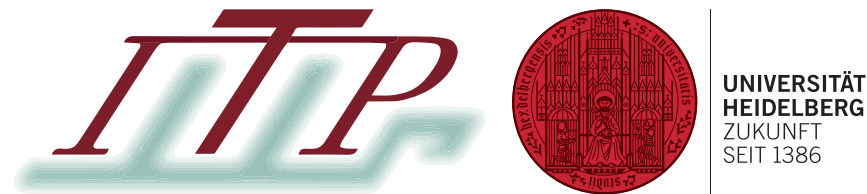


CP violation in the Higgs sector

Henning Bahl



ECFA meeting on e^+e^- to ZH angular measurements, 17.6.2024

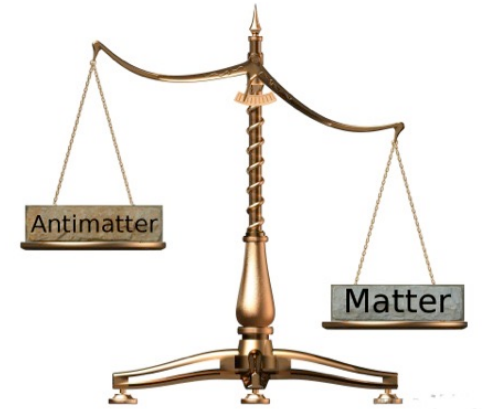
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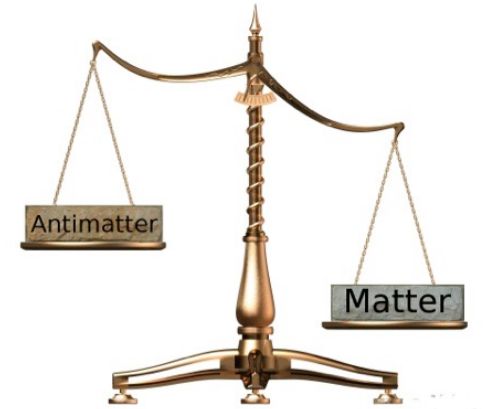
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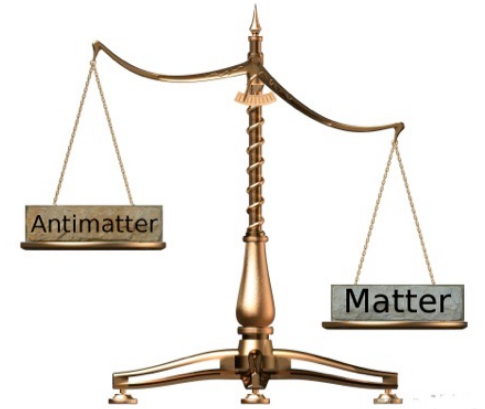
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Can BSM physics induce larger CPV Higgs couplings?

EFT perspective


EFT perspective

- CP violation in Higgs couplings introduced via dimension-six operators:
 - Gauge boson interactions: $\Phi^\dagger \Phi W_{\mu\nu} \tilde{W}^{\mu\nu}, \Phi^\dagger \Phi B_{\mu\nu} \tilde{B}^{\mu\nu}, \Phi^\dagger \Phi W_{\mu\nu} \tilde{B}^{\mu\nu}, \Phi^\dagger \Phi G_{\mu\nu} \tilde{G}^{\mu\nu}$
 - Fermion interactions: $\Phi^\dagger \Phi (Qu\tilde{\Phi}), \Phi^\dagger \Phi (Qd\Phi), \Phi^\dagger \Phi (Qe\Phi)$ with complex Wilson coefficients

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- All of them are independent (apart from RGE mixing)!
- Also independent from non-CPV Higgs coupling modifications.

