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ATLAS and LHC sensitivity to Higgs CP properties

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Introduction

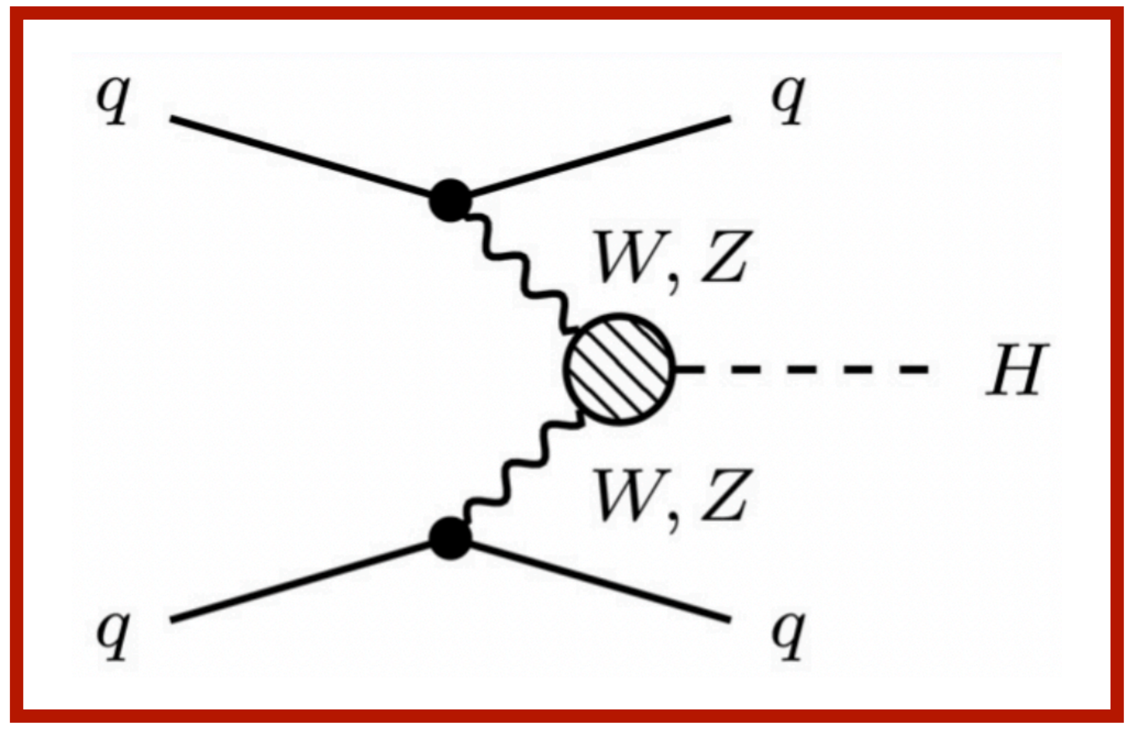
- New sources of CPV are expected to explain baryon assymmetry in the universe

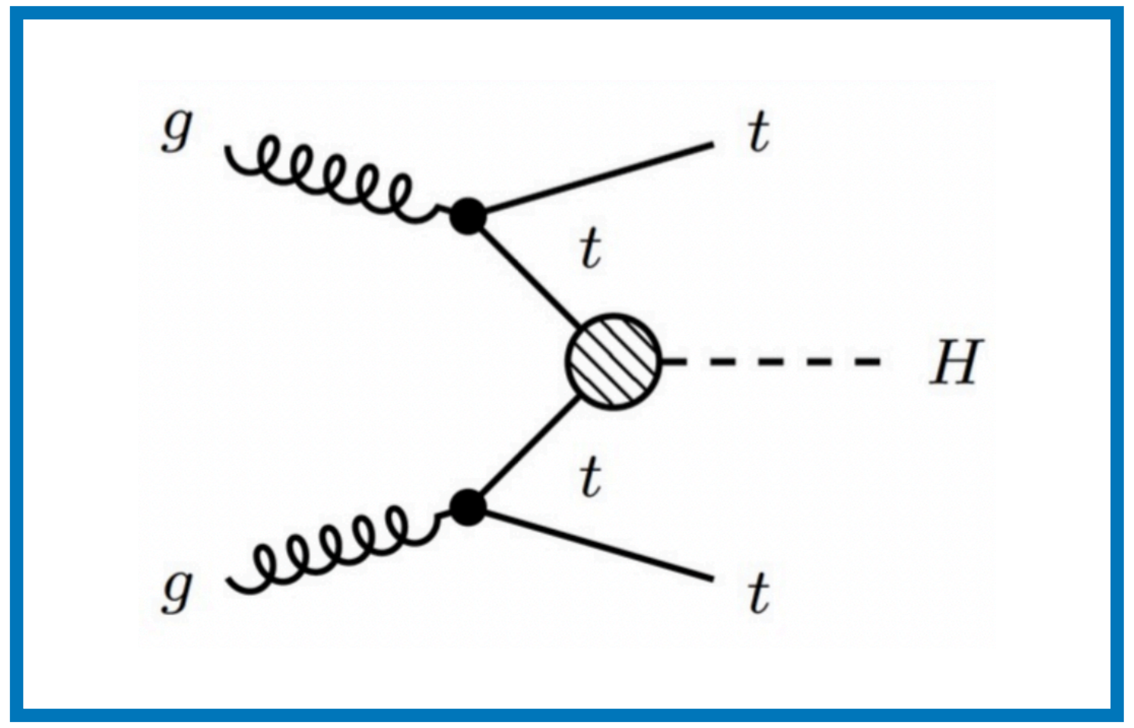
- Higgs boson is an SM scalar with no CP-violating interaction
  - CP-odd contribution would be a sign of BSM physics
  - Motivates Higgs sector as search space for additional sources of CP violation

CP structure of Higgs coupling

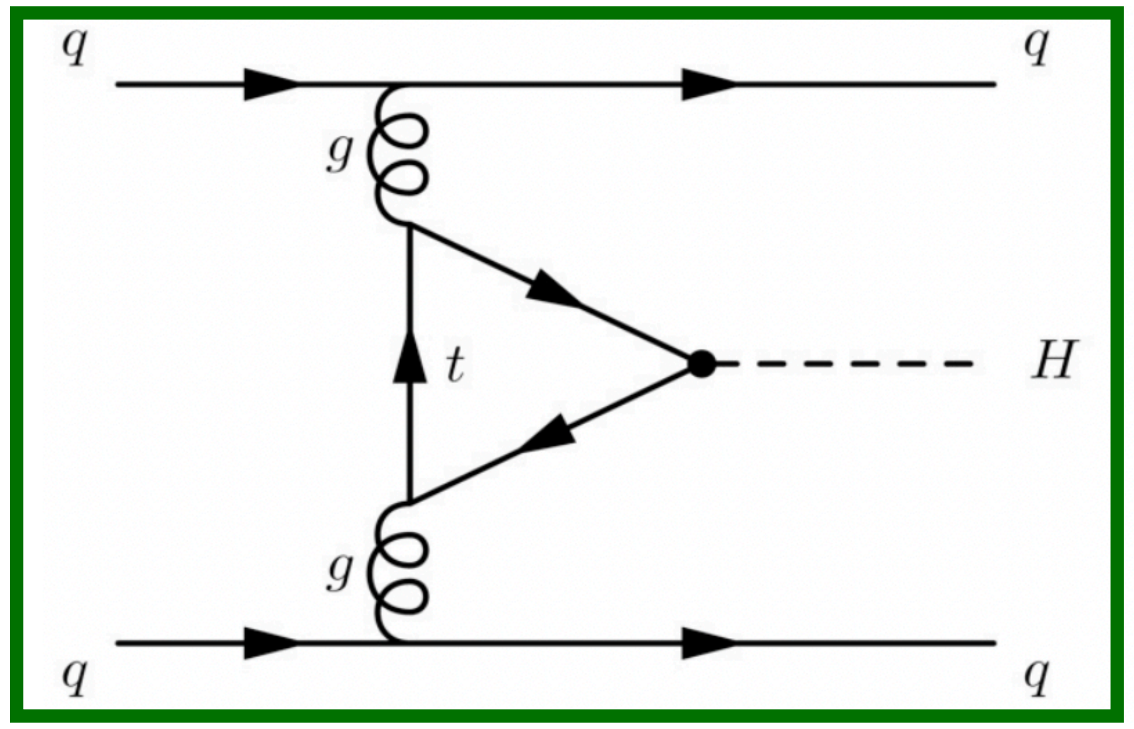
- Search for CP violation either in production or decay:
  - Search CP violation in ggF, VBF, ttH Higgs production
  - Search for CP violation in $H \to \tau\tau$ and $H \to ZZ^* \to 4\ell$ decay modes

