Non-linear top-Higgs CP violation

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Introduction

- Lack of experimental evidence of new physics may indicate a mass gap between SM and BSM scales
- BSM physics influencing the Higgs sector, two common EFTs: SMEFT and HEFT
- SMEFT Lagrangian

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i>4} \sum_{k} \frac{C_k^{(i)}}{\Lambda^{i-4}} \mathcal{O}_k^{(i)}$$

- HEFT merges chiral perturbation theory (χPT) within the scalar sector with SMEFT across fermion and gauge sectors.
- we ask the question of *"how sensitive the LHC can be to sources of non-linear CP violation?"*

CP violation in top-Higgs sector (SMEFT)

The SMEFT approach

$$\mathcal{O}_{t\Phi} = |\Phi|^2 \bar{Q}_L \Phi^c t_R$$

This operator in the broken phase generates P-violating interactions for complex Wilson coefficients.

A phenomenologically identical parametrization of

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

$\alpha \rightarrow$ CP phase $\quad \kappa_t \rightarrow$ strength of the interaction

For SM, $\kappa_t = 1, \alpha = 0$

CP violation in top-Higgs sector (SMEFT)

renormalization of the SM Yukawa couplings, leads to

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

The $t\bar{t}hh$ interactions vanish for the SM point, $(\kappa_t, \alpha)_{\text{SM}} = (1, 0)$

$$\left.\frac{\Gamma_{\bar{t}th}}{\Gamma_{\bar{t}th^2}}\right|_{\gamma^5,\text{SMEFT}} = \frac{v}{3}$$

The relative strength of CP-violating tree-level three and four-point irreducible vertex functions

CP-violation in the top Higgs sector under the assumptions of SMEFT should manifest themselves predominantly in single Higgs physics→significant statistical pull in a global analysis.

CP violation in top-Higgs sector (HEFT)

The HEFT approach

- In HEFT which highlights the Higgs boson as a custodial singlet.
- In the non-linear sigma model of $SU(2)_L \times SU(2)_R \to SU(2)_V$, GBs can be parametrized as

$$U(\pi^a) = \exp\left(i\pi^a\tau^a/v\right)$$

- This transforms as

$$U \to L\,U\,R^\dagger$$

- the top quark mass arises from

Buchalla et al.1307.5017
Brivio et al.1604.06801
Dawson et al. 2311.16897

$$\mathcal{O}_{\bar{t}t} = -m_t\,\bar{Q}_L U t_R$$

this operator can be dressed with a ``flare'' function

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

CP violation in top-Higgs sector (HEFT)

The HEFT approach

This leads to CP-violating effects

$$\mathcal{L}_{\mathrm{HEFT}} \supset Y_t(h)\,\mathcal{O}_{\bar{t}t} + \mathrm{h.c.} \supset i\,\mathrm{Im}\,c^{(1)}\frac{1}{\sqrt{2}}\bar{t}\gamma^5 th + i\,\mathrm{Im}\,c^{(2)}\frac{1}{2v\sqrt{2}}\bar{t}\gamma^5 th^2 + \ldots\,,$$

The parametrization of the HEFT interactions analogous to $\mathcal{L}_\alpha$

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

The Higgs multiplicities remain uncorrelated.

The relative strength of CP-violation for the three and four-point interactions in HEFT

$$\left.\frac{\Gamma_{\bar{t}th}}{\Gamma_{\bar{t}th^2}}\right|_{\gamma^5,\mathrm{HEFT}} = \frac{\kappa_t}{\kappa_{tt}}\,\frac{\sin\alpha}{\sin\beta}\,v$$

SMEFT vs HEFT

The SMEFT trajectory can be recovered by the HEFT choices

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

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

$$\frac{\mathrm{d}\sigma}{\mathrm{dLIPS}} \sim |\mathcal{M}_{\mathrm{SM}}|^2 + \boxed{2\mathrm{Re}(\mathcal{M}_{\mathrm{SM}}\mathcal{M}_{\mathcal{O}}^*)} + \boxed{|\mathcal{M}_{\mathcal{O}}|^2\,.}$$

Squared CP-odd contributions manifest in CP-even distributions, cross sections, transverse momentum distributions, etc.

