Search for CP violation in Higgs boson interactions at the ATLAS experiment

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on the behalf of the ATLAS collaboration

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Introduction

- Baryons asymmetry observed in the universe
- Sakharov : Charge-Parity (CP) symmetry has to be violated to have different reaction rates for baryons and antibaryons

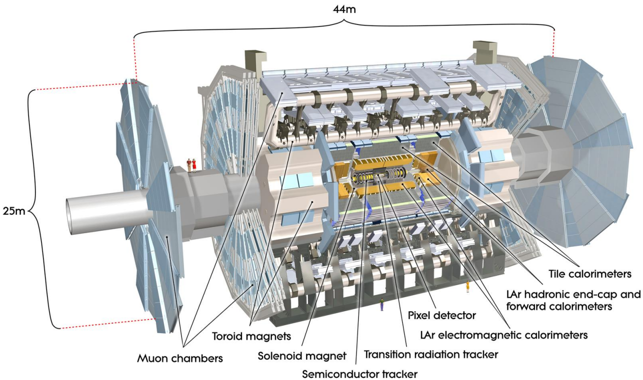
$$\Gamma(N \xrightarrow{\mathcal{L}(\Delta n_{\mathrm{Bar}} \neq 0)} f) \neq \Gamma(\bar{N} \xrightarrow{\mathcal{L}(\Delta n_{\mathrm{Bar}} \neq 0)} \bar{f})$$

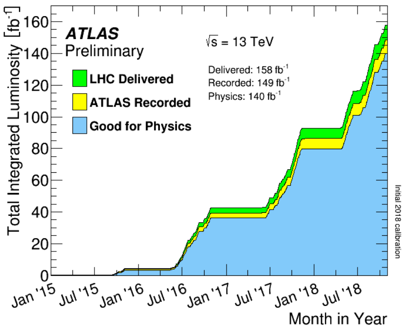
- In Standard Model (SM), CP violation is encoded in the CKM (PMNS) matrix for the quarks (leptons)
  - Source of CP violation only appears in the charged current couplings
  - Effect too small to generate the observed matter-antimatter asymmetry

- Higgs boson predicted to be a scalar ($\mathcal{J}^{CP} = 0^{++}$) in SM with no CP-violating interactions
  - The measurement of a CP-odd contribution in the Higgs boson couplings would be a sign of physics beyond the SM (BSM)
  - This motivates searches in the Higgs sector for additional sources of CP violation

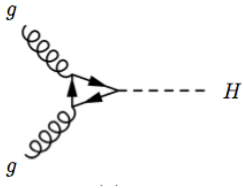
ATLAS-LHC Run 2 performance

- LHC Run 2 finished in 2018
- ATLAS is a multi-purpose particle physics detector with forward-backward symmetric cylindrical geometry
- 140 fb^{-1} dataset collected from 2015 to 2018 at $\sqrt{s} = 13$ TeV

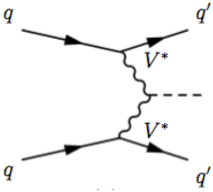




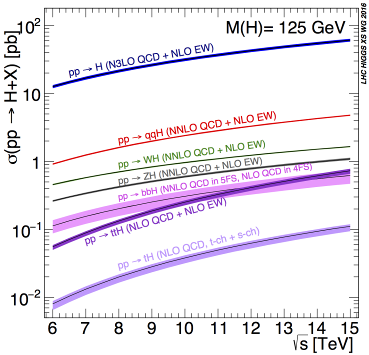
Higgs boson production modes



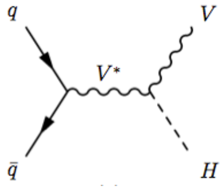
gluon fusion (ggF)



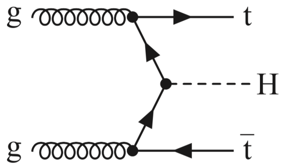
vector boson fusion (VBF)



