Christoph Englert

Higgs and CP violation

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2024 DISCRETE

THE HILL HILL HILL LIGHTER

LEVERHULME TRUST

Science and Technology Facilities Council

What is the nature of the TeV scale?

…and what are its implications ?

- ‣ plethora of *serious* theoretical/observational problems
- ‣ somehow SM correlations are unexpectedly accurate

monetise electroweak data correlations towards BSM discovery ?

- ‣ *New avenues for collider CP sensitivity ?*
- ‣ *BSM sensitivity from rare multi-Higgs processes ?*
- ‣ *What can the LHC do for us ?*

high energies? X_{α} , X_{β} and X_{β} \in $X_{\$ nign energic

"I aw energy physics highly rules the Higgs CP game" $\overline{}$ ^µ W^J^ρ $\frac{1}{\sqrt{2}}$ ρ
Ο Φοράκιος
Ο Φοράκιος $\frac{1}{2}$ + $\frac{1}{2}$ = $\frac{1}{2}$ = $\frac{1}{2}$ = $\frac{1}{2}$ $\ddot{}$ "Low energy physics highly rules the Higgs CP game."

 $\overline{}$

vs.

e.g. [Pospelov, Ritz `05] [Engel, Ramsay-Musolf, van Kolck `13]

ρ [Grzadkowski et al. `17]

 \mathcal{L}

 $B \to X_s \gamma, \ldots$ $B \to X_s \gamma, \ldots$ e.g. [Cirigliano, Crivelli ↔ e.g. [Cirigliano, Crivellin, Dekens et al. `19]

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 \rightarrow

 $\left(\begin{array}{c} \end{array}\right)$

 γ

t

 \mathcal{L} [Grzadkowski et al. `17]

 $\frac{3}{5}$ of $\frac{3}{5}$ complete set of dimension-six operators $\frac{1}{5}$ operators $\frac{3}{5}$ operator X²ϕ² ψ²Xϕ ψ²ϕ²D underlying O'v dynamics can onen imply deneau \mathbf{p} α incenatio \sim comp. underlying UV dynamics can often imply delicate cancellations → comp. Higgs …

high energies?

…

…[Brod, Cornell, Skodras, Stamou `22], [Brod, Polonsky, Stamou `23], [Degenkolb, Elmer, Modak, Muhlleitner, Plehn `24]

Figure 5: Magni!*cation of the lower le*" *plot of Fig. 4 showing the constraints on CP-even and CP-odd* [Brod, Cornell, Skodras, Stamou `22]

high energies?

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the 2 LHC constraint (blue region in lower right panel of \mathcal{A}) in two distinct regions as illustrated by

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high energies?

\dots and we are already in the deep end \ominus

[ATLAS, 2006.15458]

- ‣ asymmetry-based measurement in elw. Z+2jet production
- ‣ symmetric CP even effects cancel
- ‣ challenging to combat fluctuations

and define to the c_W / Λ^2 contribution to the EW indicate is solid line. The EW is shown as a solid line. ‣ evidence for BSM

2) and from the interference between the SM and

[ATLAS, 2006.15458]

Higgs CP violation?

B. Analysis of CP-sensitive observables

- \rightarrow asymmetry-based $\frac{d}{dx}$ *Z,* ``*,* `, and *HW B* ^f and *^W* $\mathbb{Z}_{\mathcal{A}_{\text{AdS}}}$ and $\mathbb{Z}+2j$ et production measurement in elw.
- \vdash \vdash symmetric CP even $\mathcal{S}_{\mathcal{S}}$ for the two $\mathcal{S}_{\mathcal{S}}$ fits a 2 fit, in order to obtain limits. The 2 fits a 2 fits a effects cancel
- $\frac{\sqrt{2}}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ *F* combat fluctuations <u>Edicial distribution combat fluctuations</u>
- $\ddot{\mathbf{C}}$ BCM $\ddot{\mathbf{C}}$ and denote for BSW and $\frac{1}{2}$ contribution is shown as solid lines. physics ? ‣ evidence for BSM

