Recent ATLAS Measurements Testing Higgs CP Properties

Haichen Wang
UC Berkeley and LBNL

FIND CP Violation and Electroweak Scale and Beyond Workshop

August 26 2023

Introduction

For any fundamental interaction, the ability to preserve or alter the Charge-Conjugation-Parity quantum number of a physical system is a key property of that interaction

With the discovery of the Higgs boson, we are presented the opportunity to study the CP properties of two types of new interactions:

Higgs interactions with fermions → Higgs Yukawa interactions
Higgs interactions with gauge bosons → Higgs gauge boson interactions

In the Standard Model, these interactions are CP even; however, beyond the SM physics may introduce a non-zero CP-odd component

I will present a summary of published measurements from the ATLAS experiments

Outline

- General comments on measurable effects and analysis strategies for CP measurements
- Higgs Yukawa interactions
  - Parameterization of CP properties of the Yukawa interactions
  - Relevant collider processes
  - Representative measurements from ATLAS
- Higgs-gauge boson interactions
  - Parameterization of CP properties of gauge interactions
  - Relevant collider processes
  - Representative measurements from ATLAS
- Concluding remarks

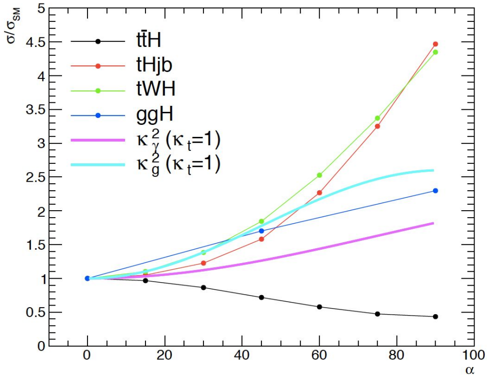
Observable effects of CP properties

Event rates
The presence of CP-odd Higgs interactions alters Higgs production and decay rates

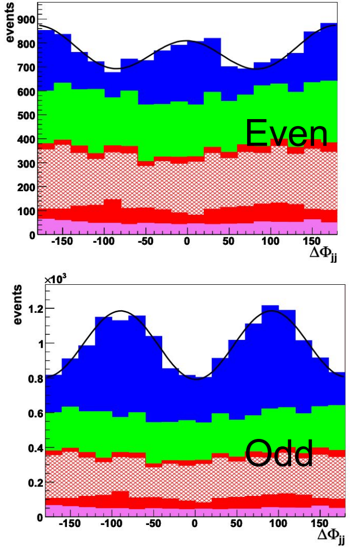
Final state kinematics
Dijet opening angle, Higgs p_T, etc.

Optimal Observable
Based on matrix element when final state is reconstructible

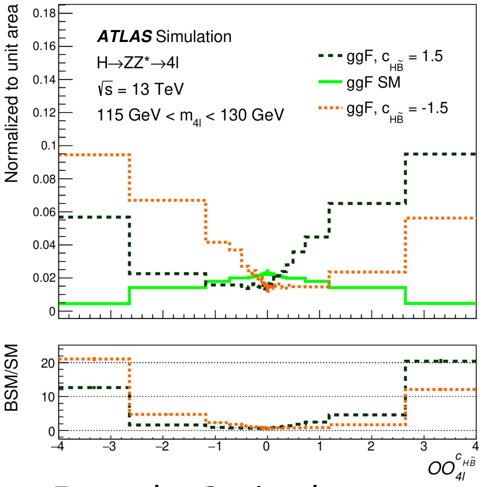
Multivariate Observable
Use machine learning to capture differences between CP-even and CP-odd samples



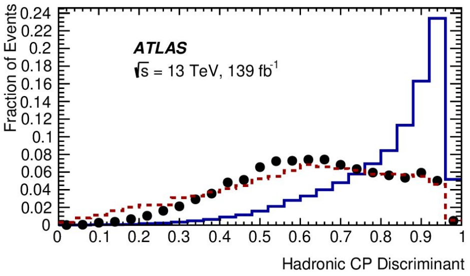
Example: cross section variation for ttH, tH, and ggF processes as a function of t-H CP mixing angle



Example: dijet opening angle in VBF-like events



Example: Optimal Observable built from matrix elements for H ⟶ 4 leptons decay



Example: A Boosted Decision Tree trained by ATLAS to separate CP-even and CP-odd ttH events

