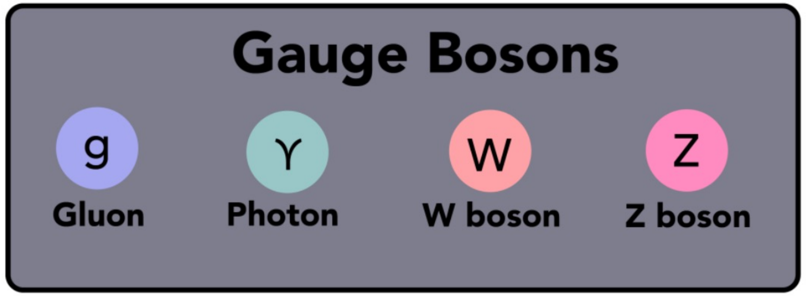
CP violation in the Higgs sector: Run 3 and beyond

Henning Bahl

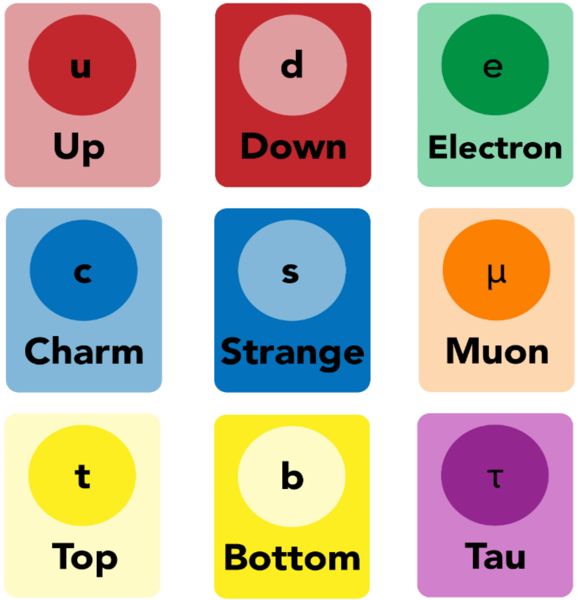
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

22nd Workshop of the LHC Higgs Working Group, 4.12.25

CP structure of Higgs couplings – status



Fermions



➡ a lot of work ahead: improve existing constraints + target so far unconstrained couplings

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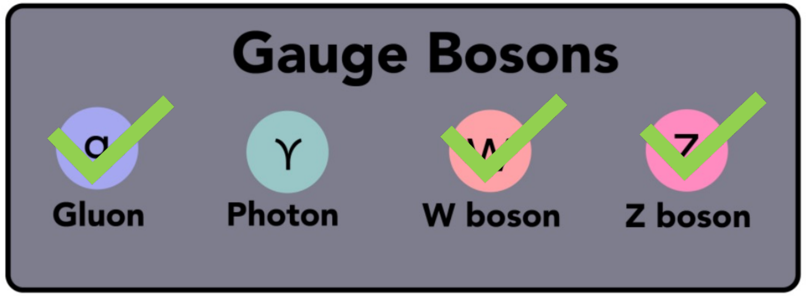

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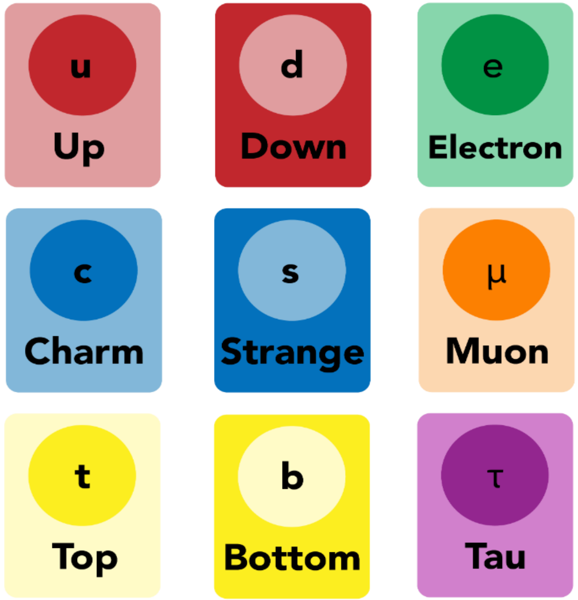

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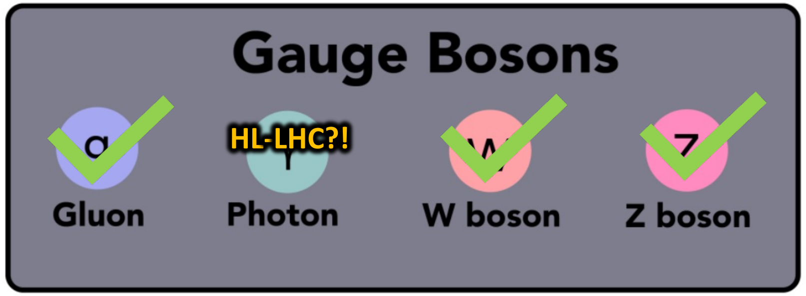

