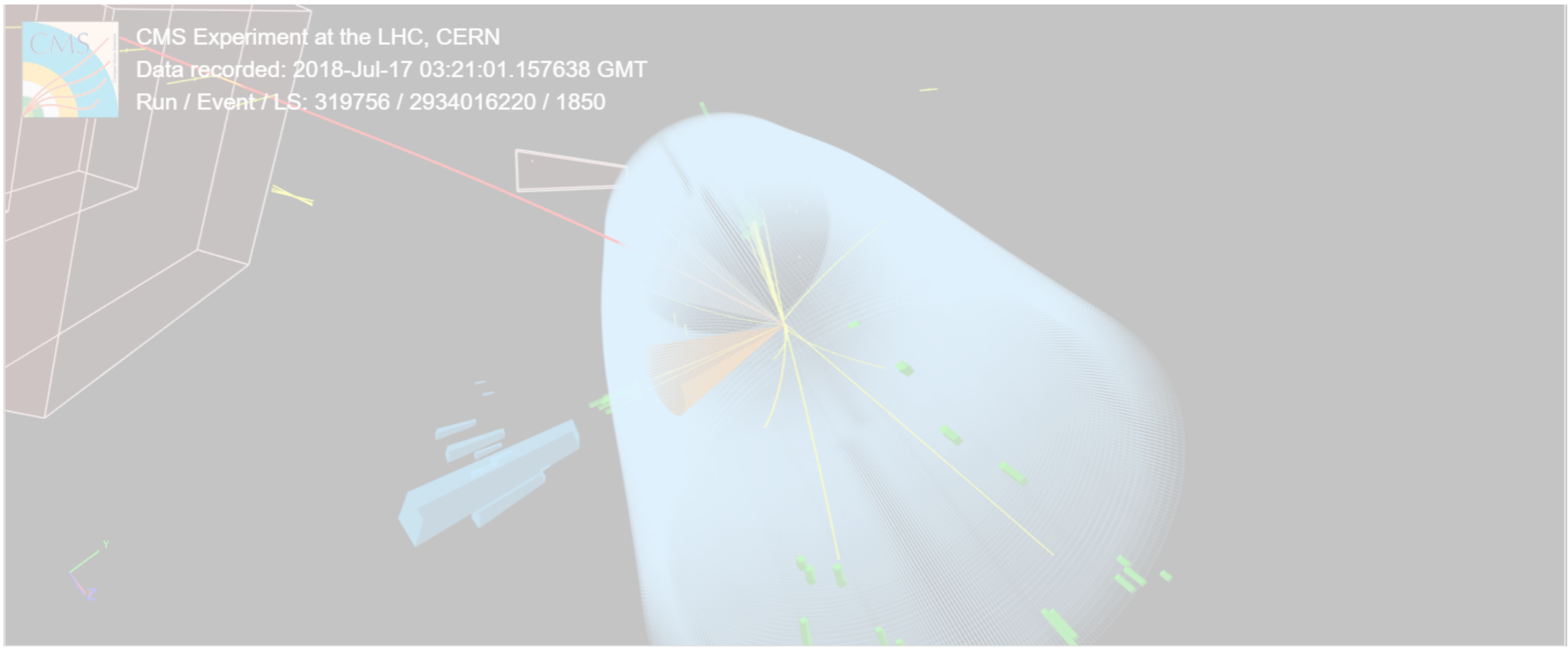
Measurement of CP structure of Higgs-tau Yukawa coupling



XXVII International workshop on Deep-Inelastic Scattering and Related subjects

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Introduction

- Motivation
  - The couplings of SM Higgs boson is even under charge-parity (CP) inversion.
  - For gauge bosons CP odd enters only at NLO or with higher order. CP odd couplings can occur for fermions already at tree level.
  - For $H \to \tau\tau$ we have model-independent measurement of the CP structure of Yukawa coupling.

- The results showed in the slides are from the CMS PAS HIG-20-006

- The analysis performed for full **Run II** data, in the channels $\tau_\mu\tau_h$ and $\tau_h\tau_h$.

Yukawa Lagrangian for $H \to \tau\tau$ decay

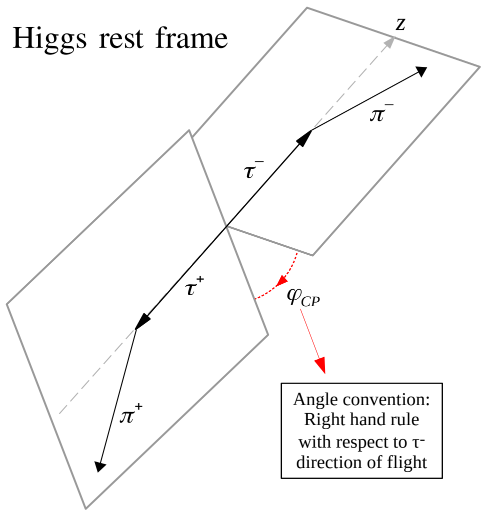
- The interaction of a Higgs boson *h* of arbitrary CP nature to τ leptons is described by the Yukawa Lagrangian.

$$\mathscr{L}_Y = -\frac{m_\tau}{v}(\kappa_\tau \bar{\tau}\tau + \bar{\kappa}_\tau \bar{\tau} i \gamma_5 \tau)h$$

Where m_τ is mass of the τ-lepton and the vacuum expectation value v has a value of 246 GeV. The effective mixing angle $\phi_{\tau\tau}$ for the H$\tau\tau$ coupling is defined in terms of the coupling as

$$\tan(\phi_{\tau\tau}) = \frac{\bar{\kappa}}{\kappa} \quad ; \quad \phi_{\tau\tau} \to 0 \ : \text{CP- even} \qquad \phi_{\tau\tau} \to \frac{\pi}{2} \ : \text{CP-odd}$$

Credits to A. Cardini for the schematic



- $H \to \tau\tau$ events differential cross section may write as,

$$\frac{d\sigma_{(H\to\tau\tau)}}{d\phi_{CP}} \propto -\cos(\phi_{CP} - 2\phi_{\tau\tau})$$

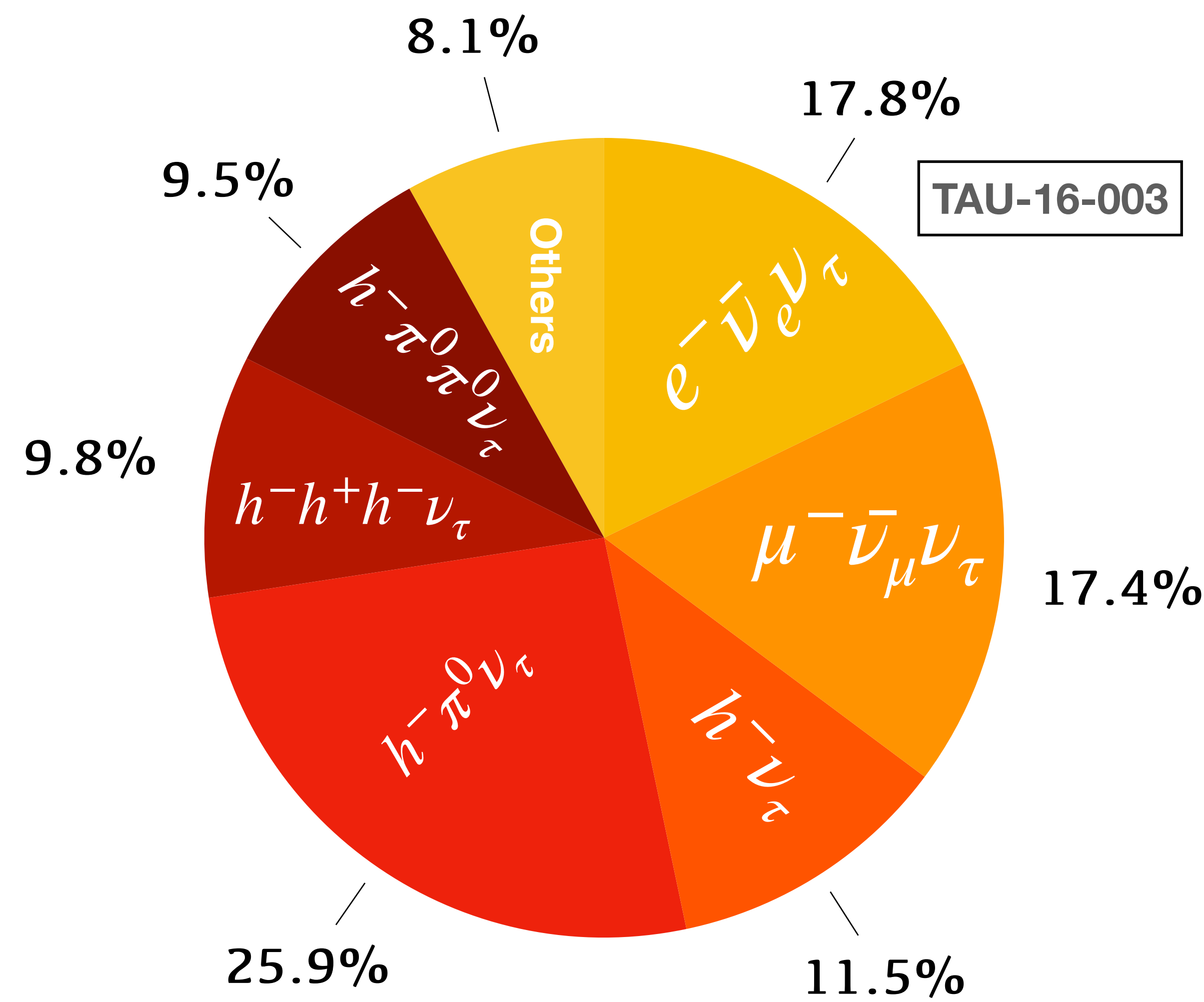
where the angle ϕ_{CP} denotes the angle between the τ lepton decay plane in the Higgs boson rest frame.