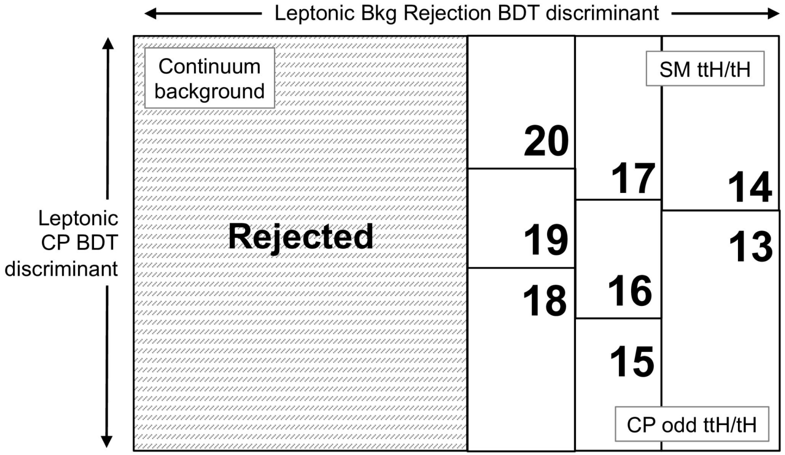
Rate-based analysis can be used to exclude different CP scenarios

CP-observables are needed to establish CP-odd or CP-mix scenarios

Analysis Strategies

Dedicated CP analyses

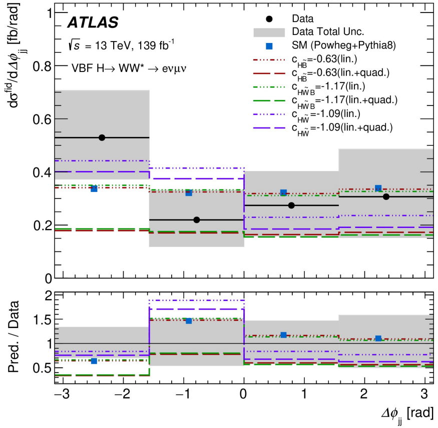
Directly test CP hypotheses (even, odd, mix) against data using reco-level CP sensitive observables



Design of analysis is explicitly exploiting CP predictions

CP interpretation as part of a Simplified Template Cross Section (STXS) or differential cross section measurements

Test CP hypotheses against differentially measured CP observables



Measurements designed without explicit CP-related model assumptions

CP properties of Yukawa couplings

- In the SM, the Yukawa interactions are CP-even. In BSM scenarios, a CP-odd component can arise at the tree-level, and therefore, a generic Higgs-fermion Yukawa interaction can be parameterized as

$$A(Hff) = -\frac{m_f}{v}\bar{\psi}_f(\kappa_f + i\tilde{\kappa}_f\gamma_5)\psi_f$$

  - The real and imaginary parts are the CP-even and CP-odd components, respectively
  - k_f and k_f~ are the coupling strength modifiers for the even and odd components, respectively. For the SM, k_f = 1, and k_f~ = 0
- In CMS results, they also report the CP-odd fraction f_{CP}^{Hff} and mixing angle α^{Hff}

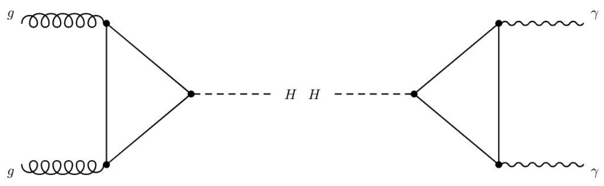
$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}\,\mathrm{sgn}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