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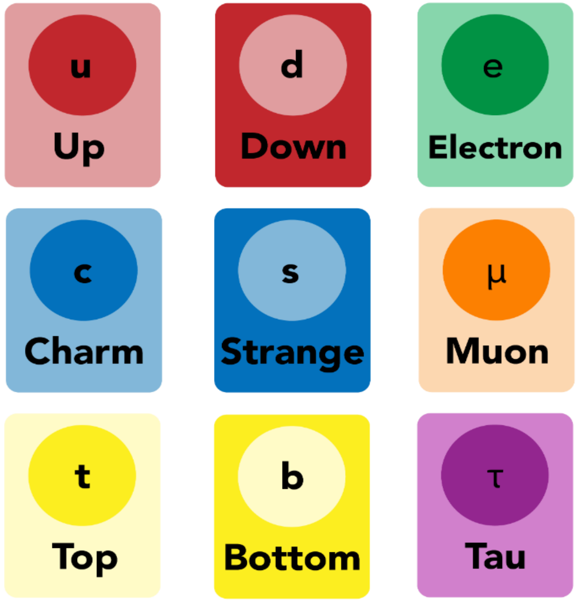

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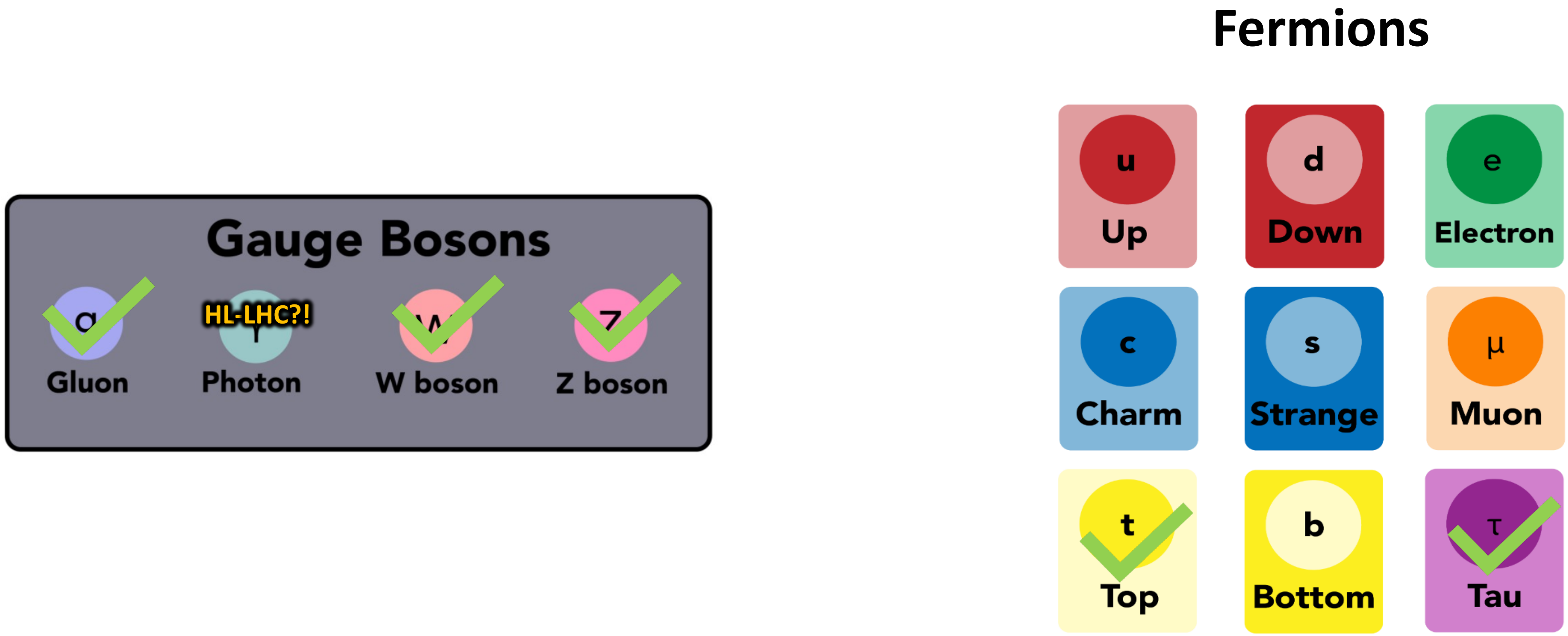

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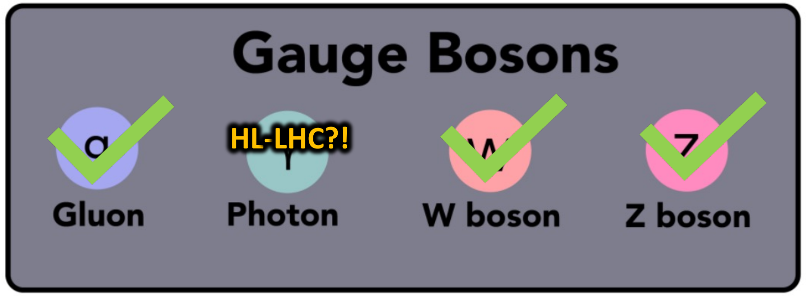

