12th Higgs Hunting
Orsay-Paris, France

Search for CP violation in the tau Yukawa coupling with CMS

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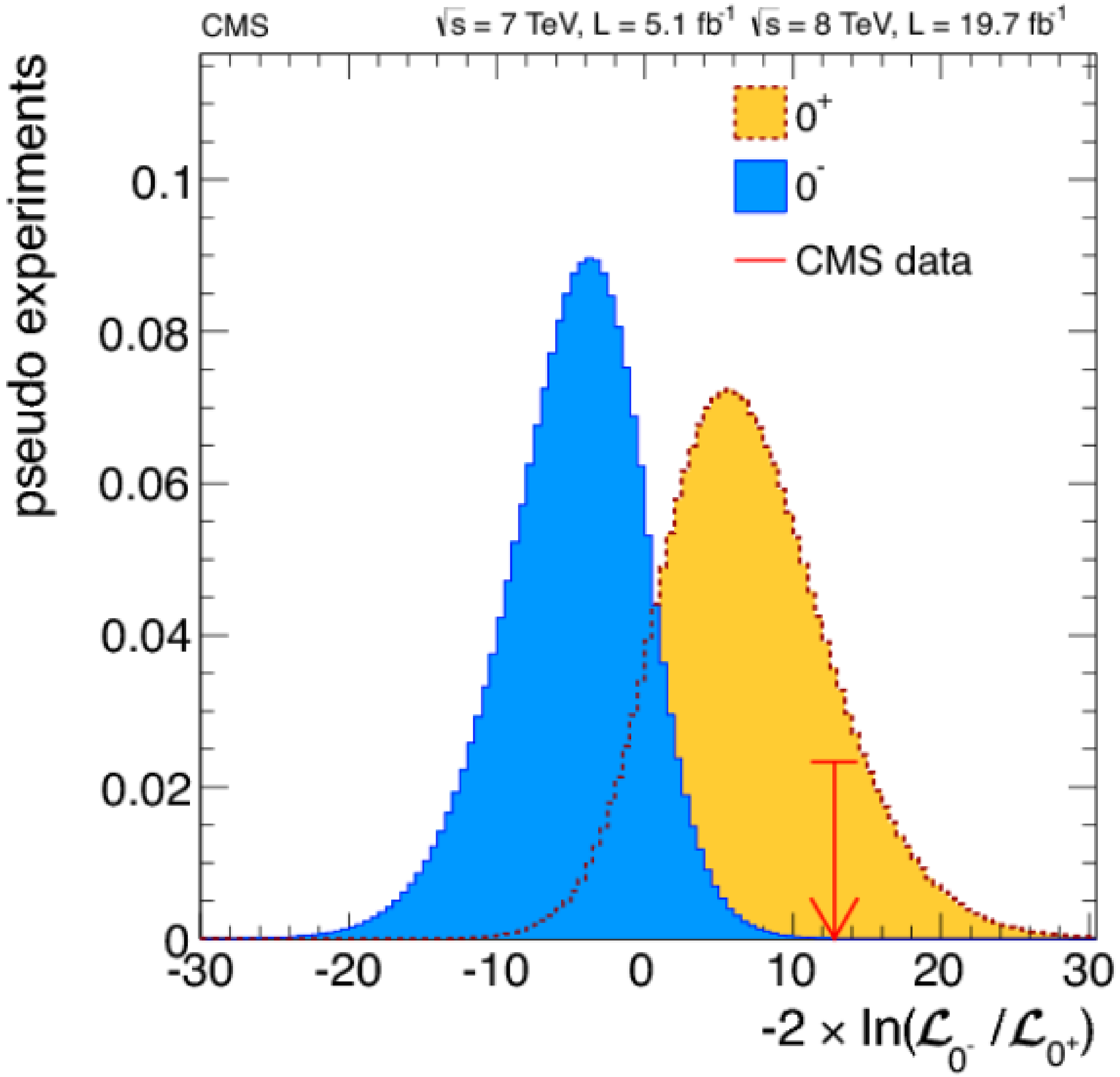
13th September 2022

Overview

- One of the SM predictions about the Higgs boson is a 0^+ spin-parity
- Measurement of CP properties in diboson couplings (Z,W) in 4 leptons final states and VBF production mode excluded the purely pseudo-scalar hypothesis (*doi:10.1103/PhysRevD.89.092007*)
- A mixed coupling is still possible in Yukawa couplings to fermions :
  - gg -> ttH production mode, e.g (*doi:10.1103/PhysRevLett.125.061801*)
  - **H -> tautau decays**, e.g (*doi:10.1007/JHEP06(2022)012*)
- This talk aims to introduce various techniques used in search of CP violation in the tau Yukawa coupling



CP properties of the tau Yukawa coupling

- Each fermionic interaction can be decomposed into a CP-even and a CP-odd coupling to the Higgs boson :

$$L_Y = -\frac{m_f \phi}{v}(\kappa_f \overline{\psi_f}\psi_f + \tilde{\kappa}_f \overline{\psi_f} i\gamma_5 \psi_f)$$

- The CP mixing is encoded in a mixing angle α^{Hll} through the expression of the CP-odd fraction of the coupling

$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} = \sin^2(\alpha^{Hff})$$

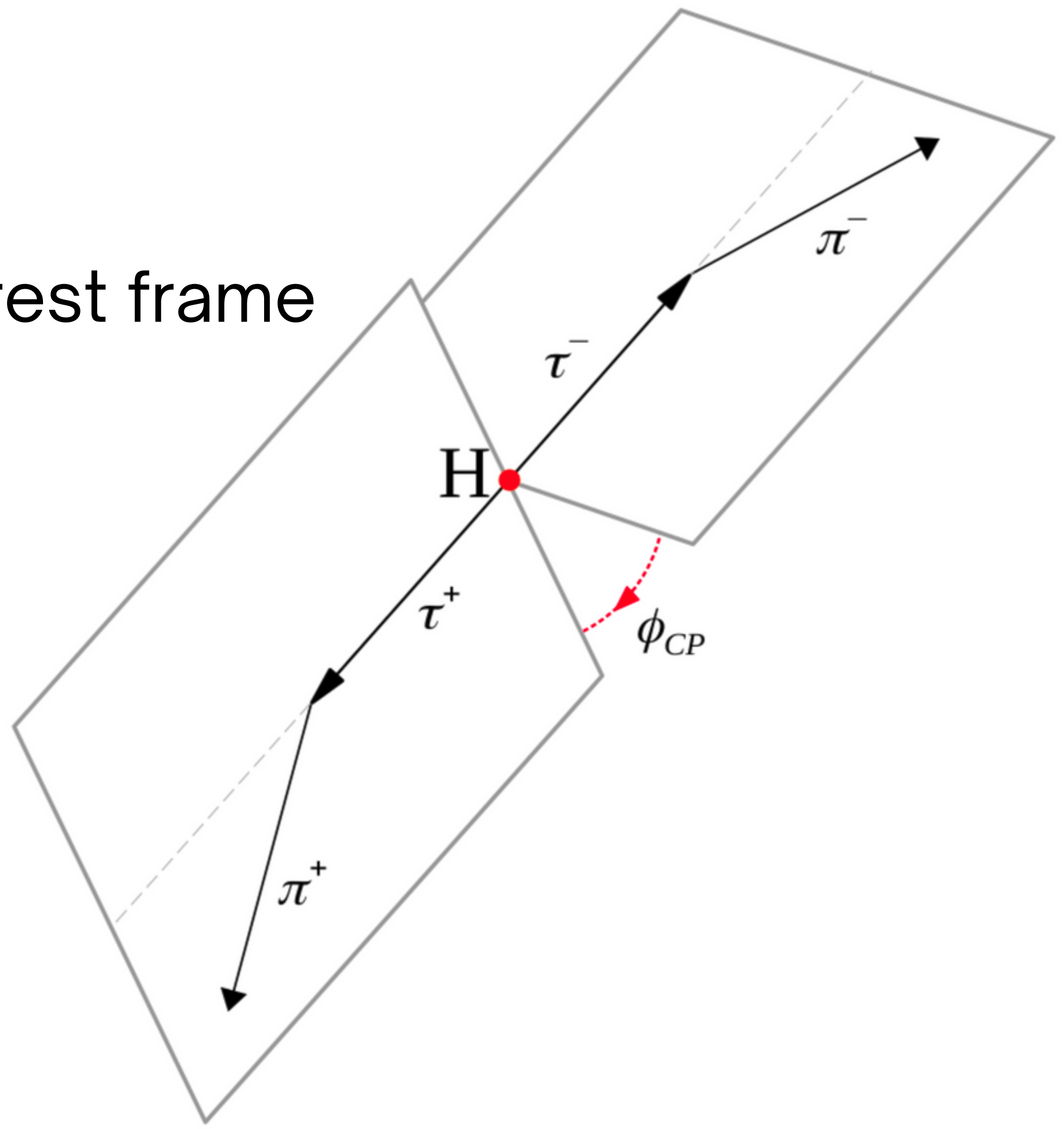
- In tau decays the CP mixing state is carried over to tau leptons through transverse-spin correlation