Higgs boson production cross section



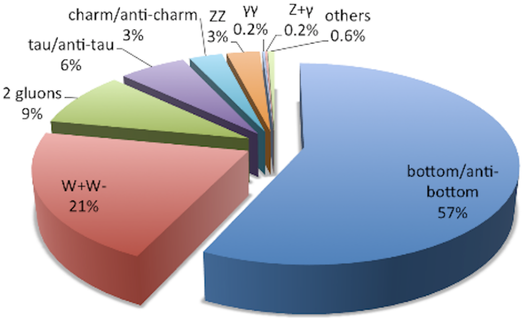
associated production with a gauge boson (VH)



associated production with a $t\bar{t}$ pair (ttH)

- Largest cross section for gluon fusion and vector boson fusion production modes

Higgs boson decay branching ratios



Higgs decay branching ratios

- Larger branching ratio (BR) for $H \to b\bar{b}$, $H \to WW^*$ and $H \to \tau\tau$, however poor mass resolution and large background contamination
- $H \to \gamma\gamma$ and $H \to ZZ^*(\to 4l)$ have lower BR, but high mass resolution; can be used for precision measurements

Higgs boson couplings

- The SM Higgs boson couplings can be summarised in the Lagrangian

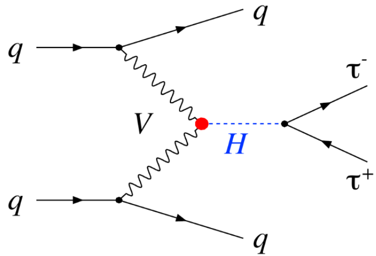
$$\mathcal{L} = -\frac{m_f}{v} f\bar{f} H + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4 + \delta_V V_\mu V^\mu \left(\frac{2m_V^2}{v} H + \frac{m_V^2}{v^2} H^2 \right)$$

- Main couplings with W, Z, and/or third generation quarks and leptons

- CP violation search in:
  - bosonic couplings: consider dimension 6 BSM couplings which are CP-mixed
  - Yukawa couplings: consider dimension 4 with *SM-like* couplings which are CP mixed

- Strong VBF signal and good resolution of reconstructed Higgs boson 4-momentum
- Considering only *HVV* couplings
- EFT Lagrangian :

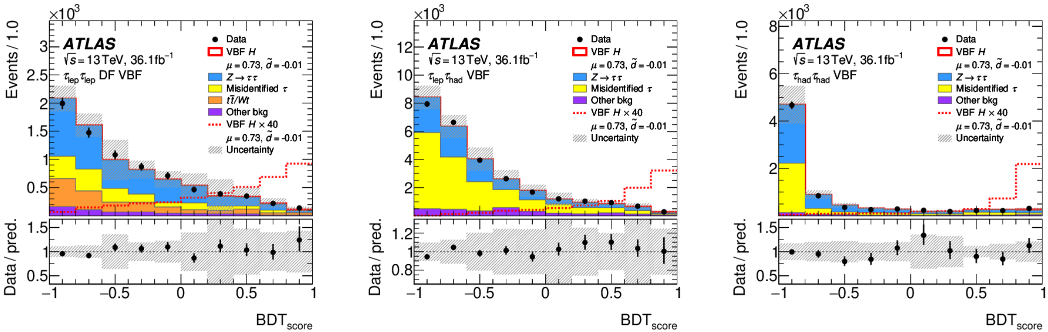
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} H^\dagger \hat{\tilde{B}}_{\mu\nu} \tilde{B}_{\mu\nu} H + \frac{f_{\tilde{W}W}}{\Lambda^2} H^\dagger \hat{\tilde{W}}_{\mu\nu} \tilde{W}_{\mu\nu} H$$



- Simplify using only one CP-violating parameter

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} = -\frac{m_W^2}{\Lambda^2} \tan^2(\theta_W) f_{\tilde{B}B}$$