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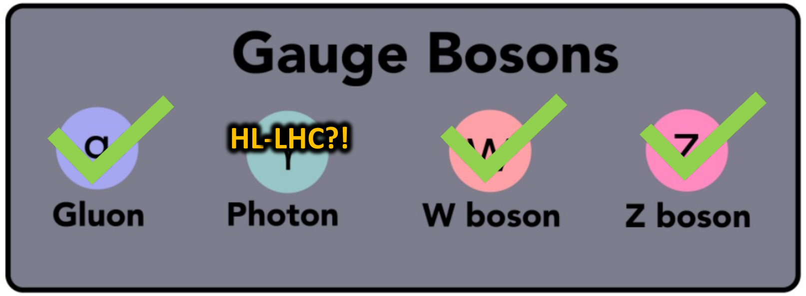


Fermions

→ a lot of work ahead: improve existing constraints + target so far unconstrained couplings

Many talks on CPV…

- *“Probing $H\tau\tau$ Coupling and CP properties at FCC-ee“* by Sofia Giappichini → analysis techniques
- *“Report from the NMSSM subgroup”* by Milada Margarete Mühlleitner → BSM models
- *“Bridging theory and experiment in the search for CP violating Higgs interactions: Parametrizations and dictionary”* by Marta Fuentes Zamoro → theory foundations
- *“Using machine learning to predict large pseudoscalar H125 couplings to fermions”* by Rafael Boto → BSM models
- *“WHbb CP analysis”* by Ricardo Barrué → analysis techniques
- *“V-associated production & vector boson fusion of Higgs bosons as an LHC signature of CP violation”* by Alvaro Lozano Onrubia → BSM models
- *“SMEFT, Anomalous Couplings and CPV from CMS and ATLAS”* by Daniel Winterbottom → experimental results
- *” CPV benchmarks”* by Rui Santos → BSM models

➡ bring these efforts together in new subgroup

New Higgs CP subgroup

Convenors:

ATLAS: Lorenzo Rossini (Freiburg U.)
CMS: Daniel Winterbottom (Imperial College)
Theory: Henning Bahl (Heidelberg U.), Jose Miguel No (IFT Madrid)

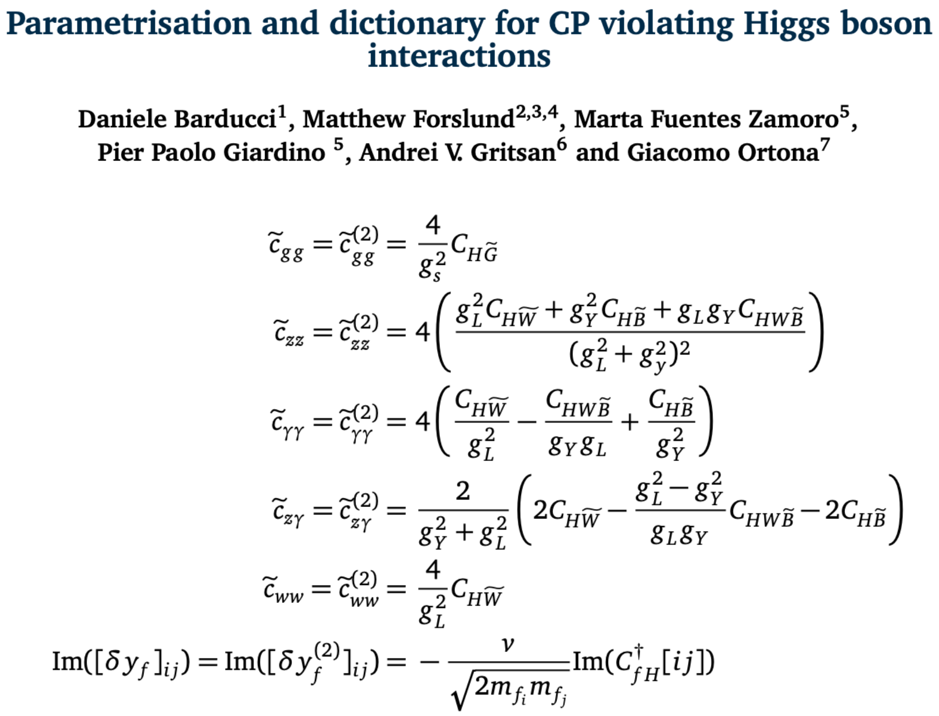
Topics:

- Parameterization of CPV interactions
- CP-sensitive STXS
- BSM benchmarks
- new analysis methods/observables
- …

lhc-higgs-prop-CPV@cern.ch
lhc-higgs-prop-CPV-convener@cern.ch
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGCPV

Higgs CPV parameterizations

- various parameterizations are used in the literature
- consider e.g. top-Yukawa interaction:
  - SMEFT Warsaw basis: $\frac{c_{t\Phi}}{\Lambda^2}\Phi^\dagger\Phi(\bar{Q}_3 t\widetilde{\Phi})$
  - SMEFT Higgs basis: $\frac{h}{v}m_t\delta y_t\bar{t}t$
  - coupling modifiers: $\frac{y_t^{\text{SM}}}{\sqrt{2}}h\bar{t}(c_t + i\gamma_5\tilde{c}_t)t$
  - angles: $\frac{y_t^{\text{SM}}}{\sqrt{2}}g_t h\bar{t}(\cos\alpha_t + i\gamma_5\sin\alpha_t)t$
  - CP-odd fractions: $f_{\text{CP}}^{h\bar{t}t} = \frac{\Gamma^{\text{CP-odd}}_{h\to t\bar{t}}}{\Gamma^{\text{CP-odd}}_{h\to t\bar{t}} + \Gamma^{\text{CP-even}}_{h\to t\bar{t}}}$



Parametrisation and dictionary for CP violating Higgs boson interactions

Daniele Barducci[1], Matthew Forslund[2,3,4], Marta Fuentes Zamoro[5], Pier Paolo Giardino [5], Andrei V. Gritsan[6] and Giacomo Ortona[7]

$$\widetilde{c}_{gg} = \widetilde{c}^{(2)}_{gg} = \frac{4}{g_s^2}C_{H\widetilde{G}}$$

$$\widetilde{c}_{zz} = \widetilde{c}^{(2)}_{zz} = 4\left(\frac{g_L^2 C_{H\widetilde{W}} + g_Y^2 C_{H\widetilde{B}} + g_L g_Y C_{HW\widetilde{B}}}{(g_L^2 + g_y^2)^2}\right)$$

$$\widetilde{c}_{\gamma\gamma} = \widetilde{c}^{(2)}_{\gamma\gamma} = 4\left(\frac{C_{H\widetilde{W}}}{g_L^2} - \frac{C_{HW\widetilde{B}}}{g_Y g_L} + \frac{C_{H\widetilde{B}}}{g_Y^2}\right)$$

$$\widetilde{c}_{z\gamma} = \widetilde{c}^{(2)}_{z\gamma} = \frac{2}{g_Y^2 + g_L^2}\left(2C_{H\widetilde{W}} - \frac{g_L^2 - g_Y^2}{g_L g_Y}C_{HW\widetilde{B}} - 2C_{H\widetilde{B}}\right)$$

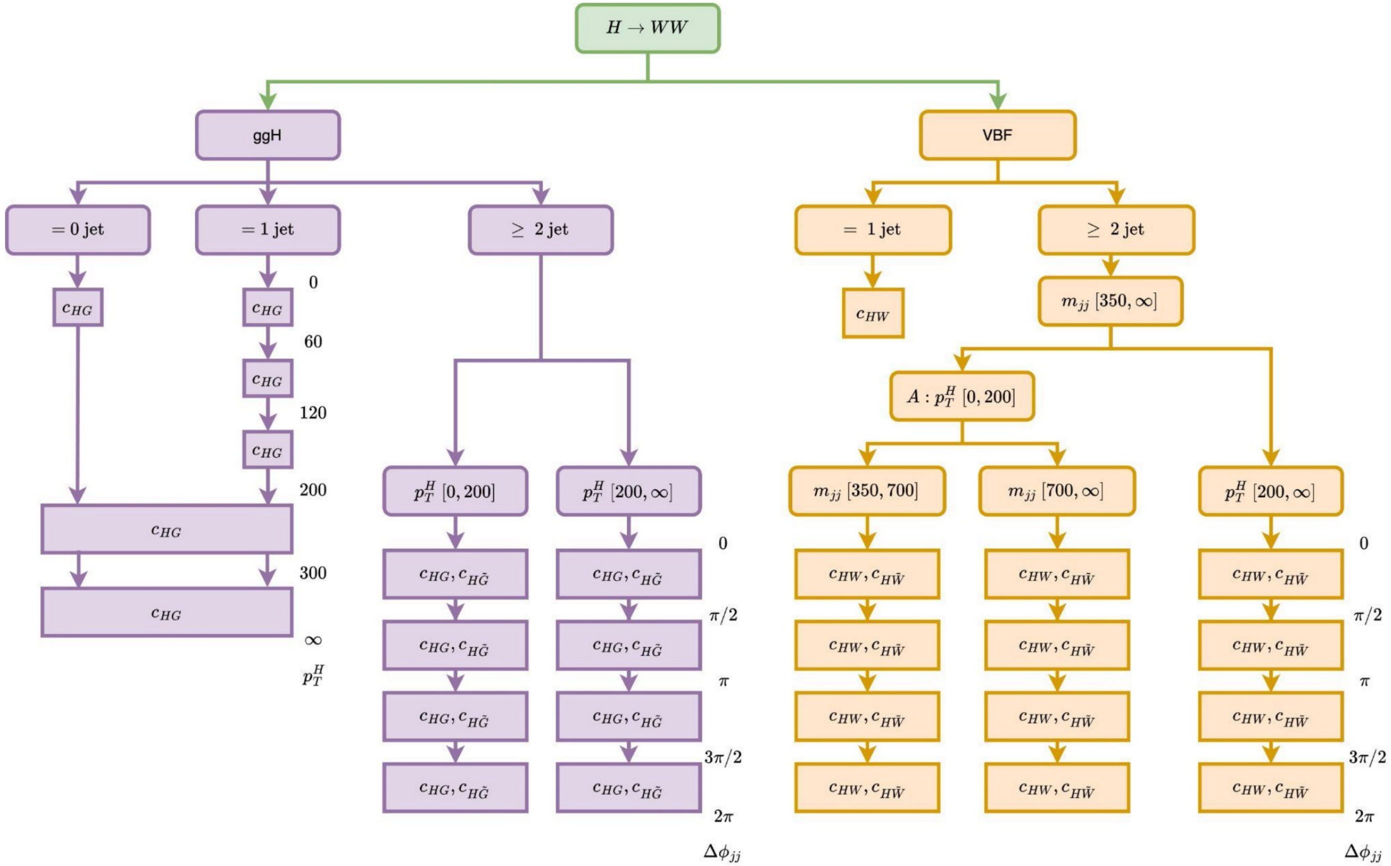
$$\widetilde{c}_{ww} = \widetilde{c}^{(2)}_{ww} = \frac{4}{g_L^2}C_{H\widetilde{W}}$$