Higgs coupling to W/Z bosons in vector boson fusion (VBF)

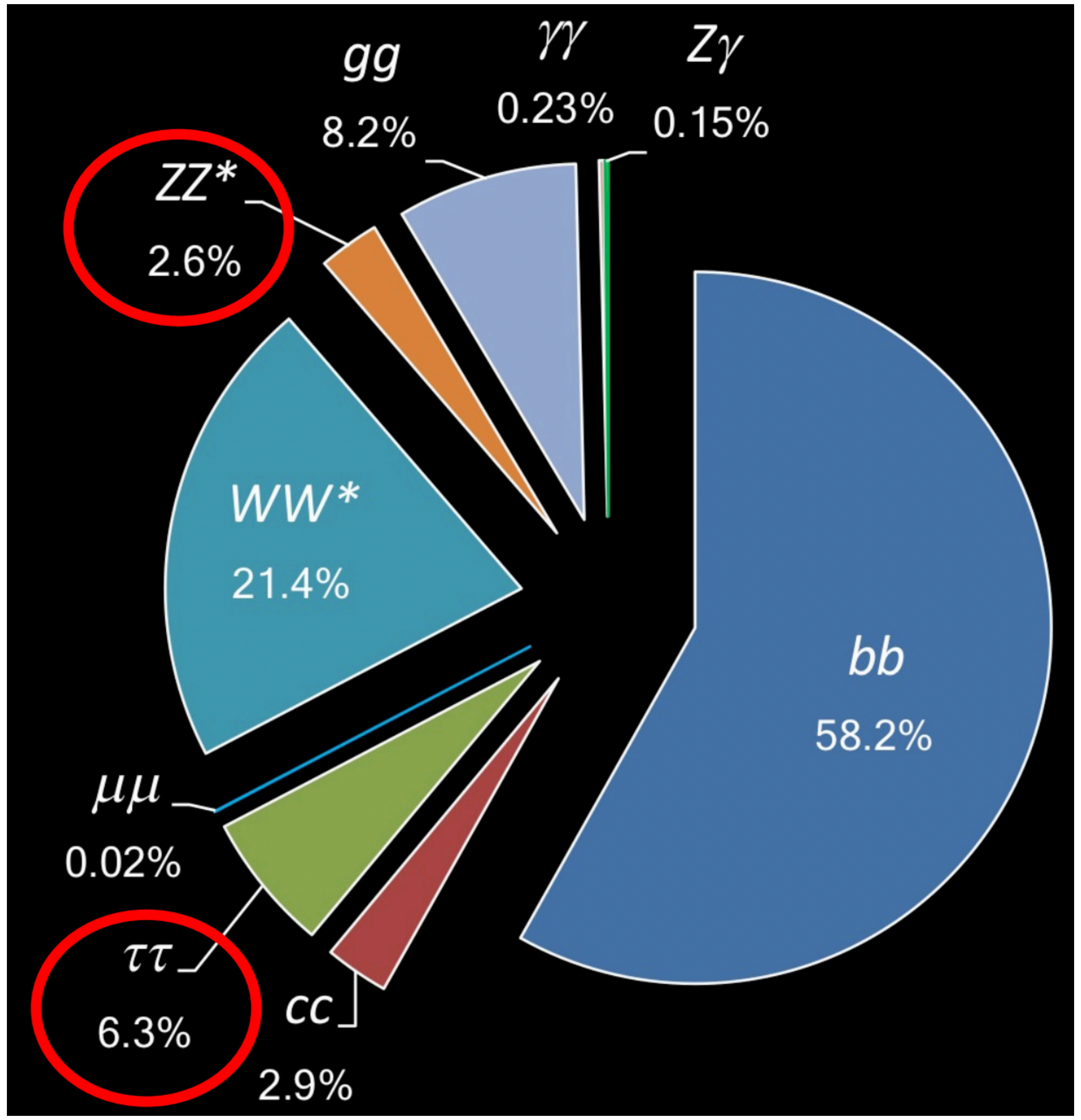




Higgs and top quark Yukawa coupling in ttH/tH process



Effective Higgs and gluon coupling in gluon-gluon fusion (ggF) process



CP structure of Yukawa coupling in tau decays

- Analyses aim to access potential mixing between scalar (CP-even) and pseudoscalar (CP-odd) in Yukawa coupling to τ-leptons

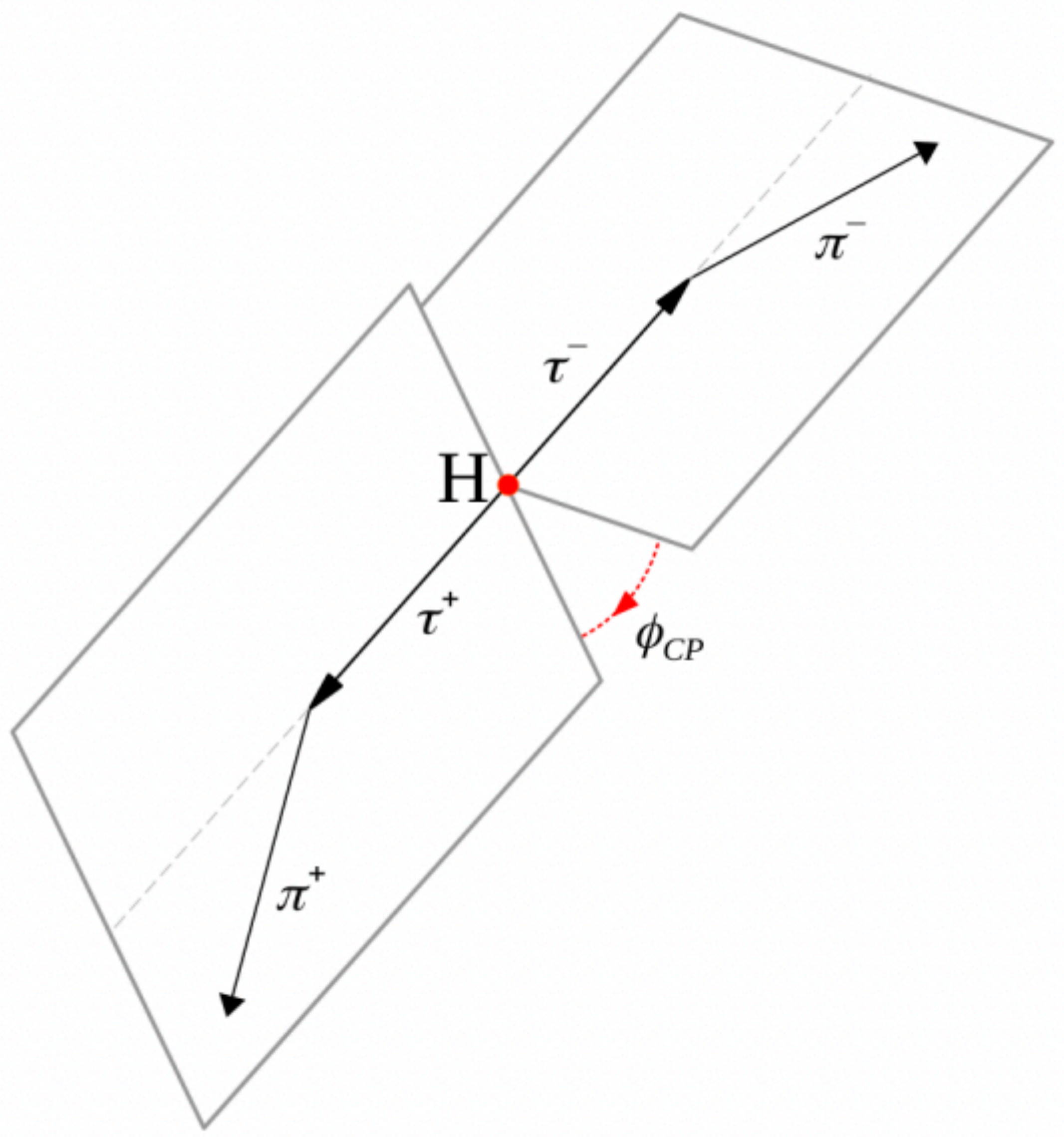
- Interaction of Higgs of arbitrary CP nature to $\tau-$leptons:

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

m_τ - mass of tau lepton
ν - vacuum expectation value (246 GeV)
$\kappa_\tau, \bar{\kappa}_\tau$ - Yukawa couplings

- Yukawa couplings can be expressed in terms of effective mixing angle $\phi_{\tau\tau}$

$$\tan\phi_{\tau\tau} = \frac{\bar{\kappa}_\tau}{\kappa_\tau} \begin{cases} \phi_{\tau\tau} \to 0, \; CP\text{-even} \\ \phi_{\tau\tau} \to \frac{\pi}{2}, \; CP\text{-odd} \\ \text{else}, \; CP\text{-mix} \end{cases}$$



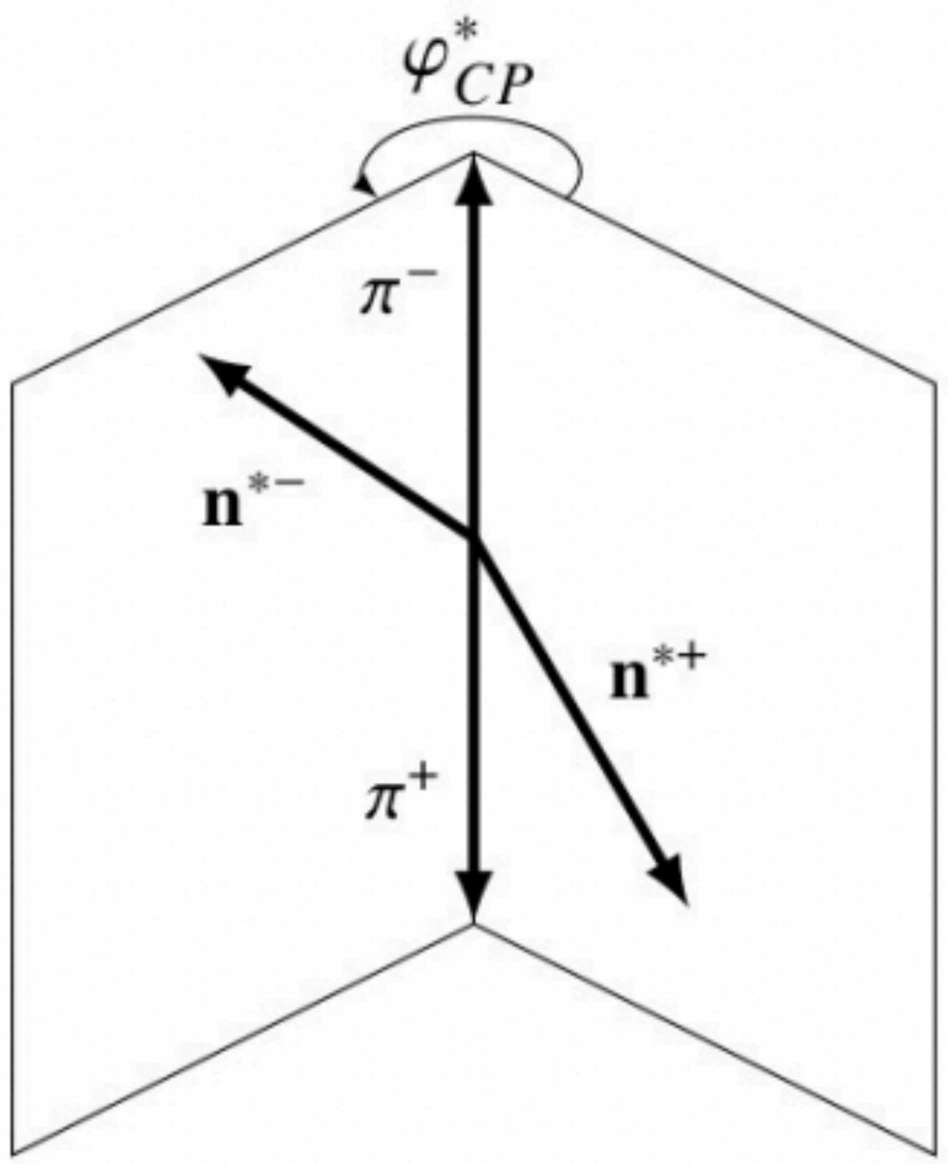
- Define ϕ_{CP} as angle between τ decay planes in Higgs rest frame.

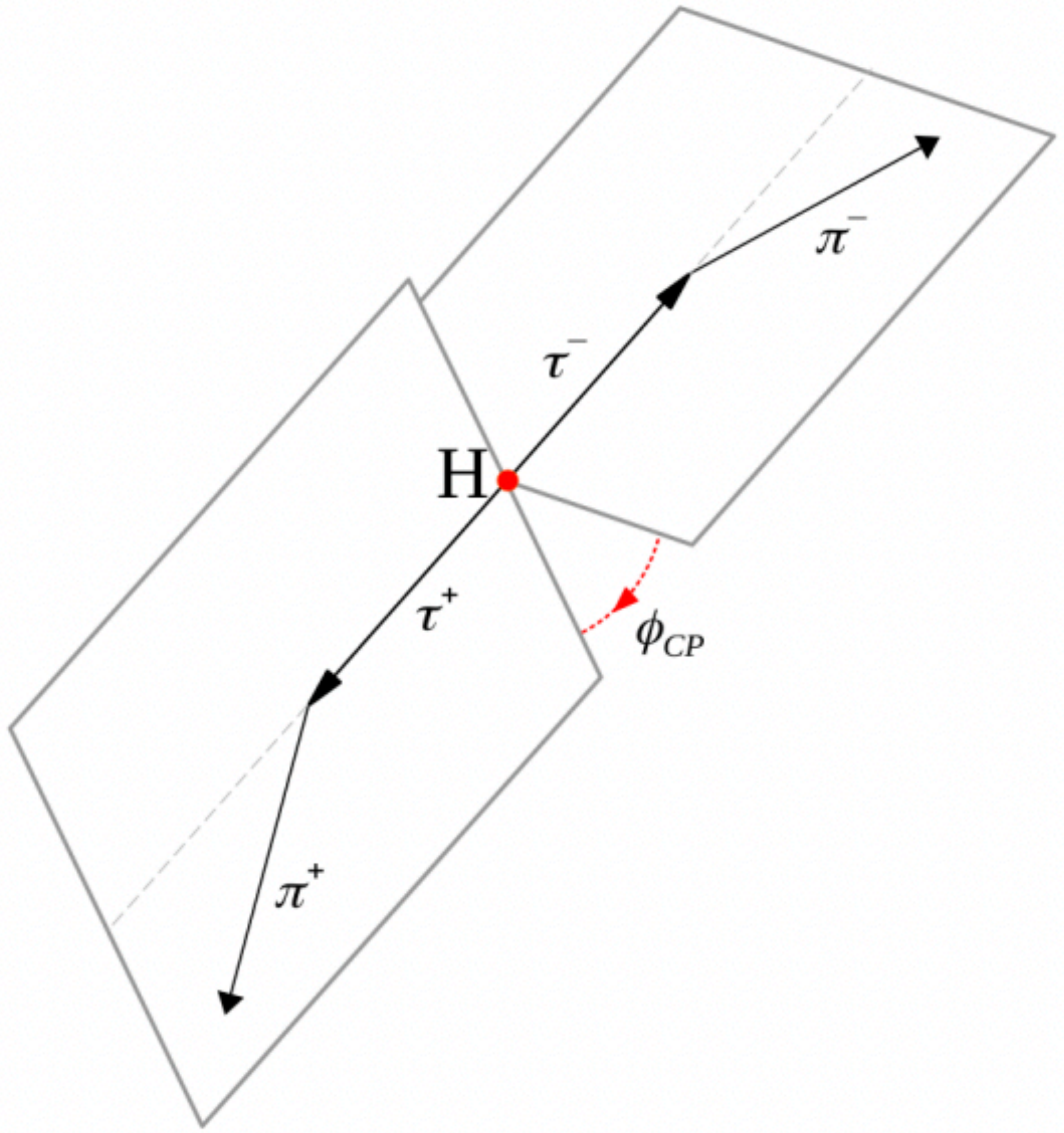
- Measure mixing angle $\phi_{\tau\tau}$ from relationship between $\phi_{\tau\tau}$ and differential cross section