- Measuring the angle ϕ_{CP} can probe the mixing angle $\phi_{\tau\tau}$ of the $H \to \tau\tau$ events. Which have the advantage that the measurement can be interpreted **model-independently**.

ϕ_{CP} Reconstruction

- Tau lepton decays **leptonically** and **hadronically**. The branching fraction is shown right.

- There are separate methods to construct the angle between two tau lepton decay planes ϕ_{CP} for each decay modes.



- For 1prong decays such as $(\mu^\pm, e^\pm, \pi^\pm)$ each decay plane constructed from charged particle momentum and **impact parameter**

- When tau decays to at least one π^0 particle, decay planes constructed from the momenta of charged and neutral pions.

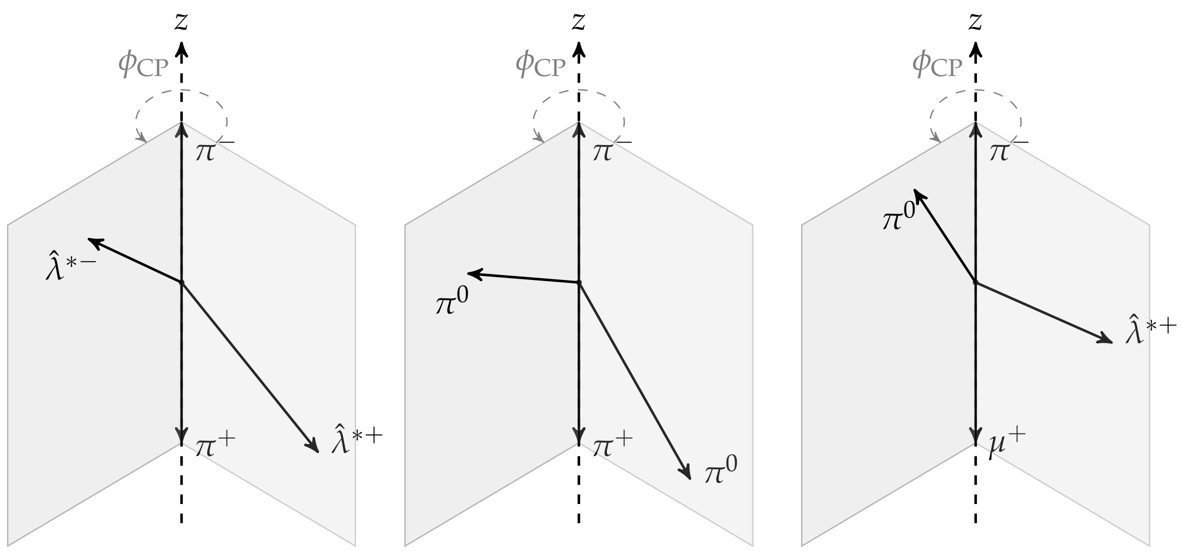
ϕ_{CP} Reconstruction

1. Impact Parameter Method: We obtained 3-dimensional IP vector by parametrise helical trajectory

   - define four-vector $\lambda^{\pm} = (\hat{n}^{\pm}, 0)$ and charged momentum vectors $q^{\pm}$.
   - Boost the vectors into $\pi^{+}\pi^{-}$zero-momentum frame(ZMF) of the charged decay products $\lambda^{*\pm}$, $q^{*\pm}$.
   - Calculate angle and sign,

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

$$O^{*} = \hat{q}^{*-} . (\hat{\lambda}^{*+}_{\perp} \times \hat{\lambda}^{*-}_{\perp})$$



   - Define $\phi_{CP} = \phi^{*}$ if $O^{*} \geq 0$ else $\phi_{CP} = 2\pi - \phi^{*}$

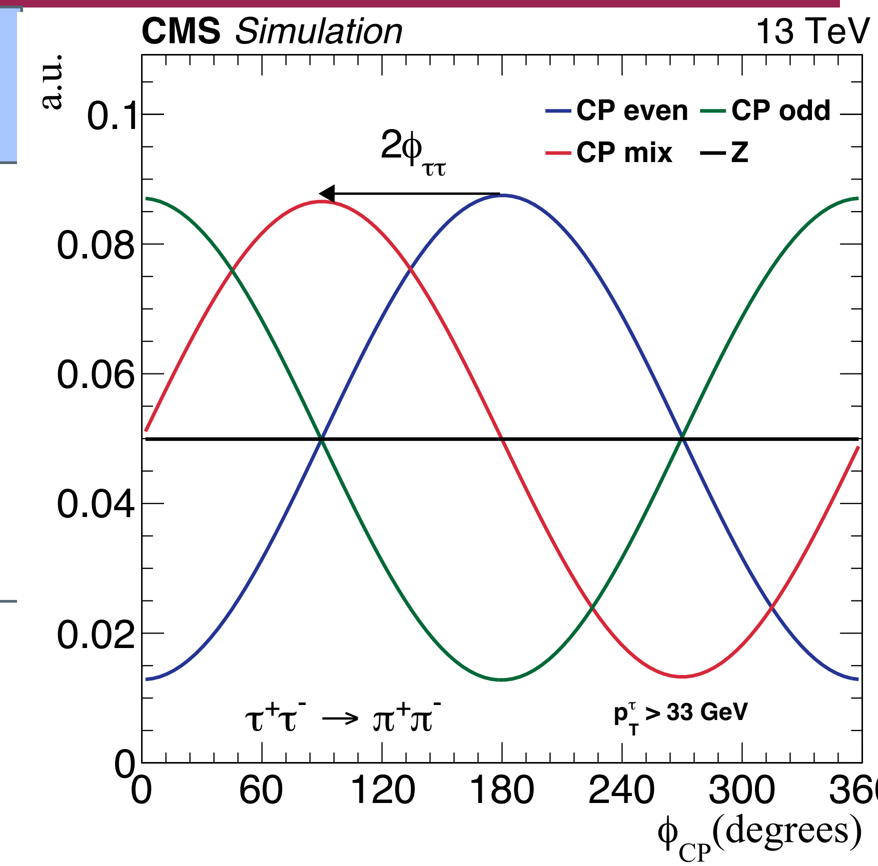
2. Neutral pion momenta:Instead of IP vector, the decay plane constructed from the momenta of charged and neutral pion.

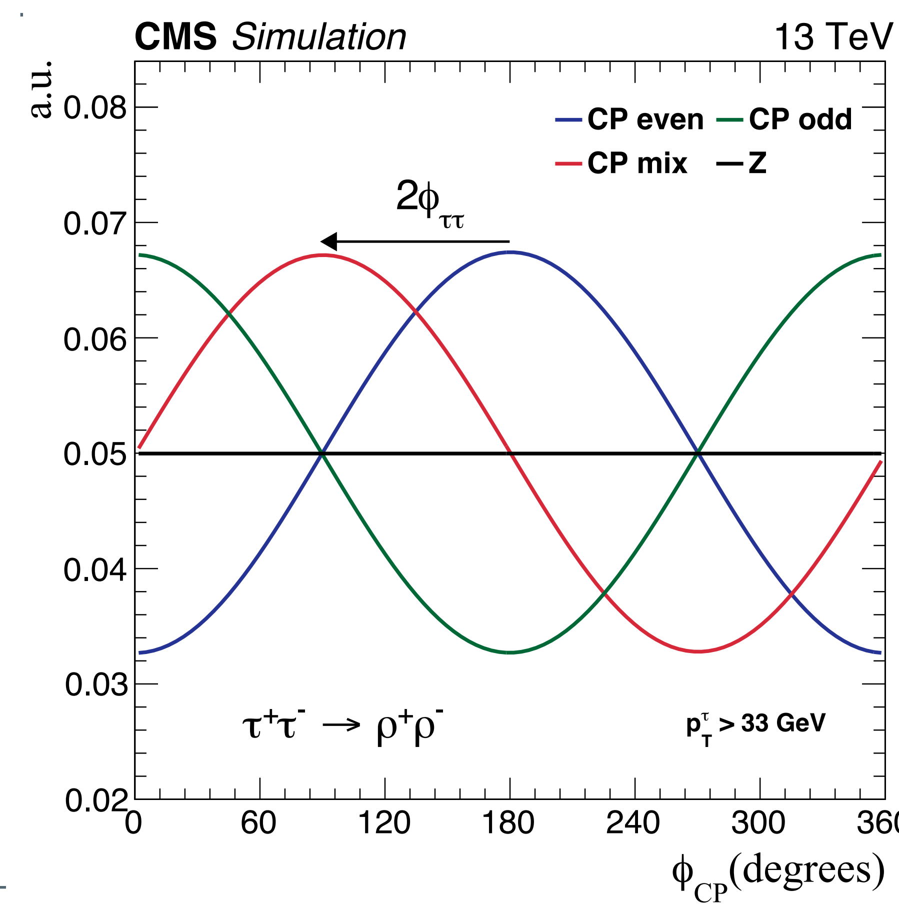
   - On special case $(a_1^{3pr} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm})$ select oppositely charged $\pi^{\pm}$ pair with invariant mass closest to ρ^{0}. Treat π with opposite charge to a_1^{3pr} as if it was neutral pion.