$$\text{Im}([\delta y_f]_{ij}) = \text{Im}([\delta y_f^{(2)}]_{ij}) = -\frac{v}{\sqrt{2m_{f_i}m_{f_j}}}\text{Im}(C^\dagger_{fH}[ij])$$

→ see Marta's talk for more details

CP-sensitive STXS for VBF and ggF+2jets

- target: CPV HVV and Hgg couplings
- use CP-odd $\Delta\phi_{jj}$ observable
- strategy: divide $\geq$ 2 jet bins into four $\Delta\phi_{jj}$ bins
- STXS stage 1.3



[Marr & Basso, VBF workshop 2024]

Still missing: SM predictions + theory uncertainties (→ Sarah's talk on Friday)

BSM benchmarks for Higgs CPV

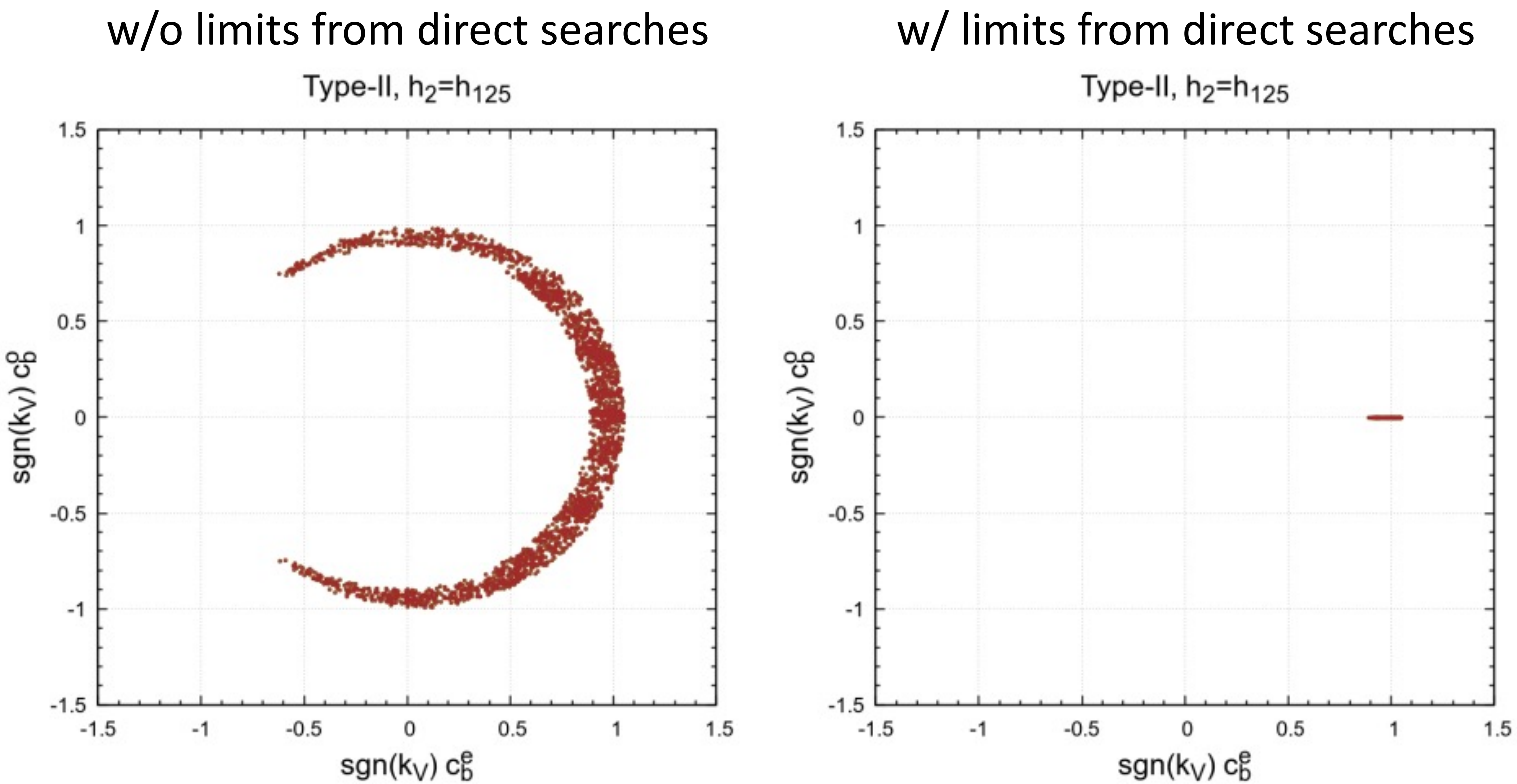
CPV Higgs coupling

↓

not too heavy BSM particle(s)