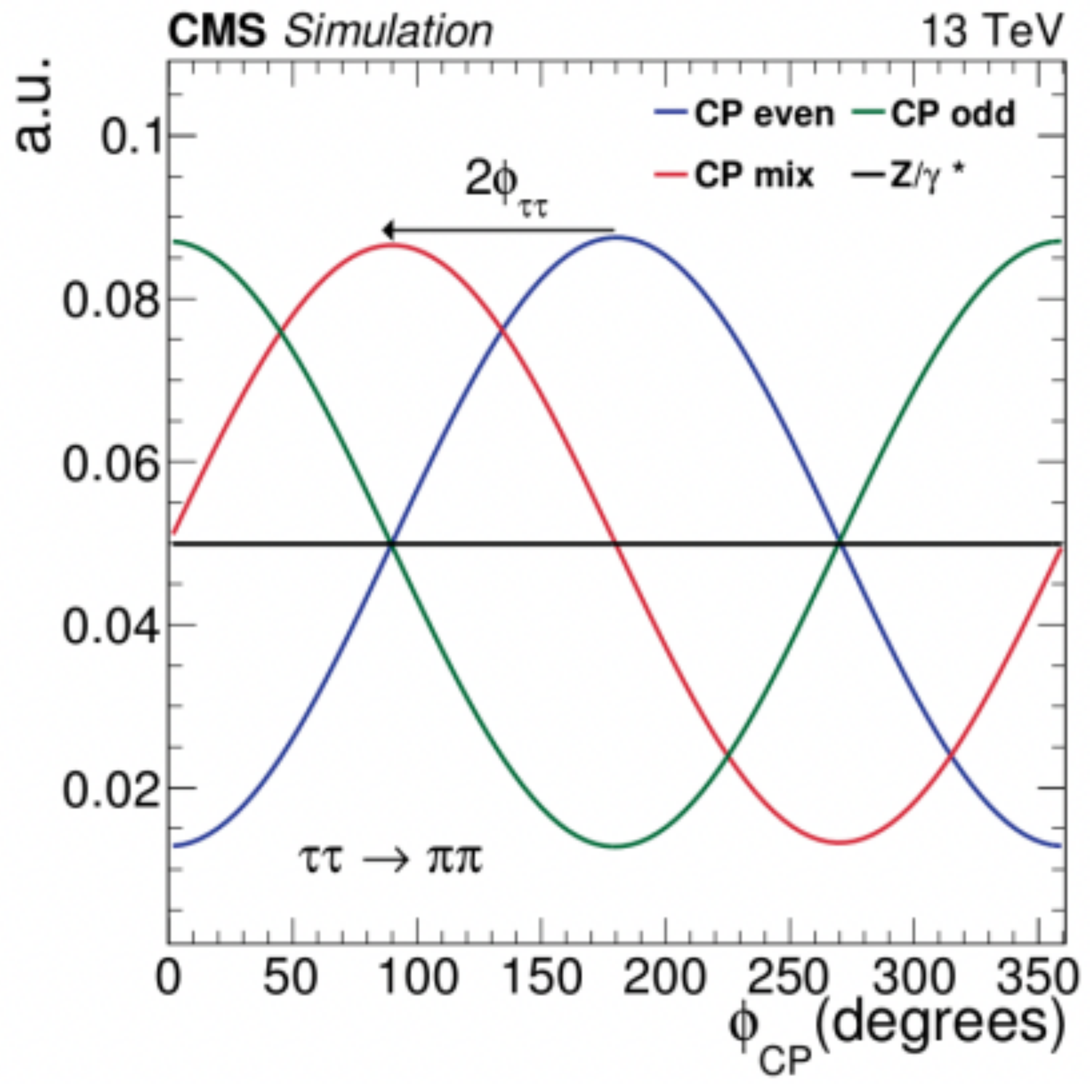
$$\frac{d\Gamma}{d\phi_{CP}} \propto -\cos(\phi_{CP} - 2\phi_{\tau\tau})$$

Determination of the decay plane

- $\tau \to \pi\nu$ Plane between impact parameter and pion direction
- $\tau \to \pi\rho \to \pi^- \pi^0$ Plane spanned by charged and neutral pion







arxiv.2110.04836

Several channels considered

Decay channel	Decay mode combination	Method	Fraction in all τ lepton pair decays
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	ℓ-1p0n	IP	7.6%
	ℓ-1p1n	IP-ρ	17.8%
	ℓ-1pXn	IP-ρ	7.3%
	ℓ-3p0n	IP-a_1	6.5%
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	1p0n-1p0n	IP	1.2%
	1p0n-1p1n	IP-ρ	5.5%
	1p1n-1p1n	ρ	6.4%
	1p0n-1pXn	IP-ρ	2.2%
	1p1n-1pXn	ρ	5.3%
	1p1n-3p0n	ρ-a_1	4.7%

(From ATLAS publication draft)