3. Mixed method: Cases where one hand is decay to 1 prong and other hand have neutral pion,

ϕ_{CP} Reconstruction

	Decay channels	Method used to construct ϕ_{CP}
$\tau_\mu \tau_h$	$\mu\pi$	IP
	$\mu\rho$	Mixed
	μa_1^{3pr}	Mixed
	μa_1^{1pr}	Mixed
$\tau_h \tau_h$	$\pi\pi$	IP
	πa_1^{1pr}	Mixed
	πa_1^{3pr}	Mixed
	$\pi\rho$	Mixed
	$\rho\rho$	Neutral pion
	ρa_1^{1pr}	Neutral pion
	ρa_1^{3pr}	Neutral pion
	$a_1^{3pr} a_1^{1pr}$	Neutral pion
	$a_1^{1pr} a_1^{1pr}$	Neutral pion
	$a_1^{3pr} a_1^{3pr}$	Neutral pion



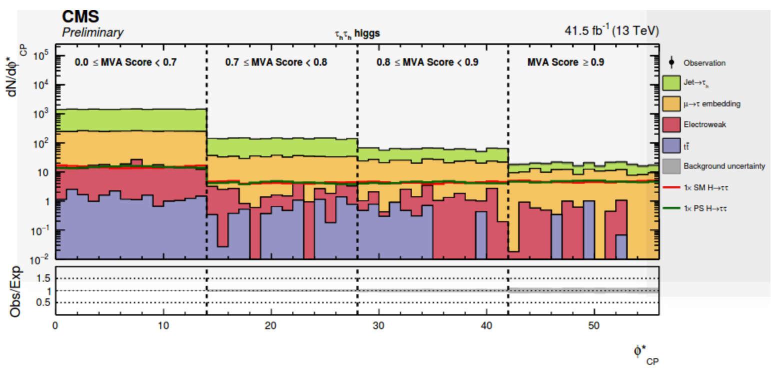


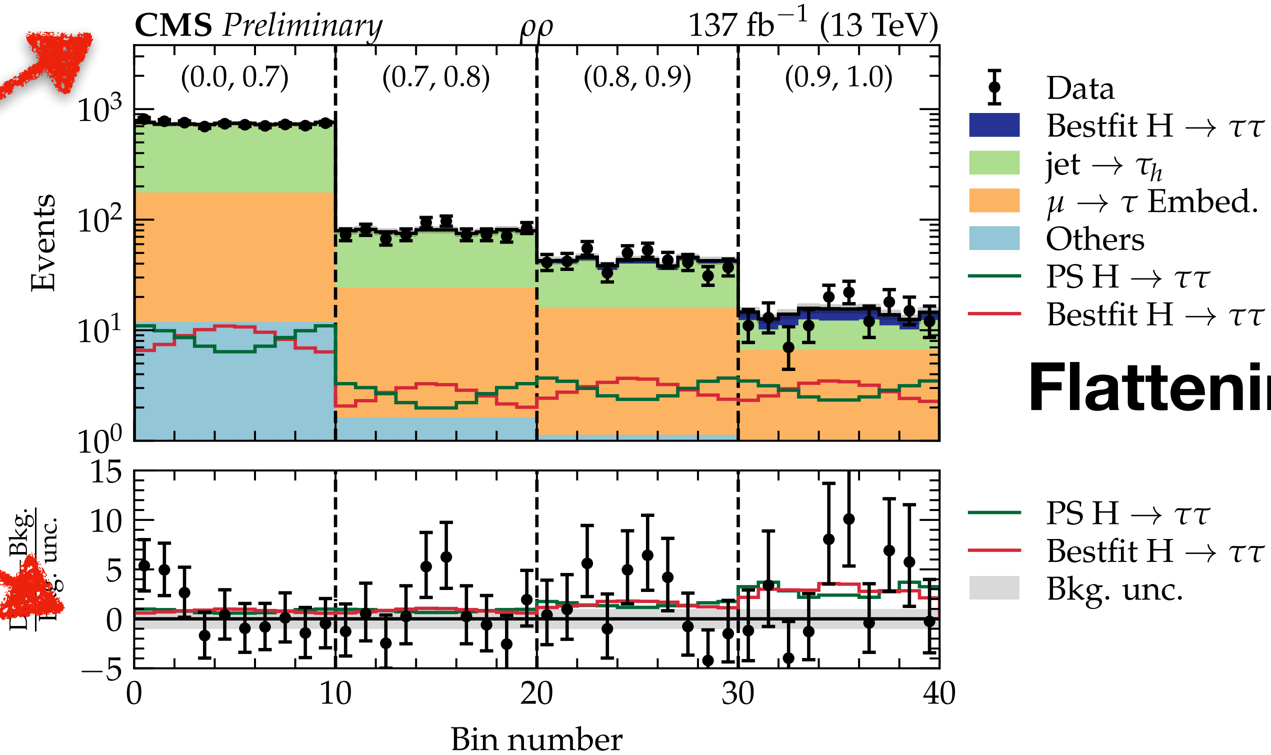
Analysis Strategy

- The event selection, bkg. estimation and corrections are outlined in the PAS.
- Special methods implemented in the analysis for the better performance
  - Vertex Refitting:(excluding tracks from tau decay and applying BeamSpot Constraints)
  - MVA decay mode identification:(new choice of DM improves sensitivity ~20%)
  - Bkg. Flattening/symmetrisation
- Extraction of signal and background events performed via ML techniques
  - Neural Network for $\tau_\mu \tau_h$ events
  - BDT for $\tau_h \tau_h$ events
- ϕ_{CP} distribution gives a good discrimination for CP-even states from the CP-odd states, from that CP-mixing angle $\phi_{\tau\tau}$ extracted using maximum likelihood fit.

