Non-linear top-Higgs CP violation

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Motivation

- In BSM scenarios, the Higgs boson interactions can introduce additional sources of CP violation, which can address one of the Sakharov conditions.
- Certain Higgs couplings are more susceptible to pronounced new physics effects.
- CP-odd Higgs-vector boson interactions can appear only through operators of dimension-six or higher
- CP-odd Higgs fermion couplings can already appear at tree level. The top quark Yukawa coupling plays a crucial role due to its magnitude.
- We study the sensitivity to CP violation of the top Yukawa in two different frameworks: SMEFT and HEFT.

SMEFT

- The Standard Model Effective Field Theory (SMEFT) is a generalization of the Standard Model (SM).
- New physics Effects are parametrized in terms of higher dimensional operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{4-d}} \mathcal{O}_i^{(d)}$$

- The operators are constructed using the SM fields only and respect the SM gauge symmetry $\mathrm{SU}_c(3) \times \mathrm{SU}_L(2) \times \mathrm{U}_Y(1)$

- **SMEFT is built out of the SU(2) Higgs doublet Φ**

HEFT

- The Higgs Effective Field Theory (HEFT) is built separately out of the Higgs and Goldstones.
- The Goldstones are embedded into $U = \exp\left(i\tau^I \pi^I / v\right)$
- **The Higgs is a gauge singlet.**
- No relationship is assumed between the Higgs scalar and the Goldstones.
- There is an expansion in the number of covariant derivatives

$$\mathcal{L}_{\text{HEFT}} \supset \frac{v^2}{4}\mathcal{F}(h)\text{Tr}(D_\mu U^\dagger D_\mu U) + \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

- with

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots, \; V(h) = \frac{1}{2}m_h^2 h^2 \left(1 + d_3\frac{h}{v} + \frac{d_4}{4}\frac{h^2}{v^2} + \ldots\right)$$

SMEFT Parametrization

- We consider the operator $\mathcal{O}_{t\Phi} = |\Phi|^2 \bar{Q}_L \Phi^c t_R$
- This operator leads to P-violating interactions for complex Wilson coefficients.
- Alternatively, we can also consider the phenomenologically identical parametrization

$$\mathcal{L}_{\alpha,1}^{\mathrm{SMEFT}} = -\frac{m_t}{v}\,\kappa_t\,\bar{t}(\cos\alpha + i\gamma^5 \sin\alpha)\,t\,h\,.$$

- This parametrization can be identified with the operator above, leading to

$$\mathcal{L}_{\alpha,2}^{\mathrm{SMEFT}} \supset -\frac{3m_t}{2v^2}\,\bar{t}(\{\kappa_t \cos\alpha - 1\} + i\kappa_t\gamma^5 \sin\alpha)\,t\,h^2\,.$$

HEFT Parametrization

- We consider the operator $\mathcal{O}_{\bar{t}t} = -m_t \bar{Q}_L U t_R \,.$
- This operator can be dressed with a “flare” function

$$Y_t(h) = 1 + c^{(1)} \frac{h}{v} + c^{(2)} \frac{h^2}{2v^2} + \ldots$$

- This leads to the CP-violating effects analogous to the SMEFT Lagrangian

$$\mathcal{L}_{\text{HEFT}} \supset -\frac{m_t}{v} \kappa_t \, \bar{t}(\cos\alpha + i\gamma^5 \sin\alpha) \, t \, h - \frac{m_t}{2v^2} \kappa_{tt} \, \bar{t}(\cos\beta + i\gamma^5 \sin\beta) \, t \, h^2 \,.$$