Interference effects between SM and new physics are resolved through purpose-built CP odd observables.

Sensitive Processes for tth and tthh interactions

- Sensitive through rate:
  > gg → h production — CMS-PAS-FTR-16-002
  > Z boson-associated Higgs production — PRD 89 013013 (2014), PRD 92 073006 (2015)
  > tthh & other di-Higgs production — PLB 743, 93 (2015), ATL-PHYS-PUB-2022-053

- Sensitive through signed asymmetric variables
  > Gluon fusion h + 2j — PRL 88 051801 (2002), PRD 90, 013010 (2014)
  > Top-associated Higgs production (tth) — JHEP 06 079 (2018), JHEP 01 158 (2022)

- Sensitive through Z polarization
  > Z boson-associated Higgs production — PRD 89 013013 (2014), PRD 92 073006 (2015)

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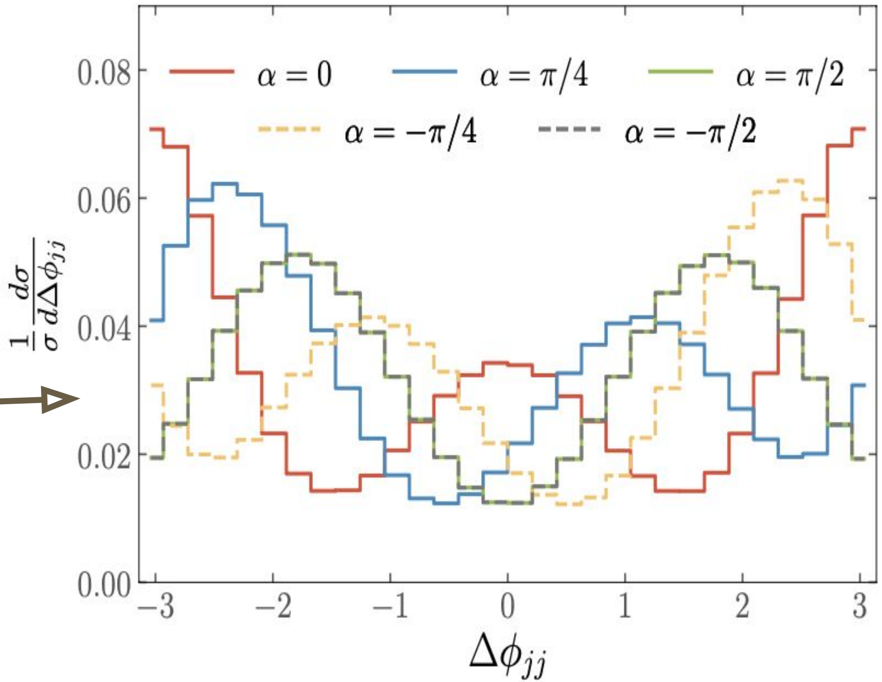
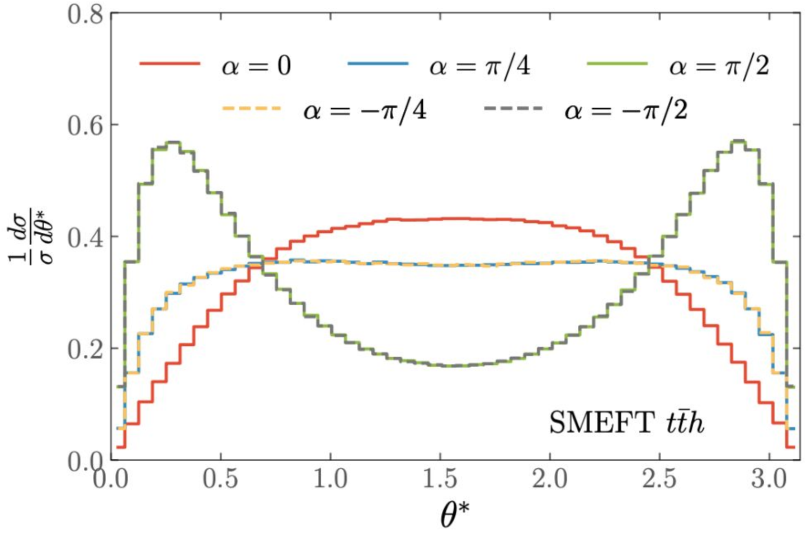
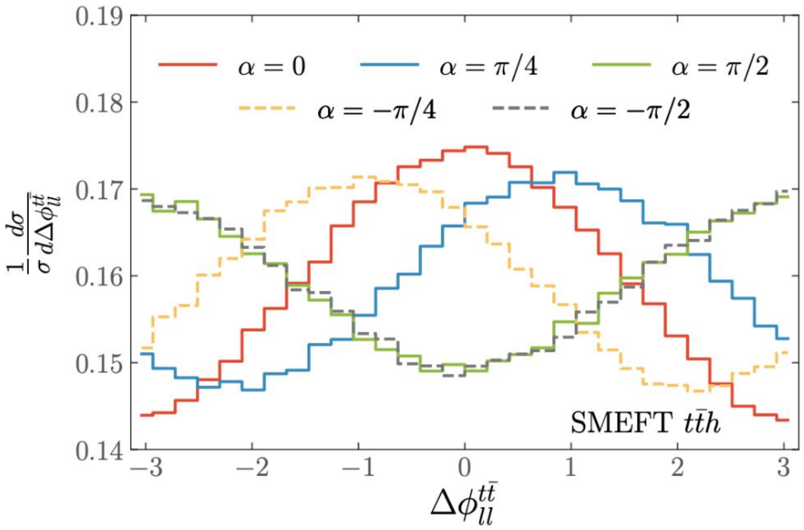


