Measuring $\mathcal{CP}$ properties of Higgs boson interactions with τ leptons with the ATLAS detector

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Overview

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3. Events Selection and Categorisation
4. Fit Results
5. Summary
6. Back Up

Higgs $\mathcal{CP}$ properties

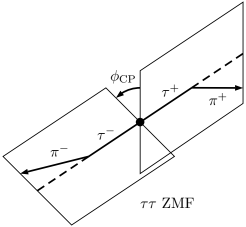
- General effective Yukawa coupling Lagrangian of $H\tau\tau$ [1]

$$\mathcal{L}_{h\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)h$$

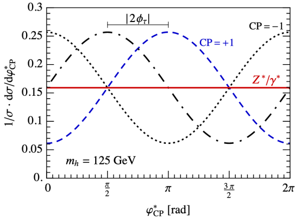
  - $|\phi_\tau| = 0$ (Pure CP-even, SM hypothesis)
  - $|\phi_\tau| = \pi/2$ (Pure CP-odd)
  - other values of ϕ_τ for CP mixing

- Relation of CP mixing angle and acoplanarity angle of τ decay plane

$$\frac{1}{\Gamma}\frac{d\Gamma(h \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu)}{d\phi_{CP}} \propto 1 - \frac{\pi^2}{16}\cos(\phi_{CP} - 2\phi_\tau)$$



a) Illustration of a $h \to \tau^+\tau^-$ decay in the $\tau\tau$ Zero Momentum Frame



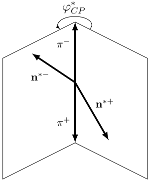
b) Different ϕ_τ hypothesis can provide a different phase shift in ϕ^*_{CP} distribution

[1] Cited from Nucl.Part.Phys.Proc. 273-275 (2016) 841-845

Observable and analysis method

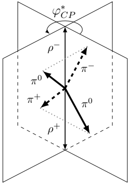
Observable: acoplanarity angle of τ decay planes in visible $\tau\tau$ ZMF

- IP-IP method: define planes both spanned by charged π & impact parameters
- ρ-ρ method: define planes both spanned by charged π & neutral pions
- IP-ρ method: define planes one spanned by charged π & IP and the other by charged tracks & neutral pions



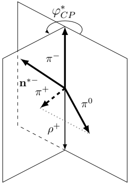
$$\phi^* = \arccos(\hat{n}^{*+}_{\perp} \cdot \hat{n}^{*-}_{\perp})$$
$$\mathcal{O}^*_{CP} = \hat{q}^*_{-} \cdot (\hat{n}^{*+}_{\perp} \times \hat{n}^{*-}_{\perp})$$
$$\phi^*_{CP} = \begin{cases} \phi^* & \mathcal{O}^*_{CP} \geq 0 \\ 2\pi - \phi^* & \mathcal{O}^*_{CP} < 0 \end{cases}$$

a) IP-IP method



$$\phi^* = \arccos(\hat{q}^{*0+}_{\perp} \cdot \hat{q}^{*0-}_{\perp})$$
$$\mathcal{O}^*_{CP} = \hat{q}^*_{-} \cdot (\hat{q}^{*0+}_{\perp} \times \hat{q}^{*0-}_{\perp})$$
$$\phi^{*\prime} = \begin{cases} \phi^* & \mathcal{O}^*_{CP} \geq 0 \\ 2\pi - \phi^* & \mathcal{O}^*_{CP} < 0 \end{cases}$$
$$\Upsilon_{\pm} = \frac{E_{\pi^{\pm}} - E_{\pi^0}}{E_{\pi^{\pm}} + E_{\pi^0}}$$
$$\phi^*_{CP} = \begin{cases} \phi^{*\prime} & \Upsilon_+ \cdot \Upsilon_- \geq 0 \\ \phi^{*\prime} + \pi & \Upsilon_+ \cdot \Upsilon_- < 0 \end{cases}$$