- The SMEFT trajectories can be recovered by the choices

$$\kappa_{tt}^2 = 9(1 - 2\kappa_t \cos\alpha + \kappa_t^2) \,,$$

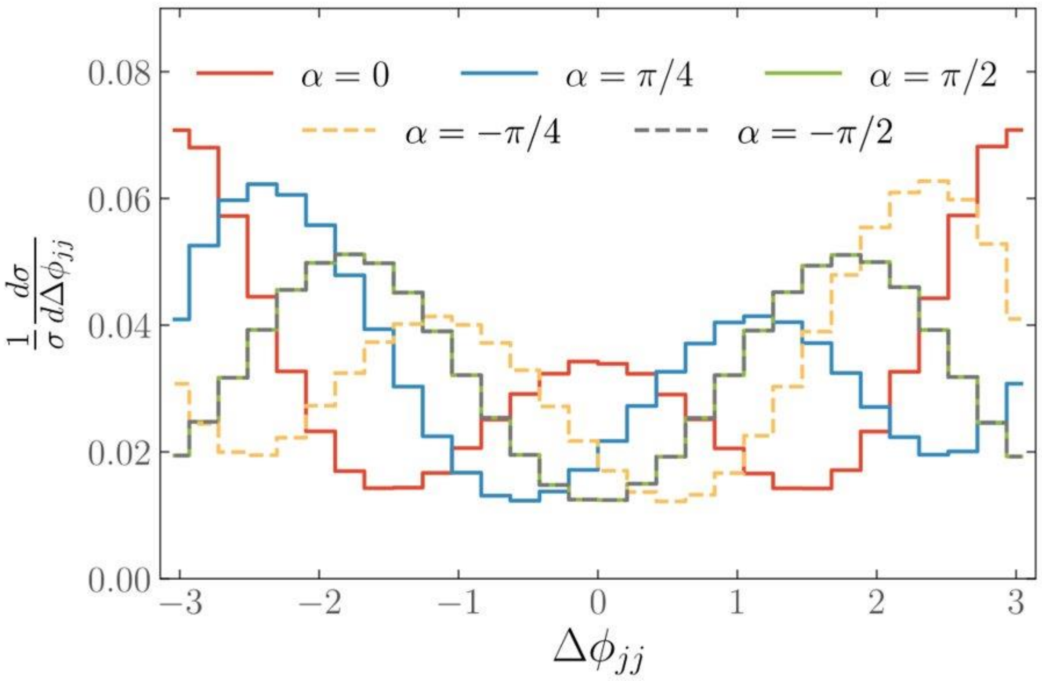
$$\tan\beta = \frac{\kappa_t \sin\alpha}{\kappa_t \cos\alpha - 1} \,.$$

Processes with one Higgs boson

- One of the process considered is the production of one Higgs in association with two jets.

- We use the "signed" angular separation between the two jets.

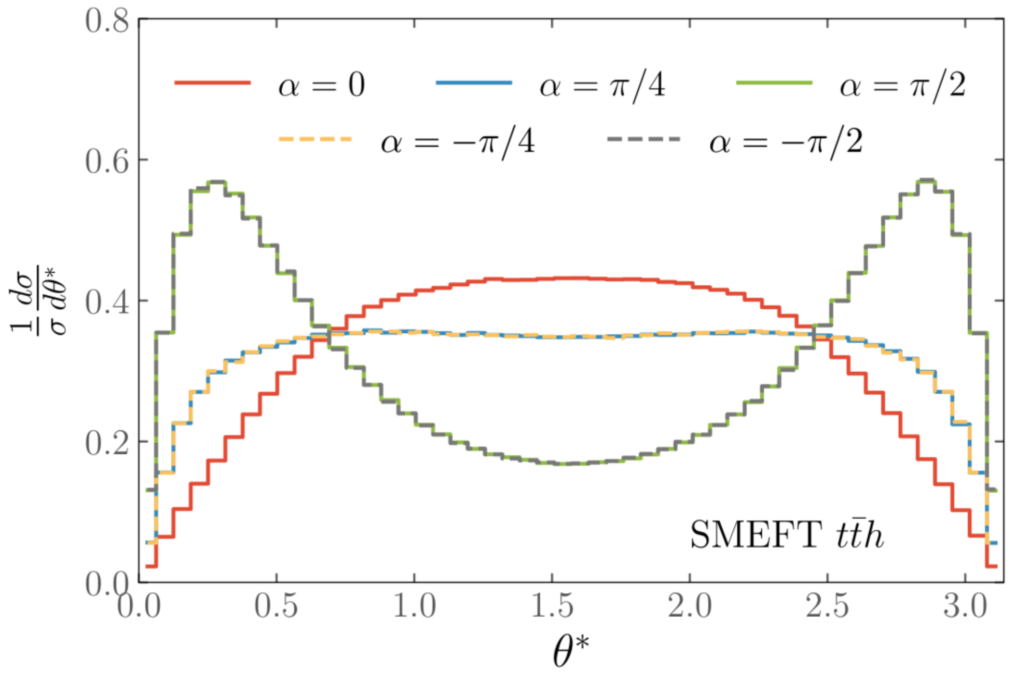
$$\Delta\phi_{jj} = \phi_{j1} - \phi_{j2}$$