- Use BDTs to separate VBF signal from background



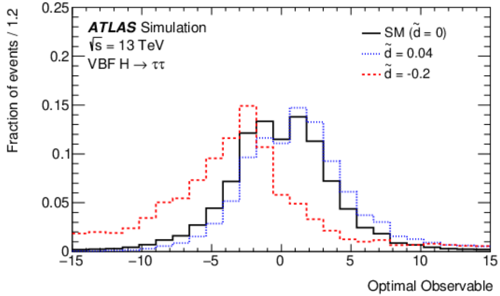
VBF H$\rightarrow \tau\tau$ analysis

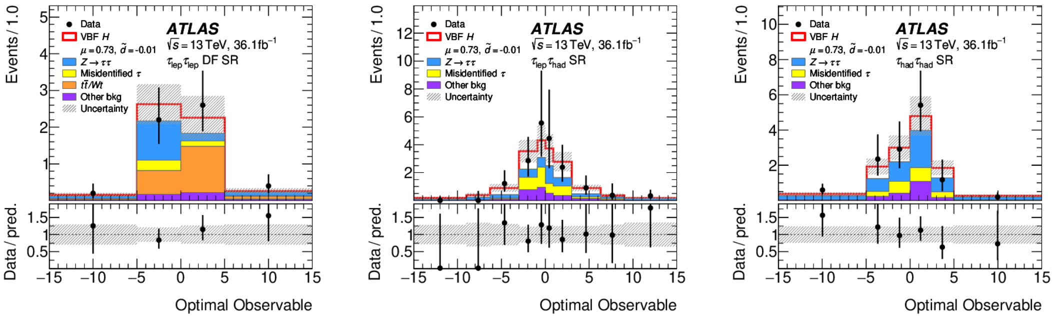
Phys.Lett.B805(2020)135426

- Use *Optimal Observable* to measure $\tilde{d}$

$$OO = \frac{Re(M^*_{SM} M_{CP-Odd})}{|M^2_{SM}|}$$

- Full phase space information in 1-dim. observable for small $\tilde{d}$
- $< OO > \neq 0 \rightarrow$ CP violation neglecting re-scattering effects by new light particles in loops



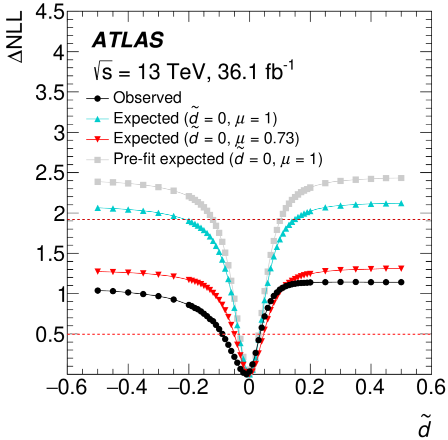


VBF H$\to \tau\tau$ analysis

Phys.Lett.B805(2020)135426

- Measured mean values in data consistent with SM expectation ($< OO >= 0$)
- Perform fit for various signal hypotheses $\to$ determine confidence intervals on $\tilde{d}$
  - no rate information used in the fit to have less model-dependent CP test

Channel	⟨Optimal Observable⟩
$\tau_{lep}\tau_{lep}$ SF	-0.54 ± 0.72
$\tau_{lep}\tau_{lep}$ DF	0.71 ± 0.81
$\tau_{lep}\tau_{had}$	0.74 ± 0.78
$\tau_{had}\tau_{had}$	-1.13 ± 0.65
Combined	-0.19 ± 0.37

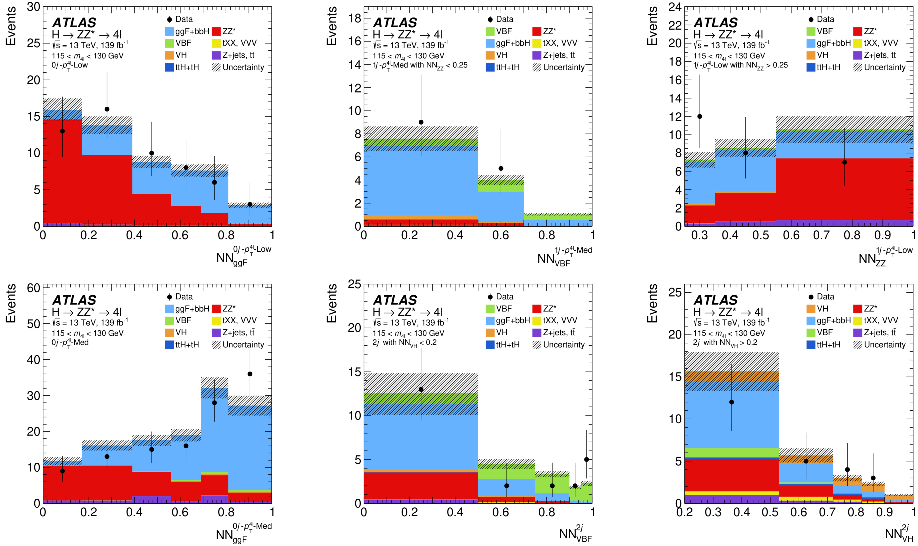


- Expected (Observed) $\tilde{d}\epsilon$ [-0,035,0.033] ([-0.090,0.035]) at 68% confidence level