LHC measurements

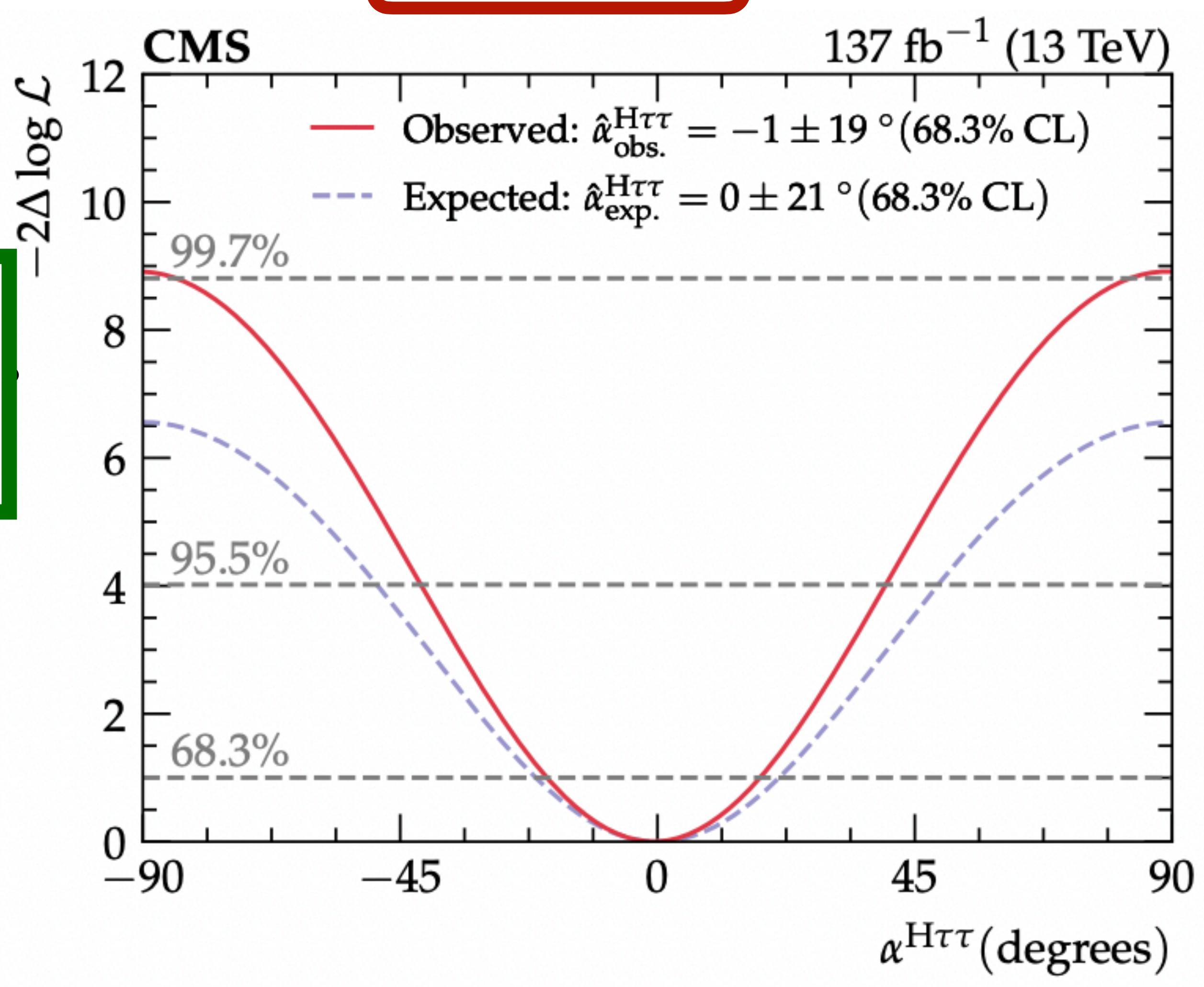
$\alpha^{H\tau\tau} = \phi_{\tau\tau}$

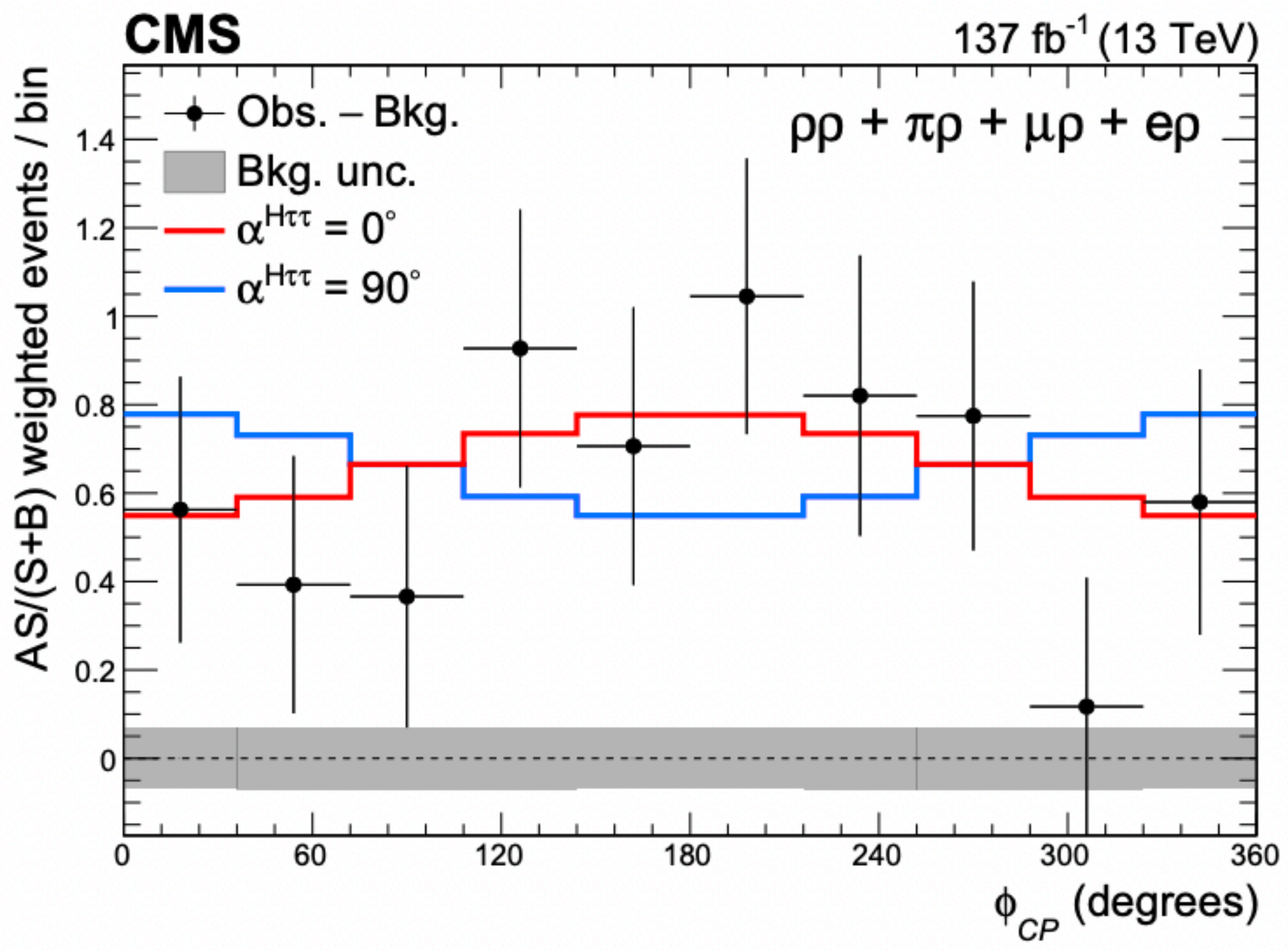
arxiv.2110.04836

- **CMS** has measured $\phi_{\tau\tau}$ with full run 2 data (137 fb^{-1})

$$\phi_{\tau\tau} = -1 \pm 19(\text{stat}) \pm 1(\text{syst}) \pm 2(\text{bin-by-bin}) \pm 1(\text{theo})$$

- Pure CP-odd scenario excluded at 3σ





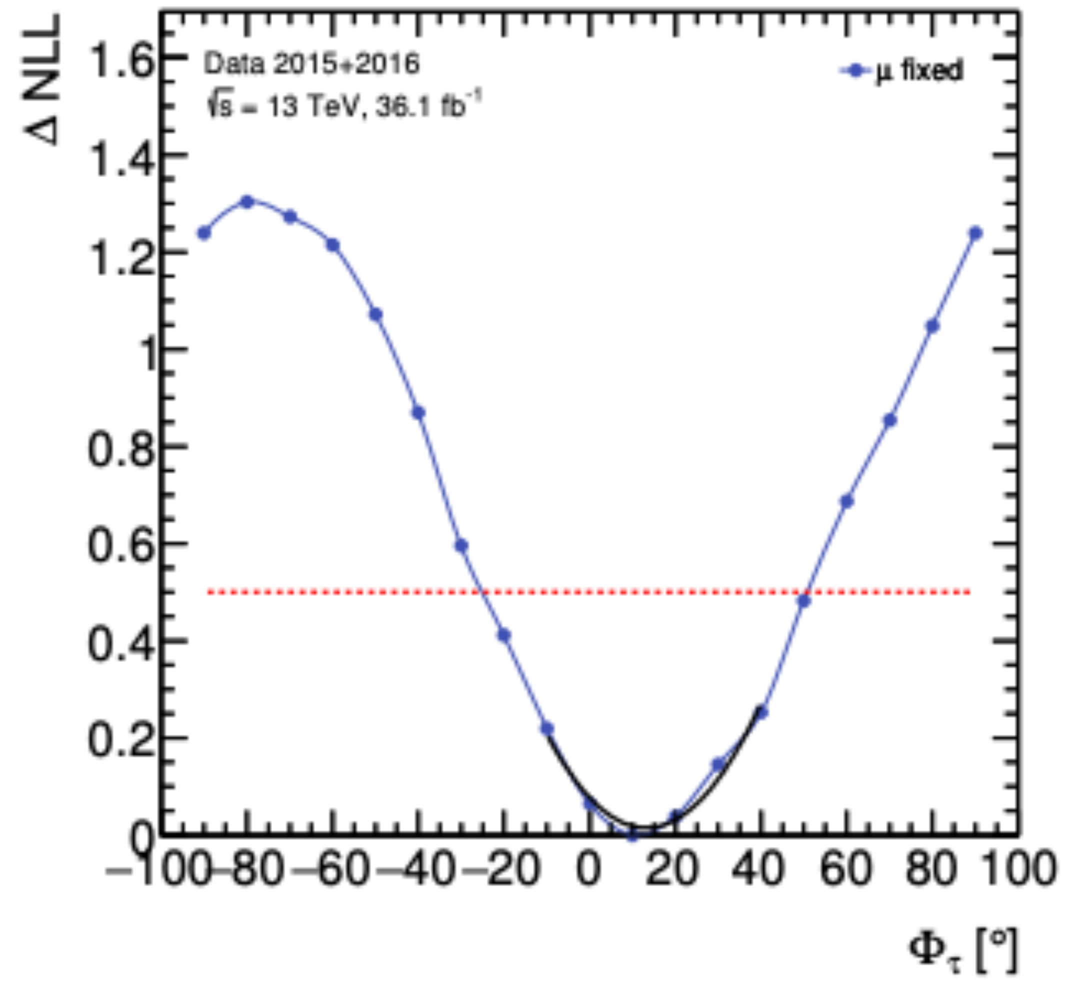
- **ATLAS**: No public results yet, but run 2 (139 fb^{-1}) analysis close to publication

