h^{\pm}h^{\mp}h^{\pm}\nu$
Type	τ_e	τ_μ	τ_h	τ_h	τ_h	τ_h
$\mathcal{B}(\%)$	17.8	17.4	11.5	25.9	9.5	9.8
Resonance	—	—	—	$\rho(770)$	$a_1(1260)$	$a_1(1260)$
Symbol	e	μ	π	ρ	a_1^{1pr}	a_1^{3pr}

- Event categories with ML (multi-class MVA):
  - $H \to \tau\tau$ signal
  - Genuine ττ (mainly $Z/\gamma^* \to \tau\tau$)
  - Fakes (mainly QCD jets & W+jets)

  => Use $m_{\tau\tau}$ and event topology & kinematics
- Reconstruct decay planes (signal cat.)
- Fit expectations to data in all categories
  - 2D fit in signal category: φ_{CP} vs MVA score
  - 1D fit in bkg. categories: MVA score





Decay plane reconstruction

- In LHC generally not possible
  - Momentum carried by υ's, not known Higgs rest frame

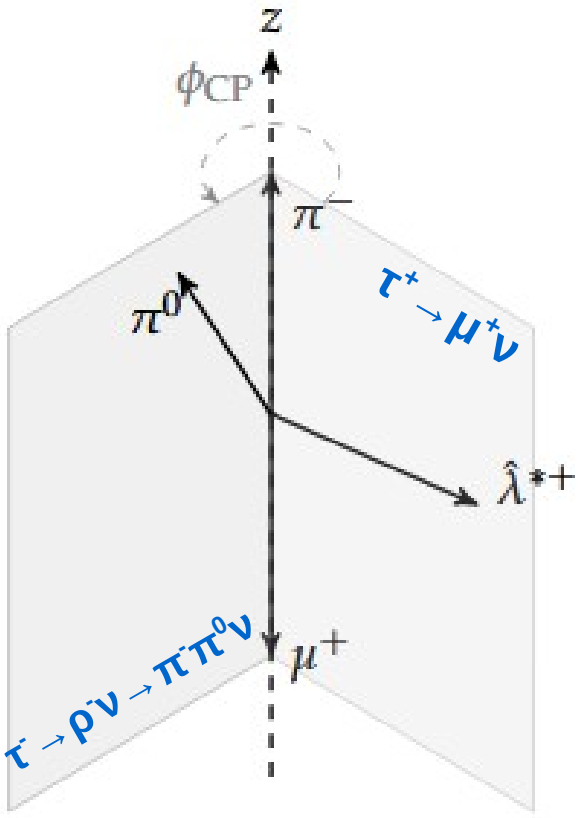
  => use approximated methods
- Impact parameter method for single charged particle ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$)

  (by S.Berge et al)

  Plane spanned by IP and momentum of charged particle
- Neutral pion method (ρ, a_1^{1pr}, a_1^{3pr})

  (by Z.Wąs et al)

  Plane spanned by momentum of charged and neutral particle
  - a_1^{1pr}: momenta of $2\pi^0$ summed up
  - a_1^{3pr}: find pair compatible with ρ and use instead of π^0
- Combine planes in zero momentum frame (ZMF) of two charged particles



Signal extraction

Fit of signal and background models to data in all categories simultaneously

- Free parameters: signal strength & $\alpha^{H\tau\tau}$

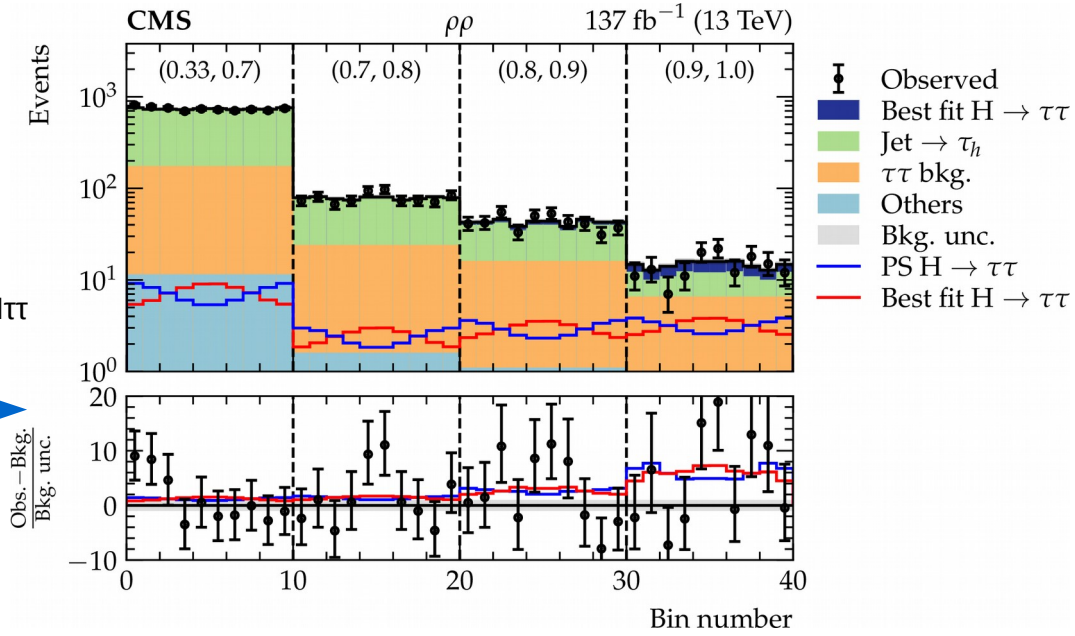
Signal category split by ττ decay channel