UV perspective

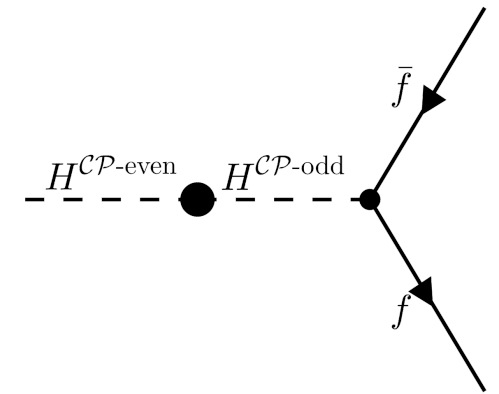
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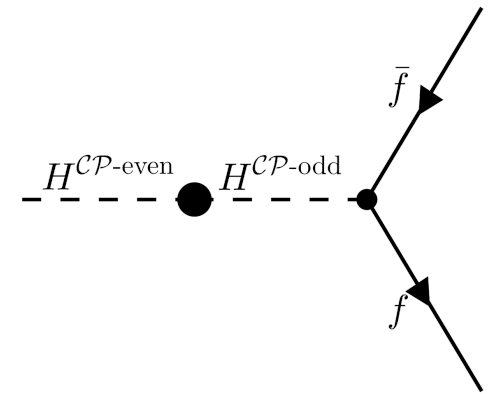
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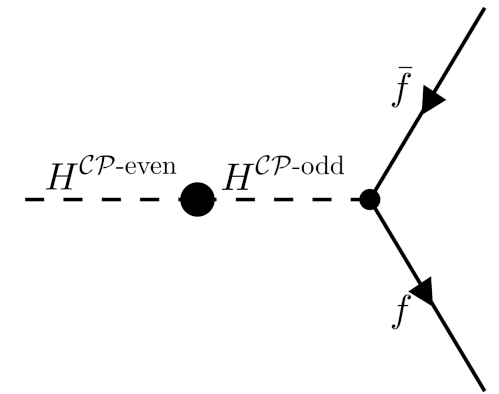
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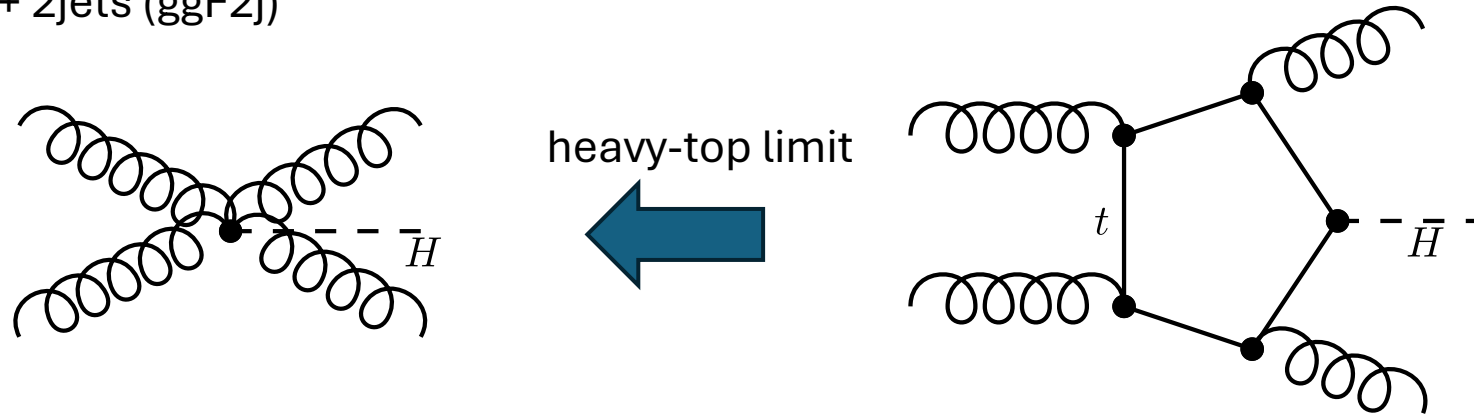


\Rightarrow Generic expectation: CPV in HVV couplings loop-suppressed in comparison to Hff couplings

CPV in HVV via CPV in Hff I

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- Example: ggF + 2jets (ggF2j)



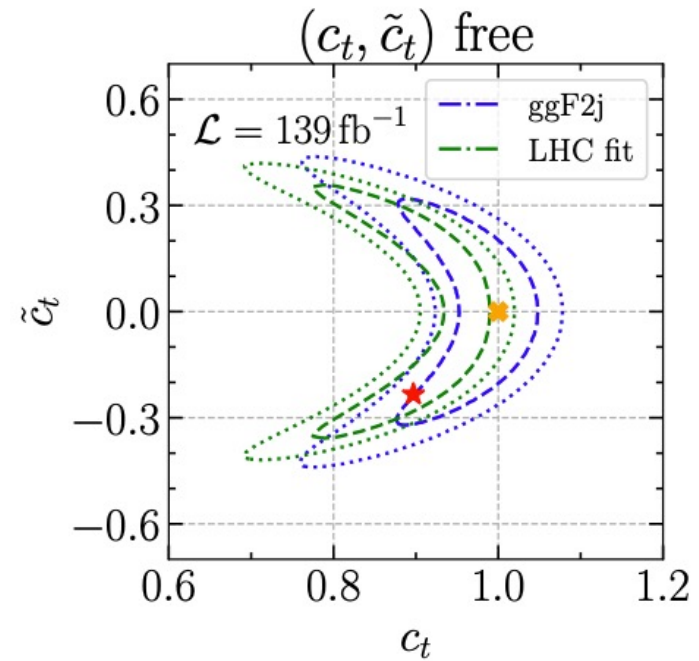
- consider CPV top-Yukawa coupling: $\mathcal{L}_{\text{top}} = \frac{y_t^{\text{SM}}}{\sqrt{2}} \bar{t}(c_t + i\gamma_5 \tilde{c}_t)tH$
- This coupling will directly affect $\bar{t}tH$ but also induce Higgs–gluon interaction:

$$\mathcal{L}_{Hgg} = -\frac{1}{4v} H \left(-\frac{g_s^2}{12\pi^2} c_g G_{\mu\nu}^a G^{a,\mu\nu} + \frac{g_s^2}{8\pi^2} \tilde{c}_g G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right)$$

with $c_g = c_t$ and $\tilde{c}_g = \tilde{c}_t$ in heavy-top limit.