↓

interplay with direct searches, EDMs, etc.



w/o limits from direct searches

w/ limits from direct searches

[Biekötter,Fontes,Mühlleitner,Romão,Santos,2403.02425]

➡ combined WG2+WG3 effort aiming at CPV BSM benchmarks → Rui's talk on Friday

New analysis methods/observables

general amplitude structure for CP measurements:

$$|\mathcal{M}|^2 = c_{\mathrm{even}}^2 \left|\mathcal{M}^{\mathrm{CP-even}}\right|^2 + \underbrace{2 c_{\mathrm{even}} c_{\mathrm{odd}} \mathrm{Re}[\mathcal{M}^{\mathrm{CP-even}} \mathcal{M}^{\mathrm{CP-odd}^*}]}_{\text{CP-odd interference}} + \underbrace{c_{\mathrm{odd}}^2 \left|\mathcal{M}^{\mathrm{CP-odd}}\right|^2}_{\text{CP-even}}$$

CP can be tested either

- directly by constraining interference term → CP-odd observables
- indirectly by distinguishing $\left|\mathcal{M}^{\mathrm{CP-even}}\right|^2$ from $\left|\mathcal{M}^{\mathrm{CP-odd}}\right|^2$ → CP-even observables
- multivariate analyses mixing CP-odd and CP-even observables
  → Ricardo’s talk

➡ Optimizing for CPV or BSM test both valid targets, concentrate on CPV tests in the following

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} best for testing CPV

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CP-odd observables for Higgs CP

- Measuring CP-odd observables requires [Brehmer,Kling,Plehn,Tait,1712.02350]

  - combination at least four independent four-vectors
  - sizeable interference term

- processes for which CP-odd observables have been measured:
  - $H \to \tau\tau$ (→ Sofia's talk)
  - $H \to 4\ell$
  - VBF
  - VH
  - $gg \to H + 2j$

- How do we construct optimal CP-odd observables?
- Can we measure CP-odd observables for other processes like $\bar{t}tH$?

Optimal CP-odd observables

- probability distribution $$p(x|\theta) = \frac{1}{\sigma(\theta)} \frac{d^d\sigma(x|\theta)}{dx^d} = \underbrace{p_e(x|\theta)}_{\text{CP-even}} + \underbrace{p_o(x|\theta)}_{\text{CP-odd}}$$
- optimal CP-odd observable: $\omega_{\mathcal{CP}\text{-odd}} = \frac{p_o}{p_e}$ only non-zero if CPV present
- optimal observable (OO) will in general depend on size and nature of CPV coupling
- OO at reco-level ≠ OO at parton-level
- optimal CP-odd observables ≠ best observable to constrain specific CPV operator

ML-based OO at reco-level

[Bhardwaj,Englert,Hankache,Pilkington,2112.05052;HB,Menen,Fuchs,Plehn,2507.05858]

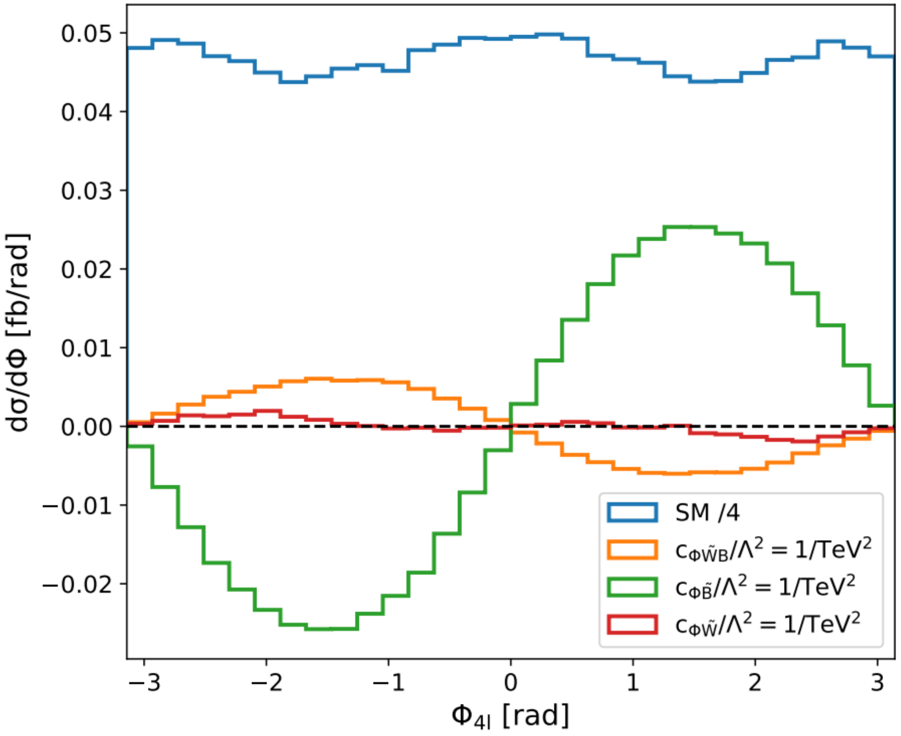
- can compute OO at parton-level but not at reco-level
- construct optimal reco-level CP-odd obs. by training a classifier on $p_e(x|\theta) \pm p_o(x|\theta)$ samples
- corresponds to $c_{H\widetilde{W}} = \pm 1$ samples
- classifier score converges towards