H→ ZZ* → 4l analysis

arXiv:2004.03447

- Distinguish between dominating processes in different event categories following *Simplified Template Cross-Section* scheme
- Classify events using neural networks (NN)
- Final discriminant from 3 NNs : 4*l* system, jets and additional event info



H$\to$ ZZ* $\to$ 4l analysis

arXiv:2004.03447

- Probe BSM effects in *SMEFT* formalism in Warsaw basis
- EFT Lagrangian :

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i^d}{\Lambda^{d-4}} O_i^d \quad \text{for d} > 4$$

- Considering only dimension-six operators affecting Higgs boson cross section at tree level

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

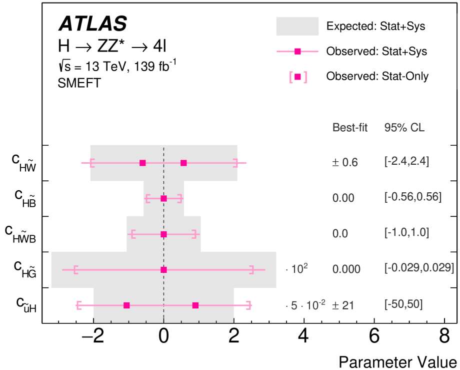
H→ ZZ* → 4l analysis

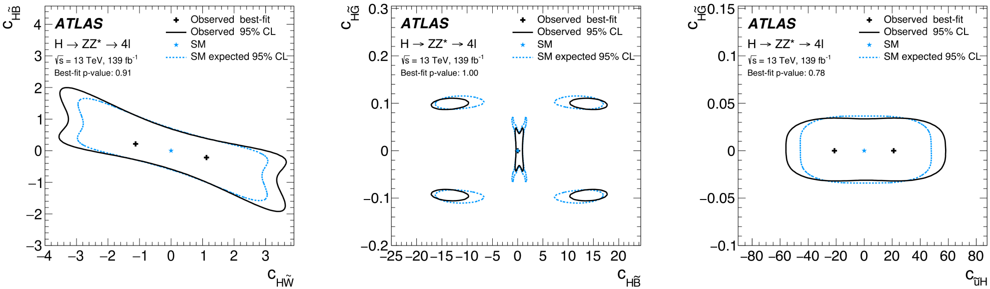
arXiv:2004.03447

- Performing fit using BSM-dependent signal strength parameters for each production bin

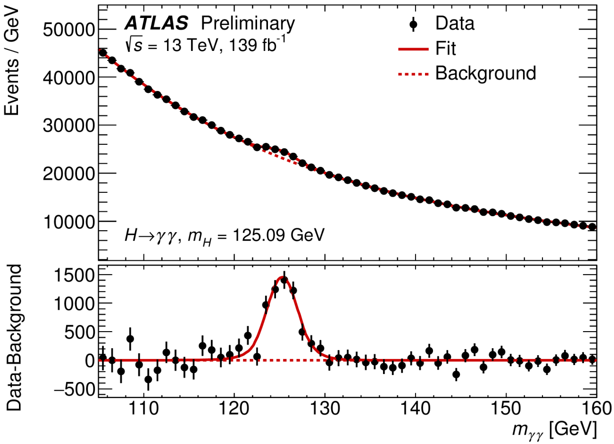
$$\mu^p(\vec{c}) = \frac{\sigma^p(\vec{c})}{\sigma_{SM}} \frac{\mathcal{B}^{4l}(\vec{c})}{\mathcal{B}^{4l}_{SM}} \frac{A(\vec{c})}{A_{SM}}$$

- Use only rate information; no CP odd observable is being probed
- Fit results with both one/two coefficient fitted at a time
- Results consistent with SM hypothesis → no sign of CP violation