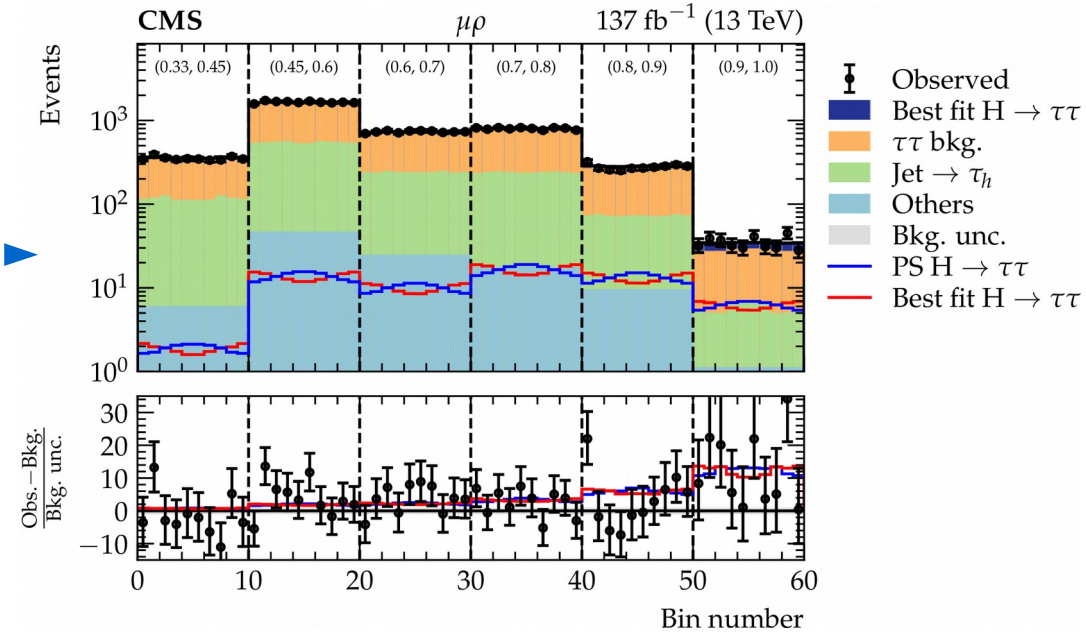
Most sensitive channels:

ρρ, πρ, μρ

- each with ~1σ separation between CP even and CP odd

Distributions of φ_{CP} in bins of MVA score shown

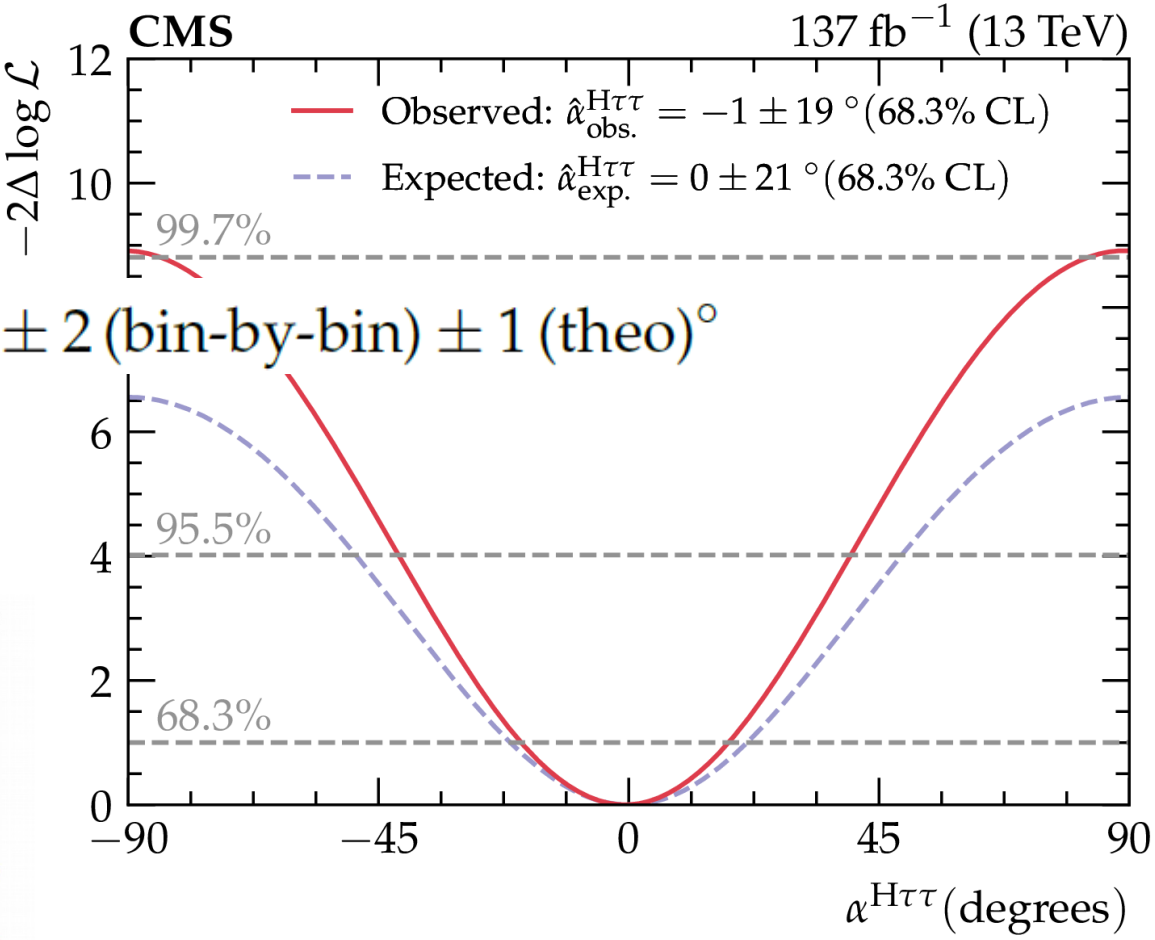


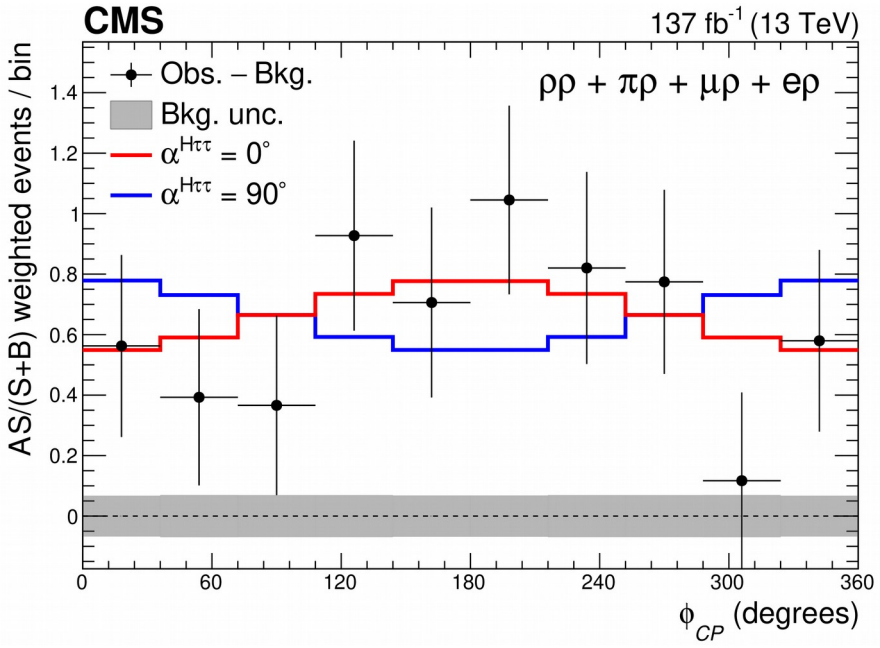


Results: CP mixing angle $\alpha^{H\tau\tau}$

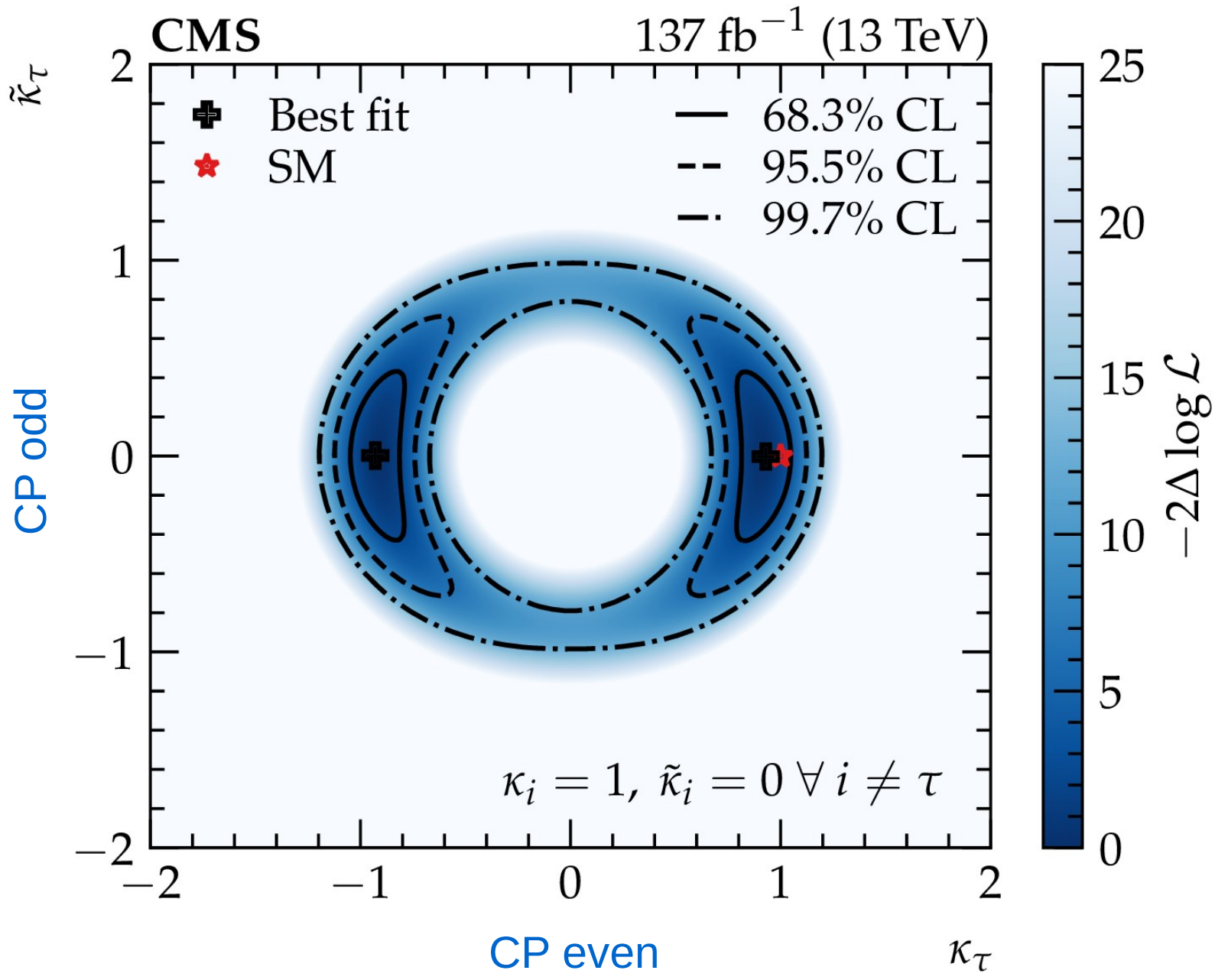
- 1st measurement of CP structure of Y_τ
- Consistent with SM: CP even preferred over CP odd with 3σ
- Uncertainty dominated by statistic

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





Results: reduced couplings



Summary

- Run-2 opened era of precise measurements of the Higgs boson
- **CP structure of tau Yukawa coupling probed**
  - CMS measurement (1st of this type!) agrees with SM (CP even coupling) and excludes pure CP odd coupling at 3σ
  - Analysis statistically limited → will be continued with new data
- Result in arXiv:2110.04836 and submitted to JHEP

Thank you!