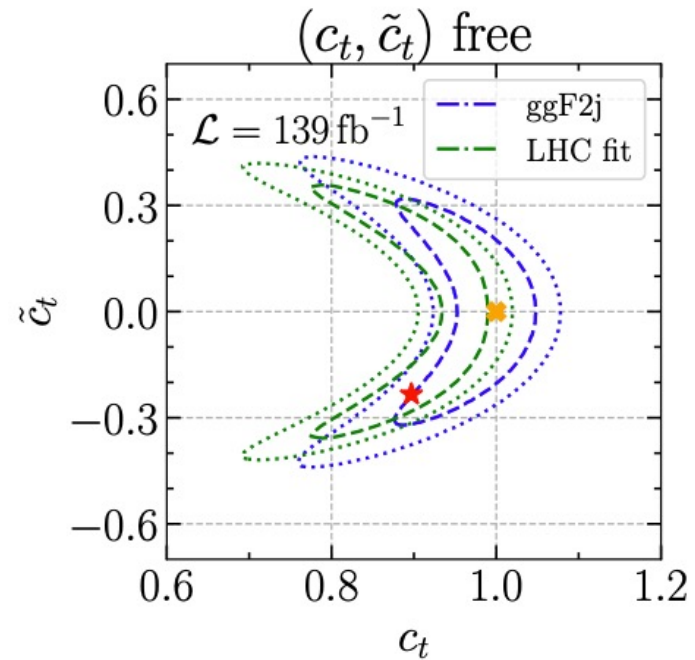
CPV in HVV via CPV in Hff II

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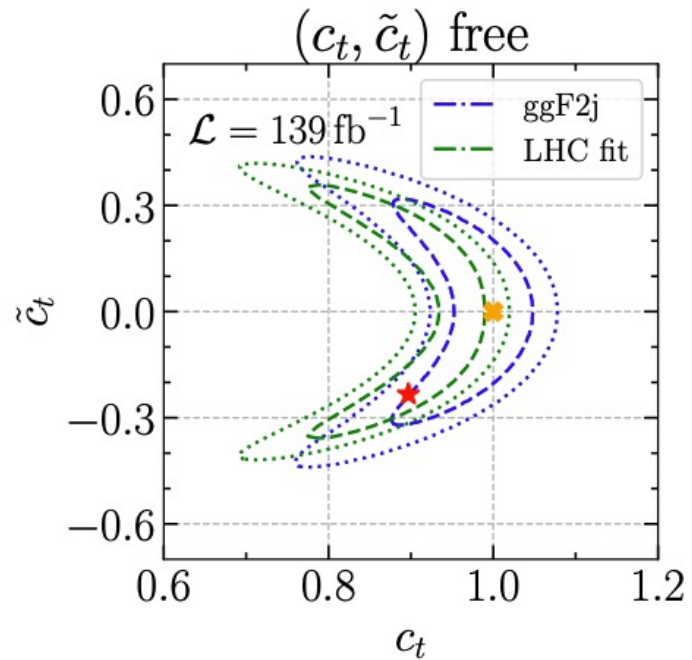
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Naïve estimate for weak gauge-boson couplings:

- CPV in HVV couplings suppressed by $\frac{g^2}{16\pi^2}$ with respect to Hff couplings.
- HWW : suppression by ~ 0.003
- HZZ : suppression by ~ 0.001

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 - CPV couplings of BSM particles can provide additional CP sources.

Benchmark model: complex 2HDM

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Perform Higgs CP measurements without assuming that other Higgs couplings are at their SM values!

- Intricate interplay between h_{125} measurements, direct searches, flavor constraints, EWPOs, EDM.

