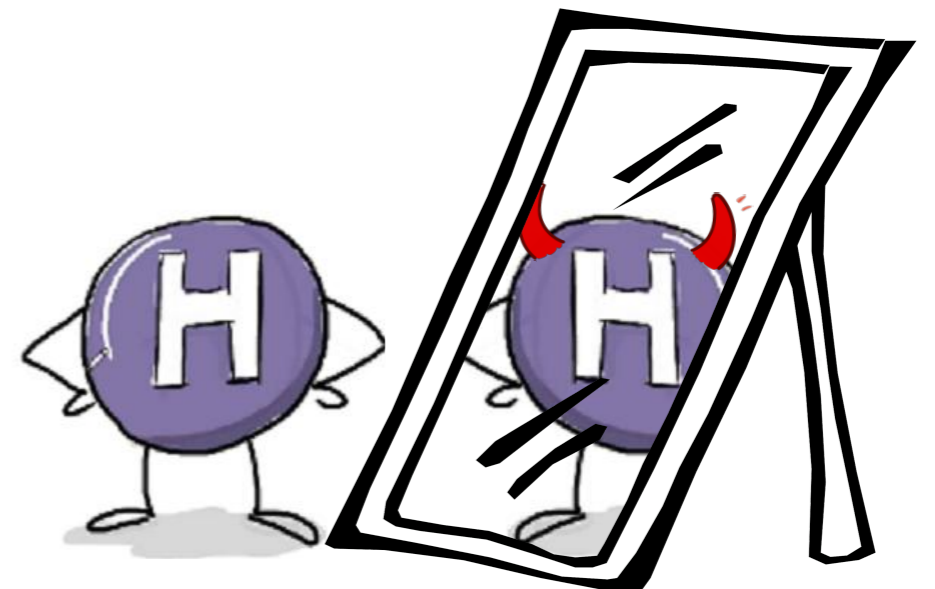


Summary of WG2 CPV activity

Daniele Barducci, Nicolas Berger, Mauro Donega, Sarah Heim, Ken Mimasu
& Giacomo Ortona

19th Workshop of the LHC Higgs Working Group

28th November 2022



Mission statement

From 18th general meeting

- Identify existing/new channels/observables sensitive to CPV
- Study how best to implement in global analyses, e.g. STXS
- Harmonise approach across experiments in view of future combinations
- Recommendations for common parametrisation & measurements to maximise CPV new physics reach at the LHC

'admixture' model $\kappa \cos \alpha + \tilde{\kappa} \sin \alpha$ \Leftrightarrow $\begin{matrix} \tilde{C}_{HWB} & \tilde{C}_{HB} & \tilde{C}_W & \tilde{C}_{tW} & \tilde{C}_{tB} \\ \tilde{C}_{HW} & \tilde{C}_{HG} & \tilde{C}_G & \tilde{C}_{tG} & \tilde{C}_{tH} \end{matrix}$ SMEFT

- Quantify LHC complementarity with other data (EDM, CP asymmetries in meson decays)

Deliverable: LHCHWG recommendations note \Rightarrow

Journal?
SciPost
CERN monograph
TWiki

Kick-off part 1


December 2021

<https://indico.cern.ch/event/1105813/>, recording available

Experimental summary

🕒 20m


Speaker: Hualin Mei (Univ. of California Santa Barbara (US))

 CP_violations_in_...

CP-odd flavor-invariants in the SMEFT

🕒 20m

Speaker: Quentin Bonnefoy (DESY)

 Bonnefoy_WG2.pdf

Matrix-Element Methods for EFT and CP measurements with the H boson

🕒 20m


Speaker: Andrei Gritsan (Johns Hopkins University (US))

 talk_LHCHiggsWG_...

Interplay with low Energy

🕒 20m


Speaker: Wouter DEKENS (university of california, San Diego)

 wdekens_WG2_Hig...

ttH phenomenology studies

🕒 20m

Speaker: Dorival Gonçalves (Oklahoma State University)

 Dorival_WG2.pdf

Discussion

🕒 20m

Kick-off part 2


January 2022

<https://indico.cern.ch/event/1116986/>, recording available

New Physics in Yukawa Couplings with Flavour Symmetries

🕒 20m


Speaker: Luca Merlo (CERN)

 Merlo, NP in Yukaw...

Constraining the CP structure of Higgs-fermion couplings with a global LHC fit, EDM and baryogenesis

🕒 20m

Speaker: Marco Menen

 Marco Menen CPV...