- Doctroral theses with measurements for 2015-2016 data (36.1 fb^{-1}):

  - Measured $\phi_{\tau} = \left(10^{+40}_{-35}\right)^{\circ}$

- Enhancement in sensitivity similar to CMS measurement expected for full run 2

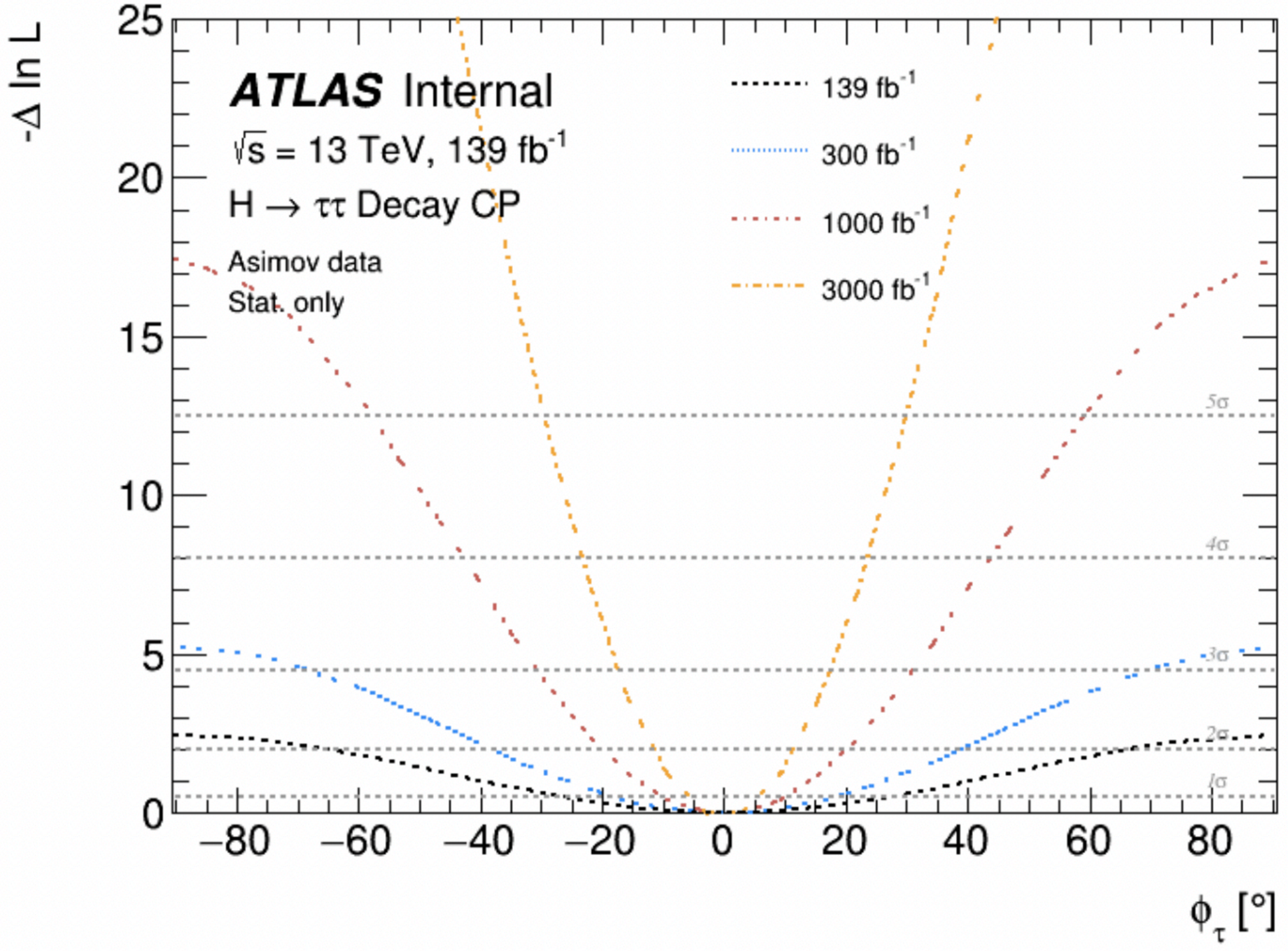
Thesis M.Hansen (2020)



Future efforts in ATLAS

Huango Li
Higgs Plenary meeting
23.03.2022

- ATLAS $H\tau\tau$ Yukawa CP measurements for run 2 finishing now, too late to contribute
- Statistics dominating uncertainty in run 2 measurements
- With HL-LHC ATLAS will deliver around 3000 fb^{-1}
- Claims from axiv.1510.03850: Uncertainty on $\Delta\phi_{\tau\tau}$ can reach:
  - 25° at $150\,fb^{-1}$
  - 14.3° at $500\,fb^{-1}$
  - 5.1° at $3000\,fb^{-1}$
- Possible prospect studies with improved ML studies and baryogensis interpretations



- Starting up now in ATLAS: CP measurements in VBF Higgs production exploiting $h \rightarrow \tau\tau$
- Last publication with 2015-2016 data, now full run 2 analysis
- In contact with analysis group trying to figure out how we can join the effort

VBF $H \to \tau\tau$ analysis

- Effective Lagrangian considered is the SM Lagrangian built up by CP-odd operators of mass dimension 6
- All couplings between Higgs and SM particles are assumed to be predicted by SM
- After EWSB Lagrangian can be written in the mass basis of $H, A, W^{\pm},$ and Z:

$$\mathcal{L}_{EFF} = \mathcal{L}_{SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

- Where $V^{\mu\nu}$ and $\tilde{V}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$ denote the field strength and dual field strength tensors respectively
- Only two of the four couplings $\tilde{g}_{HVV}$ are independent. Can be expressed by dimensionless couplings $\tilde{d}$ and $\tilde{d}_B$, the SU(2) coupling constant g and weak mixing angle θ_W:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W)$$