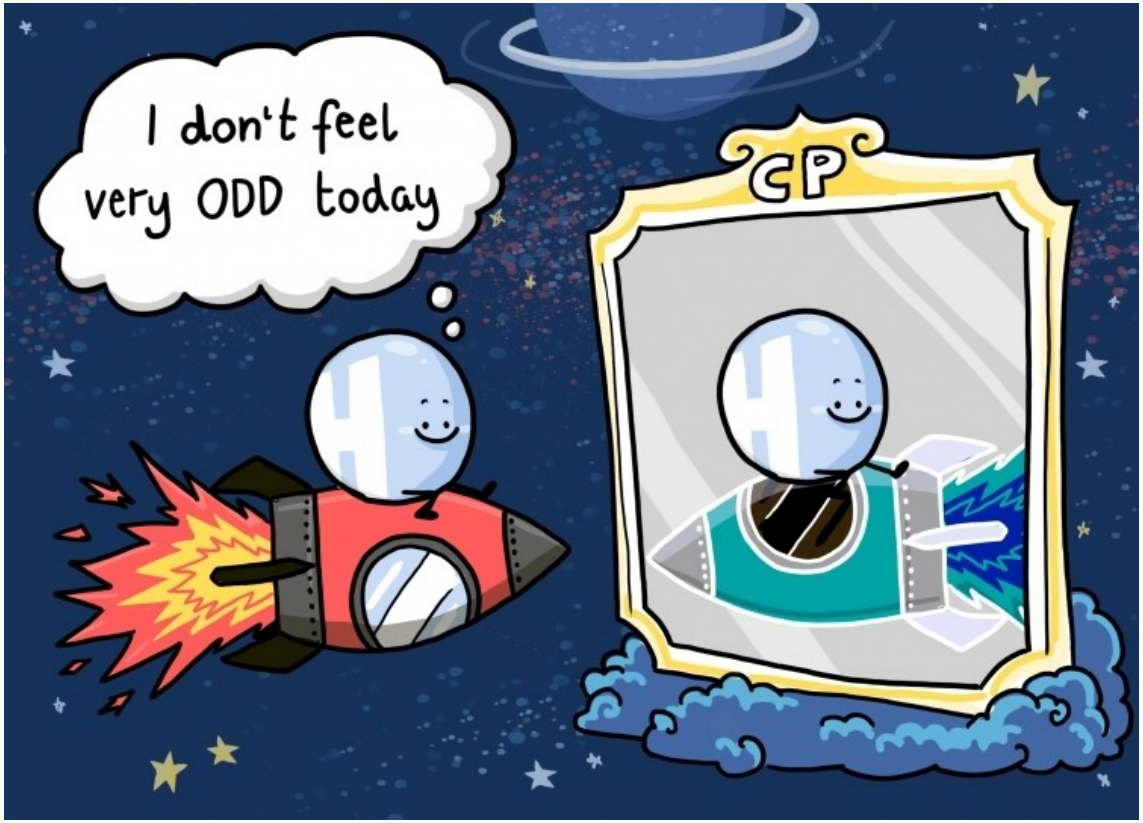
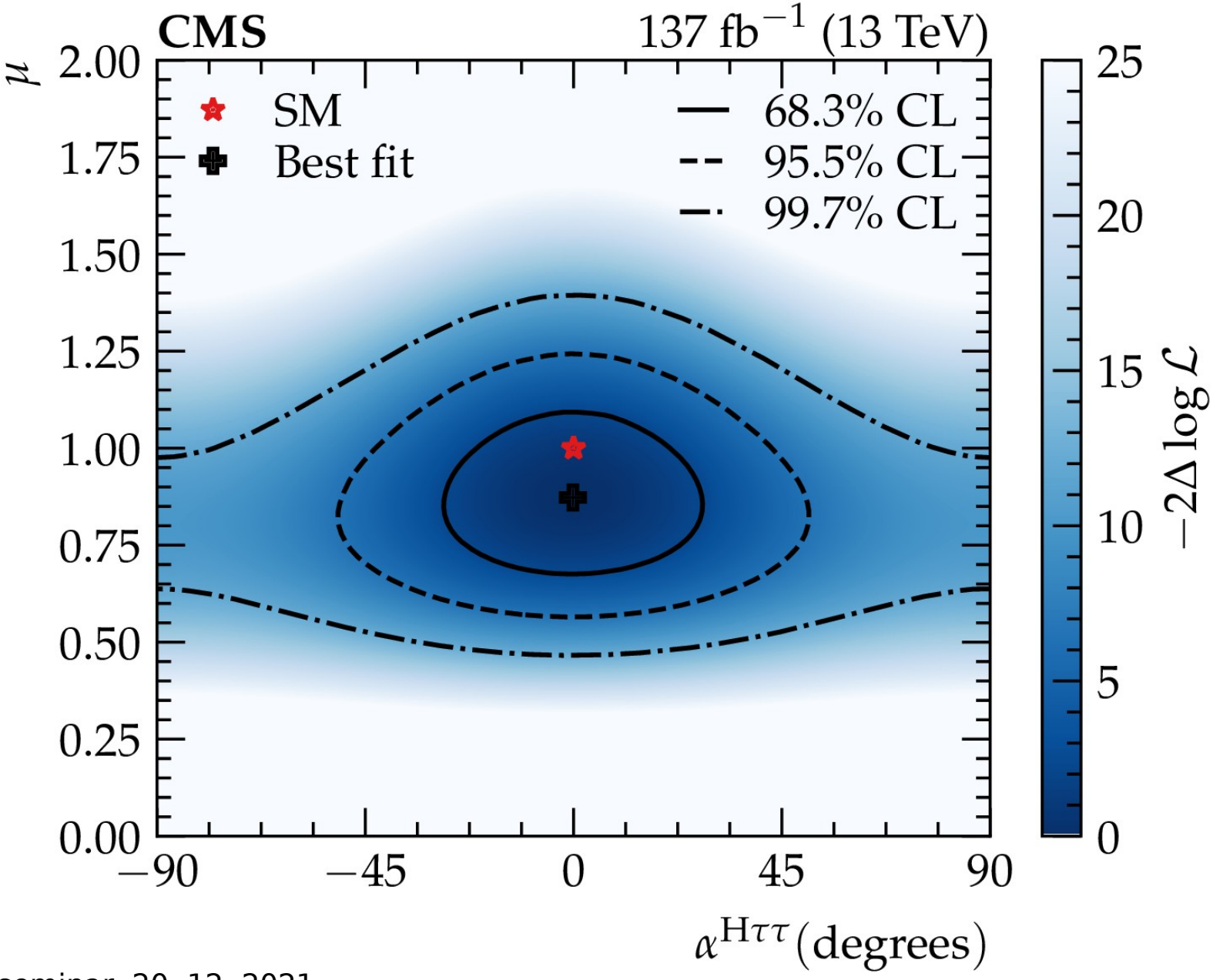