CP-violation, asymmetries and interferences in $t\bar{t}H$


🕒 20m

Speaker: Rodrigo Capucha (Centro de Física Teórica e Computacional, FCUL)

Machine-enhanced CP-asymmetries in the Higgs sector

🕒 20m

Speaker: Andrew Pilkington (University Of Manchester)

 CPVusingNN.pdf

Discussion

🕒 30m

Round table

May 2022, no recording

Sub-activities

Open google doc: [link](#)

annotations/comments welcome!

STXS bins for CPV	2
ttH phenomenological studies	3
Common <u>parametrisations</u>	4
CPV Benchmarks	5
Quantifying interplay with EDMs/low energy	6
Joint WG3 activity	7

- “Les Houches” style sign up system
- Please share with anyone you think may be interested!
- Includes minutes of round table discussion
- Established “mailing lists” & identified contact people

Benchmarks & common param.

- Tests of Higgs CP properties have been going on since 2012
 - Many individual analyses at the LHC
- Next step: **going global & enabling UV model interpretations**
 - Experimental combinations
 - Global interpretations...
 - ➡ Fits to many CPV parameters
 - ➡ Combining with CPC new physics parameters
- Can we help by providing some general guidelines...
 - Reviews/dictionaries for parametrisation:
 - ‘UV’ benchmarks: bottom-up & top-down

$\tilde{\kappa}_f, f_{\text{CP}}, \theta_{\text{CPV}},$
SMEFT/HEFT,...

Aim

- Produce a WG2 note as a reference document around these questions. *Inspired by...*

LHC-HXSWG-2019-006

BSM Benchmarks for Effective Field Theories in Higgs and Electroweak Physics

1	Introduction	2
1.1	The SM Effective Field Theory	4
2	Weakly Coupled BSM	5
2.1	Minimal extensions of the Standard Model	5
2.1.1	Models with one extra particle	8
2.1.2	Custodial models	9
2.2	Extended Scalar Sectors and the SMEFT	11
2.3	One-loop BSM	13
2.3.1	Integrating out, power counting, and general patterns	15
2.3.2	Examples	16
2.3.3	Patterns	19
3	Strongly Coupled BSM	21
3.1	SMEFT for Composite Higgs Theories	21
3.1.1	Observable consequences	23
3.2	Composite Vectors and Multipolar Interactions	24
4	Conclusions	25

Dedicated meeting

September 2022

<https://indico.cern.ch/event/1203658/>, recording available

- Contact people:
Andrei Gritsan, Haichen Wang, Luca Merlo, Elina Fuchs & Heidi Rzehak
- Summary of Snowmass activities
- Merged benchmarks & common parametrisations activities
 - Useful “first step” to establish conventions & guide other activities
- Set up draft note on overleaf, plan to release in the first half of 2023
 - Seek publication as a review in journal...

Draft note

Common parametrizations and benchmarks for CP violation in Higgs interactions

1 Introduction

2 Parametrisations and dictionaries for CPV in Higgs interactions

2.1 κ 's, angles and CP fractions

2.2 SMEFT

2.3 HEFT

2.4 General anomalous couplings

2.5 Dictionaries

2.6 Common tools

3 Experimental status & prospects

4 Benchmarks: Bottom-up approach

4.1 CPV invariants in SMEFT

4.2 Flavor symmetries

4.3 Froggatt-Nielsen inspired benchmarks

4.4 ...

5 Benchmarks: Top-down approach

5.1 2HDM extensions

5.2 Time varying Yukawa couplings

5.3 Models for Loop-induced Gauge-Higgs couplings

5.4 ...

6 Conclusions

- Review of common parametrisation & dictionaries, MC tools & exp. status
- Benchmarks: Bottom-up & top-down
- Some invited contributions
- Some additional th. studies planned for top down part
- Additional contributors welcome!

t \bar{t} H phenomenology

$$\mathcal{L}_{\text{top-Yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}} \bar{t}(c_t + i\gamma_5 \tilde{c}_t)tH$$

$$|\mathcal{M}_{t\bar{t}H}|^2 = c_t^2 |\mathcal{M}_{t\bar{t}H}^{\text{CP-even}}|^2 + 2c_t \tilde{c}_t \text{Re}[\mathcal{M}_{t\bar{t}H}^{\text{CP-even}} \mathcal{M}_{t\bar{t}H}^{\text{CP-odd}*}] + \tilde{c}_t^2 |\mathcal{M}_{t\bar{t}H}^{\text{CP-odd}}|^2$$

- Probably the most active area for in LHC pheno community concerning Higgs CPV
- Have there been new & interesting observables/channels proposed that have not been considered by the experiments?
- Room for a th/exp projection exercise to find the next generation of realistic t \bar{t} H probes?
- Much interest & signups on the gdoc
- Contact people:

Henning Bahl, Dorival Gonçalves & Haichen Wang

See talk by Dorival on Tuesday ([link](#))


Dedicated meeting

October 2022

<https://indico.cern.ch/event/1207508/>, no recording

Phenomenology status and prospects

Speaker: Henning Bahl

 2022_10_12_WG2_...