T. Plehn, D. L. Rainwater, and D. Zeppenfeld (2002)
G. Klamke and D. Zeppenfeld (2007)
M. Buschmann, C. Englert, D. Gonçalves, T. Plehn, and M. Spannowsky (2014)

Processes with one Higgs boson (*continuation)*

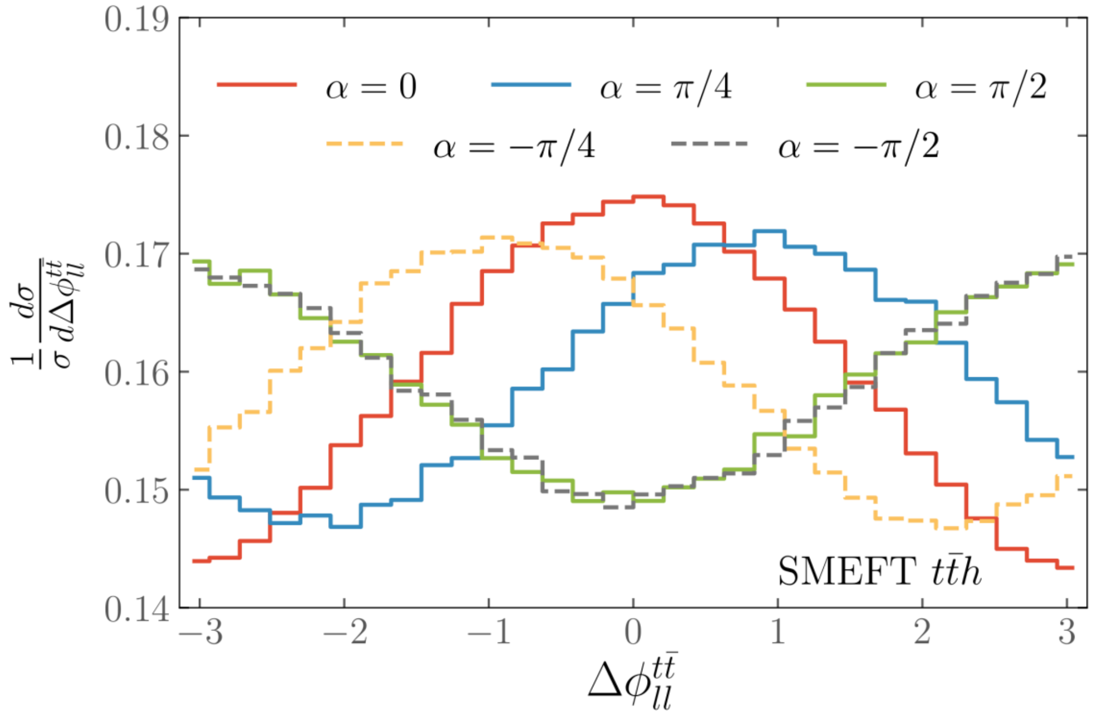
- Another process is Higgs production in association with top pair production.
- Several kinematic observables to investigate the CP structure of the Higgs-top coupling.
- The Collins-Soper angle is one of the most sensitive observables.