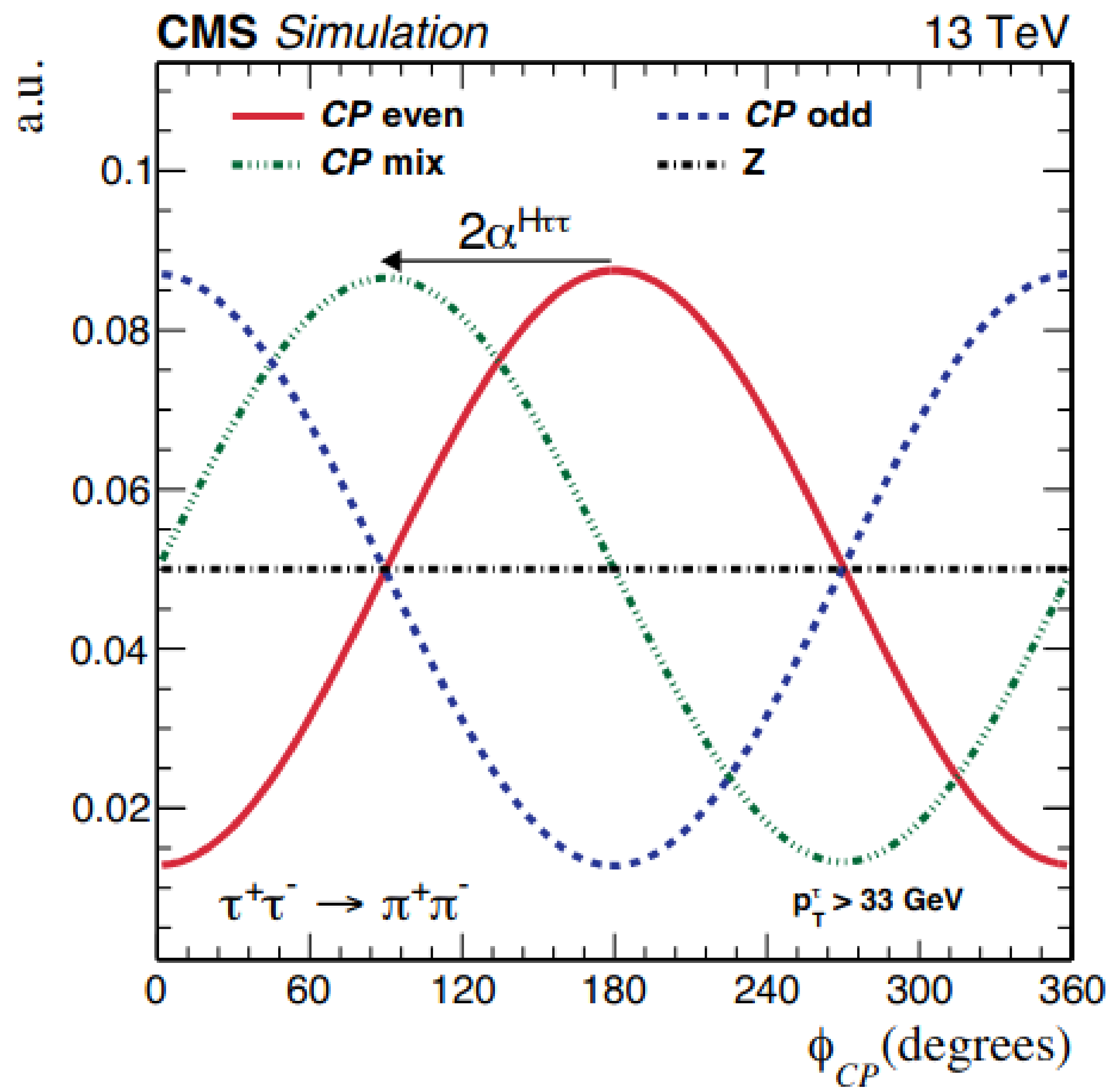
$$\Gamma(H \to \tau\tau) = \Gamma^{unpol}(1 - s_{\parallel}^{-} s_{\parallel}^{+} + s_{\perp}^{-} R(\alpha^{H\tau\tau}) s_{\perp}^{+})$$

CP sensitive observable in tau decays

- The acoplanar angle ϕ_{cp} is defined as the angle between tau decay planes
  - Assessible through visible decay products

Higgs rest frame



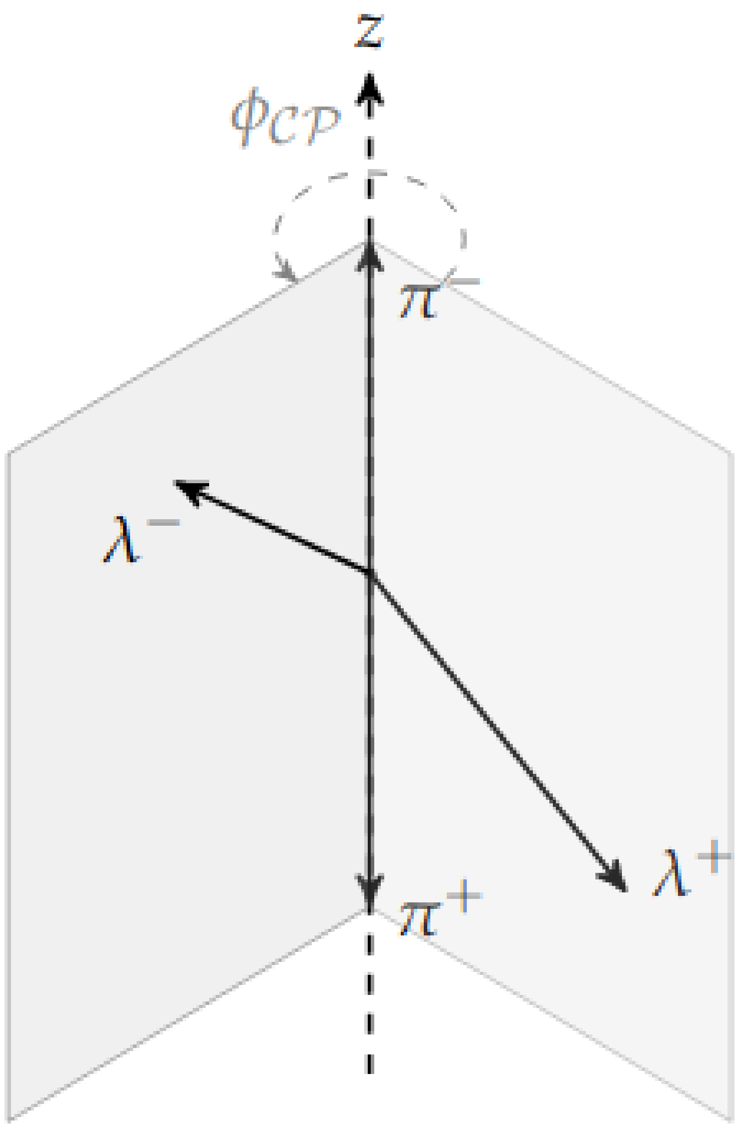


$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau\tau) \propto const - \cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