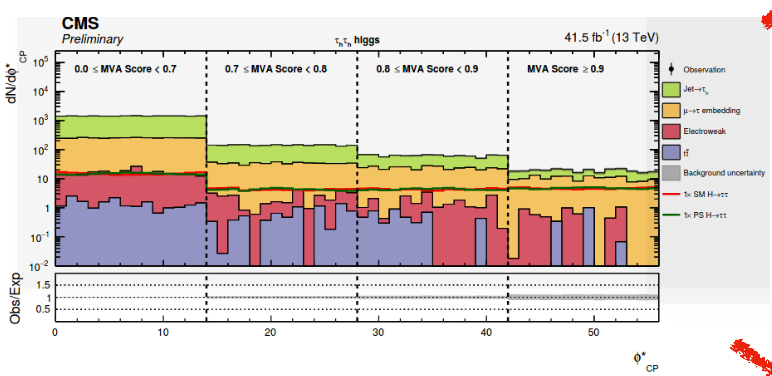
Final Discriminant

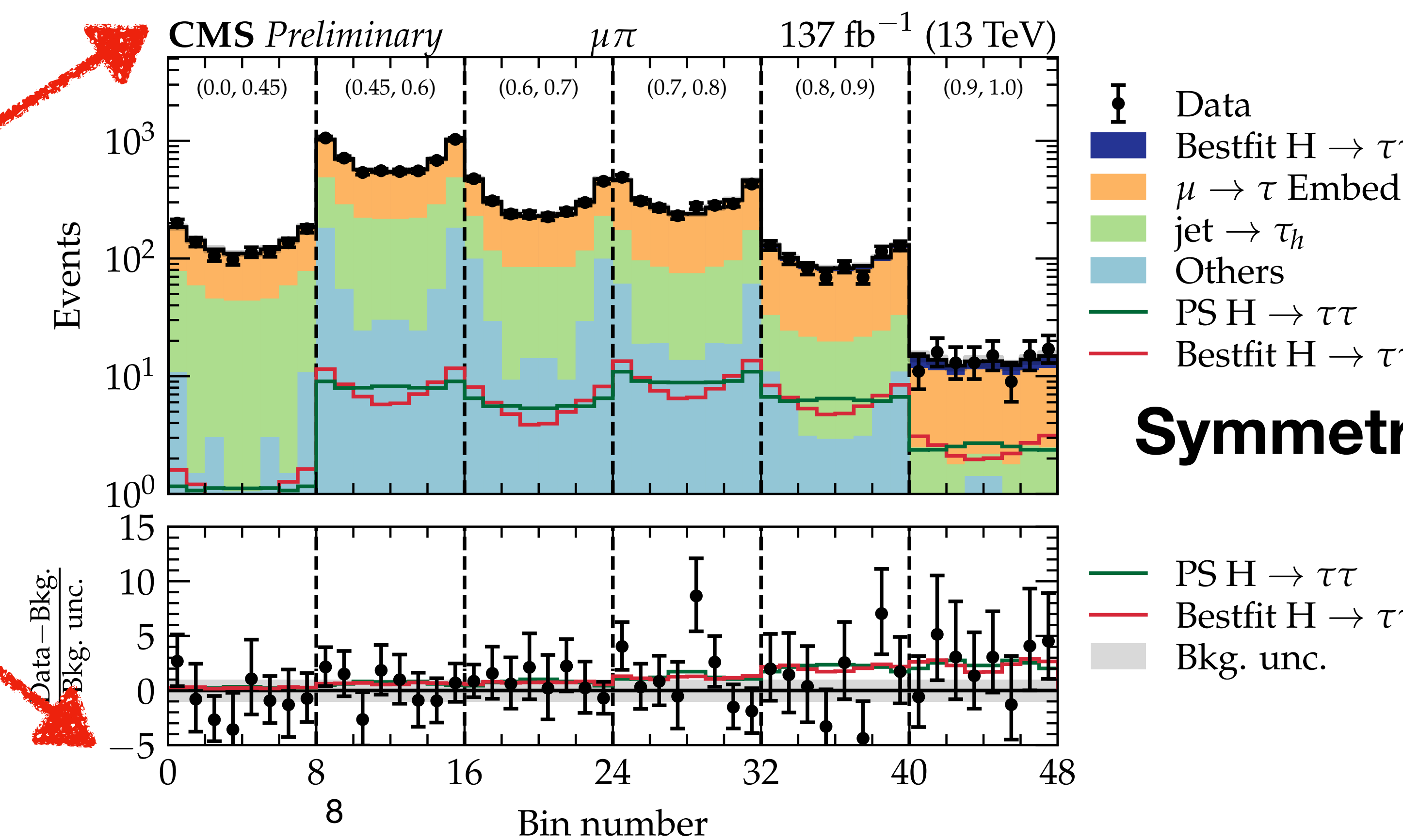
- ϕ_{CP} distributions of the events in the signal categories are analysed in windows of increasing MVA score. This final 2D enrolled distribution used as the final discriminant.





Flattening



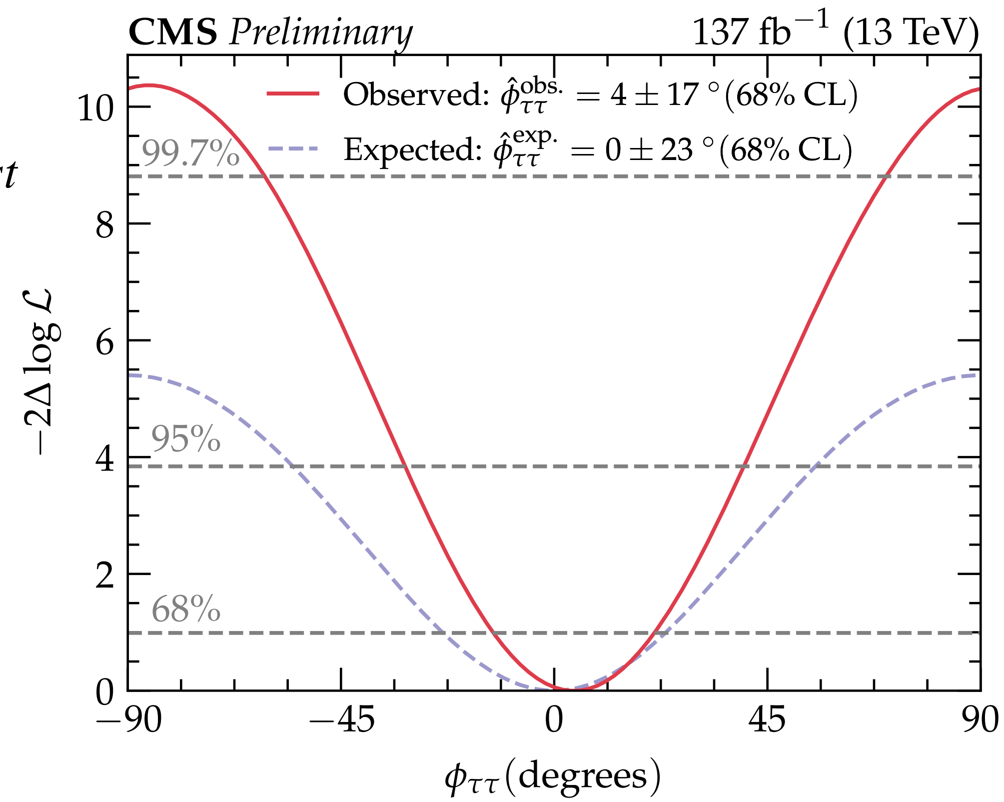


Symmetrising

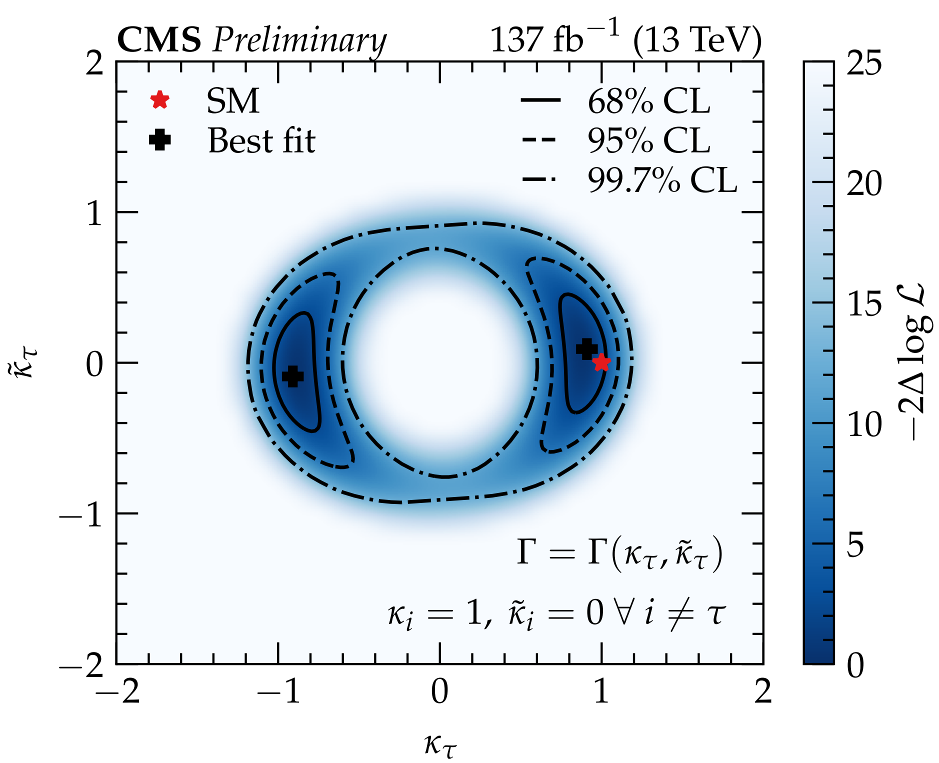
Estimation of $\phi_{\tau\tau}$: Combined fit

- The likelihood function $L(\overrightarrow{\mu}, \phi_{\tau\tau}, \theta)$, depends on Higgs boson signal strength $\overrightarrow{\mu} = (\mu_{ggH}, \mu_{qqH})$, the CP-mixing angle $\phi_{\tau\tau}$ and the nuisance parameters $\overrightarrow{\theta}$.

- While performing maximum likelihood fit, we left $\phi_{\tau\tau}$ and $\overrightarrow{\mu}$ parameters freely floating.



  - Scanning over $\phi_{\tau\tau}$ around the best fit value $\phi_{\tau\tau}^{best}$
  - $-2\Delta \ln L = -2.(\ln(L(\phi_{\tau\tau})) - \ln(L(\phi_{\tau\tau}^{best})))$



  - Dedicated 2D scan performed with the Yukawa couplings
  - The measurement appears consistent with SM prediction within 68% CL.