$$\alpha^{Hff} = \tan^{-1}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

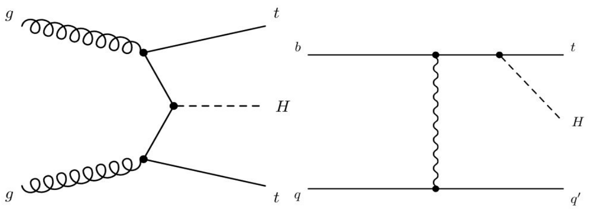
- In ATLAS ttH/tH CP paper, we have

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

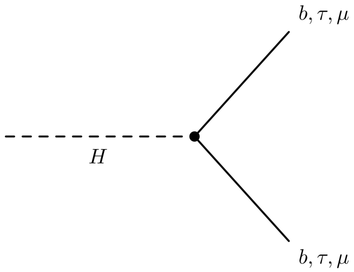
Relevant processes in the Higgs sector



(a) ggH (b) $H \to \gamma\gamma$



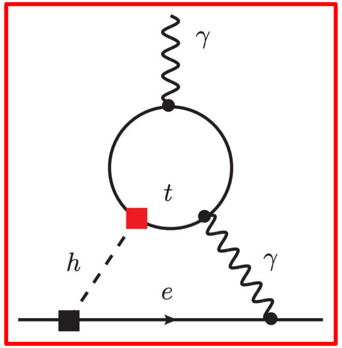
(c) $t\bar{t}H$ (d) tH



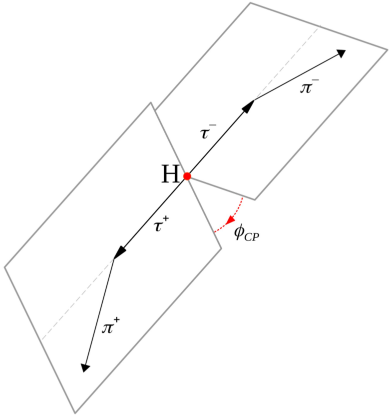
- ggH and H → γγ loop induced processes, sensitive to top-Yukawa. The observable effect is primarily rate. But for ggH, possible effects also include Higgs pT , off-shell rate, and jet kinematics
- ttH/tH provide direct access to top-Yukawa, observable effects include rate and kinematics
- Other processes that may be complementary for top-Yukawa CP include four-top, ttbar production (thru. EW corrections)
- H → ττ decay provides access to tau-Yukawa CP, because tau decays allow us to analyze the tau polarization
- CP effects on bottom-Yukawa induced processes are extremely hard to observe
  - Spin correlation not preserved in the b-hadronization
  - CP effects in production such as bbH, bH are too small (related to mass)
- H → μμ perhaps impossible

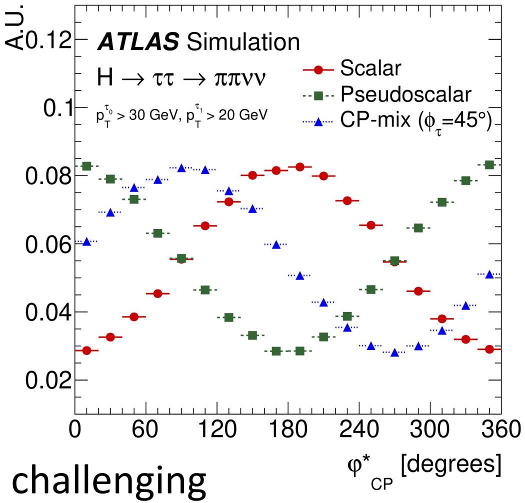
A caveat

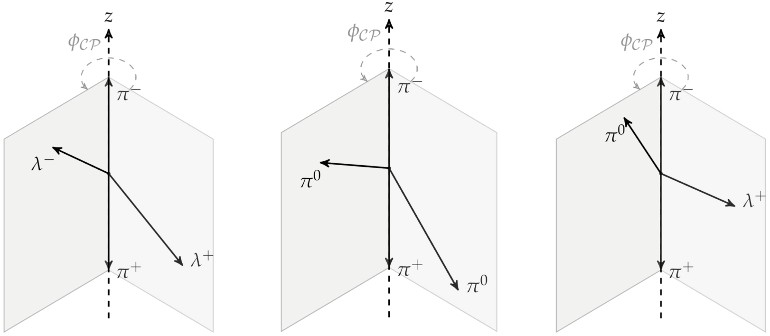
- There are constraints on the CP properties of the fermion-Higgs interaction, particularly on top-Yukawa, from low energy experiments (ACME II)
  - The non-observation of Electron Electric Dipole Moment (EDM) put stringent constraints on the top-Yukawa coupling, and so do neutron EDM measurements.
  - However, it assumes the Higgs-electron coupling is SM and there are no other cancellations
  - These assumptions, while motivated, cannot be verified experimentally. If the Higgs-electron coupling is much weaker than the SM or there's some cancellation due to BSM particles, the ACME II result would not be relevant to top-Yukawa CP study
- Low energy experiment investigations are well motivated but are not within the scope of this talk



- In the H → ττ decay, the CP property of the tau-Yukawa interaction is passed to the tau leptons
  - This information is preserved through spin correlation
  - The observable is the φ_{CP}, the angle between tau decay planes
  - A non-zero CP mixing angle results in a phase shift in φ_{CP}