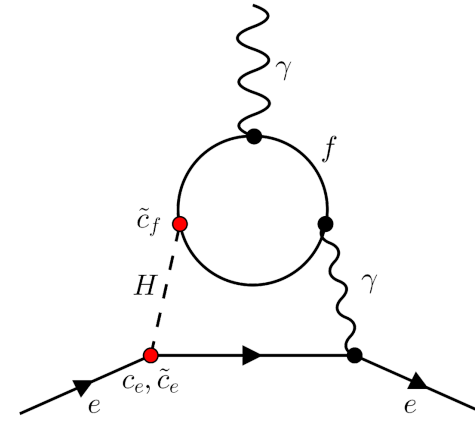
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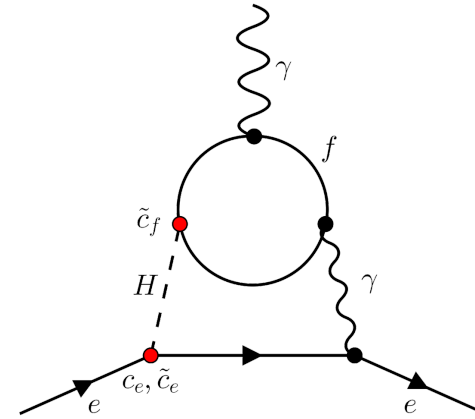
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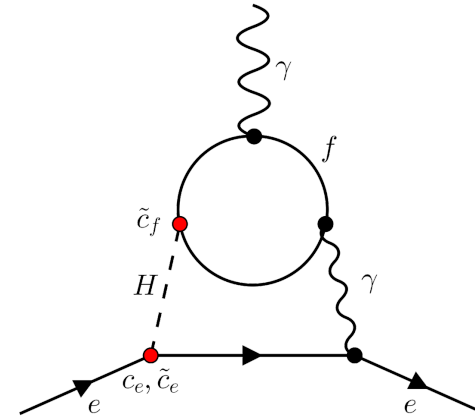
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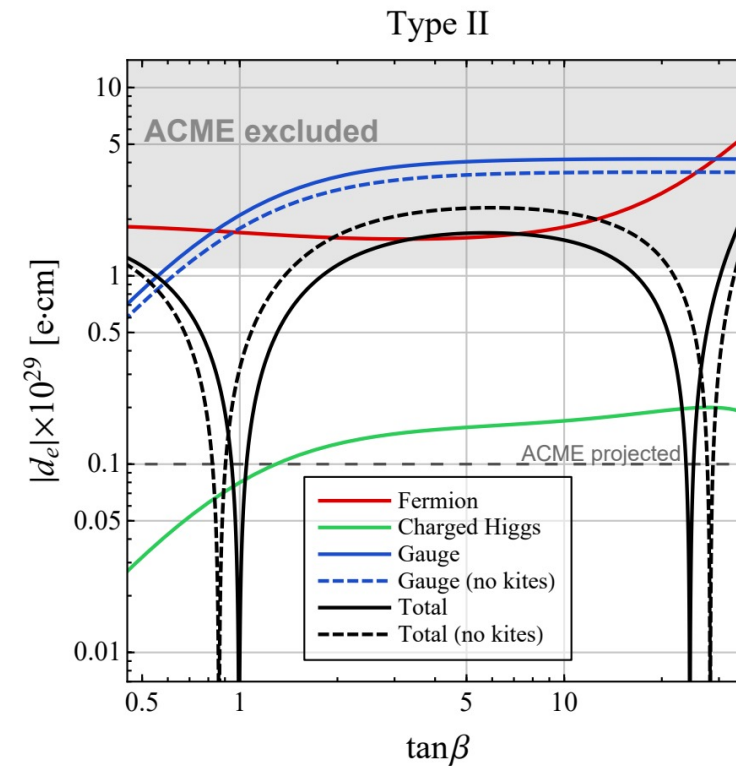
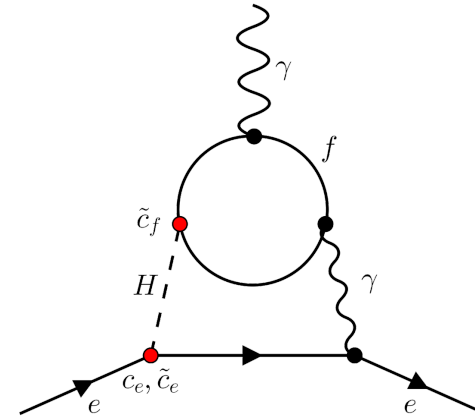
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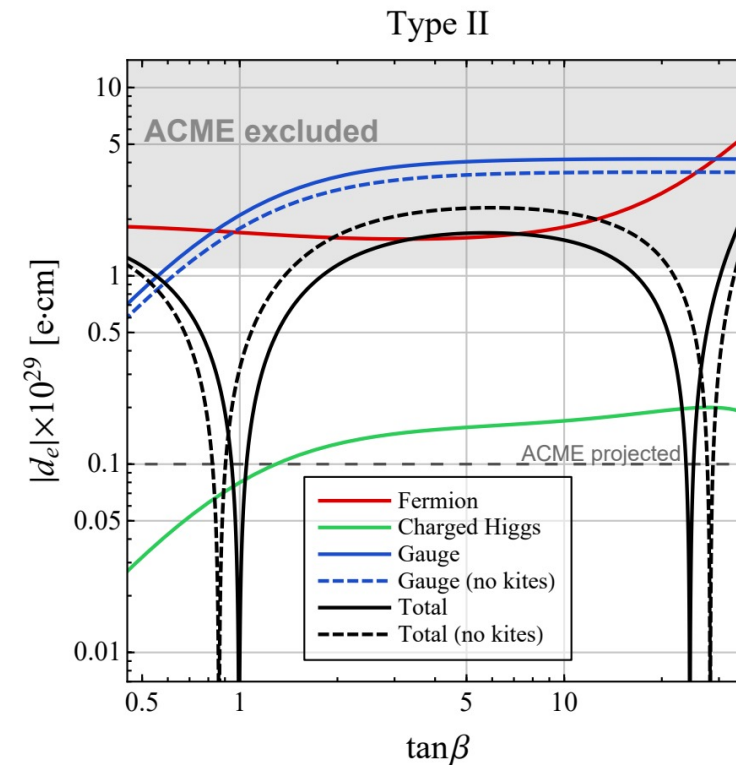
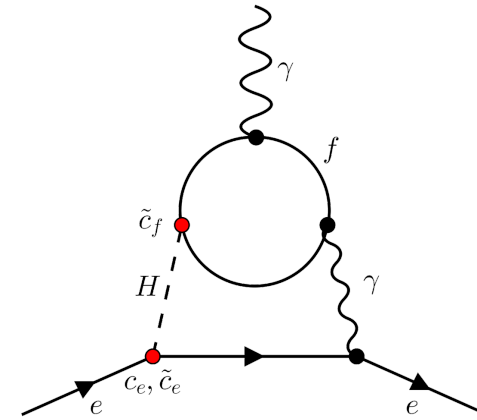
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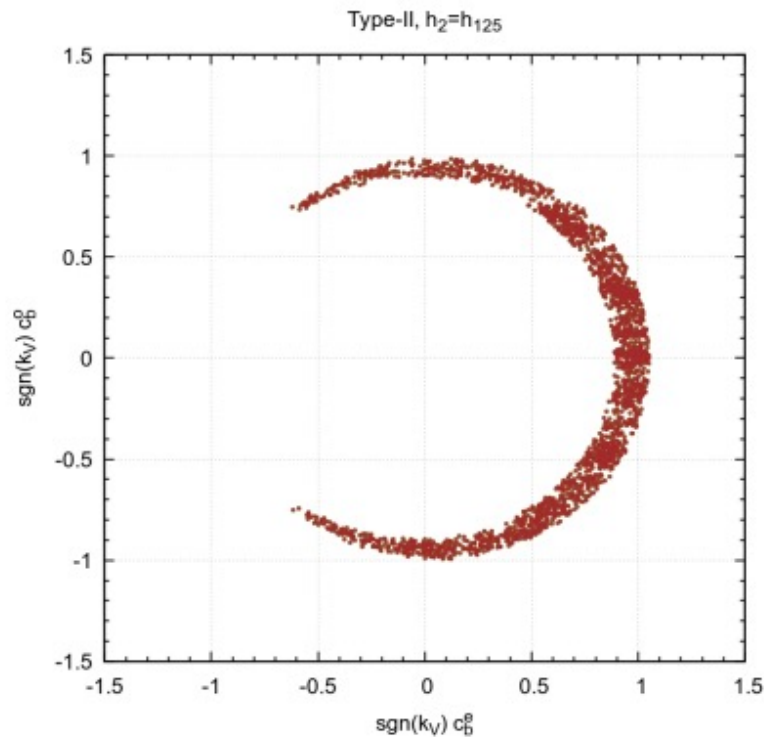
Collider measurements are important since they allow to disentangle different couplings/particles!