D. Gonçalves, K. Kong, and J. H. Kim (2018)
D. Gonçalves, J. H. Kim, K. Kong, and Y. Wu (2022)

Processes with one Higgs boson (*continuation)*

- Genuine CP-odd observables can also be defined exploiting the top quark polarization that is carried over to its decay products.
- It is possible to form tensor products involving the top and the decay products momenta.
- These products can be simplified in the top pair rest frame, leading to the azimuthal angle difference

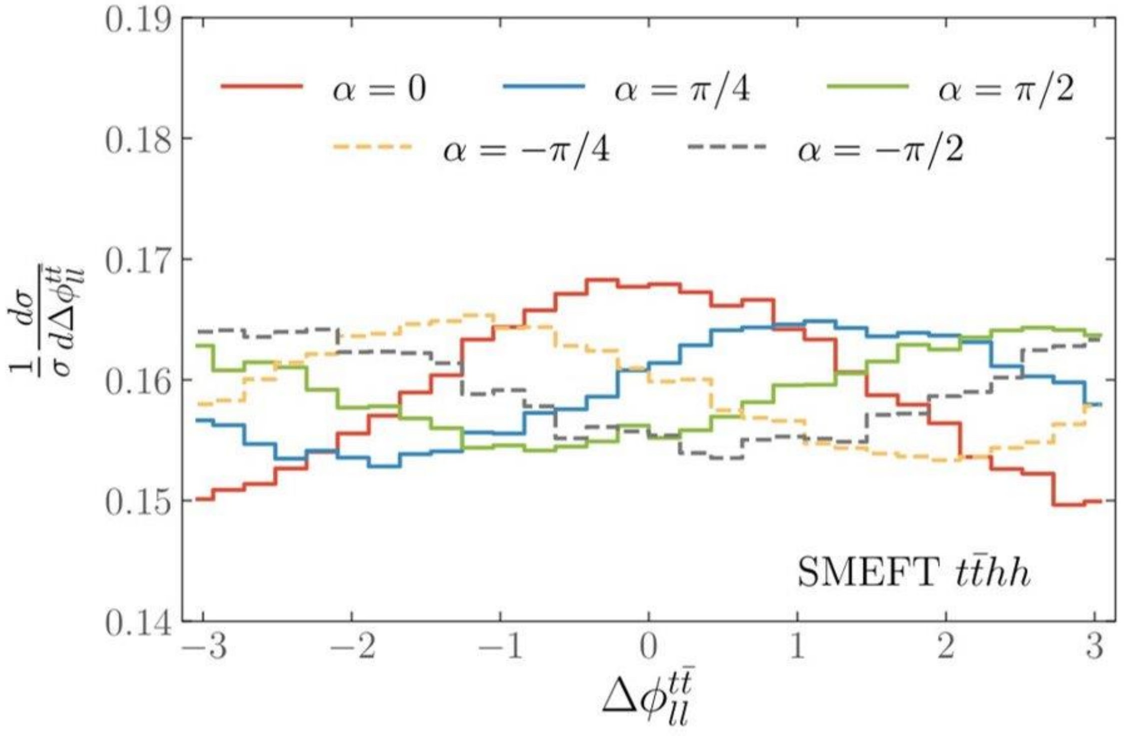


$$\Delta\phi_{ik}^{t\bar{t}} = \text{sgn}\left[\vec{p}_t\cdot(\vec{p}_i\times\vec{p}_k)\right] \arccos\left(\frac{\vec{p}_t\times\vec{p}_i}{|\vec{p}_t\times\vec{p}_i|}\cdot\frac{\vec{p}_t\times\vec{p}_k}{|\vec{p}_t\times\vec{p}_k|}\right).$$