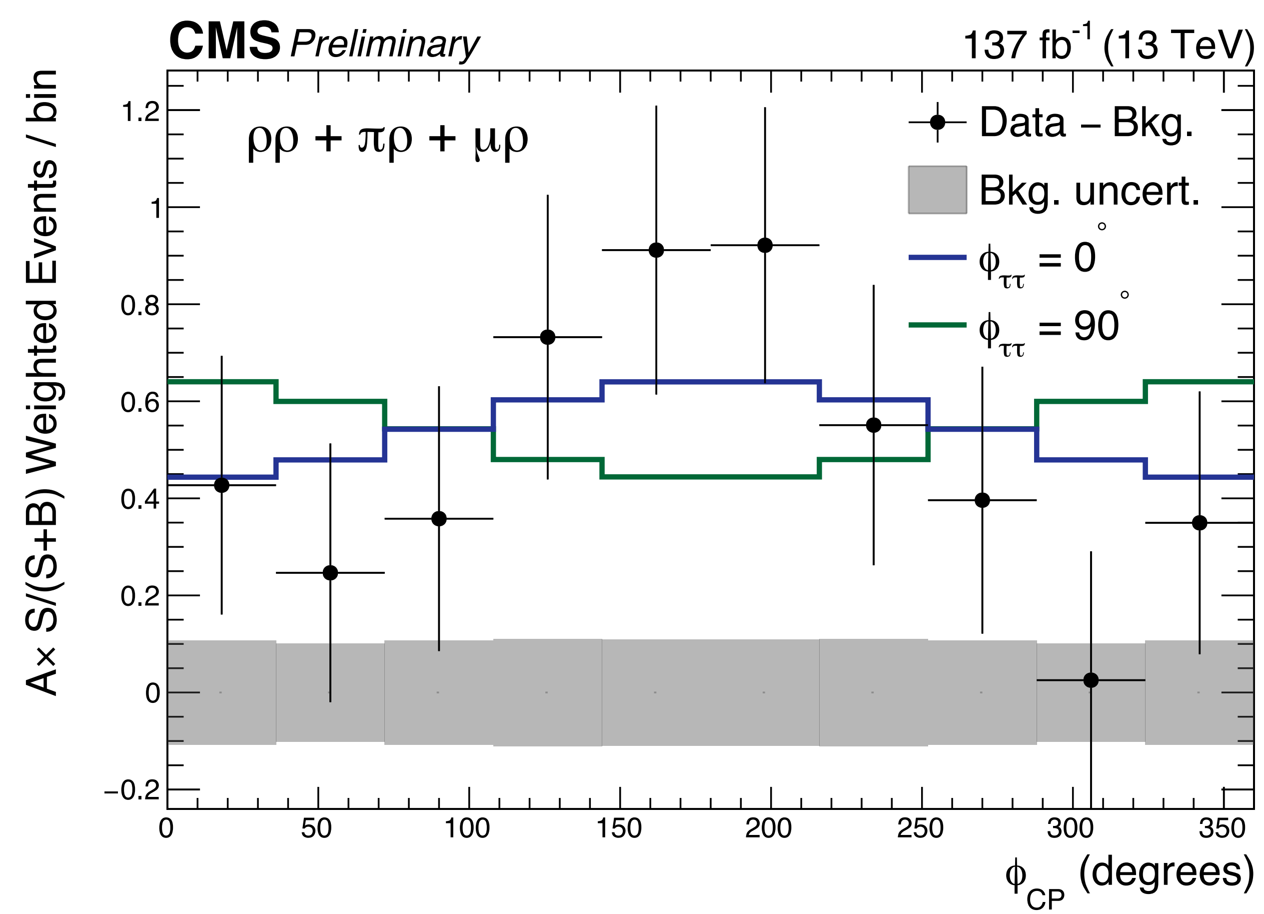
Summary

- Presented full Run II results for the measurement of the CP structure of Yukawa interaction between the Higgs boson and the τ lepton

- Current measurement performed on the $\tau_\mu \tau_h$ and $\tau_h \tau_h$ channels.

  - The observed result on the CP mixing angle at 68 % CL of

$$\phi_{\tau\tau} = 4^{\circ} \pm 17^{\circ}(stat).$$
$$\pm 2^{\circ}(\text{bin-by-bin})$$
$$\pm 1^{\circ}(\text{syst}) \pm 1^{\circ}(\text{theory})$$



  - A pure pseudo scalar boson excluded at 3.2σ significance

  - Results consistent with the SM

  - Further studies using $\tau_e \tau_h$ channel and measurement using polarimetric vector method for $a_1^{3pr} a_1^{3pr}$ decay mode will be included in the final publication

Back up

Baseline Di-τ event selection

- Tau lepton pair should be opposite charge and separated by at least ΔR = 0.5
- Offline objects should matched with trigger object.
- Only one candidate pair of di-tau events selected in the basis of isolation and p_T of candidate pairs.

$\tau_h\tau_\mu$ events:

- Large W+jets background is reduced by,
- $m_T = \sqrt{2p_T^\mu p_T^{miss}[1 - \cos\Delta\phi]} < 50GeV$
- Longitudes and transverse impact parameters $|d_z| < 0.2cm$ and $|d_{xy}| < 0.045cm$ for τ_μ
- τ_μ to pass medium MuonID, τ_h to pass medium,vvloose and tight DeepTau isolation against jets,electron and muon respectively

$\tau_h\tau_h$ events:

- τ_h to pass medium,vvloose and tight DeepTau isolation against jets,electron and muon respectively
- Longitudes and transverse impact parameters $|d_z| < 0.2cm$ for leading τ_h track.
- Selection of the visible di-tau mass applied for $m_{vis} > 40GeV$
- b-tagged jet veto (medium deepCSV)

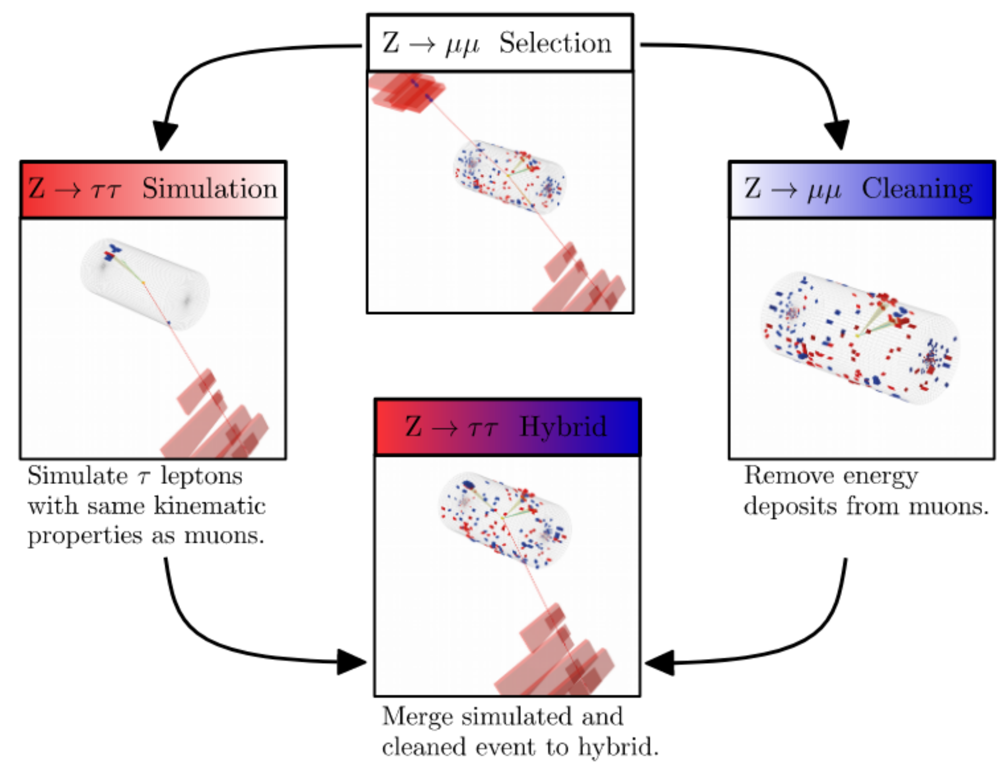
Background estimation: Data driven

- The main background process to consider are: Drell-Yan Z/γ^*, W + jets,$t\bar{t}$ + jets, QCD multi-jet, electroweak W/Z, single-top and di-boson productions

- All high fraction of backgrounds are estimated using data driven methods,

1. Embedded samples: is used to process with two genuine τ-leptons, mostly $Z/\gamma^* \rightarrow \tau\tau$ and a small fraction of $t\bar{t}$ and di-boson process.

   Derived based on principle of lepton universality.



2. Fake factors method: is used to process jet $\rightarrow \tau_h$ events.

   Mostly for,

   - QCD process ($\tau_\mu\tau_h$ and $\tau_h\tau_h$)
   - W + jets ($\tau_\mu\tau_h$)
   - $t\bar{t}$ ($\tau_\mu\tau_h$)