- Spin correlation creates a sinusoidal dependence in Higgs decay rate

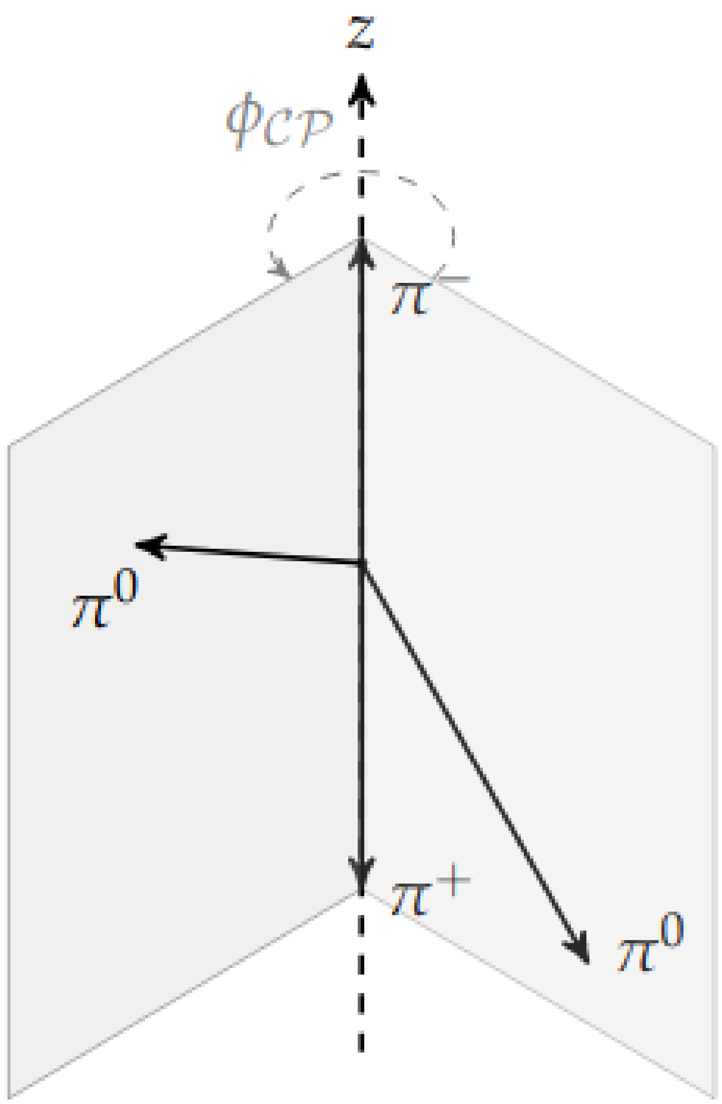
Observable measurement

- Using visible decay products, planes are defined by a particle momentum and another vector



- Impact parameter for single momentum final states

- Another momentum for multi momenta final states



Impact parameter
$\tau \rightarrow \pi, \mu$,e

Methods can be used together when taus are decaying differently

Neutral pion
$\tau \rightarrow \rho, a_1$

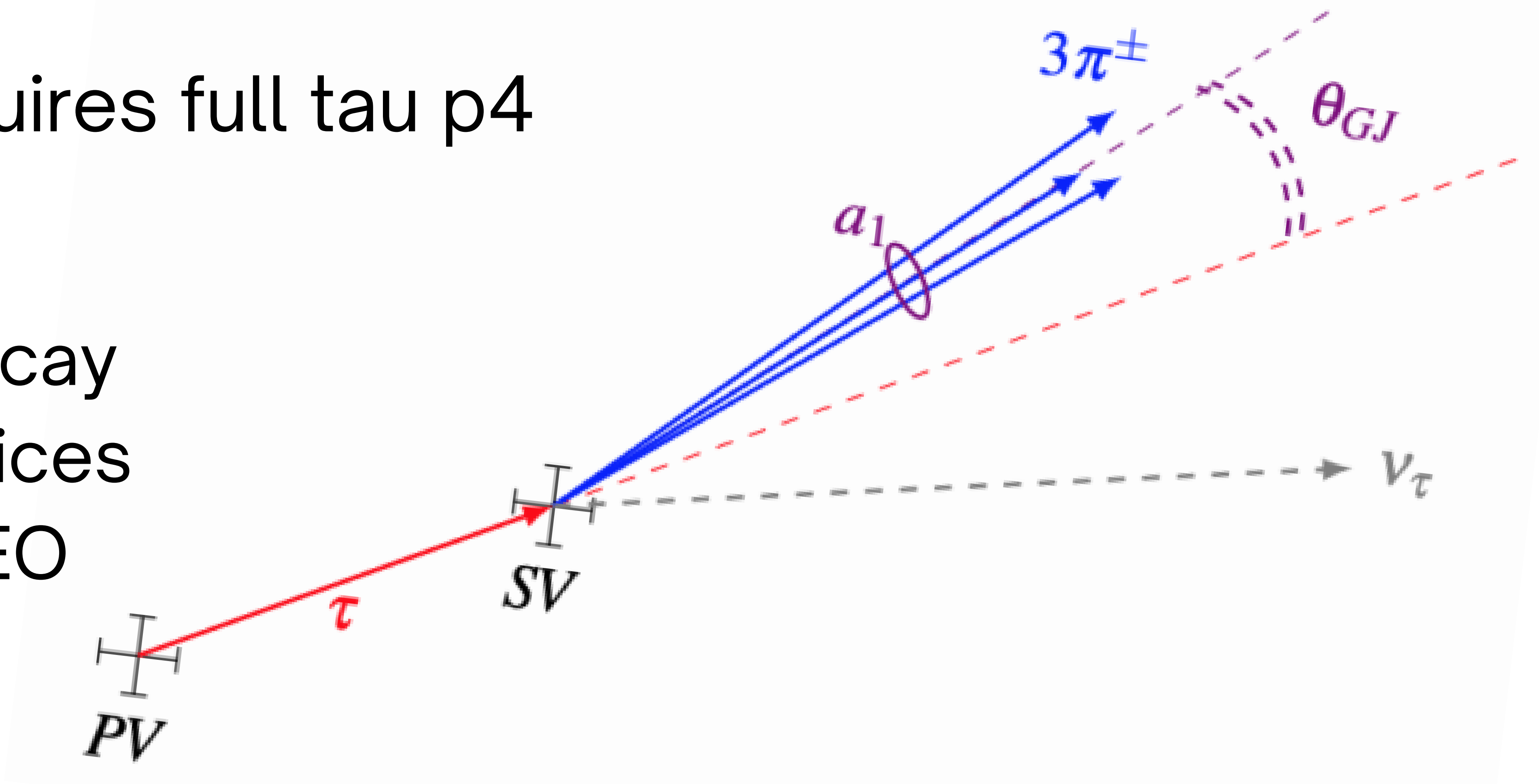
Polarimetric vector method

- Uses the polarimetric vector (most probable tau spin direction) and the undecayed tau momentum to define planes