are [–1.6, 2.0] TeV² and [–1.7, 1.7] TeV² respectively. These confidence intervals are slightly weaker unlikely but directly testable $\begin{bmatrix} -0.4 \\ W & \end{bmatrix}$ $\begin{bmatrix} 86 \\ 87 \end{bmatrix}$, $\begin{bmatrix} 87 \\ 11 \end{bmatrix}$, and measurements of EW $\begin{bmatrix} 23 \\ 23 \end{bmatrix}$ $[Das Bakshi et al. '20]$
-1.5 -1.0 -0.5 in the theoretical prediction and the theoretical prediction are more sensitive to the impact of C_{min} [Biekötter, Gregg, Krauss, Schönherr `21]

going beyond

2 CP-interference ne $H_{\rm eff}$ programme at the Large Hadron Collider. We present a simple method that allows $\mathcal{H}_{\rm eff}$ sensitive observables to be directly constructed from the output of \mathbf{C} h ing α m ι + 202 $\boldsymbol{\omega}$ the $\boldsymbol{y} \perp \boldsymbol{\omega}$ religie assessment, we take into a count religious property into a count religious property in the simulation of ▶ CP-interference net zero results from cancelling event weights ilar to the SM Higgs boson expectation \mathcal{L} hand, the motivated by an operator and the motivated by an expected by an experience of the motivated by an extending α to unitarity construction of α \limsup \limsup \limsup **bunding the overall resonance fixes the overall reson** cross section to be of the order of the order of the SM (see e.g. \sim mal observable from can create (near) optimal observable from $\mathbf{L}_{\mathbf{t}}$ distinction Ω binary ± weight distinction? \blacksquare \blacks [Bhardwaj et al. `21] e.g. [Gritsan et al. `20]

to the *X* ! *ZZ*). In this paper we focus on the an-

sults in Sec. II; Se
III; Sec. II; Sec. I

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Machine-enhanced CP-asymmetries in the Higgs sector.
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 $\mathcal{O}_{\Phi\widetilde{B}}=\Phi^{\dagger}\Phi B^{\mu\nu}\widetilde{B}_{\mu\nu}\,,$ ${\cal O}_{\Phi\widetilde W}=\Phi^\dagger\Phi W^{i\,\mu\nu}\widetilde W^i_{\mu\nu}$ $\mathcal{O}_{\Phi\widetilde{W}B}=\Phi^{\dagger}\sigma^i\widetilde{W}^{i\,\mu\nu}B_{\mu\nu}$ with EWSB by strong interactions \sim $\mathcal{O}_{\tau} \approx \Phi^{\dagger} \Phi B^{\mu \nu} B_{\mu \nu}$. \mathfrak{P}_D then turns t $U_{\Phi W} - \Psi \Psi W$ $\mathcal{O}_{\phi\widetilde{W}D} = \Phi^{\dagger} \sigma^{\iota} W^{\iota \mu \nu} B_{\mu \nu}$

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baseline is ATLAS 4l `21 (139/fb) [CERN-EP-2021-019]

i mpro $\frac{1}{2}$ *,* cos ˜ ⁼(ˆ*e^z* ⇥ *^e*ˆ*^z*⁰) *·* (p ⇥ ^p+) improvements beyond multi-dim fits

FIG. 1: Aquila, Nelson `86]… *^X* ! *ZZ* ! *^µ*⁺*µjj*. Details on the angles' definition and on cos ⁼ (p↵ ⇥ ^p) *·* (p ⇥ ^p+) [Truman `78]

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loghPt

hFta

iet1Fta

Permutation Importances (test set) improvements beyond multi-dim fits possible but re to SM necessary to gain kinematic reference point

[Plehn, Rainwater `01] *^q* (

11

(non-linear) gauge-Higgs interactions

boson fusion.

gauge-Higgs couplings 2*^V* have been constrained

$SWEFT SU(2)xU(1)/U(1)$: HEFT $SU(2)xSU(2)/SU(2)$

2 [3*.*5*,* 11*.*3] *,* 2*^V* 2 [0*.*0*,* 2*.*1] *,* (1.2)