b) ρ-ρ method



$$\phi^* = \arccos(\hat{q}^{*0+}_{\perp} \cdot \hat{n}^{*-}_{\perp})$$
$$\mathcal{O}^*_{CP} = \hat{q}^*_{-} \cdot (\hat{q}^{*0+}_{\perp} \times \hat{n}^{*-}_{\perp})$$
$$\phi^{*\prime} = \begin{cases} \phi^* & \mathcal{O}^*_{CP} \geq 0 \\ 2\pi - \phi^* & \mathcal{O}^*_{CP} < 0 \end{cases}$$
$$\Upsilon_{\pm} = \frac{E_{\pi^{\pm}} - E_{\pi^0}}{E_{\pi^{\pm}} + E_{\pi^0}}$$
$$\phi^*_{CP} = \begin{cases} \phi^{*\prime} & \Upsilon_+ \cdot \Upsilon_- \geq 0 \\ \phi^{*\prime} + \pi & \Upsilon_+ \cdot \Upsilon_- < 0 \end{cases}$$

c) IP-ρ method

Decay mode and optimization

Decay mode	Branching fraction
leptonic ($e^{\pm}$,$\mu^{\pm}$)	35.2%
$h^{\pm}$	11.5%
$h^{\pm}\pi^{0}$	25.9%
$\pi^{\pm} \geq 2\pi^{0}$	10.8%
$3\pi^{\pm}$	9.8 %

i) Single τ decay mode and branching ratio

Decay channel	Decay mode combination	Method
$\tau_{had}\tau_{had}$	1p0n-1p0n	IP-IP
	1p0n-1p1n	IP-ρ
	1p1n-1p1n	ρ-ρ
	1p0n-1pXn	IP-ρ
	1p1n-1pXn	ρ-ρ
	1p1n-3p0n	ρ-a_1
$\tau_{lep}\tau_{had}$	l-1p0n	IP-IP
	l-1p1n	IP-ρ
	l-1pXn	IP-ρ
	l-3p0n	IP-a_1

ii) $\tau\tau$ pair decay mode combination and analysis method

- Different optimization is applied for different method

a) IP-IP method

- Use d_0^s cut to divide high/low sensitivity region for optimization

$$d_0^s = |d0|/\sigma(d0)$$

b) ρ-ρ method

- Use Υ cut to divide high/low sensitivity region for optimization

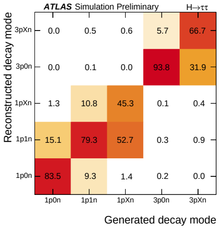
$$\Upsilon_{\pm} = \frac{E_{\pi^{\pm}} - E_{\pi^0}}{E_{\pi^{\pm}} + E_{\pi^0}}$$

c) IP-ρ method

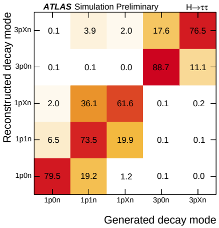
- Use both d_0^s and Υ cut respectively to divide high/low sensitivity region for optimization

Decay mode reconstruction

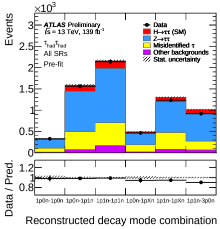
- Tau Particle Flow method is used for the reconstruction of τ decay productions
- Using BDT algorithm to reconstruct $\tau_{had\text{-}vis}$ decay mode [2]



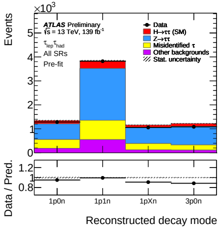
a) efficiency matrix of τ decay mode classification



b) purity matrix of τ decay mode classification



c) HH boost tight di-τ decay modes



d) LH boost tight hadronic τ decay modes

[2] More informations can be seen here Eur. Phys. J C 76(5), 1-26 (2016)

Event selection and categorisation

- Preselection cut to remove some backgrounds
- MMC window cut is used to define signal region and Z control region
- $p_T(H)$ and ΔR cuts are used for further categorisations of Boost region
- VBF tagger cut is used for further categorisations of VBF region
- d_0^{sig} and Υ cuts are used for (high+medium)/low sensitivity categories division
- Further split high/medium by decay mode combinations