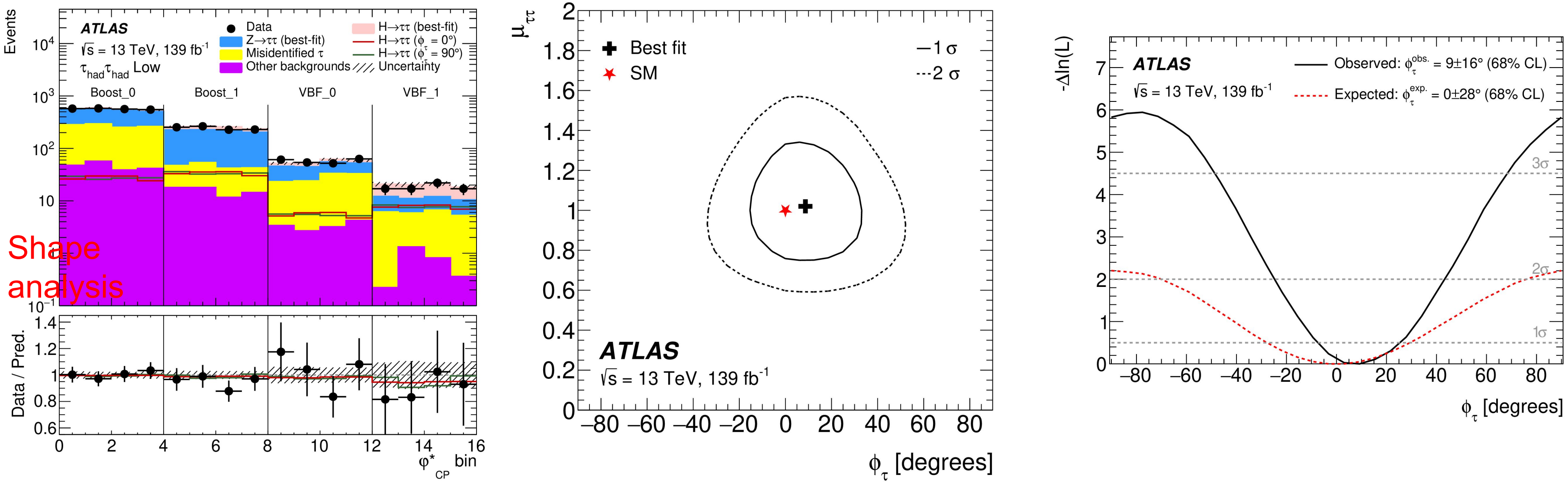


- Reconstruction of φ_{CP} is challenging
  - φ_{CP} is defined in the Higgs rest frame, experimentally, it's approximated as the Zero Momentum Frame
  - Depending on tau decay topologies, different methods are used to calculate φ_{CP}

τ-H CP with H → ττ: two dimensional analysis

HIGG-2019-10

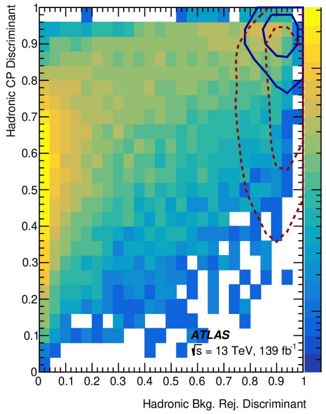
- Several signal-vs-background MVA classifiers were trained
- Final fit is performed in two dimensional SRs

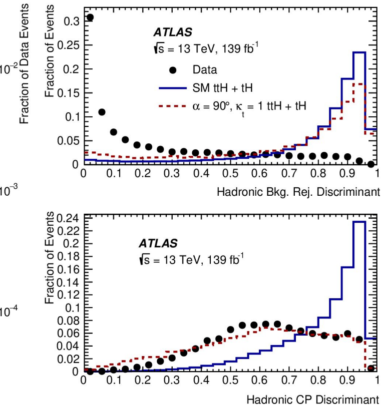


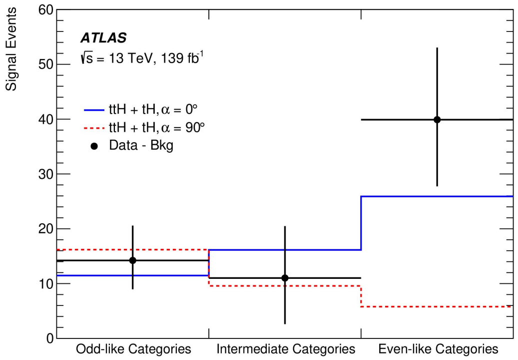
The observed (expected) value of φτ is 9°±16° (0°±28°) at the 68% confidence level (CL), and ± 34° (-70°+75°) at the 2σ level. The CP-odd hypothesis is rejected at the 3.4σ (2.1σ expected) level.

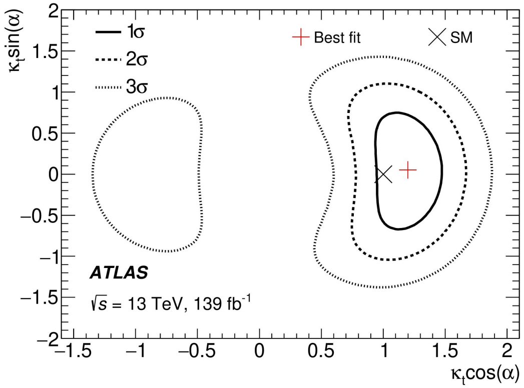
The analysis focuses on ***ttH-like events***