$$d\Gamma = \frac{1}{2m_\tau}|\overline{M}|^2(1 + h_\mu s^\mu)dLips$$

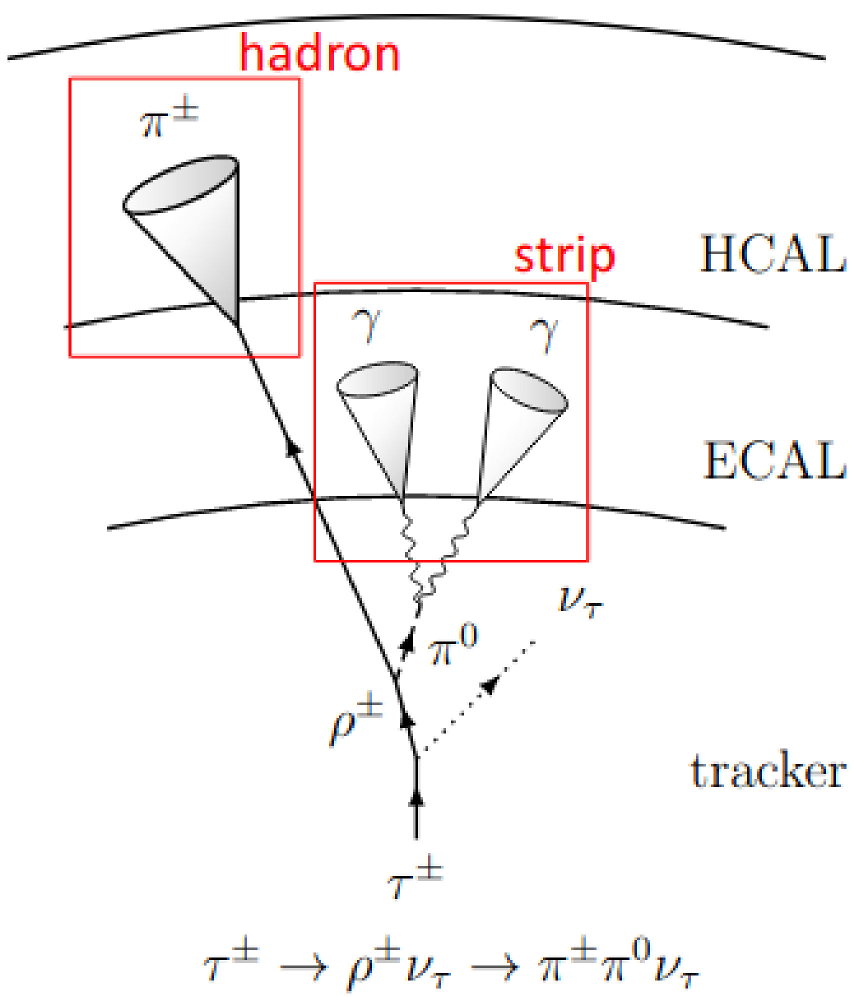
- *s* is the tau spin and *h* the polarimetric vector, function of the tau momentum and its decay products
  - Most CP sensitive technique but requires full tau p4 reconstruction

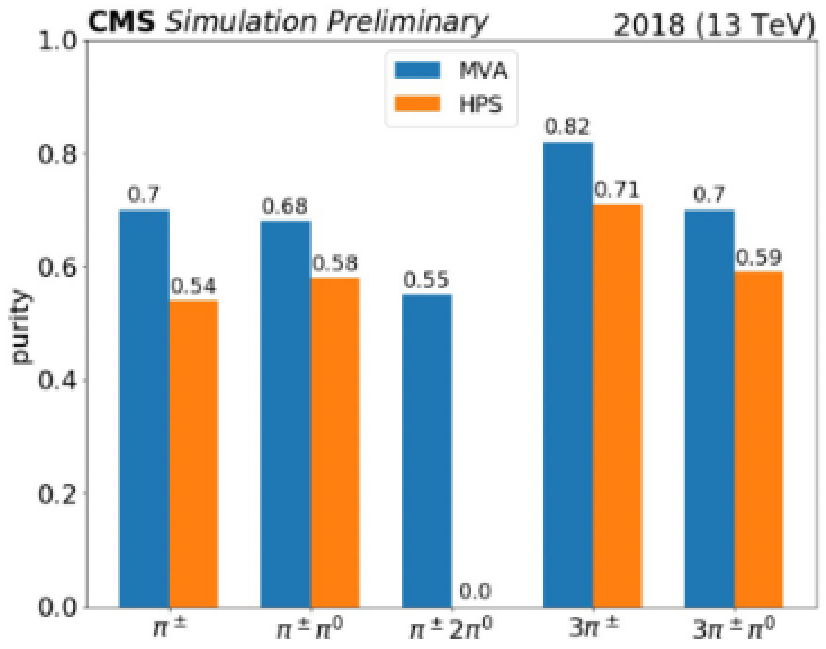
- Successfully implemented in the $a_1^{3pr}a_1^{3pr}$ decay mode using constraints on secondary vertices
  - a1 hadronic resonance model from CLEO (Phys. Rev. D61 (1999) 012002))



Tau identification in CMS

- The Hadron-Plus-Strip (HPS) algorithm is used to reconstruct hadronic taus from collimated ak4 jets (*doi:10.1088/1748-0221/13/10/P10005*)
  - PF charged hadrons and PF e/gammas from neutral hadrons are associated and a decay mode is assignated
- DeepTau algorithm used for tau identification with four output classes
  - Electron, muon, jet, tau (*doi:10.1088/1748-0221/17/07/P07023*)
  - Three final discriminants : genuine tau vs ele, mu, jet
- Dedicated BDT for decay mode identification of hadronic taus
  - Optimized for best purity (*CMS-DP-2020-041*), HPS DM as input





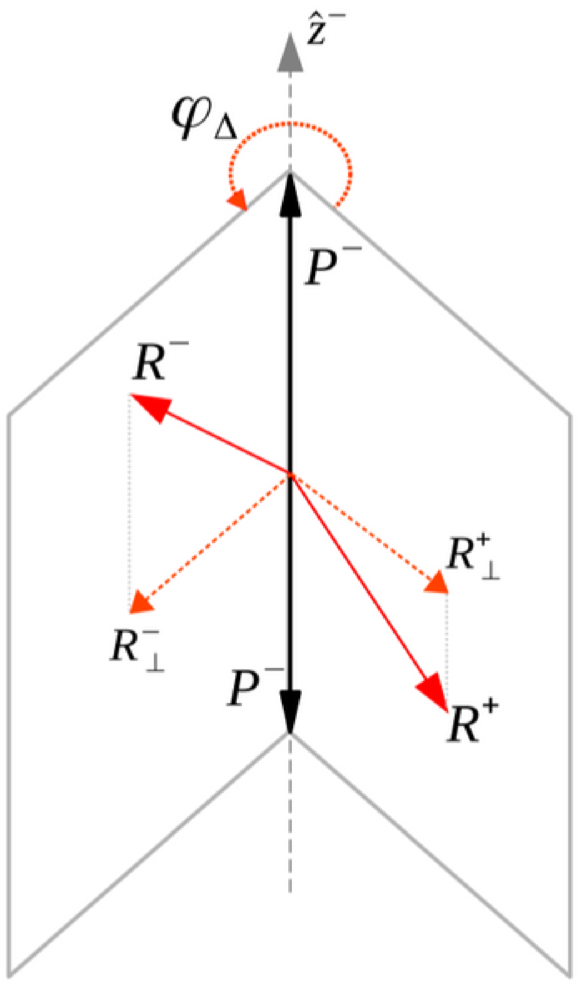
- DM 0 : $\tau_h \to \pi^\pm$
- DM 1 : $\tau_h \to \pi^\pm + \pi^0$
- DM 2 : $\tau_h \to \pi^\pm + 2\pi^0$
- DM 10 : $\tau_h \to 2\pi^\pm + \pi^\mp$
- DM 11 : $\tau_h \to 2\pi^\pm + \pi^\mp + \pi^0$

Event categorization

- 17 final states considered in Run II analysis, three categories : $\tau_h\tau_h, \tau_\mu\tau_h, \tau_e\tau_h$
- Events are further on categorized in three classes :
  - Signal, fakes, taus
  - DNN for $\tau_l\tau_h$ channels, BDT for $\tau_h\tau_h$
- Summary of methods used according to decay mode :

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 $\|\Delta\eta\|$	✓	
p_T^{miss}	✓	✓