Distribution for the $\Delta\phi jj$ (= $\phi_{j1} - \phi_{j2}$) between the two tagging jets in h+2j

Ref: PRL 88 051801 (2002), PRD 90, 013010 (2014)

CP-odd observables for tth





Collins-Soper Angle

Azimuthal angle distribution

The angle between the top quark and the beam direction in the tt CM frame.

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

Ref: JHEP 06 079 (2018), JHEP 01 158 (2022)

Non-linear CPV in Top-Higgs sector: Chi² Fit

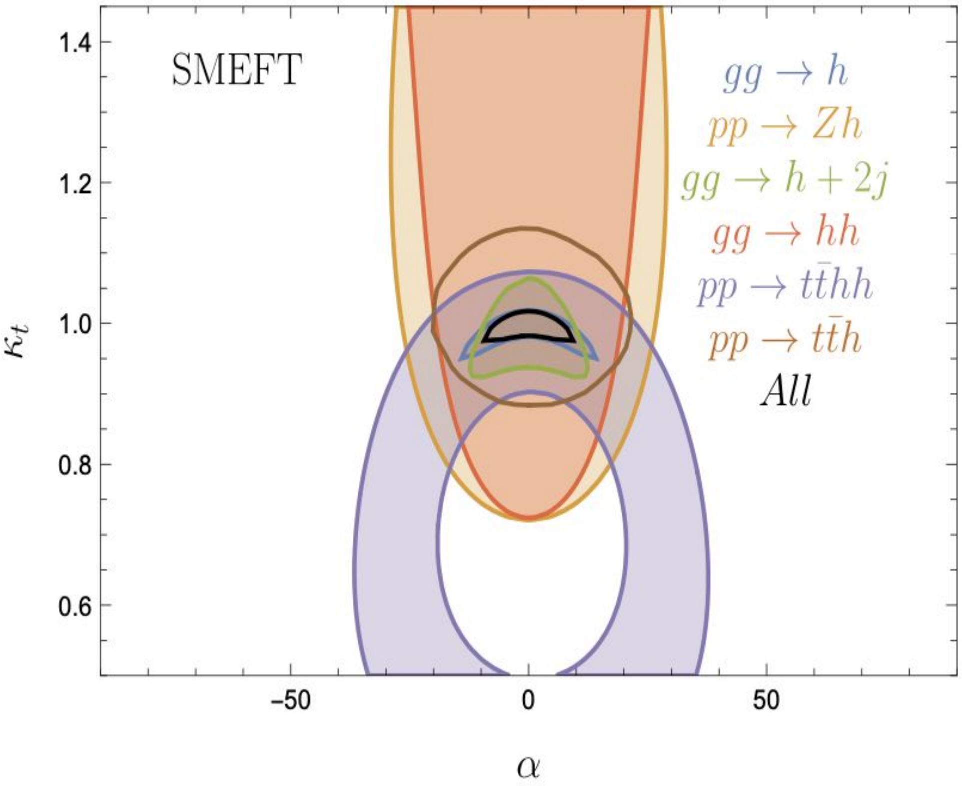
The asymmetries and total rates are used to set CL limits on the parameter space