Higgs production mode categorisation

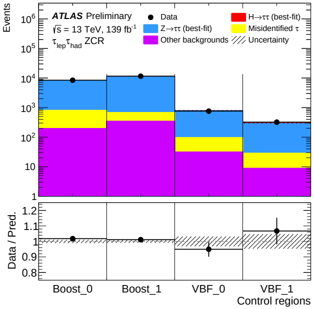
	1	0
VBF	Sub-leading jet $p_T > 30$ GeV $m_{jj} > 400$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.0$; $\eta(j_0)\cdot\eta(j_1) < 0$	
	BDT(VBF)>0.0	BDT(VBF)<0.0
Boost	Failed VBF selection $p_T(H) > 100$ GeV	
	$\Delta R \leq 1.5$ $p_T(H) \geq 140$GeV	Not tight

τ decay mode categorisation

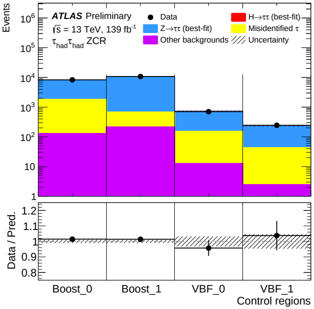
		High	**Medium**	**Low**
hh	1p0n-1p0n 1p0n-1p1n 1p1n-1p1n	both τ $d_0^s > 1.5$ $d_0^s > 1.5$ & $\lvert y\rvert > 0.1$ $\lvert y_0 y_1\rvert > 0.2$		Failed
	1p0n-1pXn 1p1n-1pXn 1p1n-3p0n		$d_0^s > 1.5$ & $\lvert y\rvert > 0.1$ $\lvert y_0 y_1\rvert > 0.2$ $\lvert y_{1p}\rvert > 0.1$ & $\lvert y_{3p}\rvert > 0.6$	
lh		lepton $d_{0e}^s > 2.5$ *or* $d_{0\mu}^s > 2.0$	lepton $d_{0e}^s > 2.5$ *or* $d_{0\mu}^s > 2.0$	Failed
	l-1p0n l-1p1n	hadronic τ $d_0^s > 1.5$ hadronic τ $\lvert y\rvert > 0.1$		
	l-1pXn l-3p0n		hadronic τ $\lvert y\rvert > 0.1$ hadronic τ $\lvert y_{3p}\rvert > 0.6$	

Background estimation

- Two main sources of background
  - $Z/\gamma^* \rightarrow \tau\tau$ estimated by MC (SHERPA v2.2.1)
  - Event with jets mis-identified as hadronic τ are estimated by data-driven method by decay mode combinations, mainly from W+jets and QCD multijets processes
- Other small background such as diboson and $t\bar{t}$ decay are modeled by MC



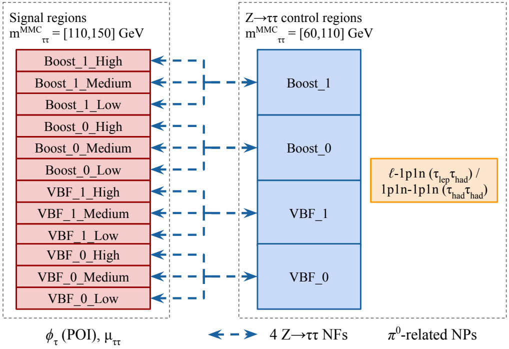
a) LH ZCR distribution



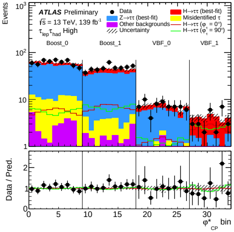
b) HH ZCR distribution

Fit model

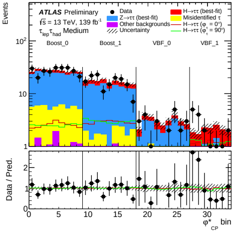
- Totally 24 SRs are devided by Higgs production, τ decay and sensitivity categorisation
  - 4 Higgs production categories: VBF 1/0 + Boost 1/0
  - 2 τ decay categories: HH + LH
  - 3 sensitivity categories: High + Medium + Low
- 8 ZCRs normalise the $Z \to \tau\tau$ process in corresponded production/decay categories using 4 Z$\tau\tau$ NF divided by production modes
- 2 another ZCRs use the ρ mass distributions to constrain π^0 related uncertainties
- One inclusive Higgs NF applied to all Higgs signals in all regions