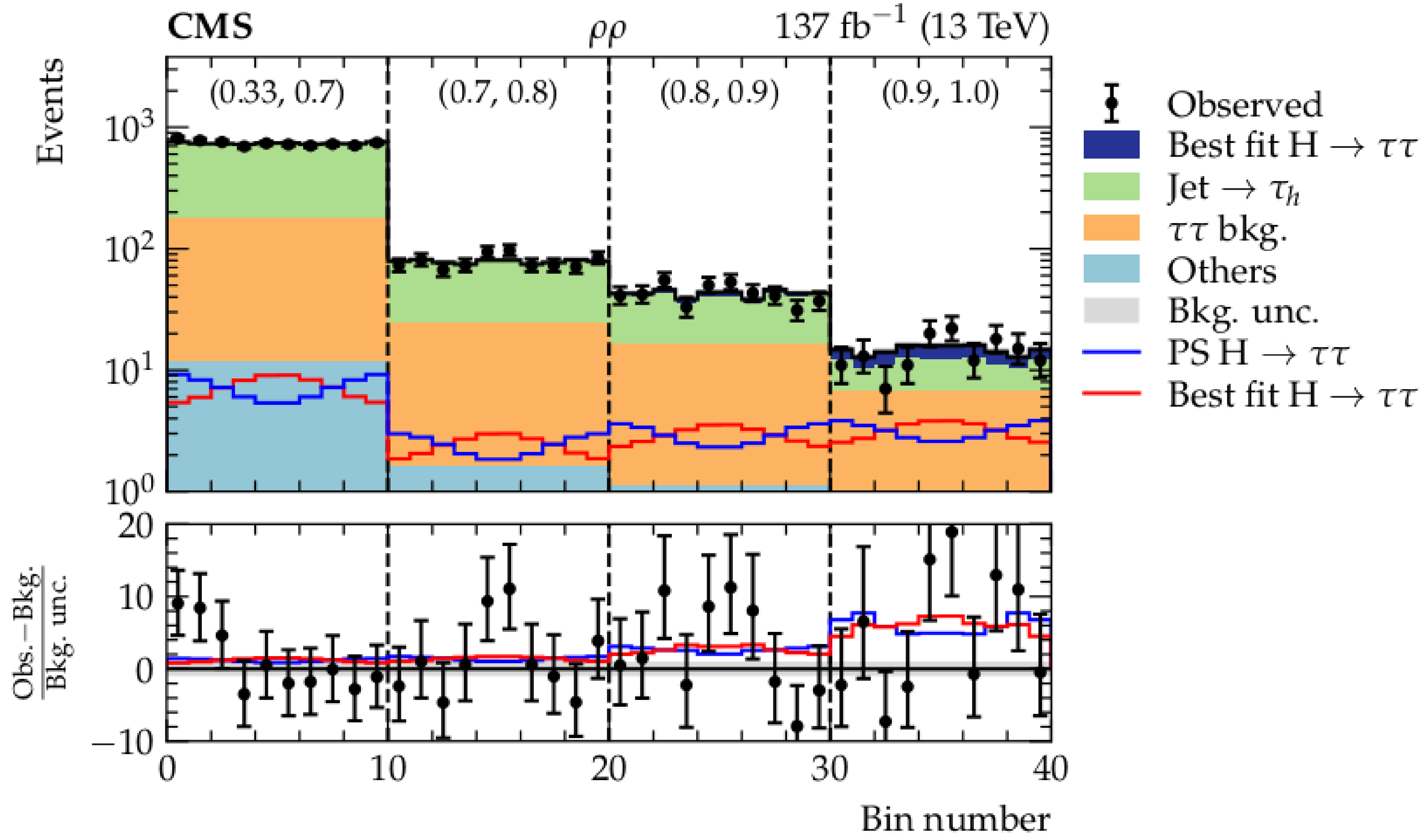
	Vectors			
Channel	P1	R1	P2	R2
$\tau_{l,\pi} \times \tau_{l,\pi}$	$\vec{p}_{l,\pi}$	$\vec{IP}_{l,\pi}$	$\vec{p}_{l,\pi}$	$\vec{IP}_{l,\pi}$
$\tau_{l,\pi} \times \tau_{\rho,a_1^{1Pr}}$	$\vec{p}_{l,\pi}$	$\vec{IP}_{l,\pi}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^0}$
$\tau_{l,\pi} \times \tau^\pm_{a_1^{3Pr}}$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

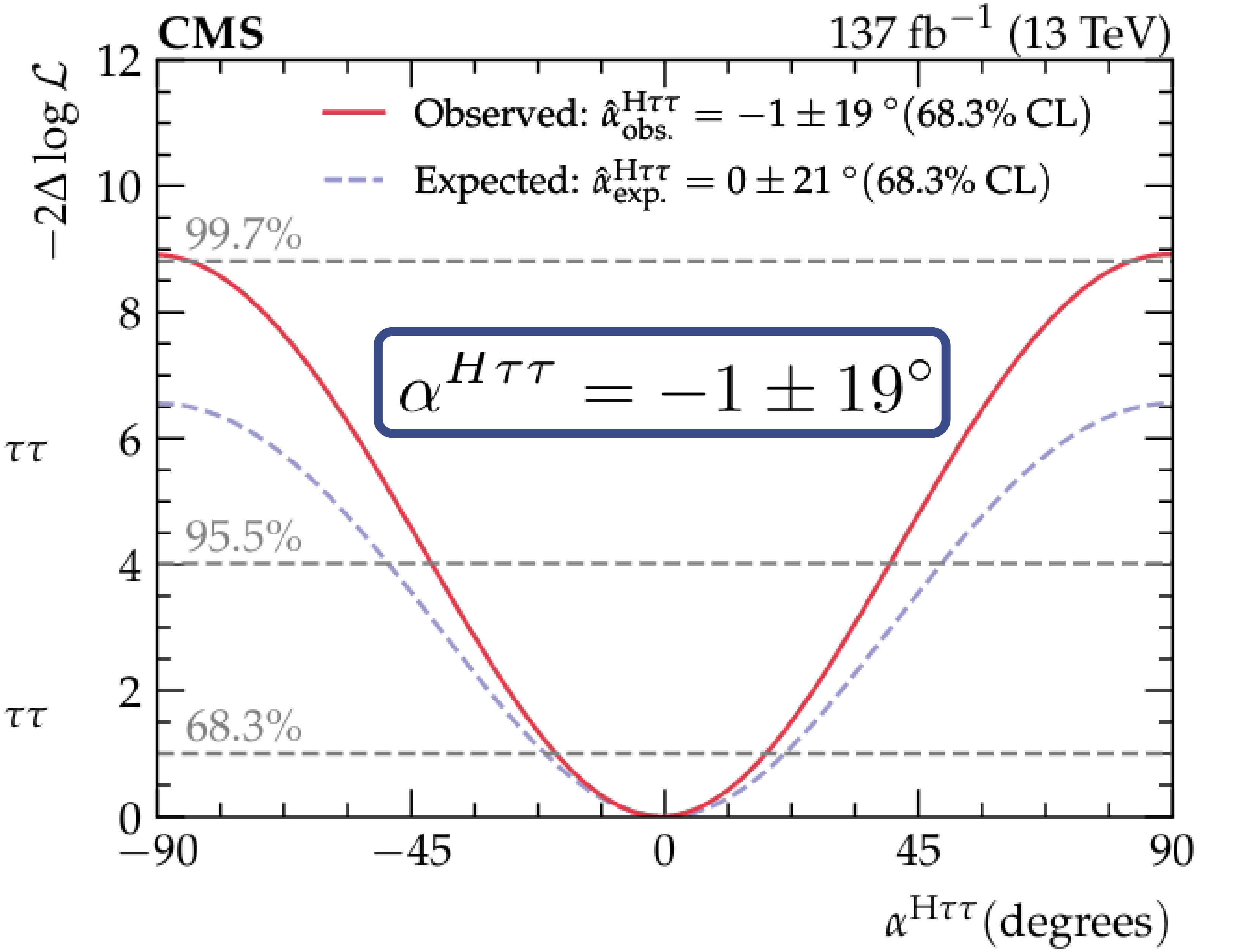


doi:10.3390/universe8050256

CP mixing angle measurement

- Simultaneous fit of the data
  - Example in signal category for rho-rho channel