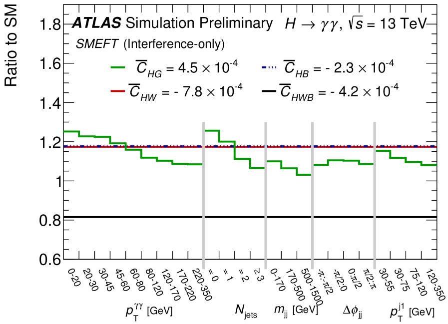
- Signal extracted from diphoton invariant mass in the range [105-160]
  - Signal parameterised using Crystal Ball function
  - Background parameterised using an exponential of a second-order polynomial

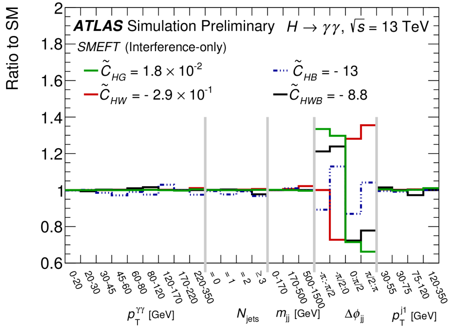


- Using both SILH and SMEFT formalism to parameterise additional CP-even/CP-odd interaction through dimension-six operators
  - use different operators to describe new Higgs boson interactions
  - results shown only for SMEFT formalism

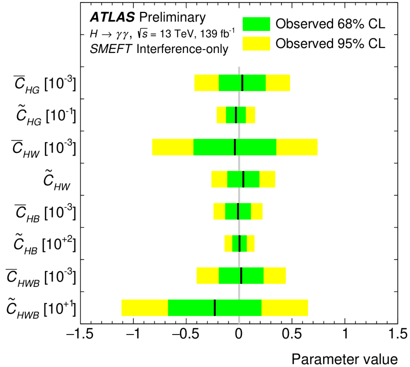
- In SMEFT formalism, CP-odd contribution exhibit sensitivity only for $\Delta\Phi_{jj}$
  - *signed* difference in the azimuthal angle between the two leading jets in an event ordered by their rapidities

- Results extracted measuring differential cross section of five different observables





- Testing two different scenarios:
  - Interference term only
  - Interference and quadratic term
- Significant differences emerge for the CP-odd coefficients for which the interference term is vanishing
- Results consistent with SM hypothesis $\rightarrow$ no sign of CP violation
- Limits set at 68% and 95% confidence level



Coefficient	95% CL, interference-only terms	95% CL, interference and quadratic terms
$\overline{C}_{HG}$	$[-4.2, 4.8] \times 10^{-4}$	$[-6.1, 4.7] \times 10^{-4}$
$\widetilde{C}_{HG}$	$[-2.1, 1.6] \times 10^{-2}$	$[-1.5, 1.4] \times 10^{-3}$
$\overline{C}_{HW}$	$[-8, 2, 7.4] \times 10^{-4}$	$[-8.3, 8.3] \times 10^{-4}$
$\widetilde{C}_{HW}$	$[-0.26, 0.33]$	$[-3.7, 3.7] \times 10^{-3}$
$\overline{C}_{HB}$	$[-2.4, 2.3] \times 10^{-4}$	$[-2.4, 2.4] \times 10^{-4}$
$\widetilde{C}_{HB}$	$[-13.0, 14.0]$	$[-1.2, 1.1] \times 10^{-3}$
$\overline{C}_{HWB}$	$[-4.0, 4.4] \times 10^{-4}$	$[-4.2, 4.2] \times 10^{-4}$
$\widetilde{C}_{HWB}$	$[-11.1, 6.5]$	$[-2.0, 2.0] \times 10^{-3}$

ttH$\to \gamma\gamma$ analysis

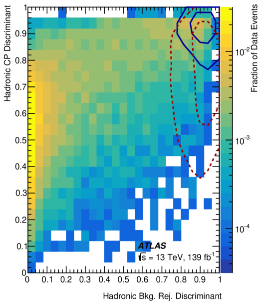
Phys.Rev.Lett.125,061802

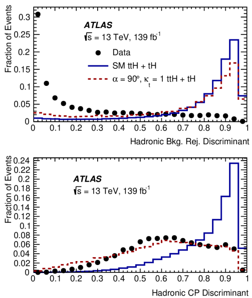
- Search for CP-odd contribution to top Yukawa coupling
- Using Higgs Characterization model :