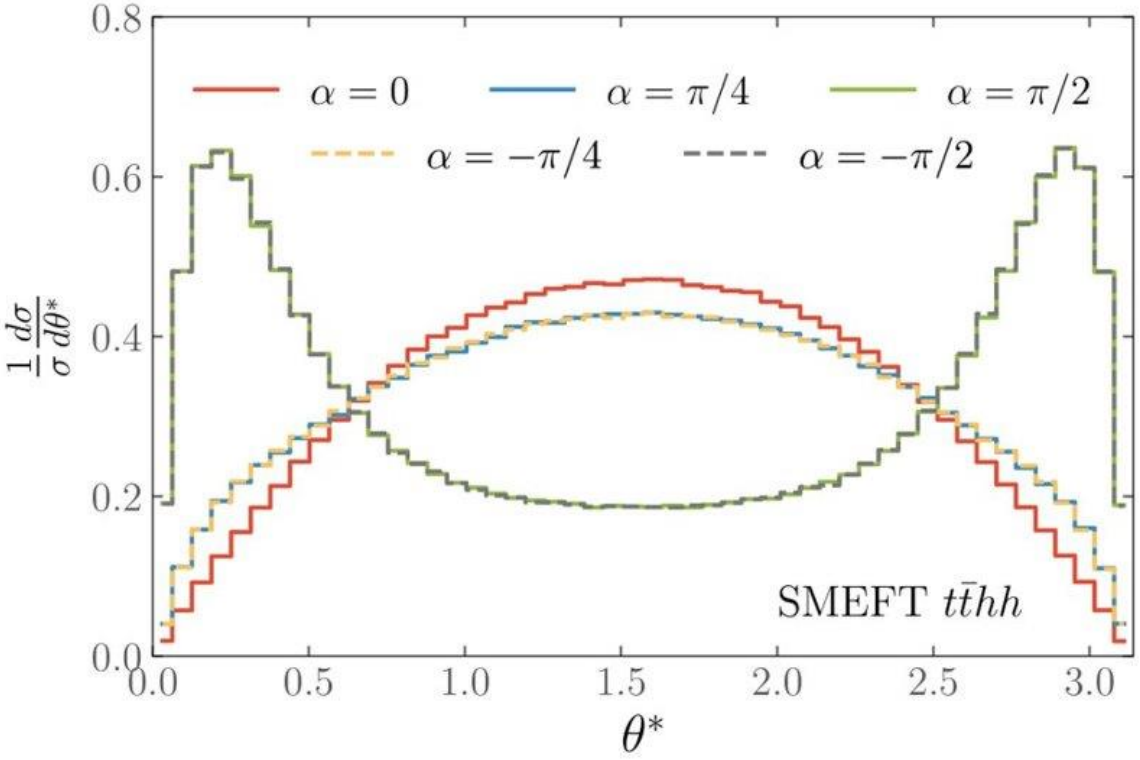
D. Gonçalves, K. Kong, and J. H. Kim (2018)
R. K. Barman, D. Gonçalves, and F. Kling (2022)