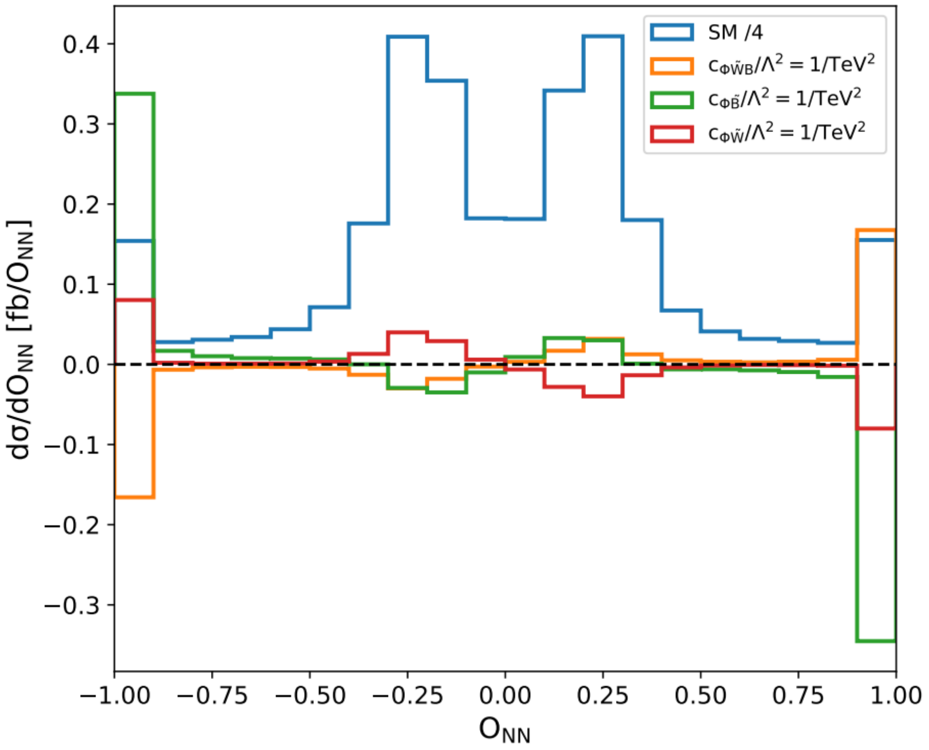
$$\begin{aligned} D(x) &= \frac{p_e(x|\theta) + p_o(x|\theta)}{p_e(x|\theta) + p_o(x|\theta) \; + \; p_e(x|\theta) - p_o(x|\theta)} \\ &= \frac{1 + \omega_{\mathcal{CP}\text{-odd}}(x)}{2} \\ \Leftrightarrow \qquad \omega_{\mathcal{CP}\text{-odd}}(x) &= 2D(x) - 1 \,. \end{aligned}$$

$H \to 4\ell$ OO

[Bhardwaj,Englert,Hankache,Pilkington,2112.05052]

CP-odd observable	$c_{\Phi\widetilde{W}B}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\tilde{B}}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{W}}/\Lambda^2$ [TeV^{-2}]
$\Phi_{4\ell}$	[-6.2,6.2]	[-1.4,1.4]	[-30,30]
$\Phi_{4\ell}$, m_{12}	[-1.9,1.9]	[-0.85,0.85]	[-3.7,3.7]
O_{NN} (binary)	[-1.5,1.5]	[-0.75,0.75]	[-3.0,3.0]
O_{NN} (multi-class)	[-1.4,1.4]	[-0.71,0.71]	[-2.7,2.7]