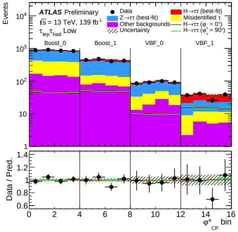
- 19 signal templates for different CP hypotheses are used to fit signal shape
- Binnings are optimised by overall sensitivity and fit model stability
- Post-fit SR plots are showed below



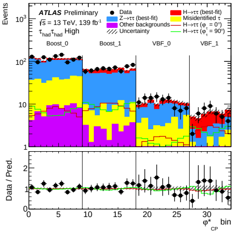
a) LH high



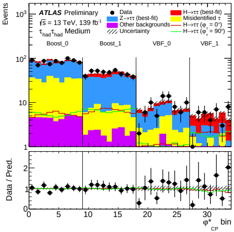
b) LH medium



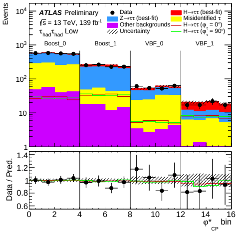
c) LH low



d) HH high



e) HH medium



f) HH low

Systematics

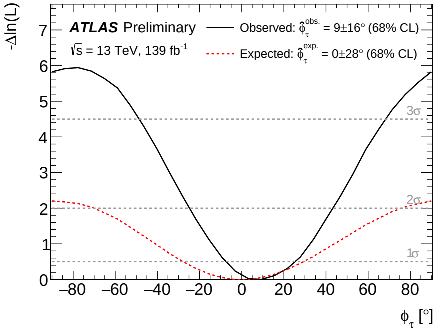
- PoI error mainly impacted by data statistical error
- Systematics are mainly came from Jet group

Set of nuisance parameters	Impact on $\phi_\tau (^\circ)$ Observed	Expected
Jet	4.3	8.9
E_T^{miss}	0.4	1.2
Electron	0.3	0.9
Muon	0.9	1.5
τ_{had} reconstruction	1.0	1.8
Fake estimation	0.6	1.5
τ_{had} decay mode classification	0.3	0.6
π^0 angular resolution and energy scale	0.2	0.5
Track ($\pi^\pm$, impact parameter)	0.7	1.0
Flavour Tagging	0.2	0.1
Luminosity	0.1	0.1
Theory uncertainty in $H \to \tau\tau$ processes	1.5	1.3
Theory uncertainty in $Z \to \tau\tau$ processes	1.1	2.8
Simulated background sample statistics	1.4	3.6
Signal normalisation	1.4	2.6
Background normalisation	0.6	1.5
Total systematic uncertainty	5.0	10.9
Data sample statistics	15.6	26.2
Total	16.5	28.3

a) Group impact for ϕ_τ measurement

Fit results

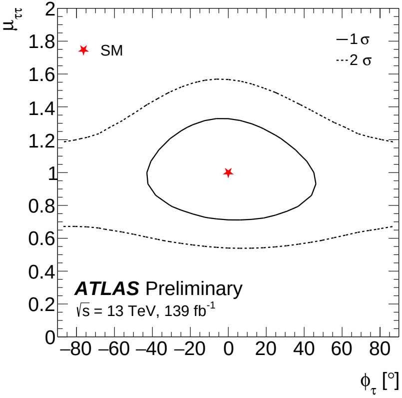
- About 1.3σ uncertainty reduction of ϕ_τ from expected to observed due to the data fluctuation



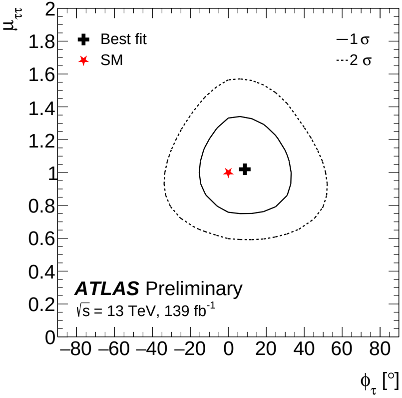
	CP-odd exclusion	Best fit ϕ_τ ($^\circ$)	1-σ limit ($^\circ$)
Expected	2.1σ	0.0	+29.1 / -27.7
Observed	3.4σ	8.7	+16.8 / -16.2