3. MC simulation: all remaining process like $Z/\gamma^* \rightarrow ll$ estimated using MC generator

Vertex Refitting

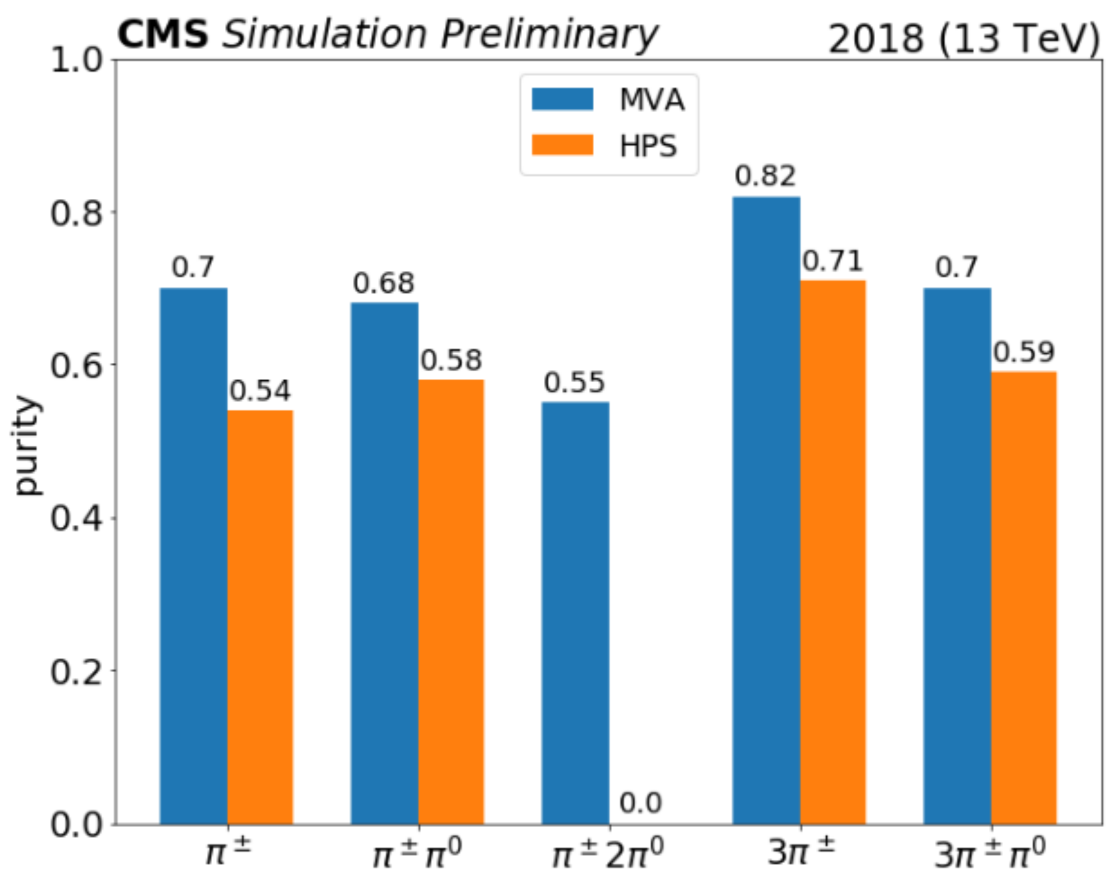
- The Impact parameter method rely on the precise measurement of the Primary Vertex.
- Tracks from high pT tau decay can bias the vertex fitting, so we chose to exclude tracks from the τ decay tracks for the vertex fitting and included beam spot constraints.

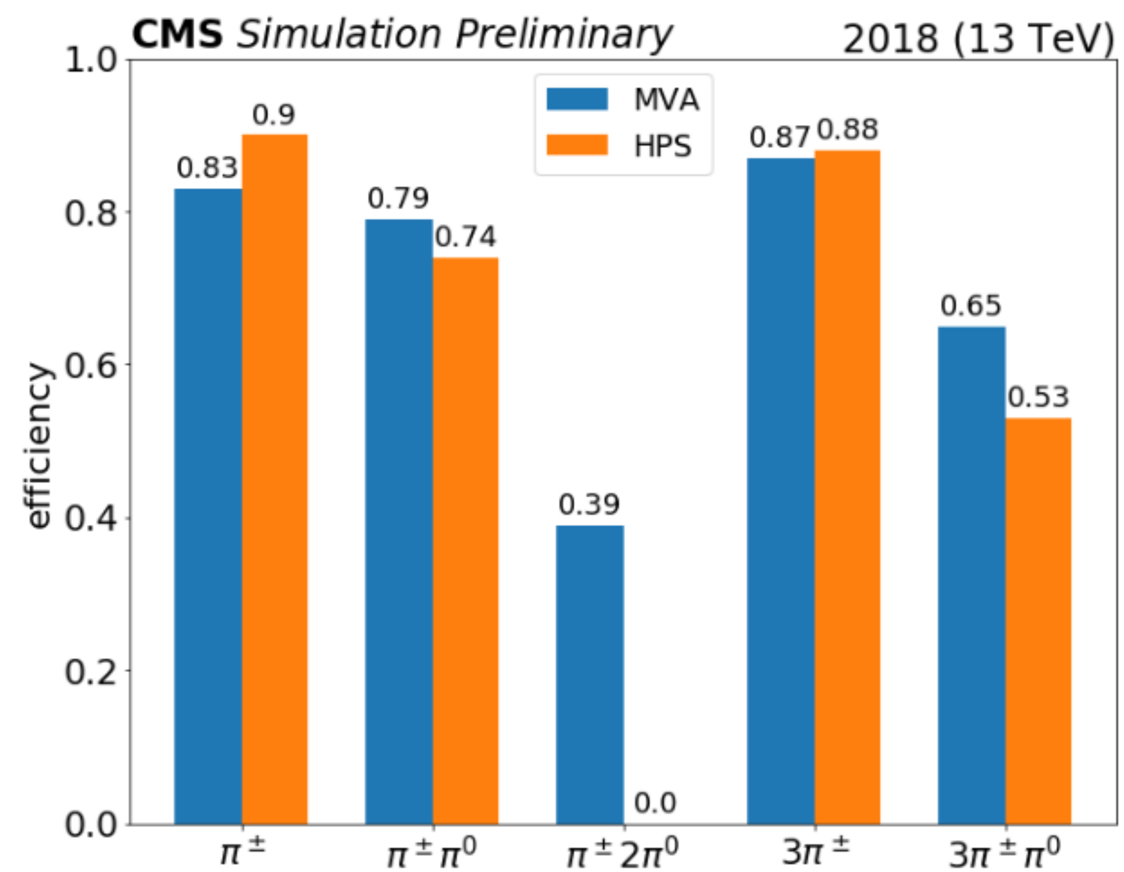
Production mode	Vertex type	σ_x^{PV}	σ_y^{PV}	σ_z^{PV}
$H \to \tau_\mu \tau_h$	Nominal	17	17	26
	Refitted Beamspot-Corrected	5	5	29
$Z \to \tau_\mu \tau_h$	Nominal	20	20	30
	Refitted Beamspot-Corrected	5	5	34

- The above table shows the resolution plots for different choice of vertex refitting.
- Approximately 3 times improvement of resolution in the transverse plane.

MVA based τ_h decay modes

- Different hadronic τ-decay modes are reconstructed from the HPS algorithm.
- BDT based MVA technique used to improve the reconstruction of decay modes.
- The new MVA based decay modes improves assignment of 1 prong + $2\pi^0$ (a_1^{1pr}) decay channel



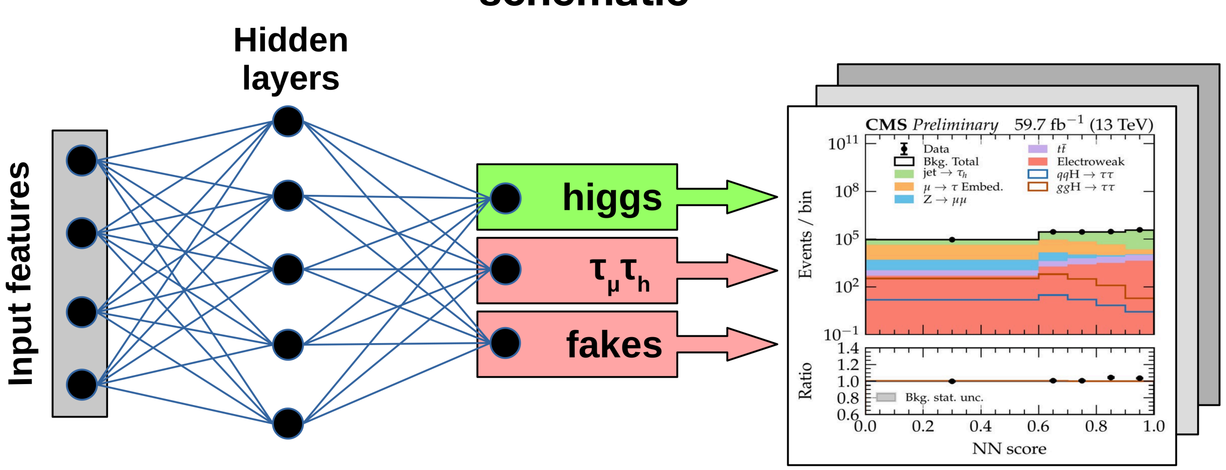


- The above bar chart showing efficiency and purity of these MVA and HPS decay mode method for different decays.
- The new MVA decay mode improved expected sensitivity up to 20% . The results are shown in https://cds.cern.ch/record/2727092

Event Categorisation

- Multi-classification ML algorithm (Neural Network for $\tau_\mu\tau_h$ and BDT for $\tau_h\tau_h$) used to categorise events into three categories,
  - **Higgs:** all signal process combined into one category
  - **Embedded:** background process involving two genuine τ-leptons
  - **jet-misidentification :** background process involving at least one jet $\rightarrow$ τ-lepton fake.
- Variables used for training MVA method for classification shown in the table.