- It used two BDTs to suppress background in the leptonic and hadronic channels
- A CP BDT is trained to separate CP even and CP odd hypotheses
- CP tests are based on simultaneous fits to $m_{\gamma\gamma}$ distributions categorized by S-vs-B and CP BDTs





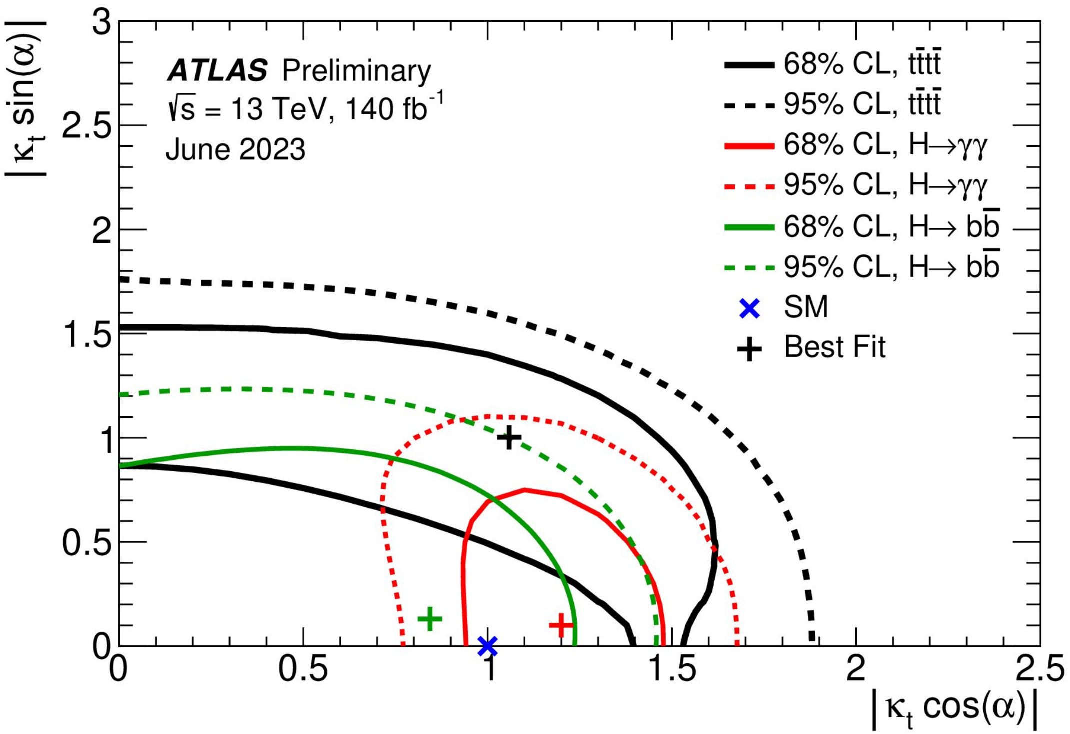




ttH and tH yields are parameterized as a function of CP parameters

ATLAS ttH/tH $\rightarrow \gamma\gamma$ 95% CL limit $|\alpha| < 43°$ obs. (56° exp.)

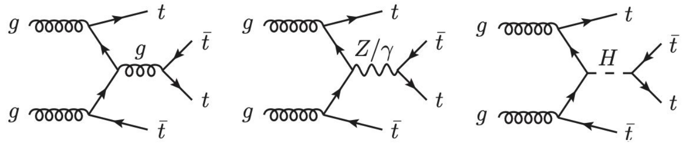
Summary of ATLAS constraints on top-Higgs Yukawa CP