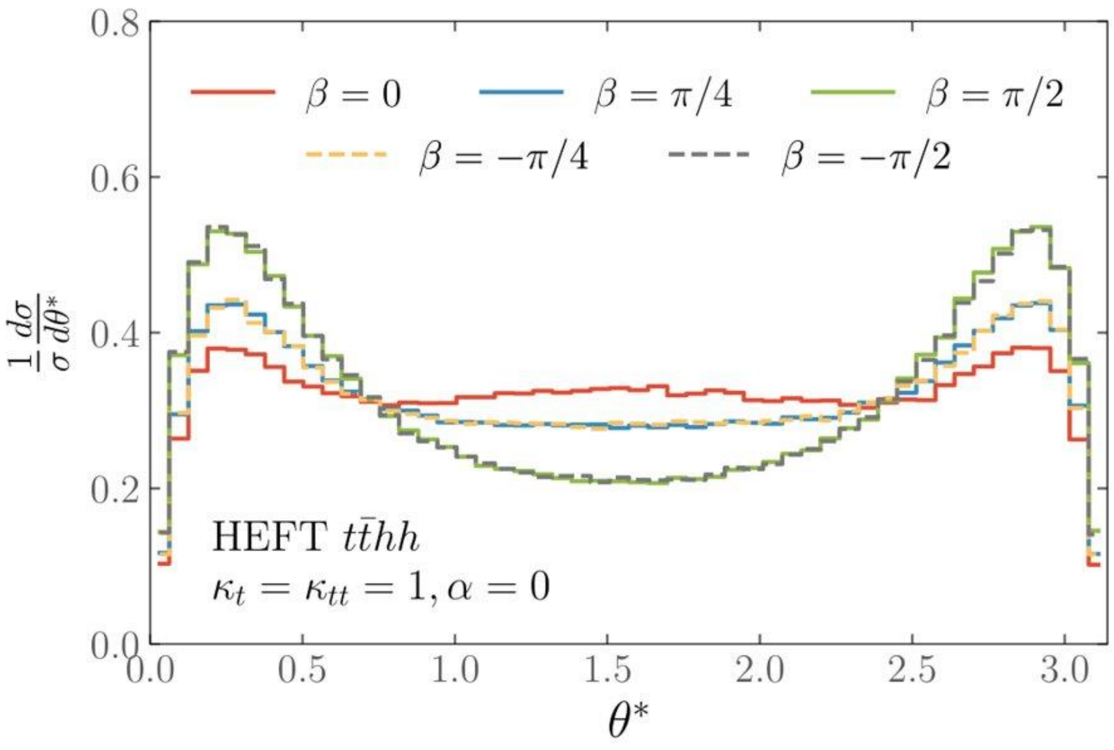
Processes with a pair of Higgs bosons

- We consider processes that provide genuine sensitivity to non-linearity via the production of final states containing a pair of Higgs bosons.
- Higgs pair production and tthh are included in our analysis.
- Similar observables as defined in the tth case can be used for tthh. Though including them is challenging as tthh is statistically limited.