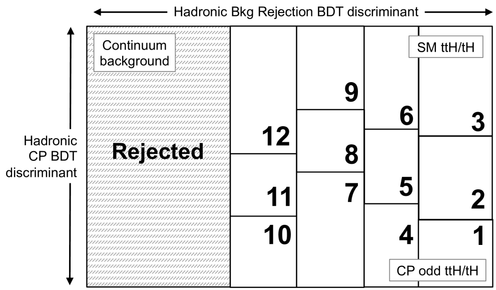
$$\mathcal{L} = -\frac{m_t}{v}\left(\bar{\Psi}_t k_t [\cos\alpha + i \sin\alpha\gamma_5]\Psi_t\right) H$$

where k_t is the coupling parameter and α is the CP-mixing angle

- Use two BDTs for event classification : signal vs background, CP-odd vs CP-even signal



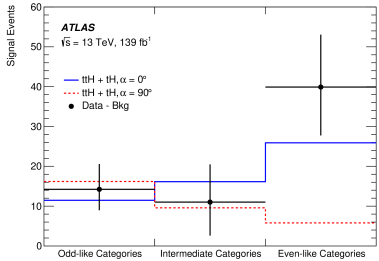


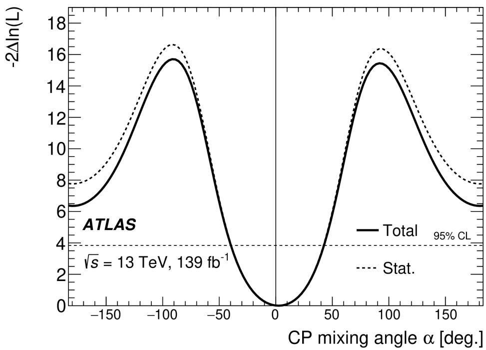


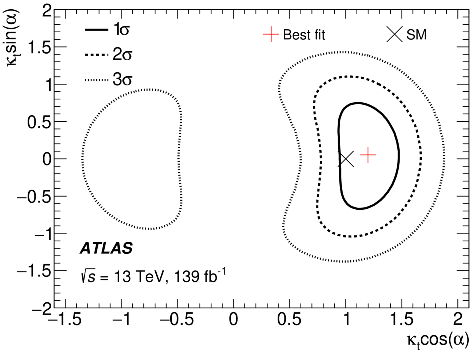
ttH→ $\gamma\gamma$ analysis

Phys.Rev.Lett.125,061802

- Results extracted from a fit of $m_{\gamma\gamma}$ spectrum
- 2D fit results for $k_t \cos\alpha$ and $k_t \sin\alpha$ show agreement with SM hypothesis
- limit on α is set without prior constraint on k_t in the fit: $|\alpha| > 43^o$ is excluded at 95% confidence level
- No sign of CP violation







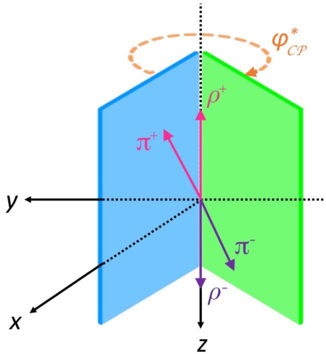
CP nature of the H$\to \tau\tau$ coupling

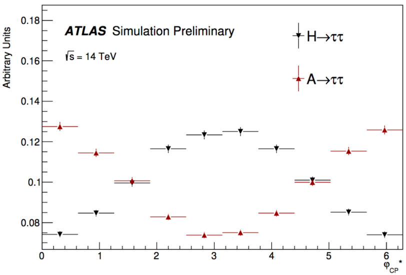
ATL-PHYS-PUB-2019-008

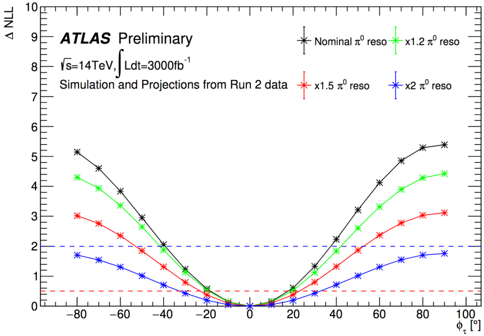
- Consider CP-violating Lagrangian:

$$\mathcal{L} = g_{\tau\tau}(\cos\Phi_\tau \bar{\tau}\tau + \sin\Phi_\tau \bar{\tau} i\gamma_5 \tau)h$$