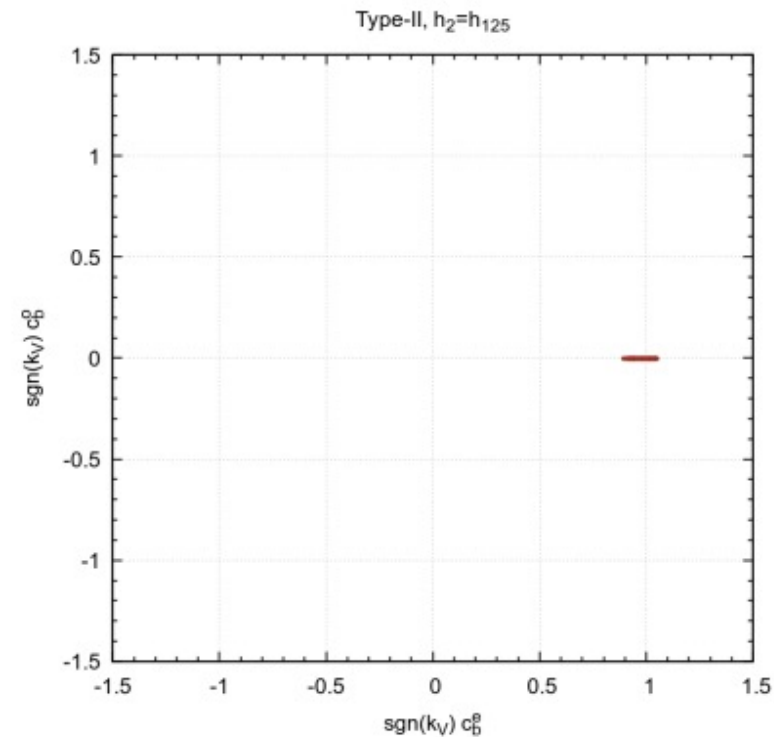
Interplay with direct searches

[Biekötter et al., 2403.02425]

All points allowed by EDM measurements.