In, *e.g.*, the recent [2], modifications of the (trilinear) Higgs self-coupling and the quartic

with similar sensitivity in other di-Higgs final state channels, *e.g.* [3–9]. The framework

also successfully captures the dominant source of coupling modifications in \mathcal{C} and \mathcal{C} is many concrete of coupling modifications in \mathcal{C}

field theory expansion $\mathcal{C}^{\mathcal{A}}$ theory expansion $\mathcal{C}^{\mathcal{A}}$ field theory expansion behoused theoretically expansion be how the field theoretically expansion be housed theoretically expansion of $\mathcal{C}^{\mathcal{A}}$

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The Higgs self-coupling corresponds to a unique operator in the dimension \mathcal{C}

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\mathcal{O}_{\Phi\widetilde{B}}=\frac{c_{\Phi\widetilde{B}}}{\Lambda^2}\Phi^\dagger\Phi B^{\mu\nu}\widetilde{B}_{\mu\nu}\qquad\qquad\vdots
$$

where the dual field strength tensors are defined as the dual field strength tensors are defined as α

*X*e*^µ*⌫ = ✏*^µ*⌫⇢*X*⇢*/*2. The operators of Eqs. (2) and (2)

can form a closed set under the RGE flow [27], and study-

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both correspond to the same $\mathcal{L}_\mathcal{D}$ operator. Hence, the same SMEFT operator. Hence, the same $\mathcal{L}_\mathcal{D}$

the correspondence between HEFT and SMEFT is given HEFT and SMEFT is given HEFT and SMEFT is given \mathcal{L}_max

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$$
\n
$$
\vdots
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\n
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(non-linear) gauge-Higgs interactions

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(non-linear) fermion-Higgs interactions II. HEFTY CONTRACTOR COMPANY AND CONTRACTOR $\overline{}$ with *inical* definition ruggs increations $\lim_{x \to \infty}$ **f**_o

U(⇡*^a*) = exp (*i*⇡*^a*⌧ *^a/v*) *,* (7)

formations as *U* ! *LUR†* so that the top quark mass

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II. HEFTY CONTRACTOR COMPANY AND CONTRACTOR

^m^t

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II. HEFTY CONTRACTOR COMPANY AND CONTRACTOR

 \rightarrow quartic top-Higgs contact interaction ity from CP-sensitive observables in *tthh* ¯ production are quartic top-Higgs contact interaction drive phenomenology *v* uartic top-Higgs *v quartic top-Higgs contact interaction drive phenomenology* ▶ quartic top-Higgs contact interaction drive phenomenology

16 [Banerjee et al. `22] $[Grober et al. '10]$

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II. HEFTY CONTRACTOR COMPANY AND CONTRACTOR $\overline{}$ *^Ott*¯ ⁼ *m^t ^Q*¯*LU t^R .* (8) with *inical* definition ruggs increations (non-linear) fermion-Higgs interactions *^Ott*¯ ⁼ *m^t ^Q*¯*LU t^R .* (8)

U(⇡*^a*) = exp (*i*⇡*^a*⌧ *^a/v*) *,* (7)

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• additional *tthi* sensitivity mitigates limitations ity from C_p-sensitive observable done for the LHC we we well to be done for the three t_{data} *(more work to be done for the Li v* uonal *unn* sensi with α as the value of t *^m^t v* additional *tthh* sensitivity mitigates limitations \rightarrow additional *tthh* sensitivity mitigates limitations dominantly in single $\frac{1}{2}$ or single Higgs physics, which provides the provides theory (more work to be done for the LHC)

the discussion of our fit to non-linear CP violation. We

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the relative strength of $ext{ATLAS }$ $[ATLAS \cdot 16]$ for the LHC [CE, Krauss, Spannowsky, Thompson `14] t_{ATLAS} in the Higgs multiplicities remain uncorrelated in this con-

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