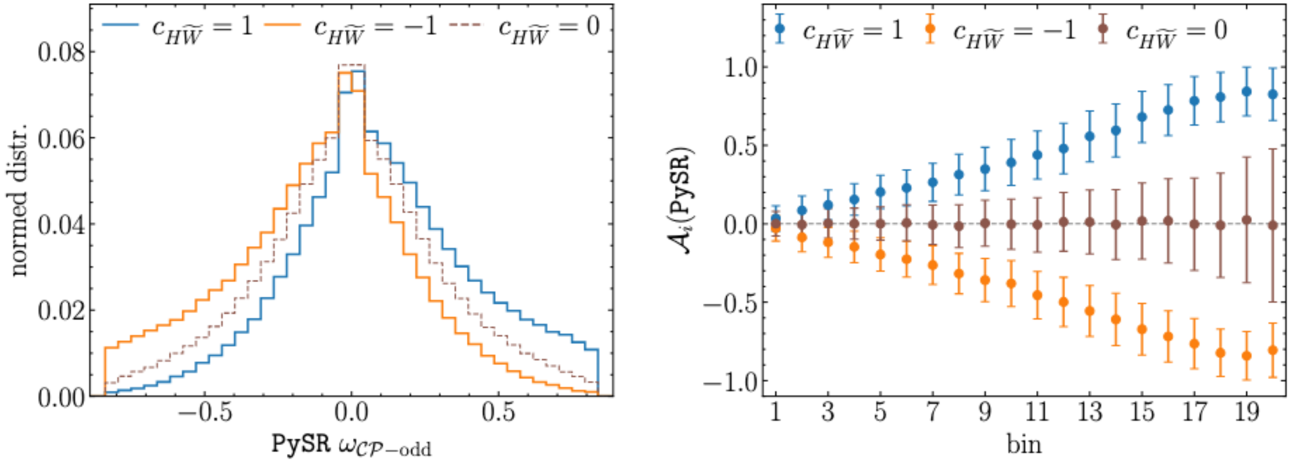
➡ large boost in sensitivity w.r.t. to simple angular observables

VBF OO at reco-level

[HB,Menen,Fuchs,Plehn,2507.05858]

- consider dim-6 operator $\frac{c_{H\widetilde{W}}}{\Lambda^2}\Phi^\dagger\Phi\widetilde{W}^a_{\mu\nu}W^{a\mu\nu}$
- use symbolic regression for classification
- constructs analytic equation for OO
- can explicitly confirm that learned observable is CP-odd

optimal and unambiguous test
for CP violation



$$d^{\mathrm{PySR}} = \frac{1.8566\,\sin\Delta\phi_{jj}}{\left|\frac{0.3080x_{j_1}\log\Delta\eta_{jj} + \log\Delta\eta_{jj}\sinh(x_{j_2} - 2.5977) + 0.3080\sinh x_h}{x_{j_1}\log\Delta\eta_{jj} + \sinh x_h}\right| + 0.6047}$$

with $x = p_T/m_h$

	$\sigma(c_{H\widetilde{W}} = 1$ vs. SM)	$\sigma(c_{H\widetilde{W}} = 0.25$ vs. SM)
$p_{T,j_1}p_{T,j_2}\sin\Delta\phi_{jj}$	6.76	2.43
trained on $c_{H\widetilde{W}} = \pm 1$		
PySR	6.98	2.47
SymbolNet	7.07	2.49
SymbolNet full	**7.84**	**2.51**
BDT	6.71	2.36

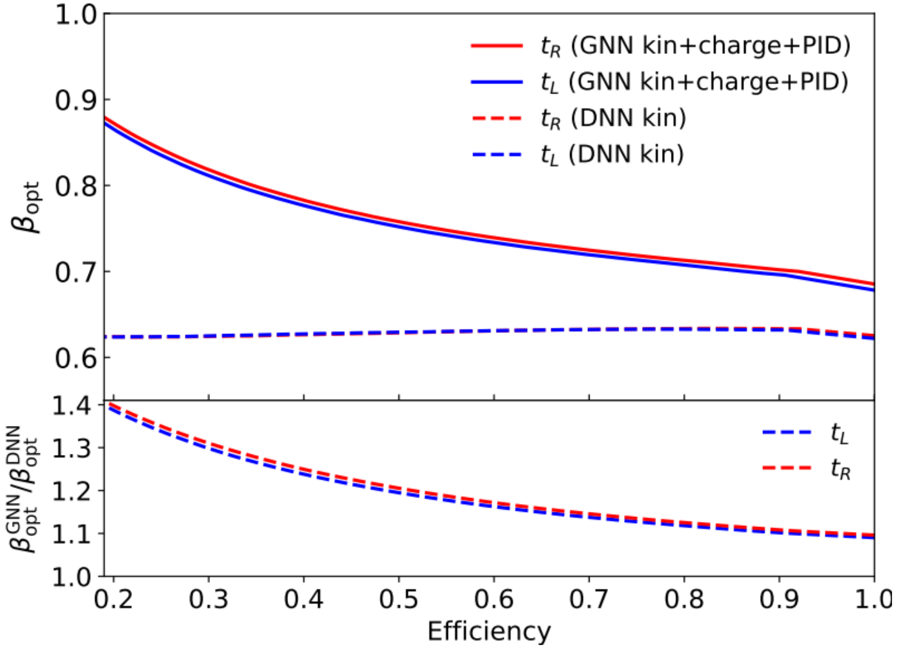
Towards CP-odd observables for $\bar{t}tH$

- measuring CP-odd observables for $t\bar{t}H$ requires top polarization information

- polarization accessible in full leptonic final state but
    - rate too low
    - CP-even/CP-odd interference very small

- future prospects
    - run-3/HL-LHC giving us more data
    - extract substructure info. via ML-based jet taggers
    - enhance spin analyzing power for hadronically decaying tops

[Dong,Gonçalves,Kong,Larkoski,Navarro,2407.01663]



Conclusions

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Thanks for your attention!