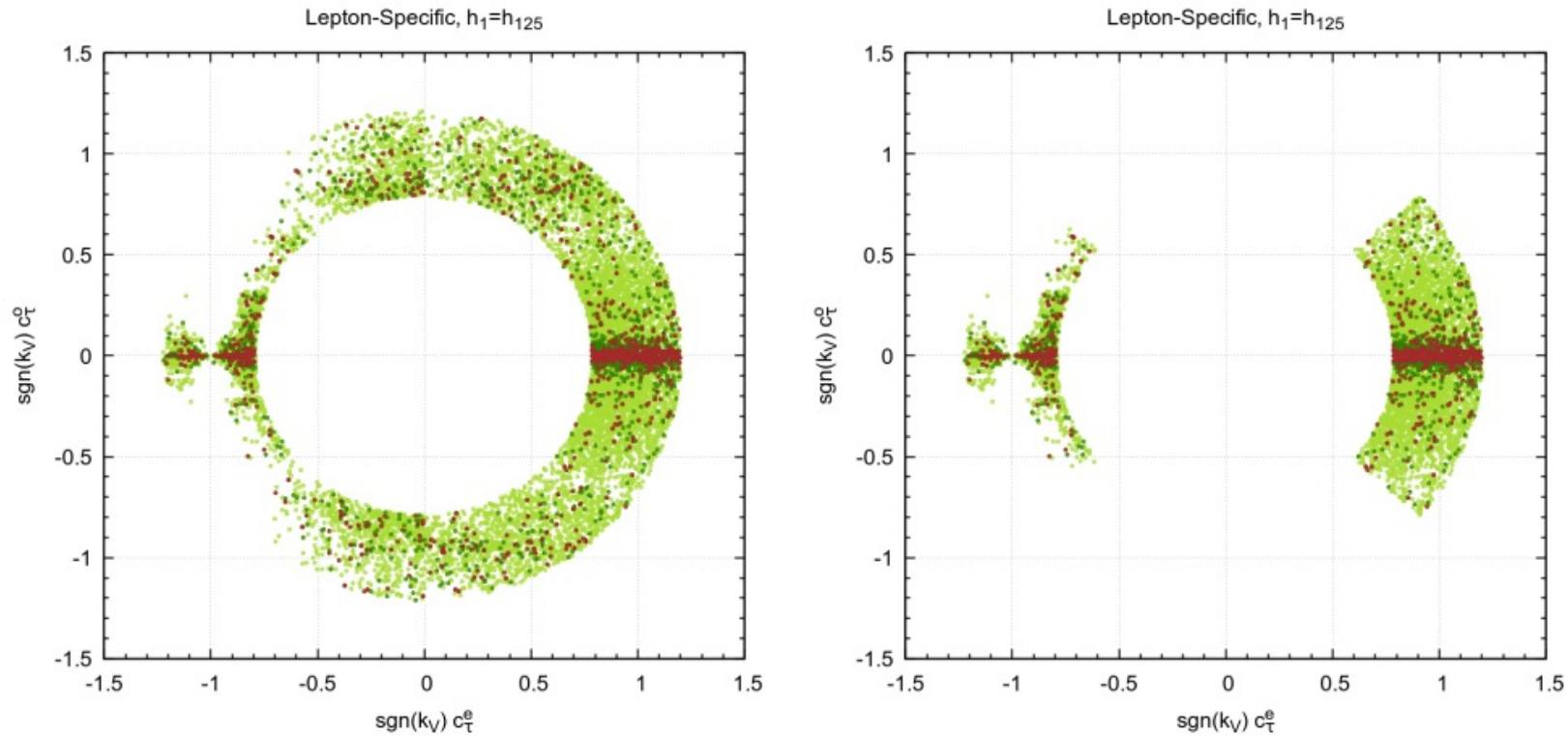
Left: points allowed without considering direct searches.



Right: points allowed with considering direct searches.

Impact of LHC measurements

[Biekötter et al., 2403.02425]



Left: points allowed without LHC $H \rightarrow \tau\tau$ CP measurement.

Right: points allowed with LHC $H \rightarrow \tau\tau$ CP measurement [CMS, 2110.04836].