2D likelihood scan

- 2D likelihood scan is performed between the signal strength modifier $\mu_{\tau\tau}$ and CP mixing angle ϕ_τ
- No strong correlation between the signal strength modifier $\mu_{\tau\tau}$ and CP mixing angle ϕ_τ
- SM expectation is within 1-σ contour of observed limits



a) 2D LHscan for Expected fit



b) 2D LHscan for Observed fit

Summary

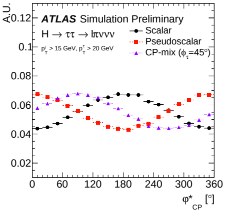
- Reconstruct the Higgs $\mathcal{CP}$ sensitive variable ϕ^*_{CP} for different di-τ decay mode combination using different method
- Perform the fit on Higgs $\mathcal{CP}$ mixing angle ϕ_τ and the results are presented
- The pure $\mathcal{CP}$-odd hypothesis is disfavoured at 3.4 standard deviations, the observed(expected) value of ϕ_τ is $9 \pm 16^\circ (0 \pm 28^\circ)$ at the 68% CL

Thank you!

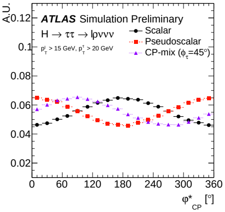
Back Up

ϕ^*_{CP} shape for decay mode combination

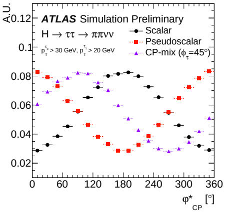
- Signal samples generated by POWHEG+PYTHIA 8 are unpolarised
- $\tau\tau$ pair spin correlations are induced by TauSpinner for different $\mathcal{CP}$ hypothesis
- ϕ^*_{CP} distributions are in good shapes as expected
- Amplitude of $\phi_{CP}*$ distribution is related to the sensitivity



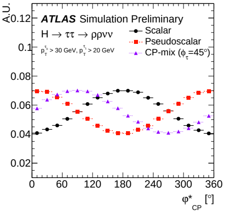
a) l-π



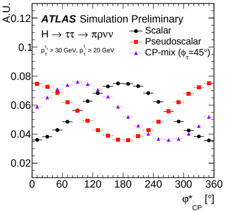
b) l-ρ



c) π-π



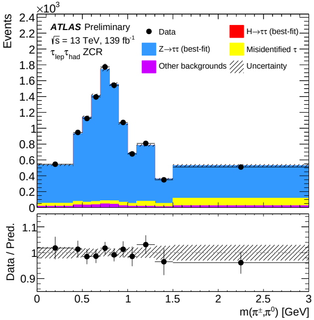
d) ρ-ρ



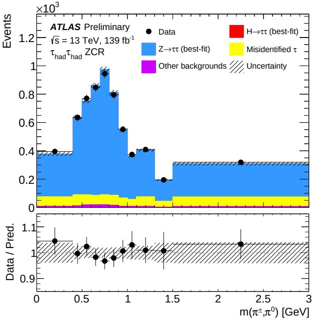
e) π-ρ

π^0 related NPs

- TAUS_PI0_RECALC_PHI_STAR_ETA_SMEAR; TAUS_PI0_RECALC_PHI_STAR_PHI_SMEAR
  - 5 $\times$ the average resolutions $\sigma(\pi^0_\eta)$ and $\sigma(\pi^0_\phi)$
- TAUS_PI0_RECALC_PHI_STAR_ENERGY_SCALE
  - A flat 20% uncertainty is applied to π^0 4-vector in 1p1n
  - A flat 40% uncertainty is applied to the sum of π^0 4-vector in 1pXn



a) LH ZCR1 post-fit



b) HH ZCR1 post-fit