Credits to A.Cardini for schematic



Observable	used in $\tau_\mu\tau_h$ channel	used in $\tau_h\tau_h$ channel
p_T of leading τ_h or τ_μ	✓	✓
p_T of (trailing) τ_h for $\tau_\mu\tau_h$ ($\tau_h\tau_h$) channel	✓	×
p_T of visible di-τ	✓	✓
p_T of di-τ_h + $\vec{p}_T^{\,\text{miss}}$	×	✓
p_T of $\tau_\mu + \tau_h$ + $\vec{p}_T^{\,\text{miss}}$	✓	×
Visible di-τ mass	✓	✓
$\tau_\mu\tau_h$ or $\tau_h\tau_h$ 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}	✓	✓

Final Discriminant

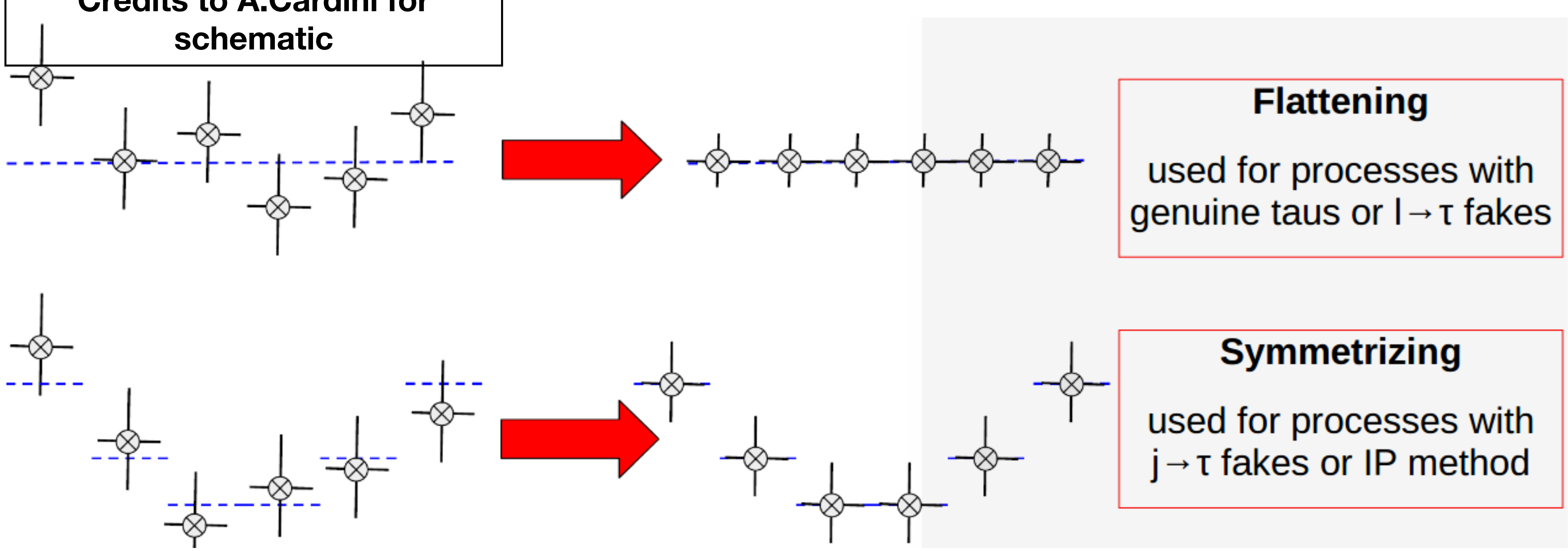
- ϕ_{CP} distributions of the events in the signal categories are analysed in windows of increasing MVA score. This final 2D enrolled distribution used as the final discriminant.

- **<u>Bkg. Flattening/Symmetrising:</u>**

  - Due to the nature of the ϕ_{CP} distribution we can exploit symmetries in the bkg process to reduce statistical fluctuations in MC

  - Backgrounds for where both side IP methods used(e.g. $\mu\pi$, $\pi\pi$) and jet $\rightarrow \tau_h$ backgrounds symmetrise rest of backgrounds flatten.

Credits to A.Cardini for schematic



ϕ_{CP} Reconstruction

2. <u>Neutral pion momenta:</u>

   - Instead of IP vector, the decay plane constructed from the momenta of charged and neutral pion.
   - On special case ($a_1^{3pr} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}$) select oppositely charged $\pi^{\pm}$ pair with invariant mass closest to ρ^0. Treat π with opposite charge to a_1^{3pr} as if it was neutral pion.
   - Calculate angle and sign,

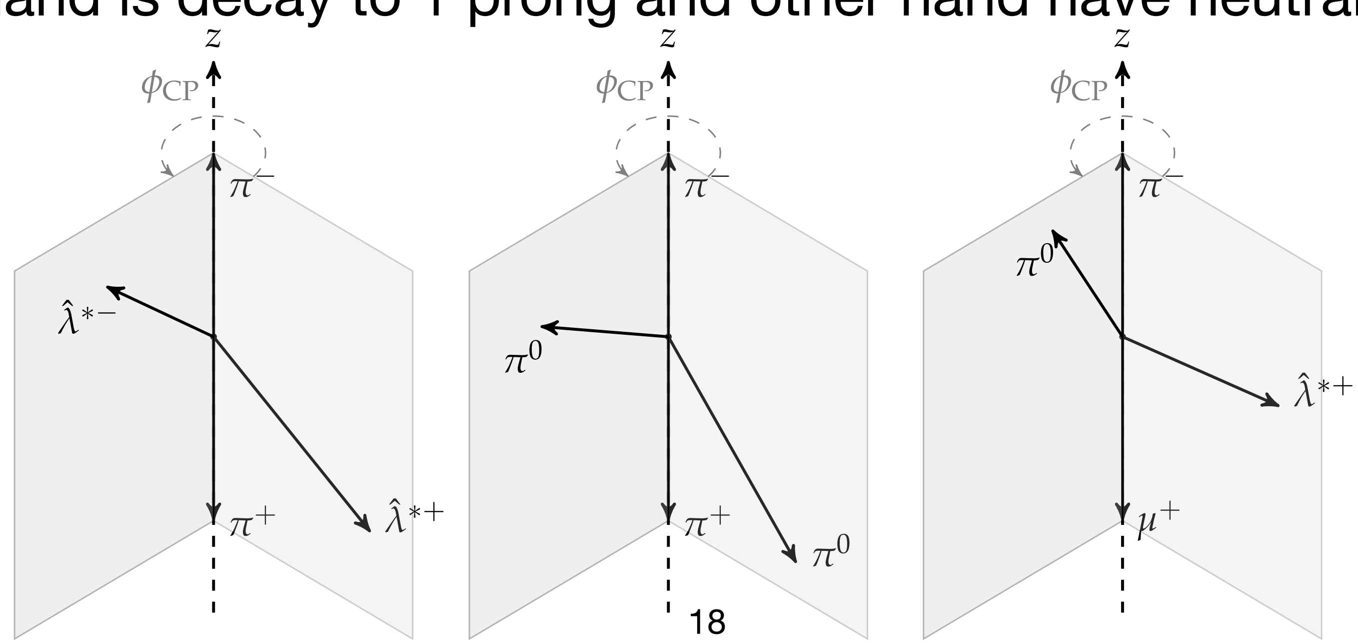
$$\phi^* = \arccos(\hat{q}_{\perp}^{+\pi_o} . \hat{q}_{\perp}^{-\pi_o})$$

$$O^* = \hat{q}^{*-} . (\hat{q}_{\perp}^{+\pi_o} \times \hat{q}_{\perp}^{-\pi_o})$$

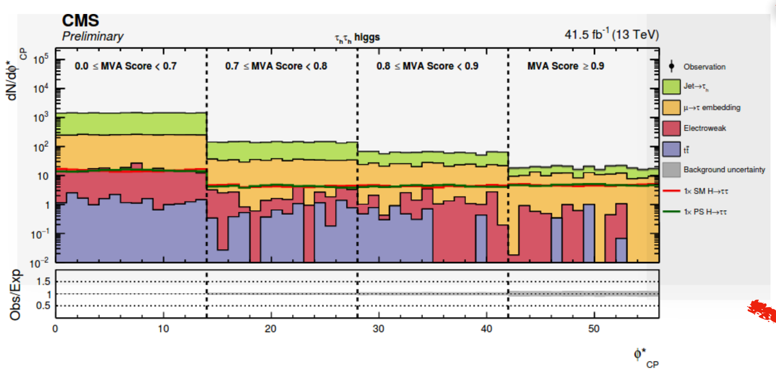
   - $\phi_{CP} = \phi^*$ if $O^* \geq 0$ else $\Phi_{CP} = 2\pi - \phi^*$