$$\tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}$$

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$

$$\tilde{g}_{HAZ} = 0$$

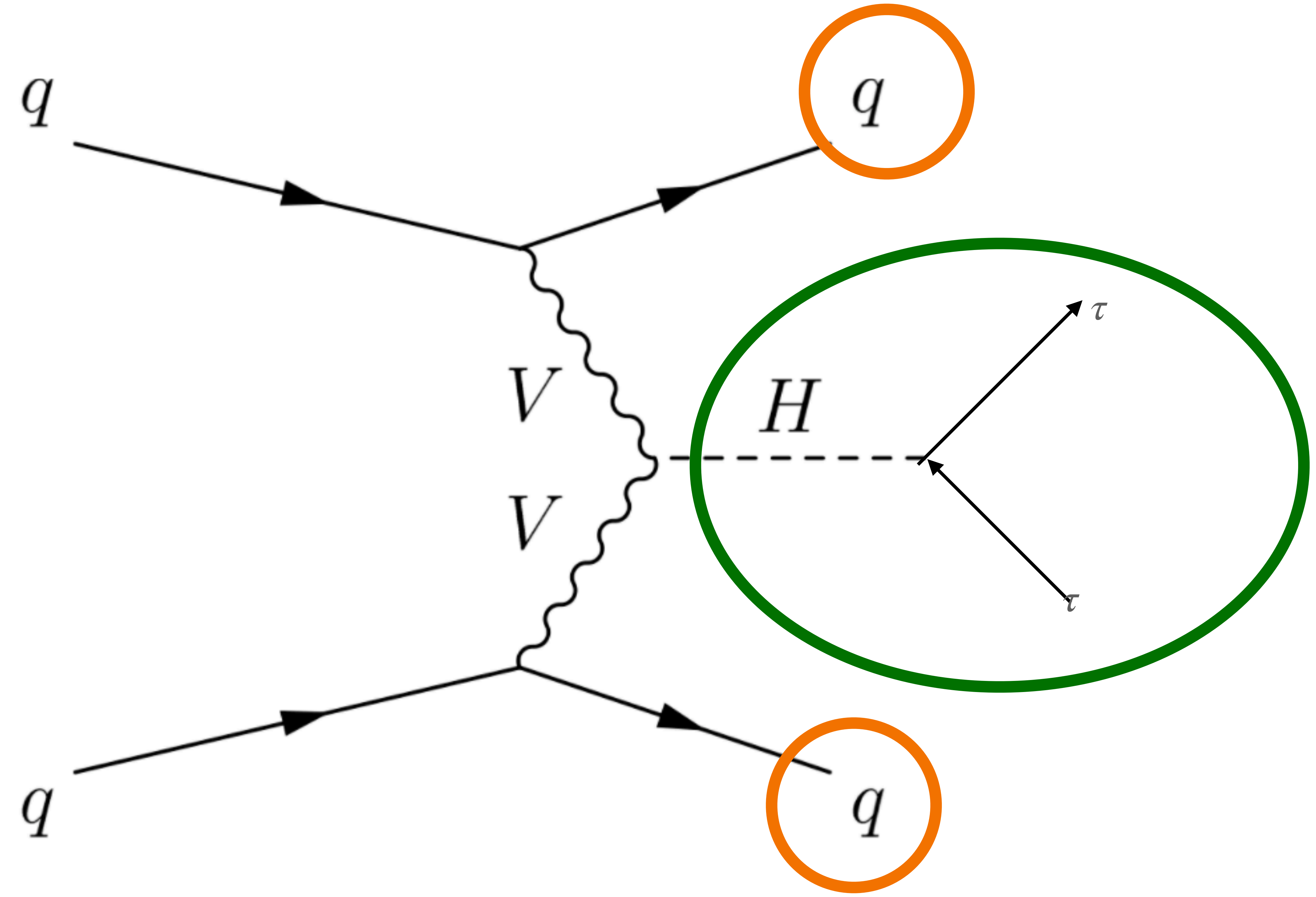
For arbitrary choice $\tilde{d} = \tilde{d}_B$

VBF $H \rightarrow \tau\tau$ analysis

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\mathrm{SM}}|^2}_{\text{CP-even}} + \underbrace{\tilde{d} \cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}_{\text{CP-odd}} + \underbrace{\tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2}_{\text{CP-even}}$$

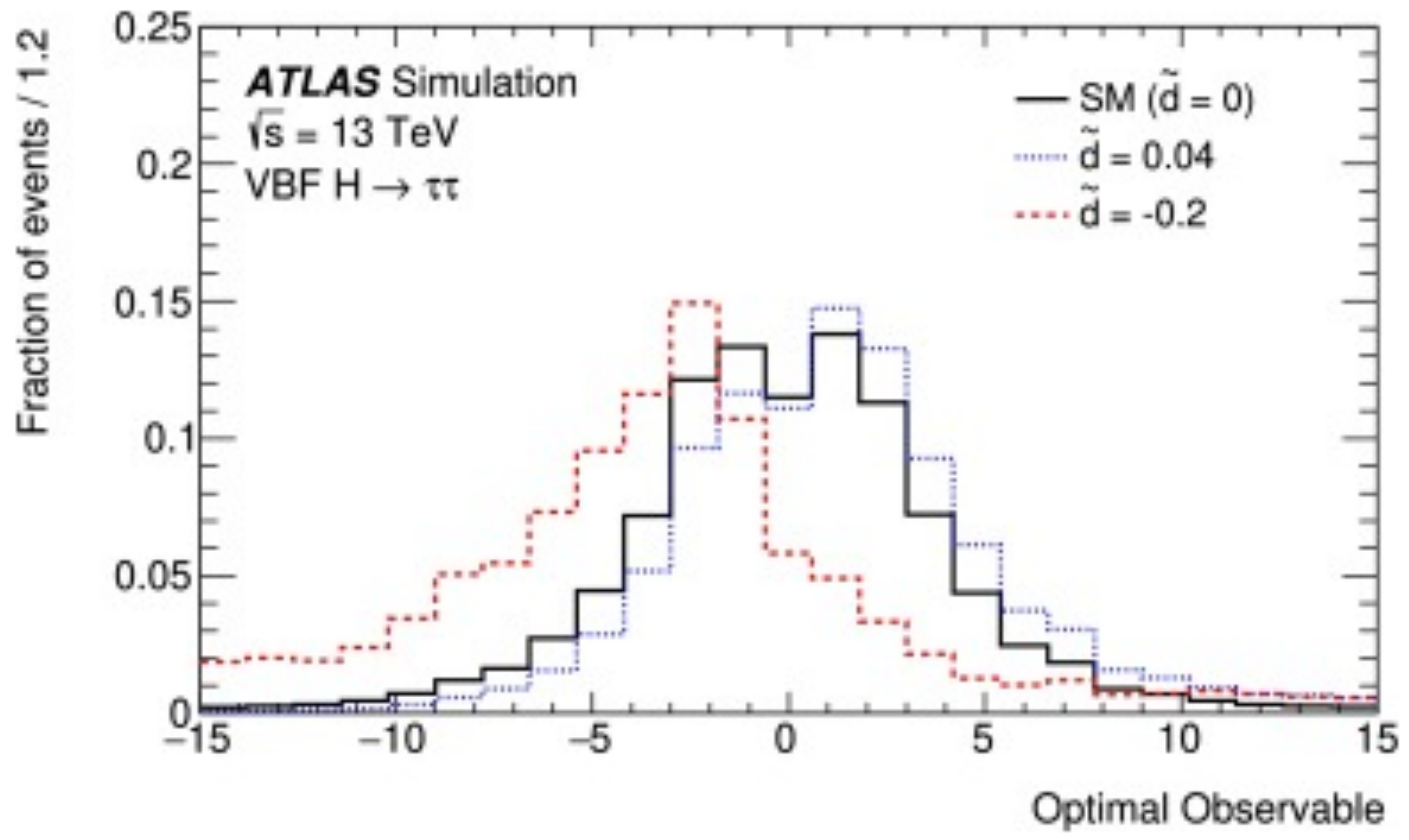
- Strength of CP-violation described by parameter $\tilde{d}$
- CP optimal observable constructed from matrix elements
- Final state:
  - 2 tagging jets (Jets with highest momenta)
  - Reconstructed decay of Higgs ($\tau\tau$)
- Optimal observable combines 7-dimensional phase space into single observable
- Probing HVV vertex using 4-momenta of final state objects as inputs

$$\mathcal{O}_{opt} = \frac{2 \cdot \mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