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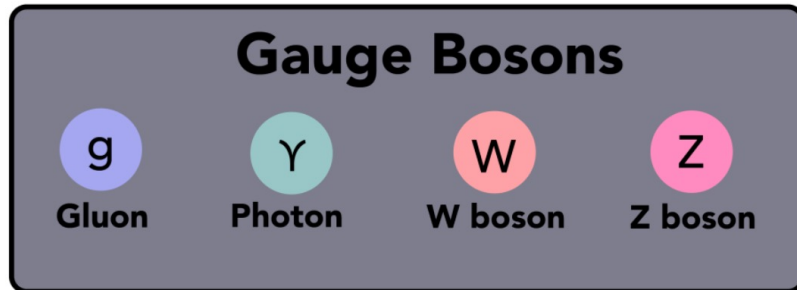
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**Thanks for your
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Appendix

CP structure of Higgs couplings

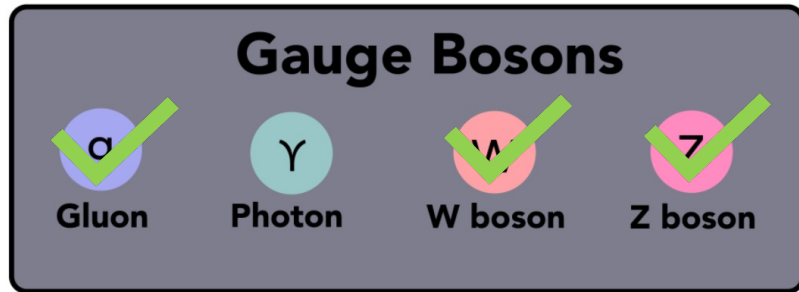


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Fermions



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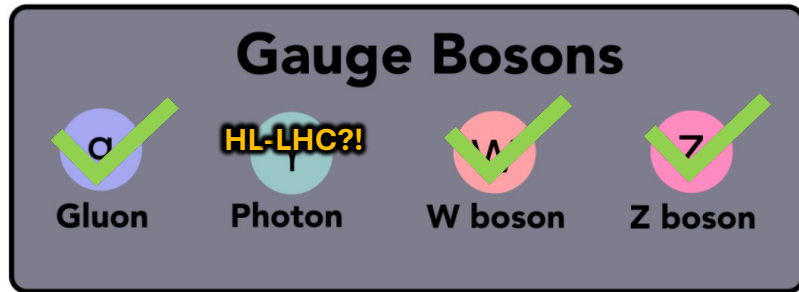


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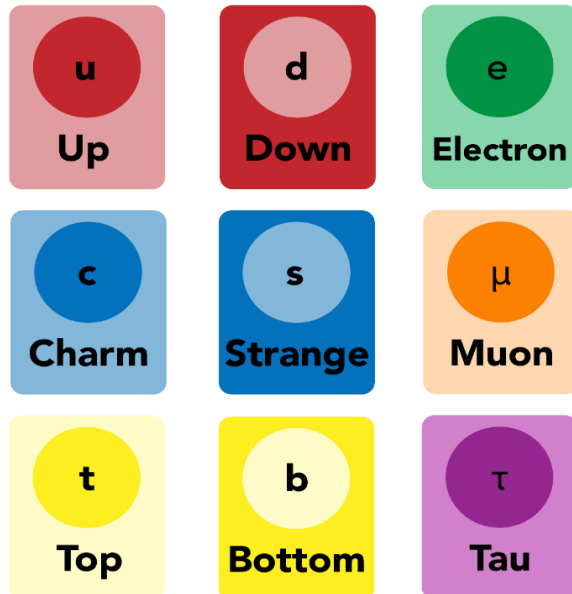


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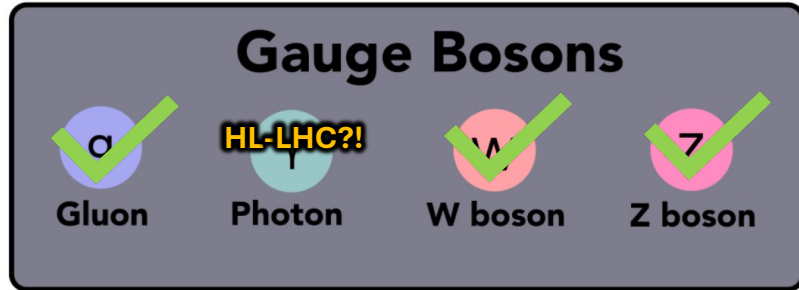


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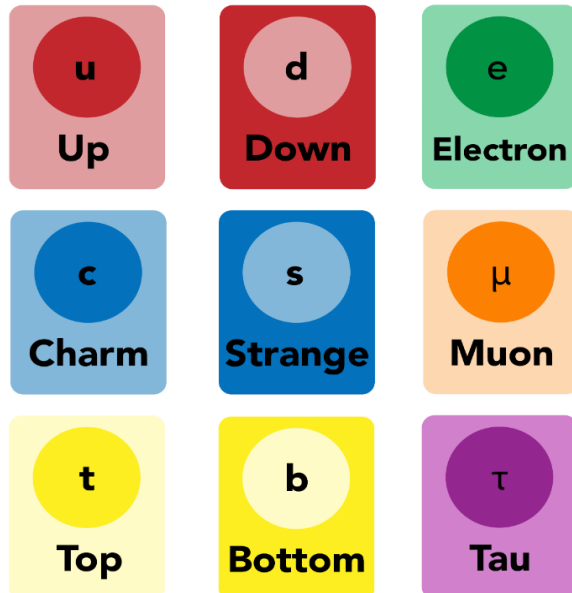