image: DESY/designdoppel

Additional material

Results: CP mixing angle $\alpha^{H\tau\tau}$ vs signal strength μ

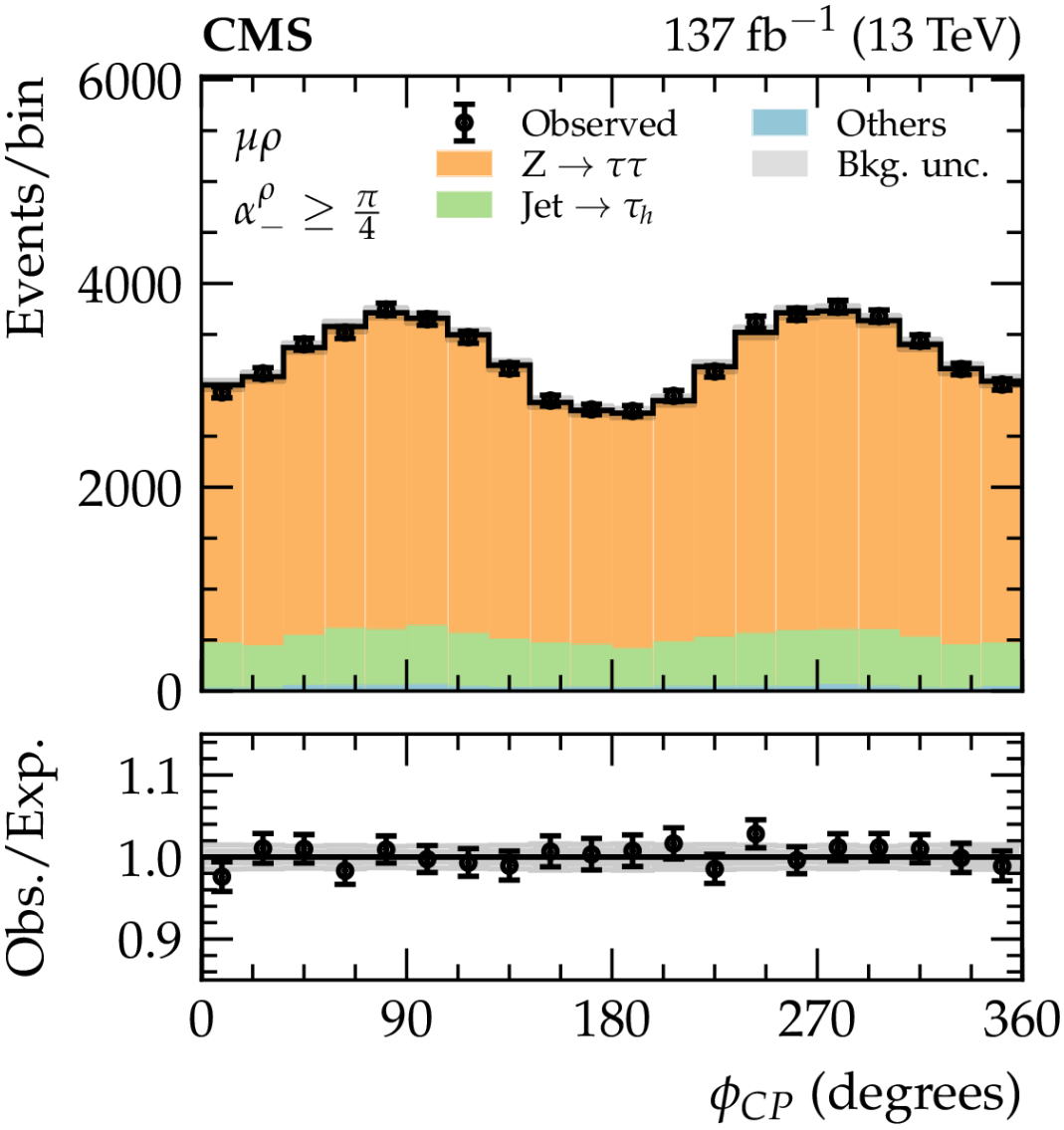


Check with $Z \rightarrow \tau\tau$

φ_{CP} flat for $Z \rightarrow \tau\tau$,
but can be modulated when events “nearly perpendicular” ($\alpha > \pi/4$, here) or “nearly coplanar” ($\alpha < \pi/4$) to production plane are selected