ATLAS ttH/tH → γγ
HIGG-2019-01

ATLAS ttH/tH → bb
HIGG-2020-03

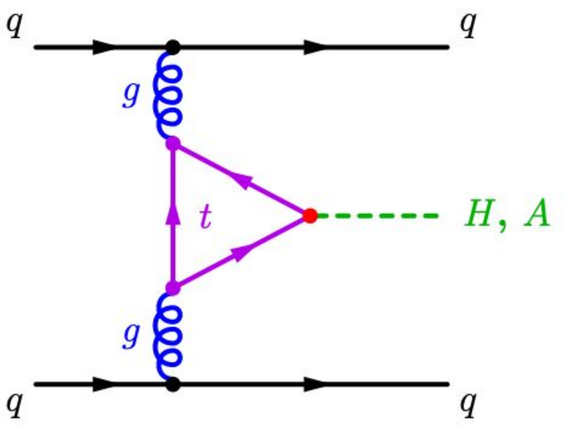
ATLAS four top observation
TOPQ-2021-18

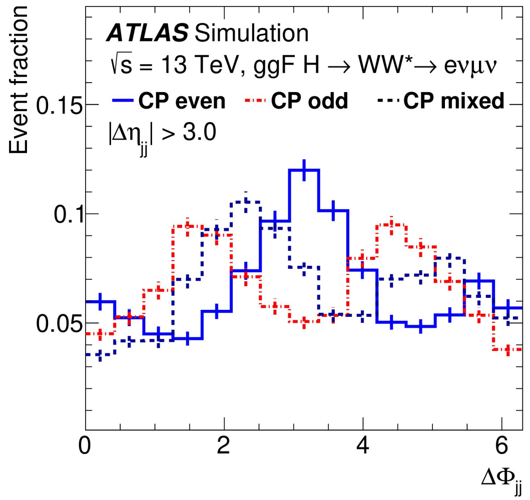


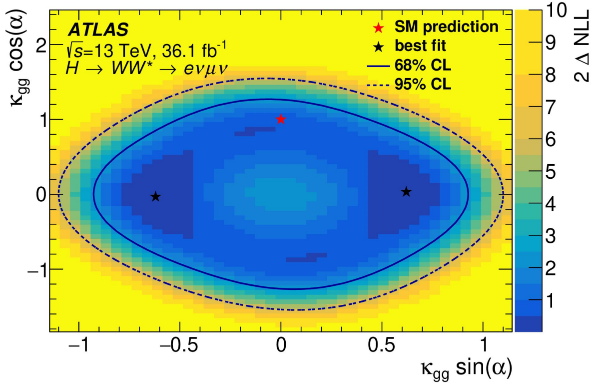
Qinghong Cao, et. al.

One more example on top-H CP through VBF-like ggH, H → WW

The CP properties of the top-Higgs Yukawa interaction can also be probed through the *VBF-like* **gluon fusion** process, where top quarks mediate the production of the Higgs







Analysis was done with partial Run-2 data, not yet competitive, included here for the sake of completeness

Gauge Interaction CP Test Overview

The most general tensor structure of a Higgs-gauge boson interaction could be parameterized as

$$T^{\mu\nu}(q_1,q_2) = a_1(q_1,q_2)\ g^{\mu\nu} + a_2(q_1,q_2)\ [q_1\cdot q_2 g^{\mu\nu} - q_1^{\mu} q_2^{\nu}] + a_3(q_1,q_2)\ \epsilon^{\mu\nu\alpha\beta} q_{1,\alpha} q_{2,\beta}$$

a_1 scales SM (CP-even) term

a_2 scales BSM CP-even term

a_3 scales BSM CP-odd term

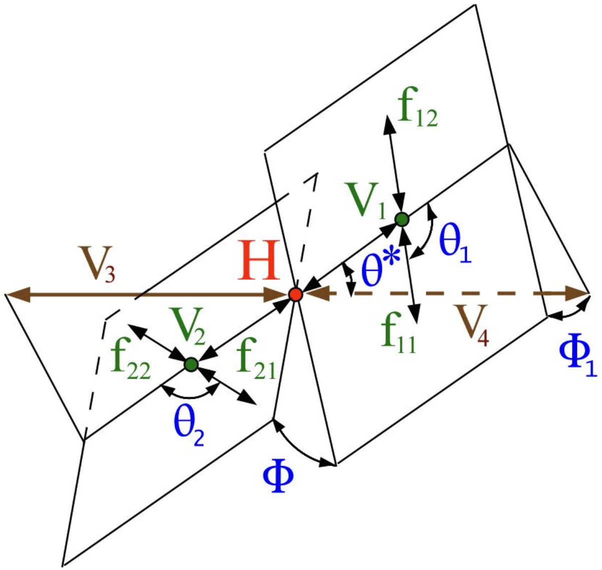
Les Houches 2019 Report

ATLAS interpretation uses EFT framework

- ***Dimension-6 operators, i.e. higher orders than SM, suppressed by $1/\Lambda^2$***
- ***Warsaw basis: Wilson coefficients (WC) for CP-odd interactions*** $C_{HW\sim}$, $C_{HB\sim}$, $C_{HW\sim B}$
- ***Higgs basis, CP-odd WCs:*** $\tilde{c}_{zy}$, $\tilde{c}_{yy}$, $\tilde{c}_{zz}$

These two representations are equivalent and can be translated from one to another. See link

Processes that allow the investigation of the CP properties of H-V interactions



Credit: link

Vector Boson Fusion (VBF)

- $V_3V_4 \rightarrow H$

H to four fermion decays: $H \rightarrow WW$ and $H \rightarrow ZZ$

- $H \rightarrow V_1V_2 \rightarrow f_{11}f_{12}\, f_{21}f_{22}$

Associated Production with a Vector Boson (VH)

- $V_3H \rightarrow V_4H\ (\rightarrow V_1V_2)$

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

HIGG-2018-30 ***full Run-2 data***

Discriminating variable: "**Optimal Observable**"

$$OO = \frac{2\Re\left(\mathcal{M}_{\rm SM}^{*}\mathcal{M}_{\rm BSM}\right)}{|\mathcal{M}_{\rm SM}|^2}$$