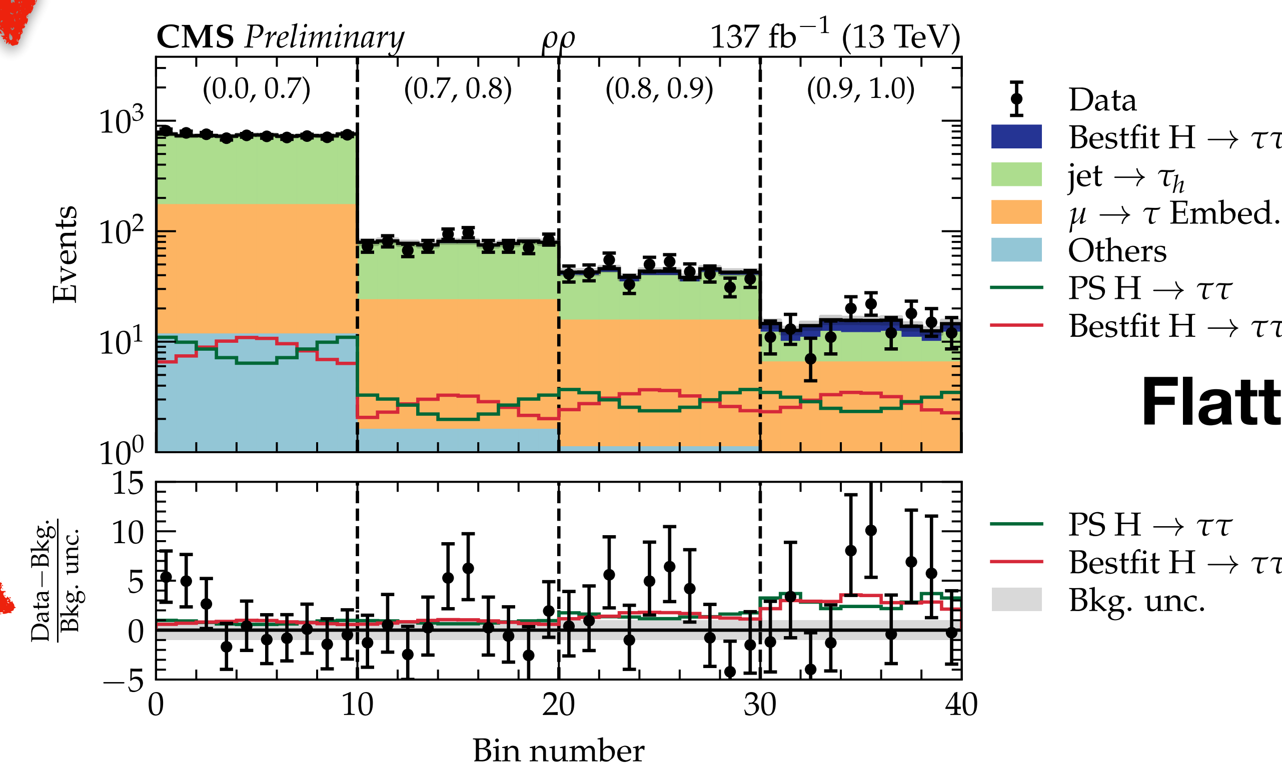
3. <u>Mixed method:</u>

   - Cases where one hand is decay to 1 prong and other hand have neutral pion,

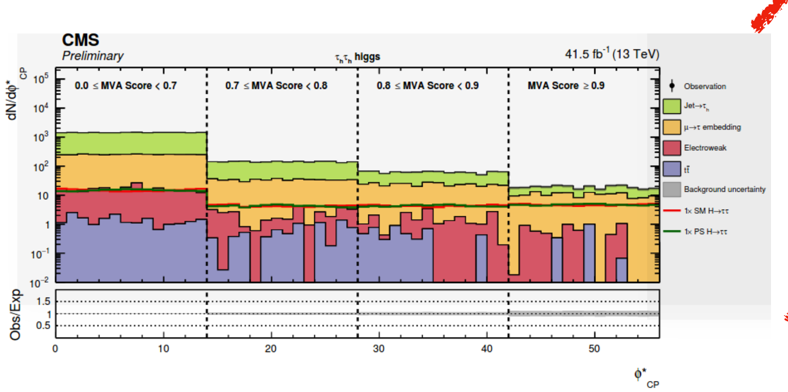


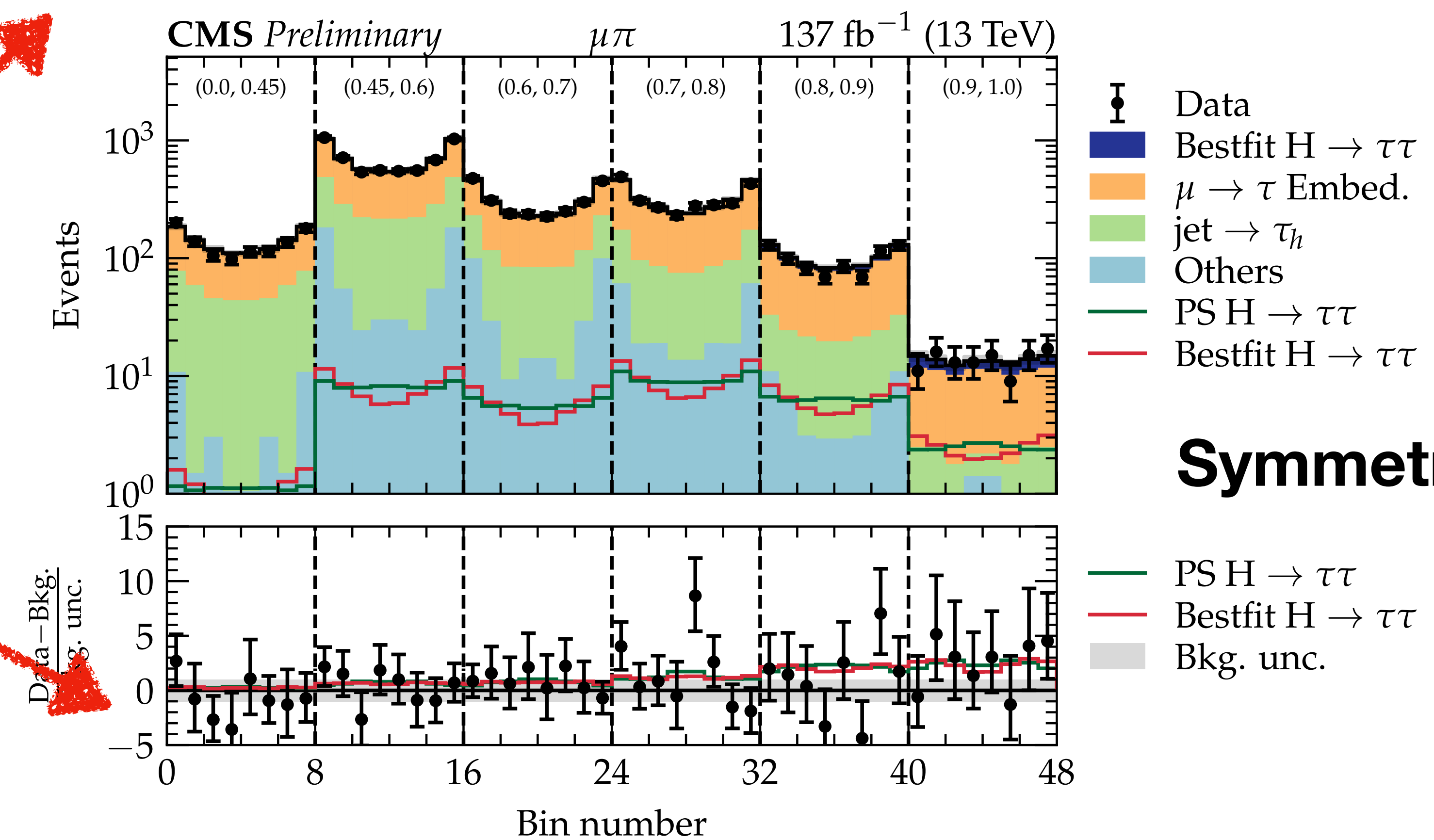
Final Discriminant





Flattening





Symmetrising

Estimation of $\phi_{\tau\tau}$: Uncertainties

- The full uncertainty information described in the right table.
- The bin-by-bin uncertainties for flattened background templates are fully correlated.
- One nuisance parameter per pair of symmetrise bins for symmetric background templates.

Uncertainty	Magnitude	Correlation	Incorp. fit
τ_h ID	p_T/decay-mode dependent (2–3%)	no	Gaussian
Muon reconstruction	1%.	yes	log-normal
$e \to \tau_h$ ID	5(1)% 2016(2017,2018)	no	Gaussian
$\mu \to \tau_h$ ID	20–40%	no	Gaussian
μ ID	1%	yes	Gaussian
b-jet veto	1–9%	no	log-normal
Luminosity	2.5%	partial	log-normal
Trigger	2% for μ, p_T-dep. for τ_h	no	Gaussian
Embedded yield	4%	no	log-normal
$t\bar{t}$ cross section	4.2%	yes	log-normal
Diboson cross section	5%	yes	log-normal
Single top cross section	5%	yes	log-normal
W + jets cross section	4%	yes	log-normal
Drell-Yan cross section	2%	yes	log-normal
Signal cross sections	[82]	yes	log-normal
top p_T reweighing	10%	yes	Gaussian
Z p_T reweighing	10%	partial	Gaussian
Prefiring (2016, 2017)	Event-dependent (0–4%)	yes	log-normal
τ_h energy scale	1% (sim), 1.5% (emb.)	no	Gaussian
$e \to \tau_h$ energy scale	0.5–6.5%	no	log-normal
$\mu \to \tau_h$ energy scale	1%	no	log-normal
Muon energy scale	0.4–2.7%	yes	Gaussian
Jet energy scale	Event-dependent	partial	Gaussian
Jet energy resolution	Event-dependent	no	Gaussian
p_T^{miss} unclustered scale	Event-dependent	no	Gaussian
p_T^{miss} recoil corrections	Event-dependent	no	Gaussian
Jet$\to$ τ_h mis-ID	described in text	partial	Gaussian
$t\bar{t}$/diboson in embedded	10%	yes	Gaussian
S_{IP} in μ and π decays	25%	no	Gaussian