- cf. S.Berge et al, arXiv:1410.6362

Can be used to check data/MC of φ_{CP} with $Z \rightarrow \tau\tau$ enriched sample
=> Observed agreement is very good

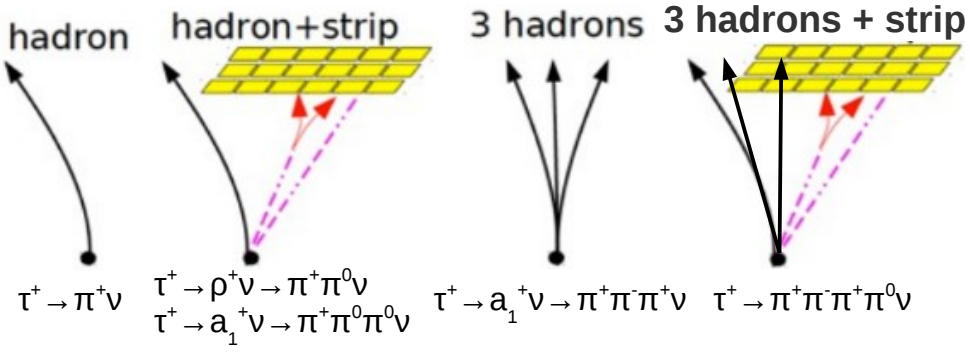


Anatomy of $H \rightarrow \tau\tau$ measurements

τ reconstruction in CMS

- Only visible τ decay products reconstructed
  - νs contribute to p_T^{miss}
- Leptonic decays undistinguishable from prompt e and μ
- Decays to hadrons+ν (τ_h) with hadron-plus-stips (HPS) algorithm
  - Main τ_h decay modes (with particles by PFlow)

Decay mode	Resonance	$\mathcal{B}$ (%)
Leptonic decays		35.2
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	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		3.3



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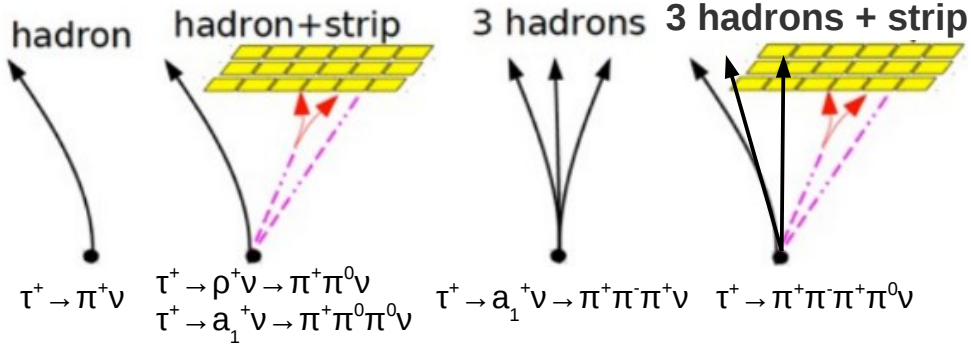
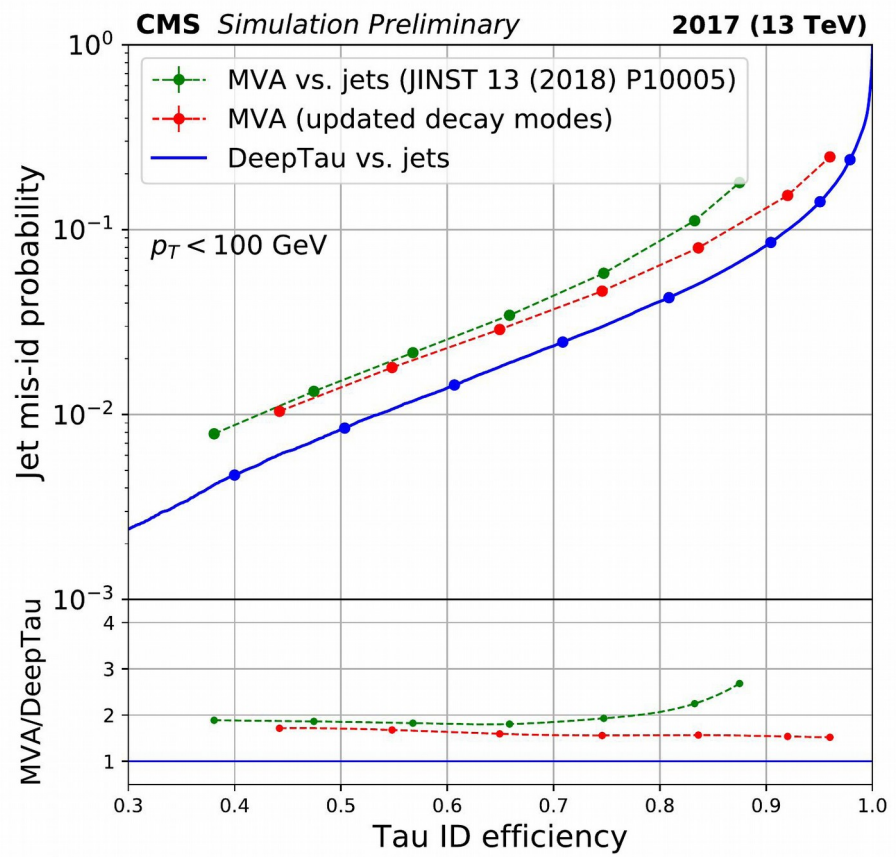
- Decays to hadrons+ν (τ_h) with hadron-plus-stips (HPS) algorithm
  - Main τ_h decay modes (with particles by PFlow)
- Further identification with DNN
  - τ_h quantities & quantities of particles around τ_h (global and per-particle)