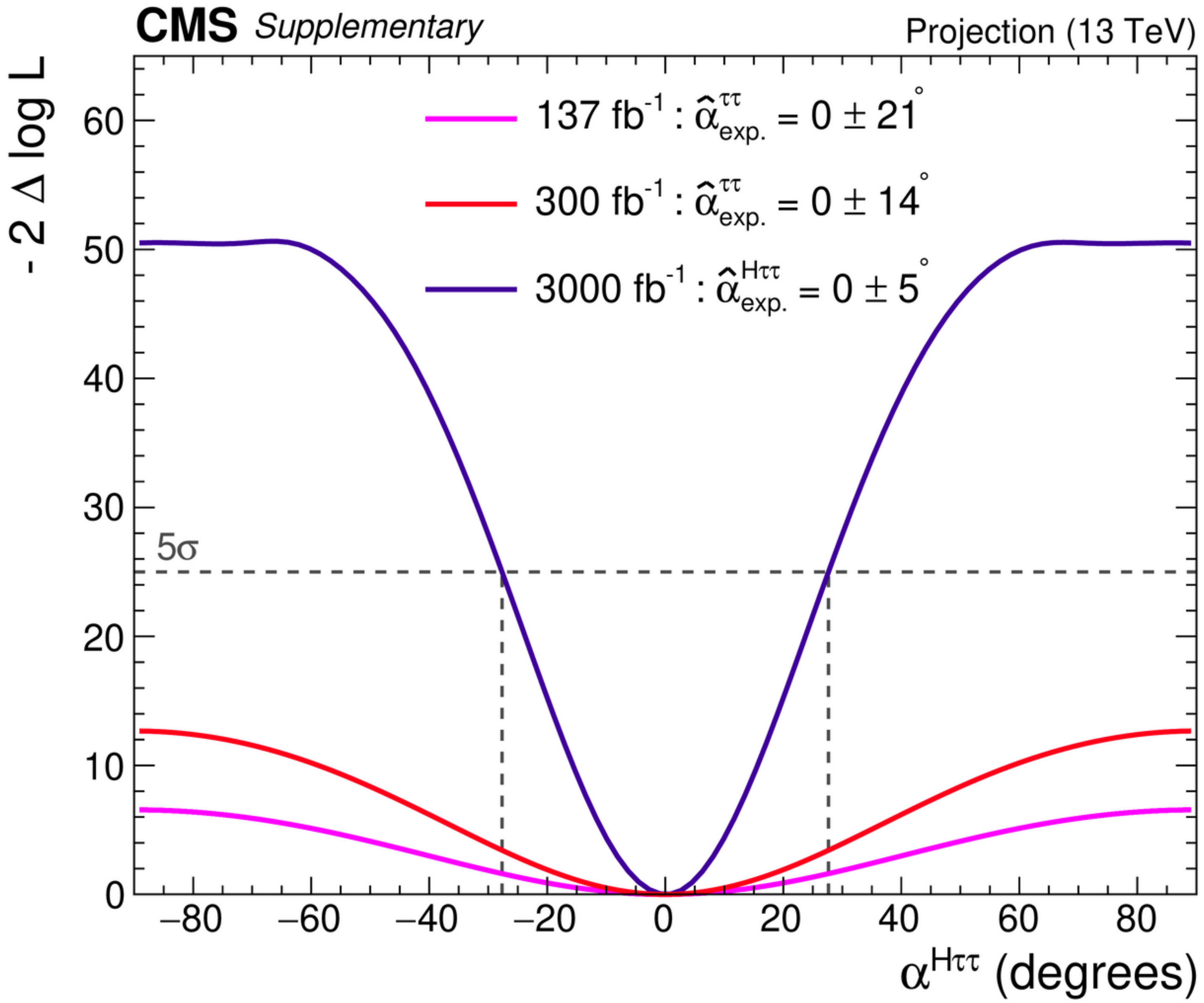
$$\alpha^{H\tau\tau} = -1 \pm 19(stat) \pm 1(syst) \pm 2(bin) \pm 1(theo)°$$

Exclusion of CP-odd hypothesis :

- Observed (exp.) significance = $3.0(2.6)\sigma$

Conclusion and prospects

- Run II analysis results are still compatible with SM predictions within the experimental uncertainties
- Run 3 is expected to bring more data and therefore reduce the dominant uncertainty on this measurement
- Wider use of the polarimetric vector method for greater sensitivity
  - Possible in channels employing an a1 resonance with the GEF algorithm (*doi:10.48550/arXiv.1805.06988*)
  - New tau reconstruction techniques will be developed for this purpose



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Thank you for your attention

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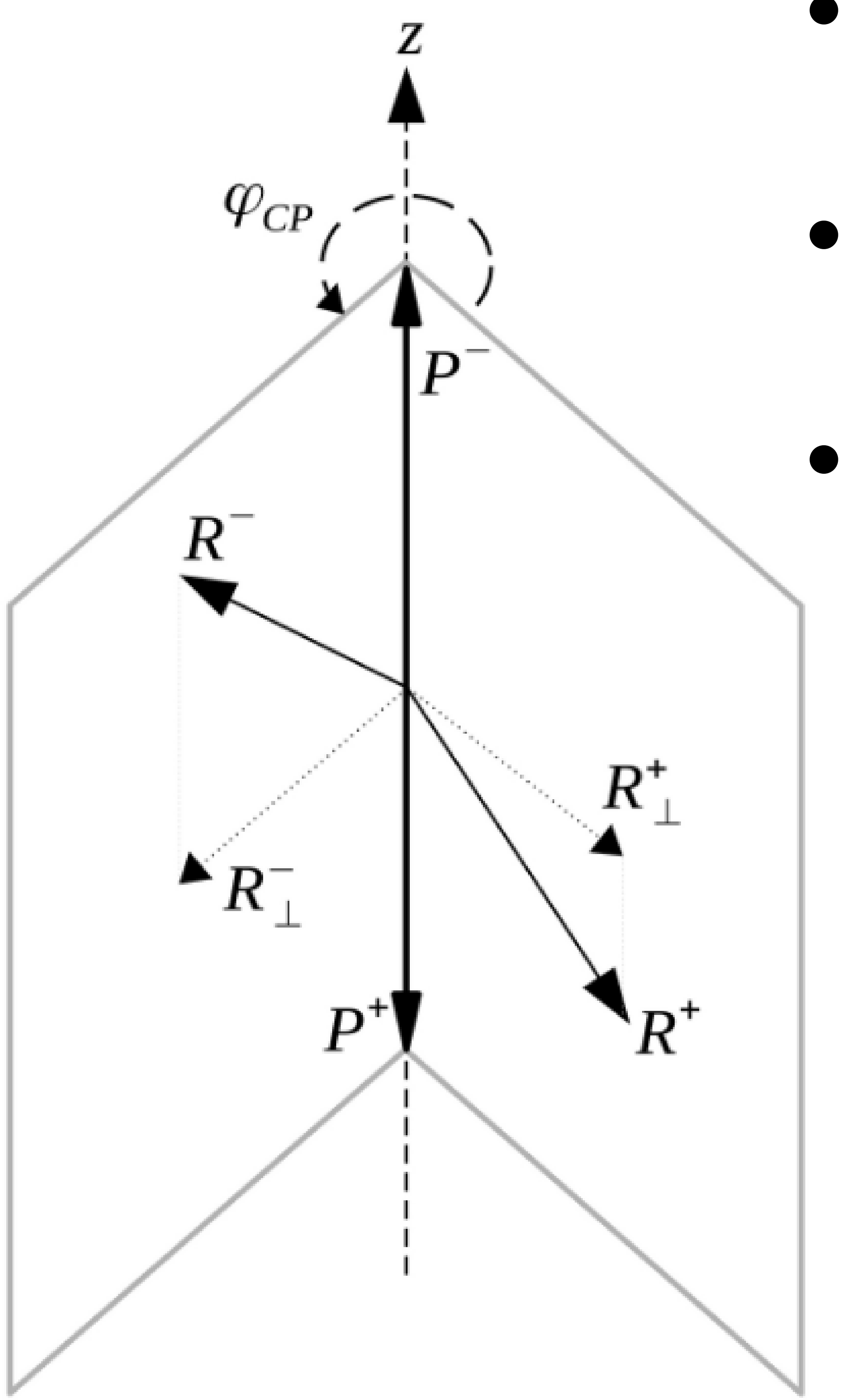
Acoplanar angle measurement