Processes with a pair of Higgs bosons *(continuation)*



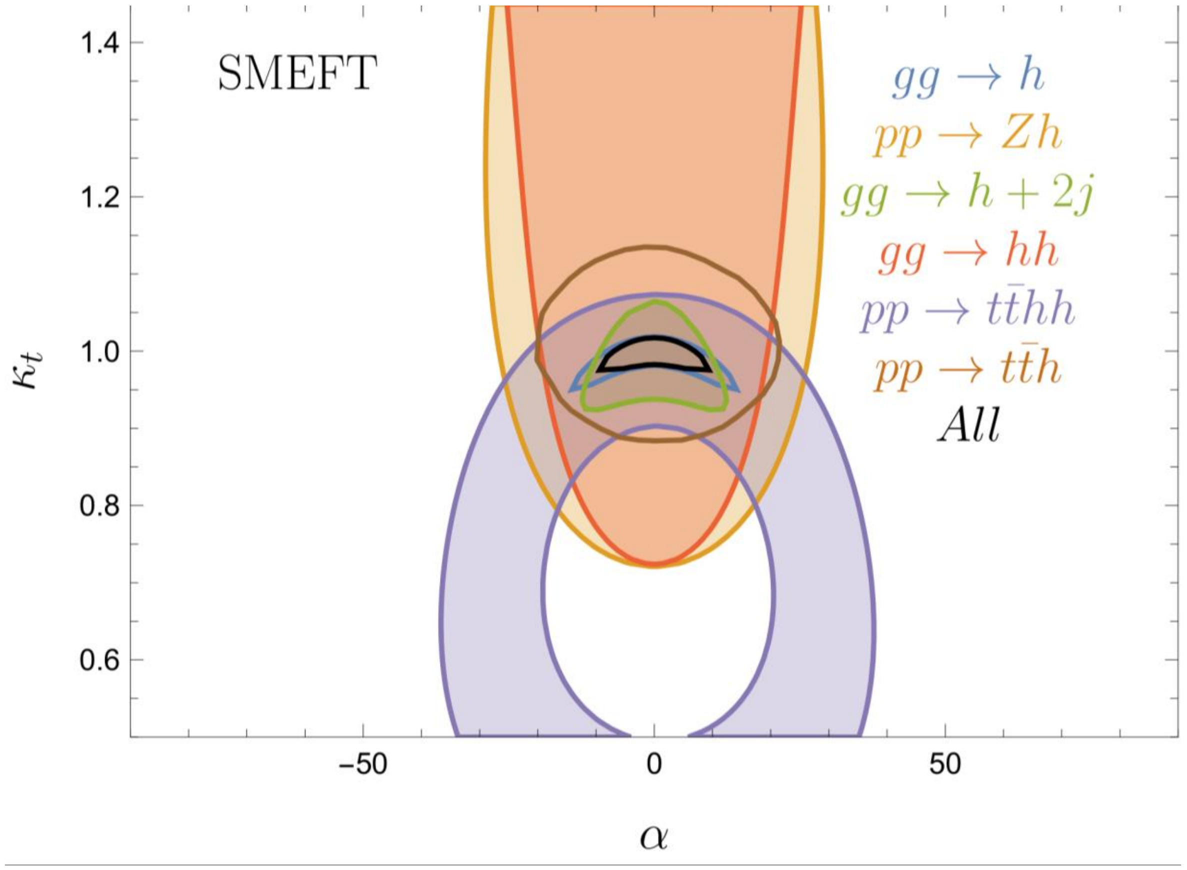


Global Fits

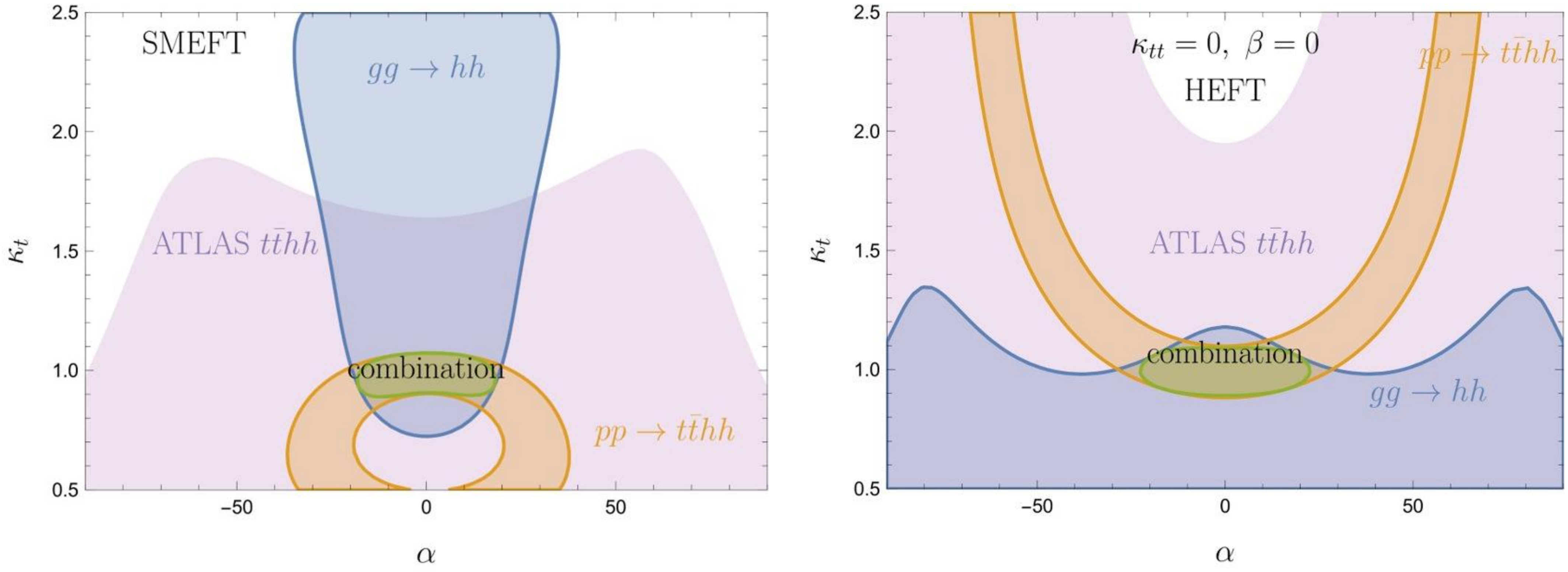
- The asymmetries and total rates are used to set CL limits on the parameter space, assuming the SM as the null hypothesis.

$$\chi^2 = \sum_i \frac{(N_i - N_i^{\mathrm{SM}})^2}{\sigma_i^2} \, .$$

- N denotes the number of expected events for the HL-LHC.