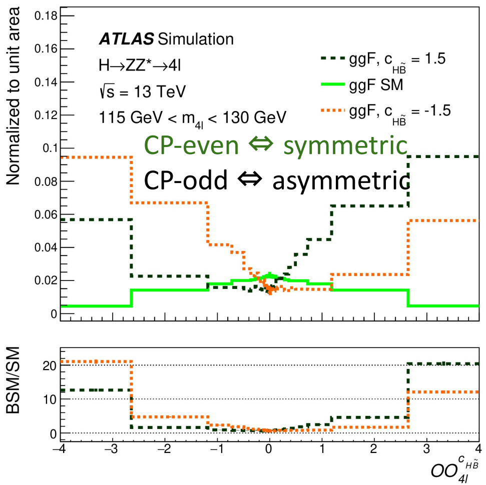
Matrix elements are functions of final state particle four vectors

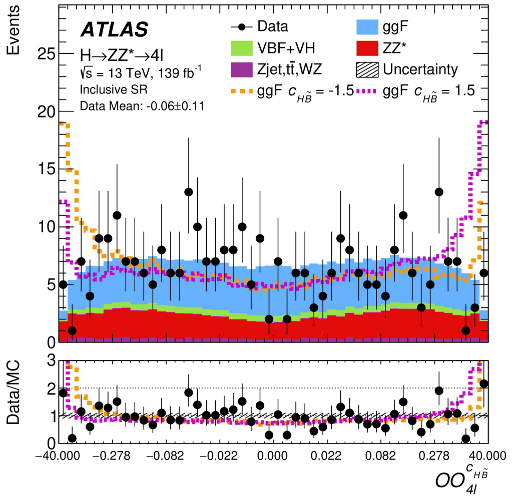
The *H→ZZ→4l decay* provides rich info. to constrain the H-V CP property

- Four leptons → ***decay level*** **OO**

The *VBF production* also provides additional constraint on H-V CP property

- Jets, 4l-system → ***production level*** **OO**



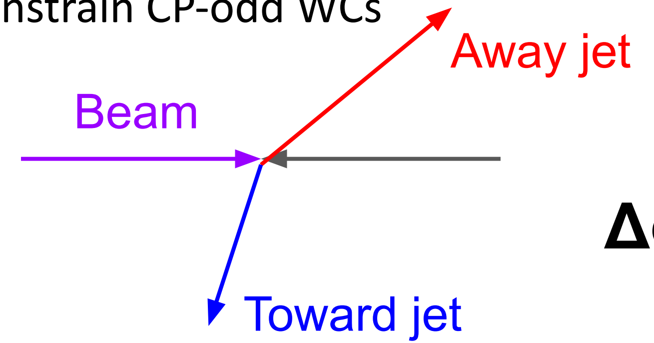


EFT coupling parameter	Observed 68% CL	Observed 95% CL	Fit type
$c_{H\tilde{B}}$	[−0.42, 0.31]	[−0.61, 0.54]	decay
$c_{H\widetilde{W}B}$	[−0.56, 0.53]	[−0.97, 0.98]	decay
$c_{H\widetilde{W}}$	[−0.07, 1.09]	[−0.81, 1.54]	comb

WCs measured one at a time; CP-even WCs assumed to be zero

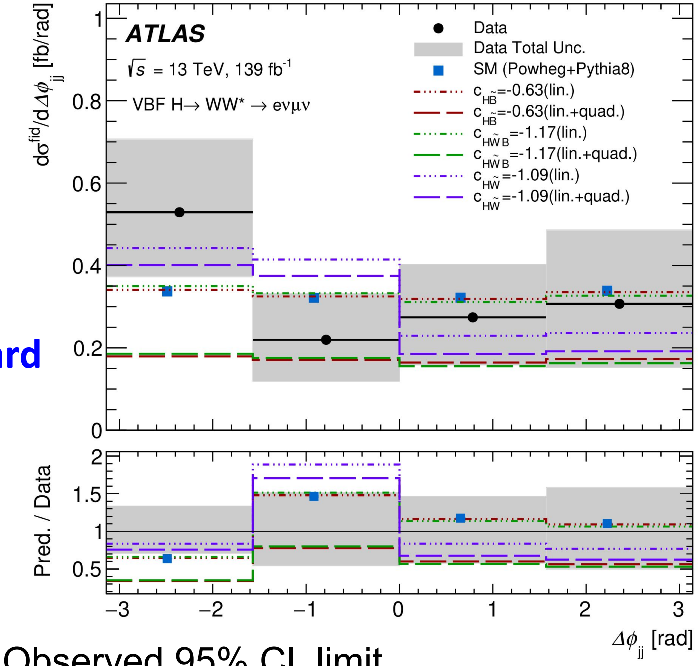
VBF $H \to WW \to e\nu\mu\nu$ differential cross section analysis   HIGG-2020-25 *full Run-2 data*