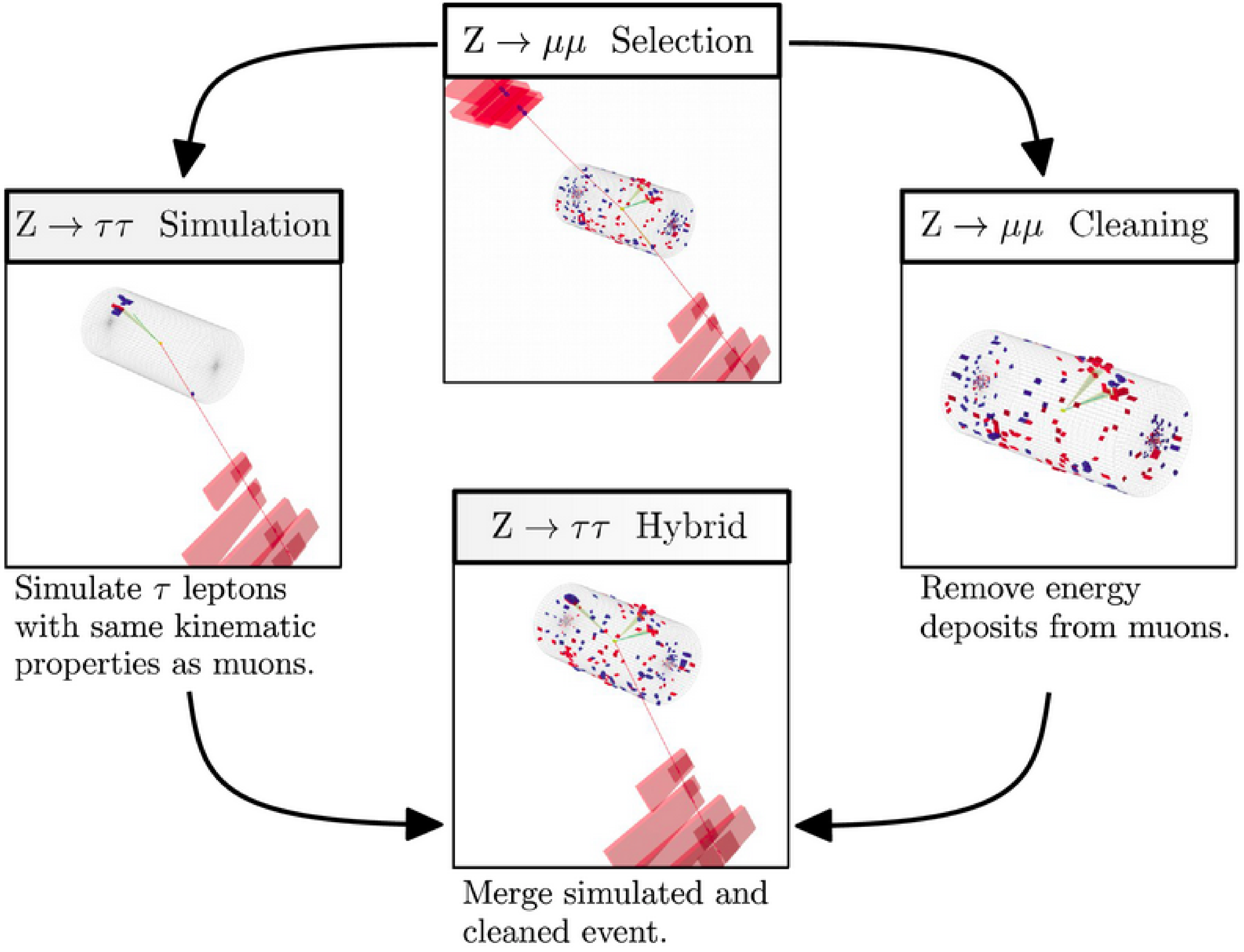
- Define planes using for each tau a momentum P and a vector R defined according to method
- Boost all vectors in zero momentum frame defined by the two momenta sum
- Use transverse component of each vector R w.r.t to its associated momentum P

$$\phi^* = (\hat{R}^+_\perp . \hat{R}^-_\perp)$$

$$O^*_{CP} = \hat{P}^- . (\hat{R}^+_\perp \times \hat{R}^-_\perp)$$

$$\phi_{CP} = \begin{cases} \phi^* & if \quad O^*_{CP} \geq 0 \\ 2\pi - \phi^* & if \quad O^*_{CP} < 0 \end{cases}$$

Embedding technique



- Used to estimate processes involving a pair of genuine taus
- Relies on lepton universality
- No need to simulate jets and pile up

Tau reconstruction in CMS

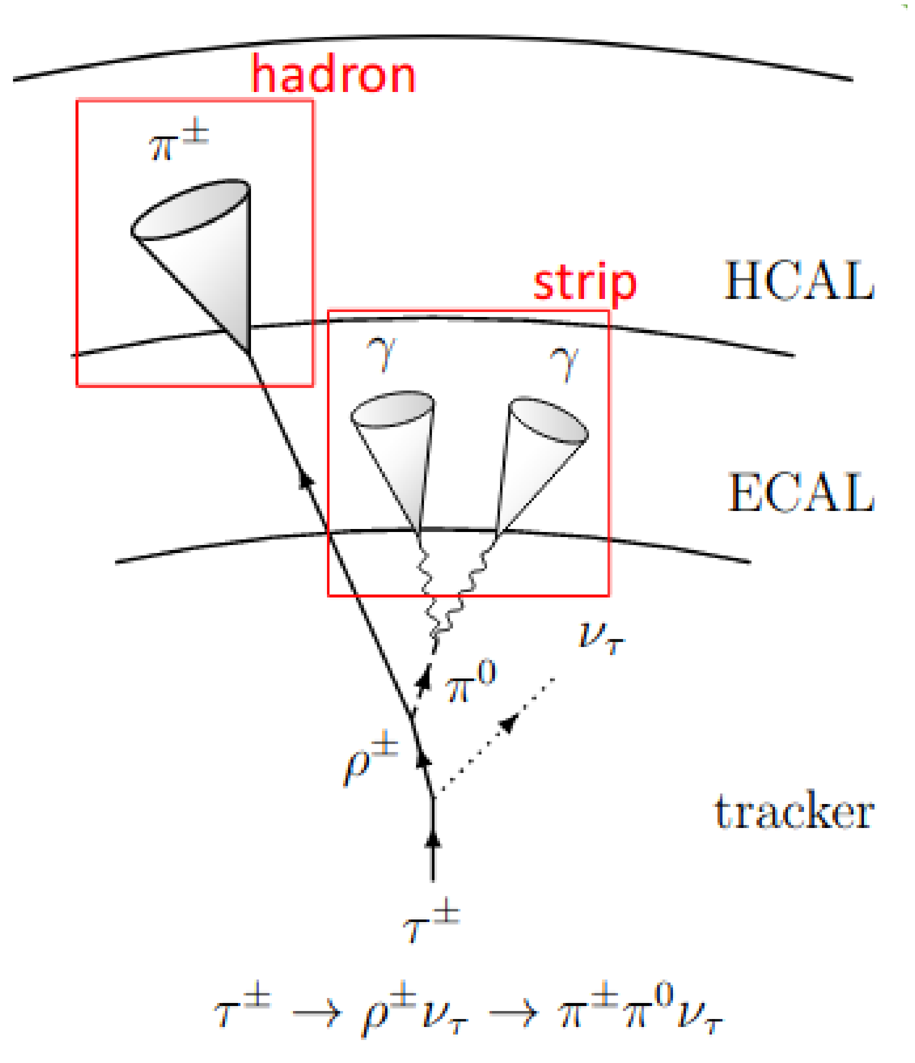
- Electrons, muons, photons, and hadrons are reconstructed by the Particle Flow algorithm
- HPS combines PF charged hadrons to neutral hadrons identified as strips in the ECAL from PF e/gammas
- 4 decay modes identified by HPS :