Review of snowmass studies ¶

Speaker: Dorival Goncalves

 Dorival_WG2_2022....

ttH reconstruction in ATLAS and CMS for CP sensitive measurements

Speaker: Haichen Wang (Lawrence Berkeley National Lab. (US))

 WG2 ttH reconstru...

Discussion

Discussion points

pheno review by Henning ([link](#))

- Many pheno papers out there with different techniques
 - CP-sensitive vs. CP-violating observables
 - Can we help to bring exp. & th. together to produce more realistic sensitivity projections?
 - Proper reco-level analysis w/ bkg, combinatorics etc.
review of ttH reco by Haichen ([link](#))
- Heavy use of MVA both in reco and signal extraction
 - Current analyses use NN/BDT trained with pure CP-odd signal model $\tilde{c}_t^2 |\mathcal{M}_{t\bar{t}H}^{\text{CP-odd}}|^2$
- What is the impact of these measurements in global context?
 - Allowing for CP-conserving new physics in ttH
 - Other measurements e.g. ggF, $h \rightarrow \gamma\gamma$, EDMs...

Concrete studies

1. Improved MVAs for CPV signal discrimination

- Parametrised models depending on CP-angle
- Using CP-odd observables as input
- Impact of tH?
- Explore use of fully hadronic ttH?

$$c_t \tilde{c}_t \text{Re}[\mathcal{M}_{t\bar{t}H}^{\text{CP-even}} \mathcal{M}_{t\bar{t}H}^{\text{CP-odd}*}]$$

2. “Global” CPV fit exercise $\{\tilde{C}_{t\phi}, \tilde{C}_{tG}, \tilde{C}_{\phi G}\} + \{C_{t\phi}, C_{tG}, C_{\phi G}\}$

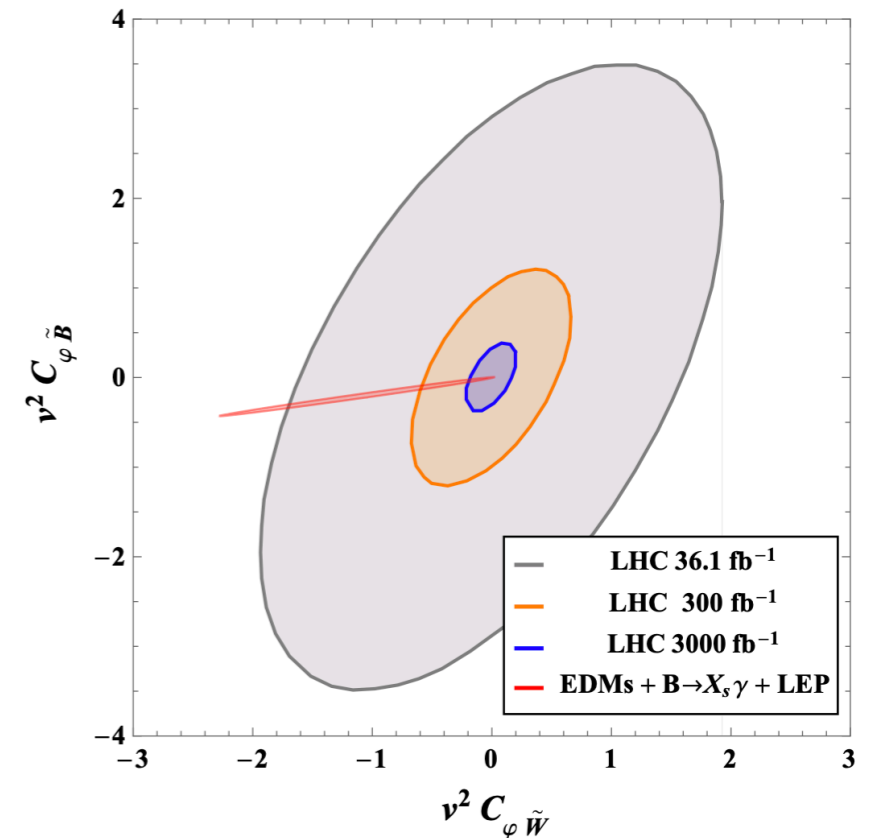
- Combined analysis with Higgs signal strengths
- Experimentally, ggF rate is profiled
- Theoretically, likely to be correlated with ttH modification
- Other CPV modifications e.g. dipoles, CPV ggH coupling

Interplay with EDMs

Kick off meeting talk by Wouter ([link](#))

- Contact person: Wouter Dekens

Would LHC experiments like to quantify impact of data on the global picture including EDMs & other low energy data?