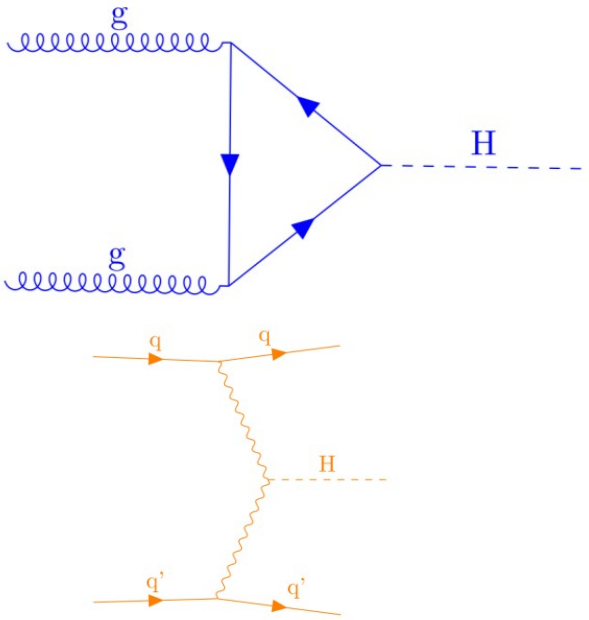
=> significant gain in performance wrt previous tauID





Anatomy of $H \rightarrow \tau\tau$ measurements

- Use the $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, and $e\mu$
- Exploit event topology
  - Production: 0-, 1- and 2-jet (VBF)
  - p_T of the di-τ+p_T^{miss} (Higgs)
  - VH($\tau\tau$) channels analysed separately



Anatomy of H → ττ measurements

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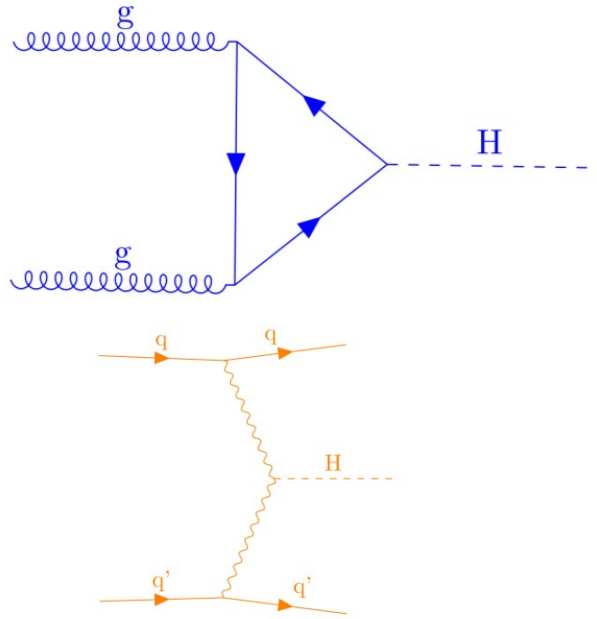
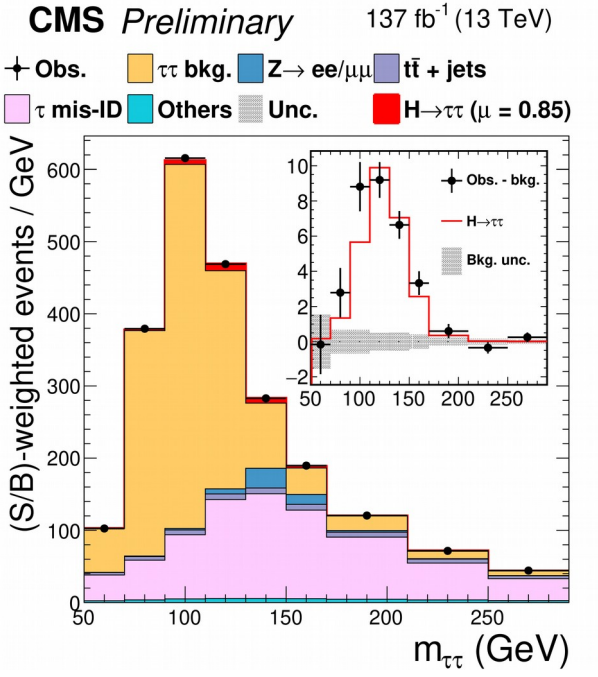
  - Production: 0-, 1- and 2-jet (VBF)
  - p_T of the di-τ+p_T^{miss} (Higgs)
  - VH(ττ) channels analysed separately
- Fully reconstructed $m_{\tau\tau}$ (res. of ~20%)
  - vis. momenta & p_T^{miss} w/ max likelihood