$$\tau_h \rightarrow \pi^{\pm}$$

$$\tau_h \rightarrow \pi^{\pm} + \pi^{0}$$

$$\tau_h \rightarrow 2\pi^{\pm} + \pi^{\mp}$$

$$\tau_h \rightarrow 2\pi^{\pm} + \pi^{\mp} + \pi^{0}$$

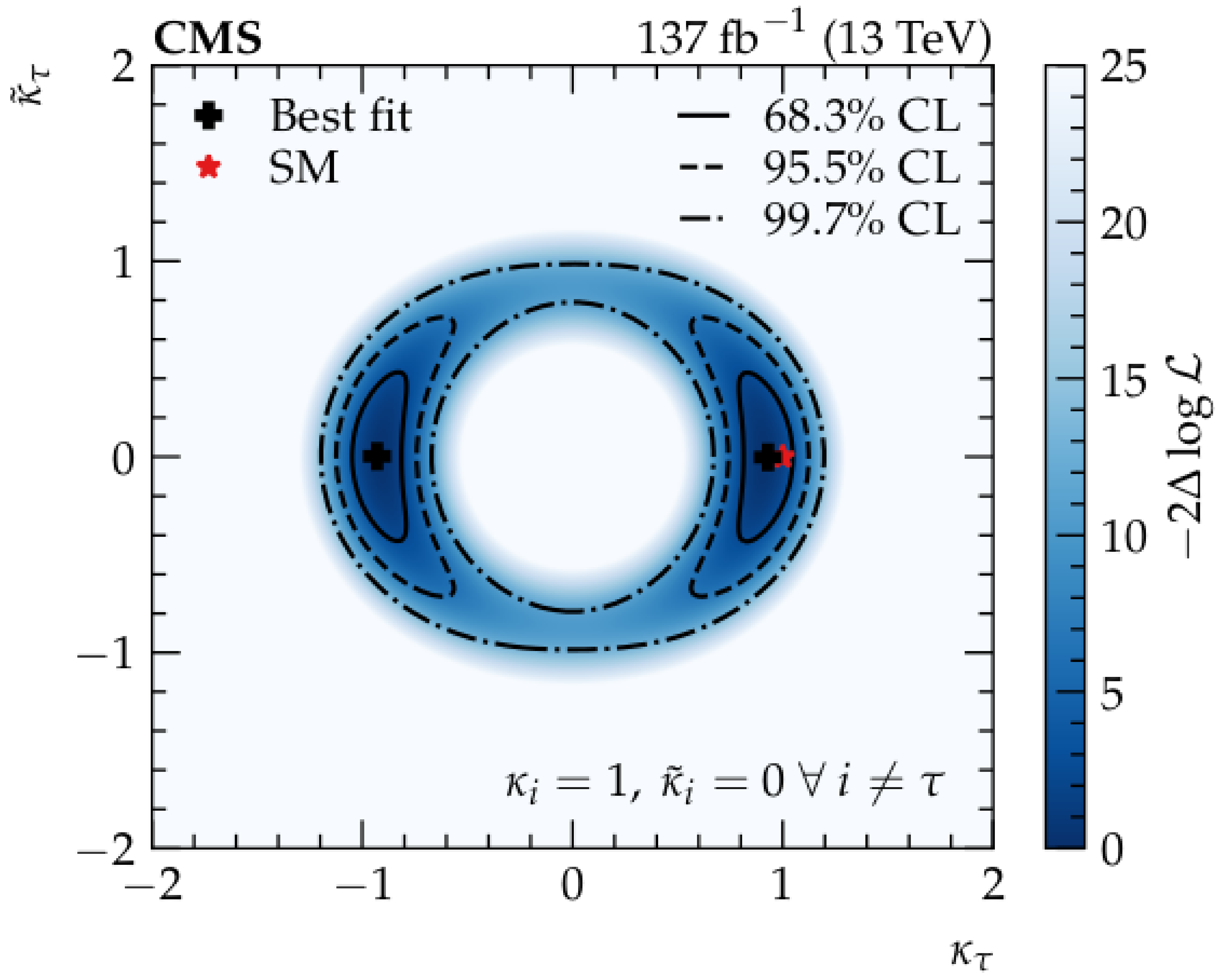


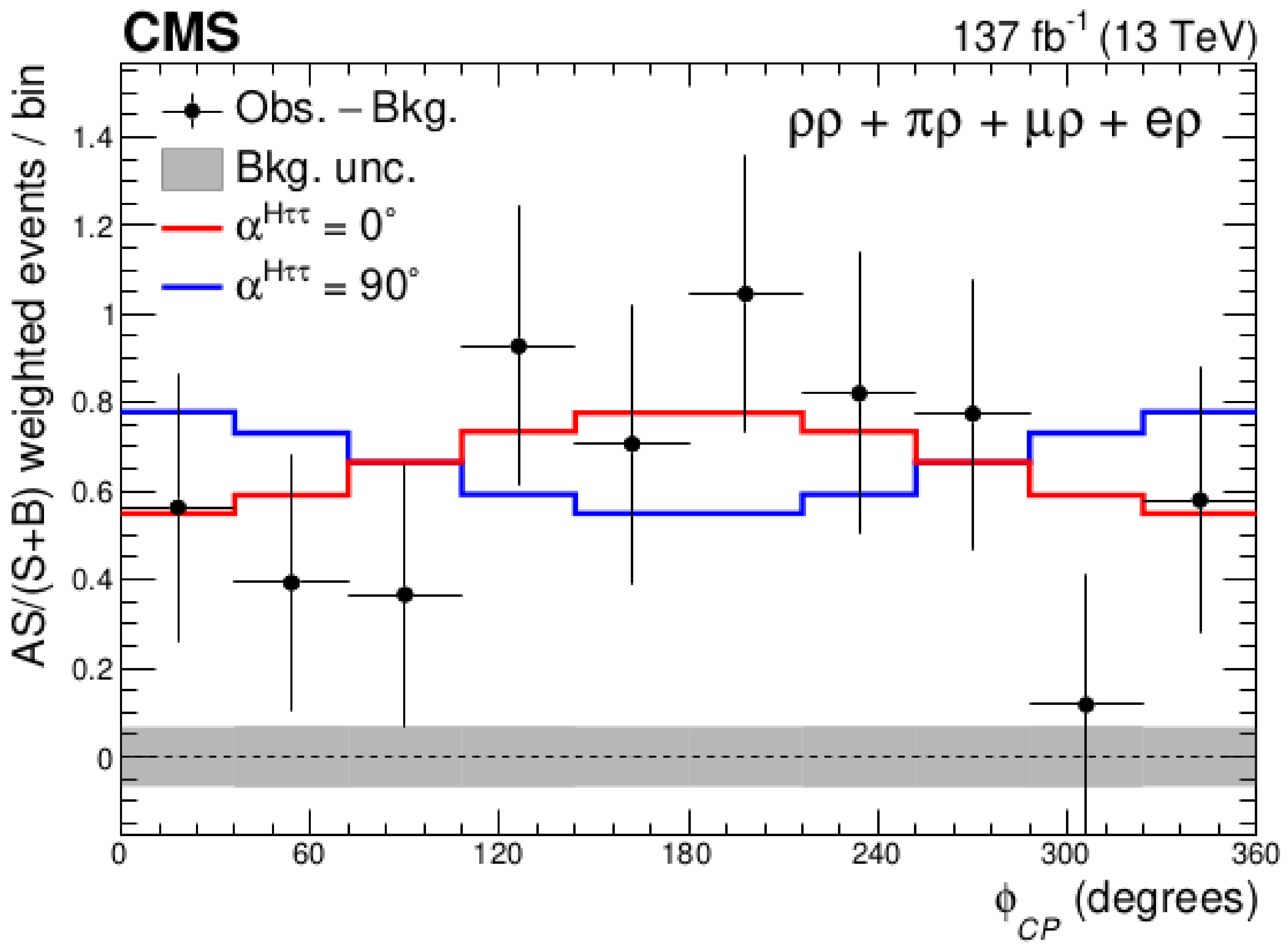
Decay mode identification

- Good CP sensitivity relies on good DM purity
- HPS not optimized for this task : dedicated BDT for DM identification
- Increases sensitivity of about 20% and identify 1 additional DM

$$\tau_h \rightarrow \pi^{\pm} + 2\pi^0$$

	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%


CMS
137 fb^{-1} (13 TeV)
Best fit
SM
68.3% CL
95.5% CL
99.7% CL
$\kappa_i = 1, \tilde{\kappa}_i = 0 \; \forall \, i \neq \tau$
$\tilde{\kappa}_\tau$
κ_τ
$-2\Delta \log \mathcal{L}$


CMS
137 fb^{-1} (13 TeV)
Obs. – Bkg.
Bkg. unc.
$\alpha^{H\tau\tau} = 0°$
$\alpha^{H\tau\tau} = 90°$
ρρ + πρ + μρ + eρ
AS/(S+B) weighted events / bin
ϕ_{CP} (degrees)