$$(\kappa_t, \alpha, \kappa_{tt}, \beta)$$

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

Directly probing the top Yukawa coupling through the tth channel also leads to relevant complementary constraints.

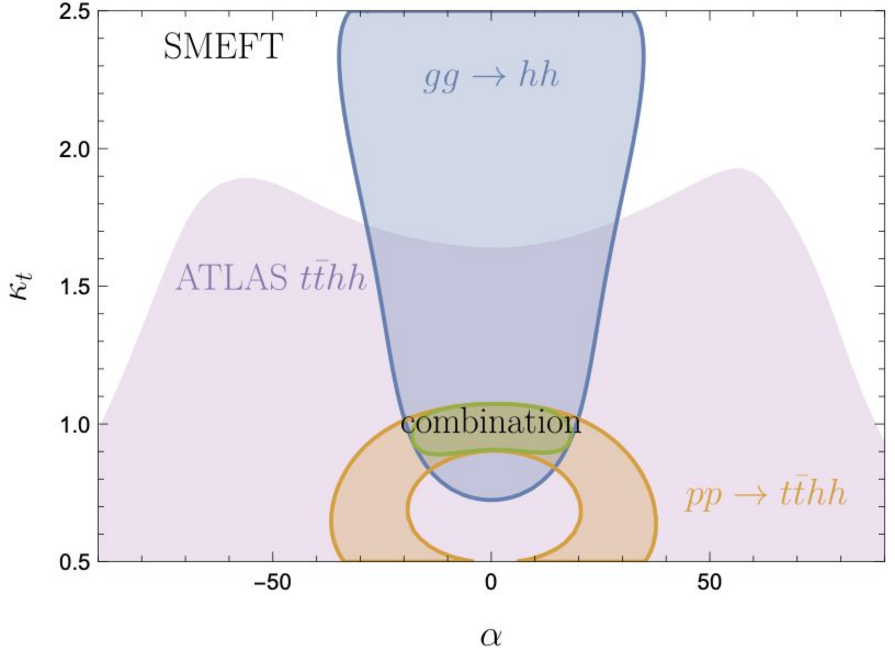
highest statistical abundance → most sensitive