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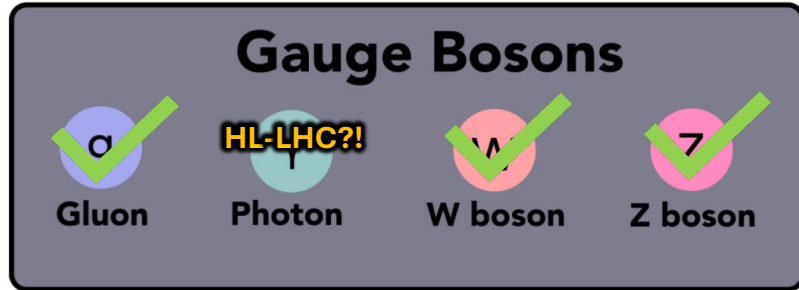
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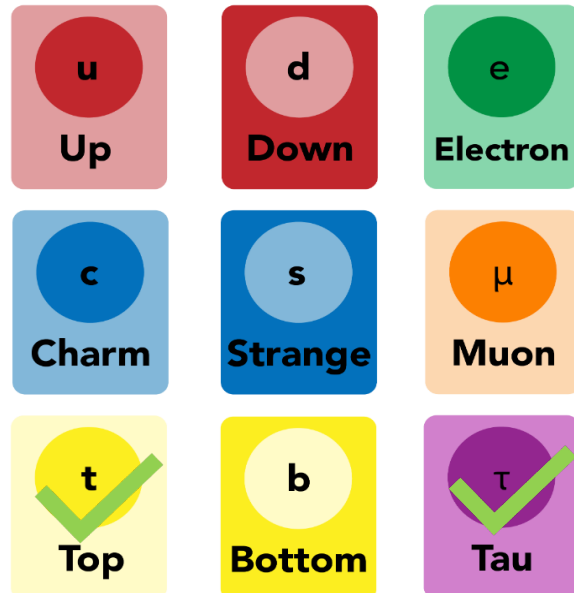
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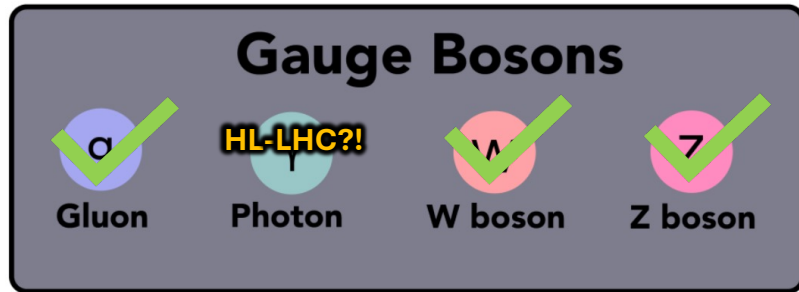
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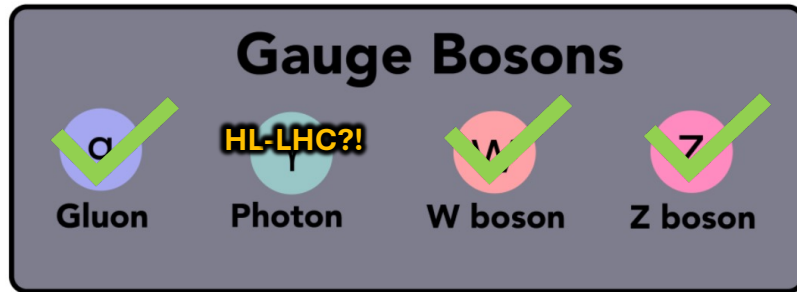
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CP structure of Higgs couplings



Fermions



- How can we constrain CP-violating couplings at the LHC?
 - Direct constraints: CP-odd observables.
 - Indirect constraints: CP-even observables.
 - Multivariate analyses: potentially mixing CP-odd and CP-even observables.

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Improving Higgs CP measurements

General amplitude structure for CP measurements:

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

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Higgs CP has become a testing ground for new analysis ideas/methods!

Complementarity with EDM constraints

- Several EDMs are sensitive to CP violation in the Higgs sector via 2L Bar-Zee diagrams.
- Bounds strongly depend on assumptions about
 - first-generation Yukawa coupling,
 - absence of other CP-violating BSM physics.
- Significant increase in precision expected within the next years! (see e.g. [Snowmass report, 2203.08103])
- Evaluation of NLO corrections will become necessary. (see e.g. [Brod et al., 2306.12478])