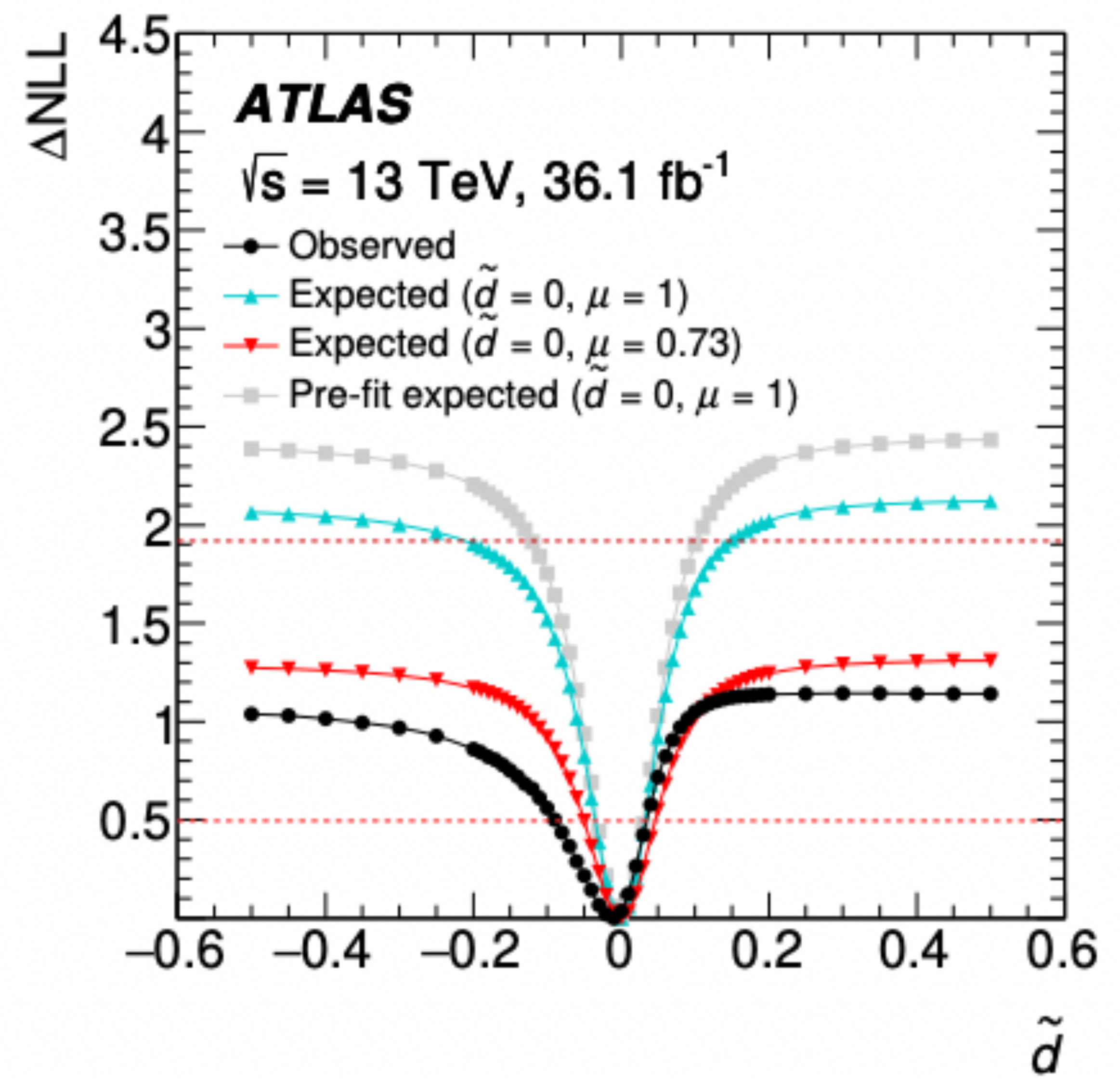


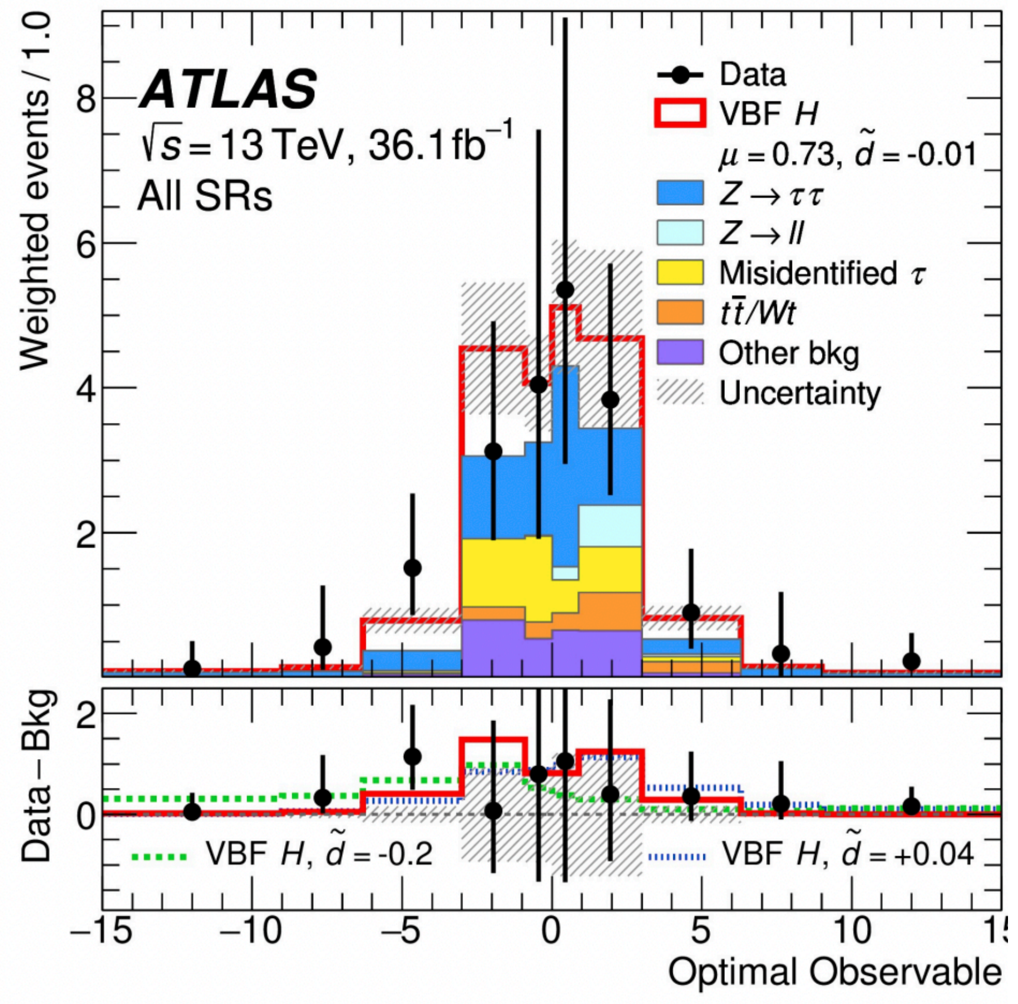
Optimal observable

- Shown to have the highest sensitivity to $\tilde{d}$ and neglects contributions proportional to $\tilde{d}^2$
- Measure mean value to obtain model independent test for CPV
- No CPV —> $< \mathcal{O}_{opt} > = 0$
- Observation of non-vanishing mean value or asymmetry in $\mathcal{O}_{opt}$ distribution would indicate new physics
  - SM: Symmetric $< \mathcal{O}_{opt} > = 0$
  - Non-vanishing $\tilde{d}$: Asymmetry with $< \mathcal{O}_{opt} > \neq 0$



- Previous measurement (36.1 fb^{-1}): arxiv.2002.05315
- Observed 68% CI of $\tilde{d} \in [-0.090, 0.035]$





Plans for run 2 analysis

- Many plans..
- Need to meet with analysis team to get some details and figure out where we can contribute
- As far as I can tell this is the only ongoing $h \to \tau\tau$ CP analysis in ATLAS

Plans for analysis based on the full Run-2 dataset

From HLepton meeting 28.02.2022

Markus Schumacher

UNI FREIBURG

First attempt:

- same methodology as in publication based on 2015/16 data (also use lep lep SF)
  fit to optimal observable to determine confidence intervals (CI) on d-tilde (HIGZ basis)
- use new reconstruction and identification tools
- apply NN for selection of signal events
- re-use as much as possible from $H\to\tau\tau$ cross section / coupling / STXS paper
  in particular background estimation techniques
- exploit synergies with other new analysis based on full Run-2 dataset

Need additional information in (standard) ntuples with relaxed cuts

- truth level information: flavour/Id, momenta of in and out going partons, Higgs boson, …
  more than 2 (i.e up to 4) truth level jets
- reco level information: more than 2 two reco jets (i.e. up to 4)
- different MET derivations including syst. variations

Advancements of analysis: (not full list, just first thoughts)

- optimize selection etc. w.r.t. to expected length of CI incl. sys. uncertainties

- consider other EFT operator basis i.e. Warsaw/Higgs basis
  → adaption of optimal observable to change of basis.
- consider also more than one non vanishing Wilson coefficient
- consider also CP-odd effective Higgs-gluon coupling

- binning of optimal observables (e.g. flat signal as in H→4l and MSc thesis of Alena Loesle)
- optimize statistical model
- unfold distribution of optimal observable(s) ?
- consider other methods/observables e.g.
  A. Butter et al., "Back to the Formula -- LHC Edition", arXiv:2109.10414
  A. Bhardwaj et al., "Machine-enhanced CP-asymmetries in the Higgs sector", arXiv:2112.05052

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Summary

- Measurements of CP in Higgs Yukawa coupling to τ-leptons have been performed by the CMS collaboration
- ATLAS close to publishing similar result
- Will try to join VBF $H\tau\tau$ analysis that is starting now
- In terms of collaboration with Warsaw (Task 4) it would be great with some inputs