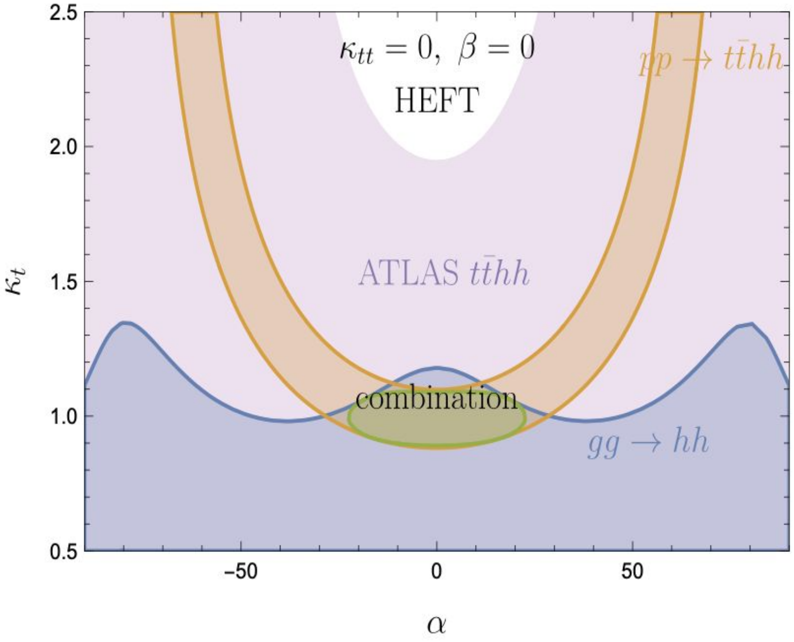


95% CL limits for the 13 TeV HL-LHC with 3 ab^{-1} [SMEFT]

SMEFT vs HEFT

Multi-Higgs production serves as means to distinguish non-linearity



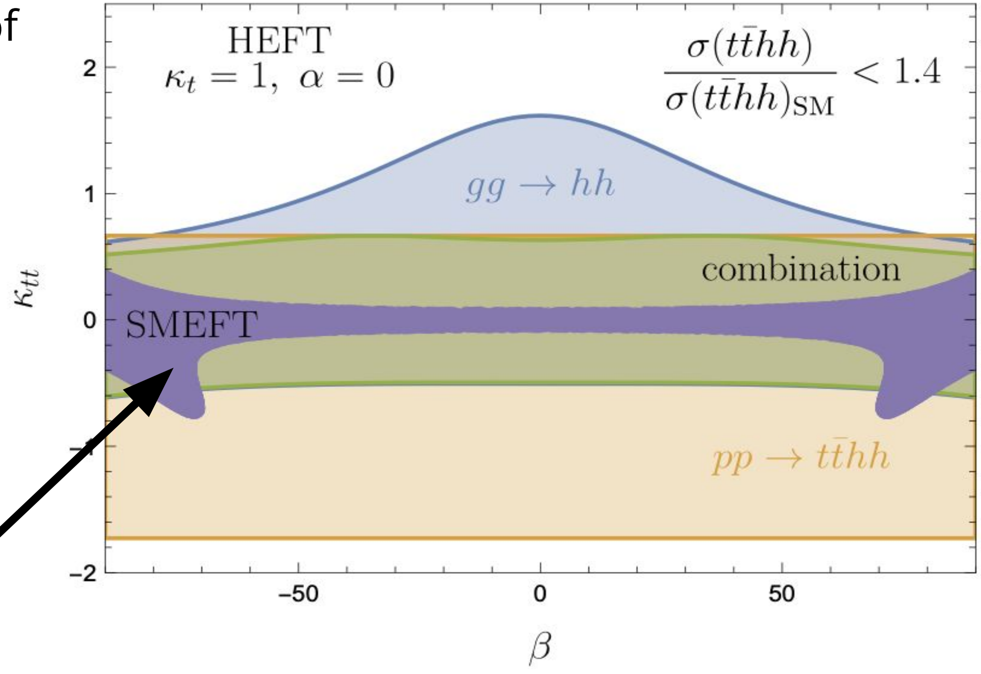


95% CL limits at the 13 TeV HL-LHC with 3 ab^{-1} of data for hh and tthh channels

C. Englert,1409.8074, ATL-PHYS-PUB-2016-023, ATL-PHYS-PUB-2022-053

Non-linear CP violation

- Sets constraints on the magnitude of the contact interaction (κ_{tt})
- $gg \to hh$ production is very sensitive to κ_{tt} and associated CPV in HEFT
- The role of tthh production remains critical, even when only the κtt effects are considered



SMEFT region selected from a fit to single Higgs data

$$\kappa_{tt}^2 = 9(1 - 2\kappa_t \cos\alpha + \kappa_t^2)$$
$$\tan\beta = \frac{\kappa_t \sin\alpha}{\kappa_t \cos\alpha - 1}$$