- CP violation encoded in the correlation between trasverse spin components of the taus
- Access the spin correlation by reconstructing the angle ϕ^*_{CP} between the tau decay planes
- HL-LHC could bring sensitivity to H$\to \tau\tau$ vertex due to increased data statistics







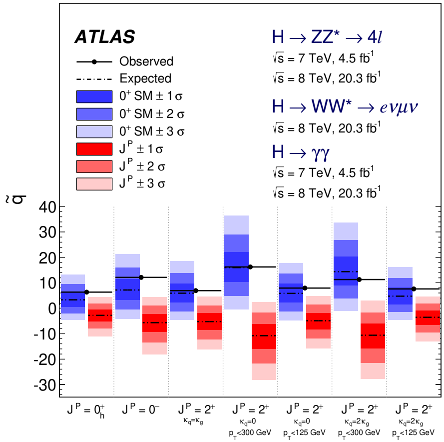
Conclusion

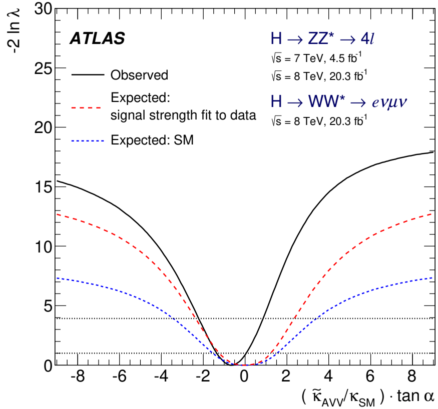
- Baryons asymmetry observed in the universe cannot be explained only with CP-violation predicted by Standard Model
- Higgs boson predicted to be a scalar with no CP-violating interactions
  - additional sources of CP violation in the Higgs sector would bring to new physics
- Different channels have been exploited probing Yukawa and bosonic couplings but so far no sign of CP violation
- Looking forward to new searches while waiting for Run 3 data-taking and HL-LHC

Thanks For Your Attention

Backup

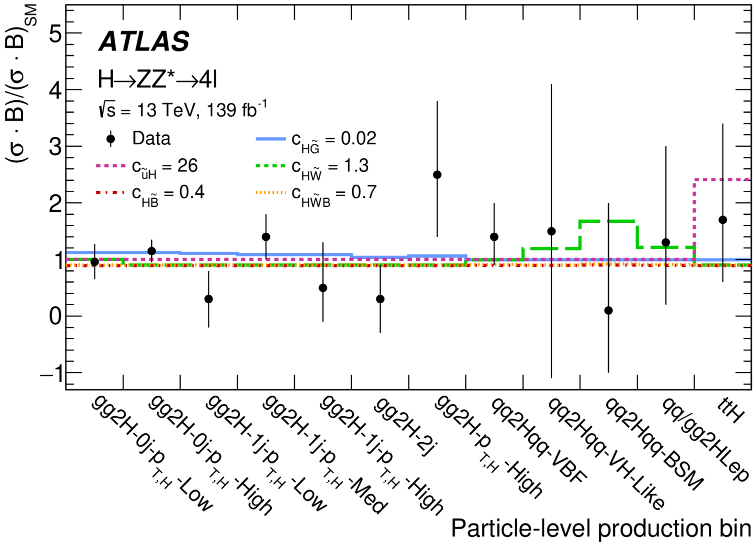
CP measurement in Run 1





Phys. Rev. D 98, 030001 (2018)

- In all investigated scenarios, data are compatible with $J^{CP} = 0^+$ hypothesis
- Need to improve precision to exclude CP-odd mixing



The expected signal yield ratio for chosen CP-odd EFT parameter values together with the corresponding cross-section measurement in each production bin of Reduced Stage 1.1. The parameter values correspond approximately to the expected confidence intervals at the 68% CL obtained from the statistical interpretation of data.