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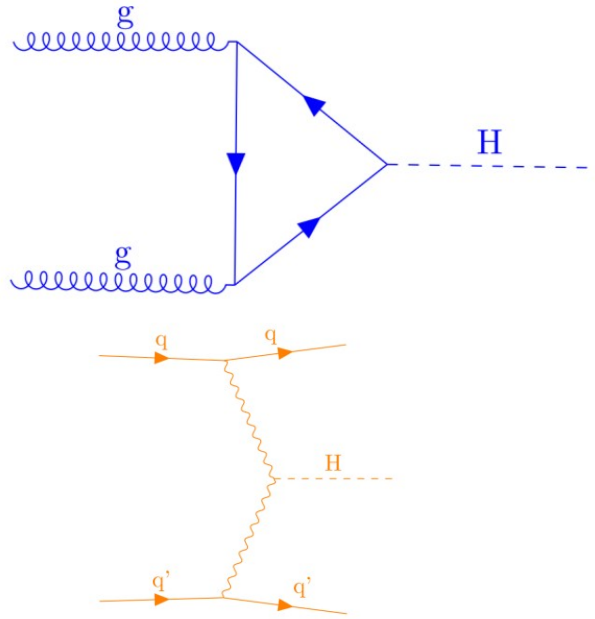
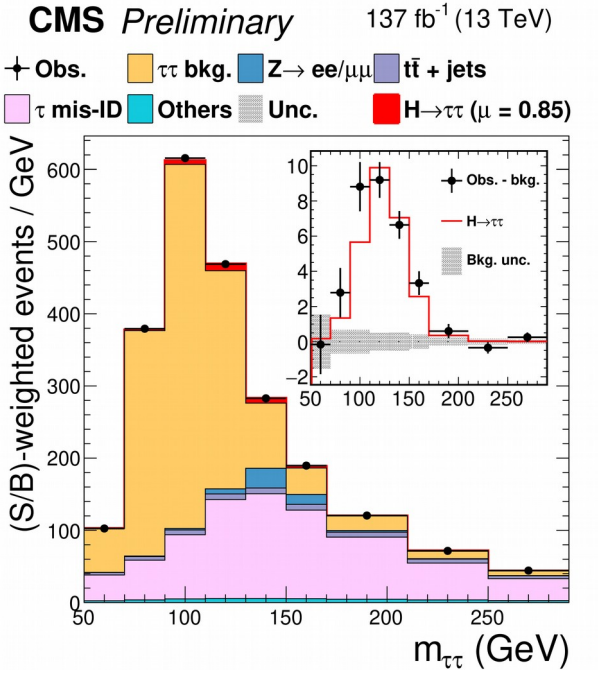
  - vis. momenta & p_T^{miss} w/ max likelihood

  => Cut-based or MVA-based event categories with different yields & S/B
- Fit S&B expectations to data to find event yields
  - All categories fit simultaneously
  - Systematics as nuisance parameters





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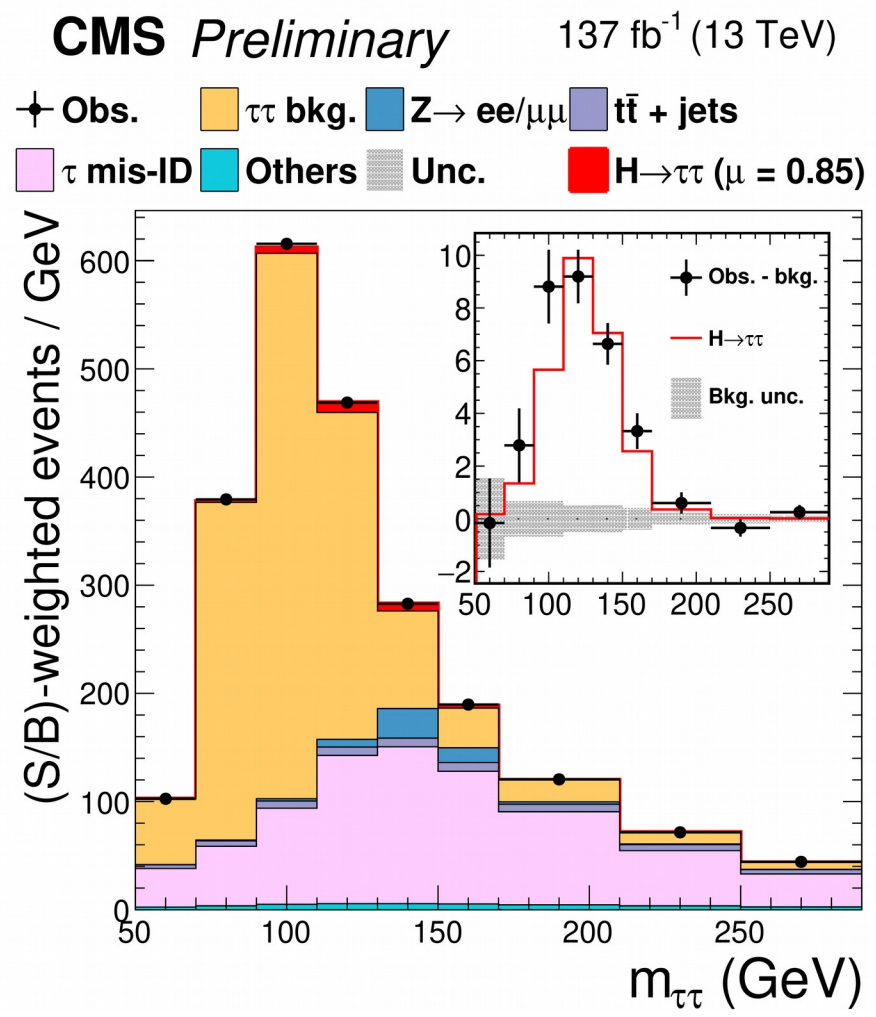
Background in H → ττ measurements

Genuine ττ
Mainly Z/γ* → ττ
Embedding technique:
Replace μs in (Z/γ* →)μμ data by simulated τs

Mis-ID τs (fakes)
Mainly QCD jets, W+jets w/ jet → τ
Fake factors technique:
Apply mis-ID probability to τ-free events

Z/γ* → ee/μμ,
tt+jets,
Others (VV, single-t, ...)
Simulation (with MC/data corrections)



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MVA τ_h decay-mode ID

Decay mode migrations lead to incorrect φ_{CP} estimates

=> Dedicated BDT developed to improve decay mode identification on top of HPS

Inputs include:

- Inv. masses of tau decay products,
- angular distribution of photons in strips,
- HPS decay mode

Substantial gain in purity and Efficiency => Improves φ_{CP} sensitivity by ~15-20%

CMS-DP-2020-041