Measure **differential cross section w.r.t. signed $\Delta\varphi_{jj}$** to constrain CP-odd WCs



ref

$$\Delta\varphi_{jj} = \varphi_{away} - \varphi_{toward}$$



Diff. xsec. parameterized as a function of CP-odd WCs

$$\sigma \propto SM^2 + 2\cdot\underline{SM\cdot BSM} + \underline{BSM}^2$$

linear   quadratic

Observed 95% CL limit

$c_{H\tilde{W}}$	lin.	[-1.8, 1.3]
	lin. + quad.	[-1.1, 1.4]
$c_{H\tilde{B}}$	lin.	[-32, 22]
	lin. + quad.	[-0.63, 0.63]
$c_{H\tilde{W}B}$	lin.	[-17, 12]
	lin. + quad.	[-1.2, 1.1]

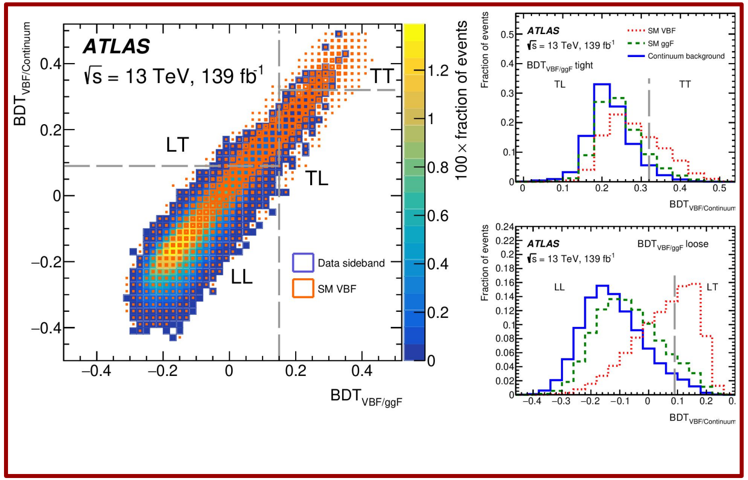
Constraints are derived using either ***only the linear*** or ***both linear and quadratic terms***

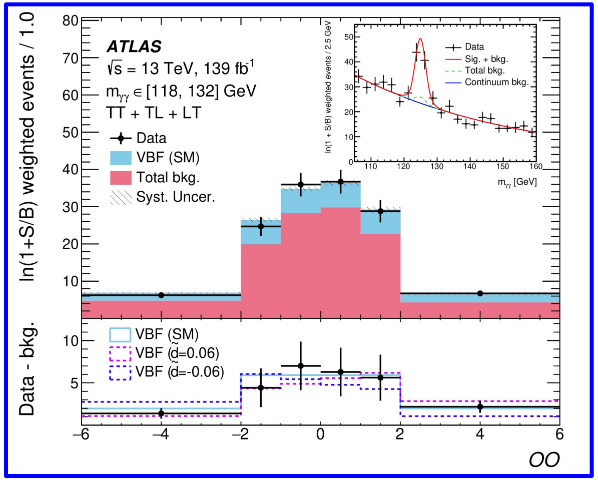
Same assumption as prev. slide used here.

H-V CP with VBF H → γγ

The analysis focuses on ***VBF-like events***

- It used two BDTs to suppress continuum and gluon fusion background
- Events are separated into different categories using these BDTs; lowest scored events are discarded





	68% (exp.)	95% (exp.)
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]
	68% (obs.)	95% (obs.)
$c_{H\tilde{W}}$ (inter. only)	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.15, 0.67]	[−0.55, 1.07]

Optimal Observable as the discriminant

- Events are further categorized using the OO based on four-vectors of jets and Higgs
- Simultaneous fit to these categories based on BDT values and OO values to constrain CP parameters (cHW~)

Summary

ATLAS is carrying out an active physics program that tests the Higgs CP properties

- Exploit all the major production and decay modes
- Cover both Yukawa and gauge interactions
- Use complementary analysis strategies and a variety of CP-sensitive variables

Reference table ⇒

Color code
Interaction tested
Status
Observable with reference link

	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggH		H-V Published OO	H-t Published $\Delta\varphi_{jj}$	H-τ Published Decay angle	
VBF	H-V Published OO	H-V Published OO	H-V Published $\Delta\varphi_{jj}$	H-V Published OO	
ttH/ tH	H-top Published MVA	H-top Published OO			H-top Published b2/b4/rate