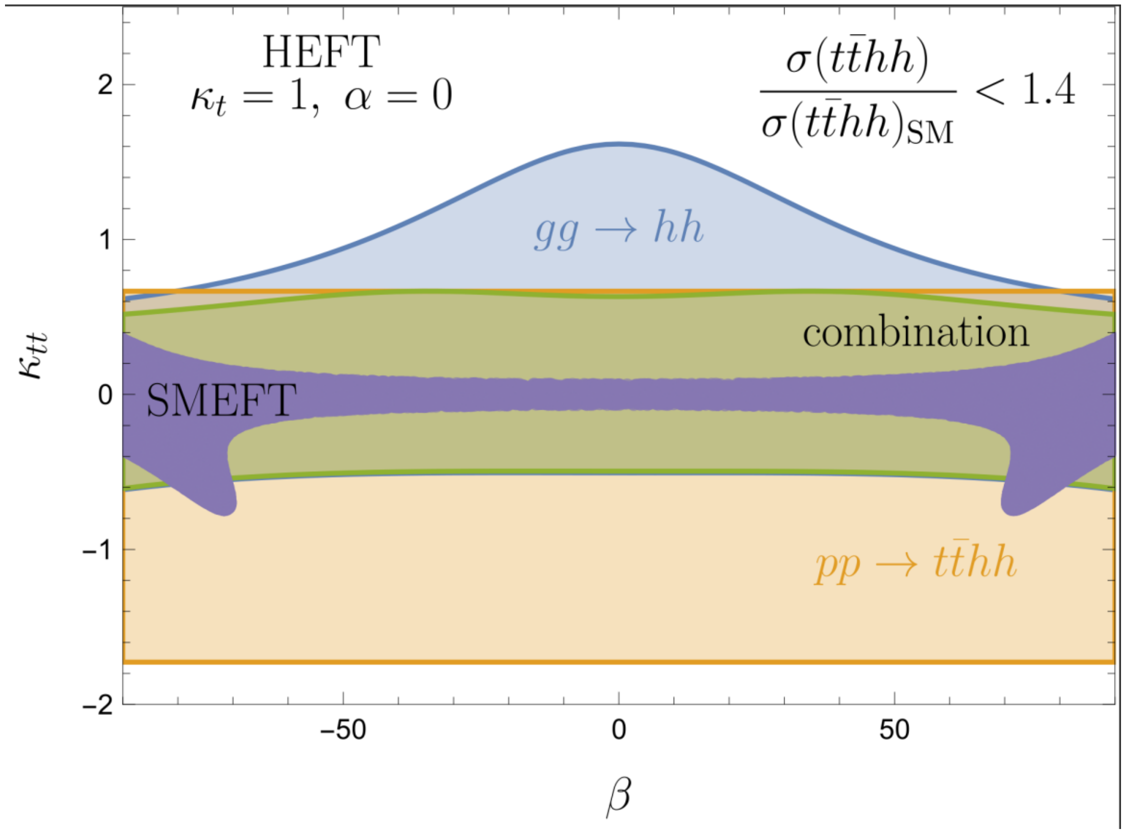


Fit to non-linear CP violation



Fit to non-linear CP violation *(continuation)*

- Given the correlation predicted by SMEFT-like extensions of the SM, we can therefore employ these production modes to highlight the expected sensitivity for (κ_{tt}, β) when comparing SMEFT and HEFT.



Summary

- We examined the potential of the LHC to constrain CP phases of the top-Yukawa interactions combining the sensitivity of a range of single and double Higgs production processes.
- Single Higgs processes encompass all the relevant correlations in dimension-six SMEFT, and multi-Higgs production does not lead to significant sensitivity gain.
- This paradigm shifts when considering non-linear sources of CP violation.
- The LHC shows sensitivity, in particular when discriminating between SMEFTy and HEFTy CP violation in the top-Higgs sector