- Sometimes LHC is more sensitive than EDMs, e.g., $h \rightarrow \mu\mu$
- Ingredients are there for theoretical EDM parametrisation
- Requires contact with other experiments to interpret Likelihoods
- Had an internal meeting with ATLAS/CMS Higgs convenors
 - Conclusion: some interest but maybe its a bit early
 - Resume discussion after parametrisation & benchmark note

Joint WG2/WG3 activity

- CPV in Higgs interactions often means extended scalar sector
- Many interesting signatures of spontaneous/explicit CPV in extended Higgs sectors

Discovery of BSM Higgs in multiple decay channels \Rightarrow CPV

Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \rightarrow h_2 Z$	$h_2 \rightarrow h_1 Z$	$h_3 \rightarrow h_1 Z$	$h_3 \rightarrow h_2 Z$	$h_3 \rightarrow ZZ$
	$h_2 \rightarrow h_1 Z$	$h_1 \rightarrow ZZ$	$h_1 \rightarrow ZZ$	$h_2 \rightarrow ZZ$	$h_2 \rightarrow ZZ$
	$h_3 \rightarrow h_1 Z$	$h_2 \rightarrow ZZ$	$h_3 \rightarrow ZZ$	$h_3 \rightarrow ZZ$	$h_1 \rightarrow ZZ$

h_{125} -style CP properties study for BSM scalars \Rightarrow CPV

- Undoubtedly complementarity with h_{125} CP properties
- Establish some **benchmark models** & identify **regions of parameter space** where one or the other can provide complementary sensitivity

Dedicated meeting

June 2022

<https://indico.cern.ch/event/1173518/>, recording available


Electroweak Baryogenesis and Dark Matter with an Inert Doublet

Speaker: Sven Fabian (Max-Planck-Institut für Kernphysik)

 Talk-CERN Extende...

BSM Higgs Flavoured Correlations

Speaker: Arturo de Giorgi (Universidad Autónoma de Madrid (UAM) - Institute of Theoretical Physics (IFT))

 deGiorgi_FSH-Pres...

P-even, CP-violating Signals in Scalar Mediated Processes

Speaker: Dr Venus Keus (Dublin Institute for Advanced Studies (DIAS))

 VKeus_scalar-CPV...


Direct and indirect probes of Higgs CP violation

Speaker: Stefania Gori (UC Santa Cruz)

 TalkLHCHWG.pdf


CP-violation in $t\bar{t}\Phi$: asymmetries and interferences

Speaker: Duarte Azevedo (ITP/IAP - Karlsruher Institut für Technologie)

 cp_violation_wg23_...


Electroweak phase transition in a dark sector with CP-violation

Speaker: Lisa Biermann

 LBiermann_WG23_...

Di-Higgs-Production and Baryogenesis in the C2HDM

Speaker: Milada Muhlleitner (KIT - Karlsruhe Institute of Technology (DE))

 CPMeetingLHCWG-...

- Plan a round table discussion in 2023

Summary & next steps

CPV in Higgs is a core WG2 activity for 2023

- Common parametrisation & benchmarks
 - Note in preparation, contributors welcome
 - Will define framework for future CPV activities
- ttH pheno
 - Established 2 directions for concrete studies
 - Any interested parties welcome to join effort
- WG2/WG3 joint activity
 - Round table meeting planned for early 2023
- EDMs
 - On the backburner for now

Sign up & stay tuned!

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG>

WG2 CPV gdoc ([link](#)) is public & freely editable

Hope that this initiative will lead to a concrete joint activity

- Outputs: LHCWG recommendation note(s), journal publication(s)

Sign up here
by searching:

<https://e-groups.cern.ch/e-groups>

WG3 extended

Higgs:

lhc-higgs-neutral-extended-scalars@cern.ch

lhc-higgs-neutral-extended-scalars-convener@cern.ch

WG3 general:

lhc-higgs-bsm@cern.ch

lhc-higgs-bsm-convener@cern.ch

WG2 general:

lhc-higgs-properties@cern.ch

lhc-higgs-properties-convener@cern.ch