95% CL limits on (κ_{tt}, β) at the 13 TeV with 3 ab^{-1} of data for hh and tthh channels in HEFT

Conclusion

- ❑ We explored CPV in top-Higgs sector at the LHC by combining the sensitivity of a range of single and double Higgs production processes.
- ❑ In SMEFT, multi-Higgs production does not lead to any significant sensitivity gain as single Higgs processes encompass all the relevant correlations in dim-6.
- ❑ But, the paradigm shifts when considering non-linear sources of CP violation.
- ❑ LHC shows sensitivity when discriminating between SMEFTy and HEFTy CP violation in the top-Higgs sector.
- ❑ Due to statistical limitations of multi-H study at the LHC, future hadron colliders are necessary

Thank you

Back up

$$\mathcal{L}_{\mathrm{SMEFT}} \supset \frac{C_{t\Phi}}{\Lambda^2}\mathcal{O}_{t\Phi} + \mathrm{h.c.}$$

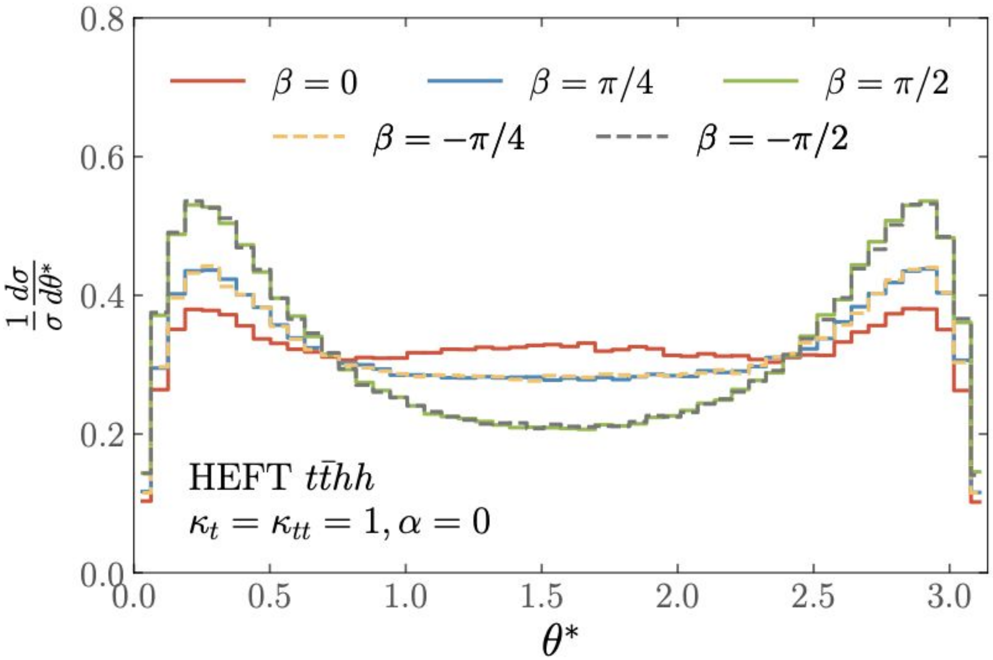
$$\supset i\,\mathrm{Im}(C_{t\Phi})\frac{v^2}{\sqrt{2}\Lambda^2}\bar{t}\gamma^5 t h + i\,\mathrm{Im}(C_{t\Phi})\frac{3v}{2\sqrt{2}\Lambda^2}\bar{t}\gamma^5 t h^2 + \ldots .$$

After renormalisation of the SM Yukawa couplings and assuming a purely CP-even SM coupling of the top quark

$$\frac{1}{\Lambda^2}\begin{pmatrix}\mathrm{Re}\,C_{t\Phi}\\ \mathrm{Im}\,C_{t\Phi}\end{pmatrix} = -\frac{\sqrt{2}\,m_t}{v^3}\begin{pmatrix}\kappa_t\cos\alpha - 1\\ \kappa_t\sin\alpha\end{pmatrix}.$$

Beyond linearity: tthh inclusive hh production

The angle between the top quark and the beam direction in the tt CM frame

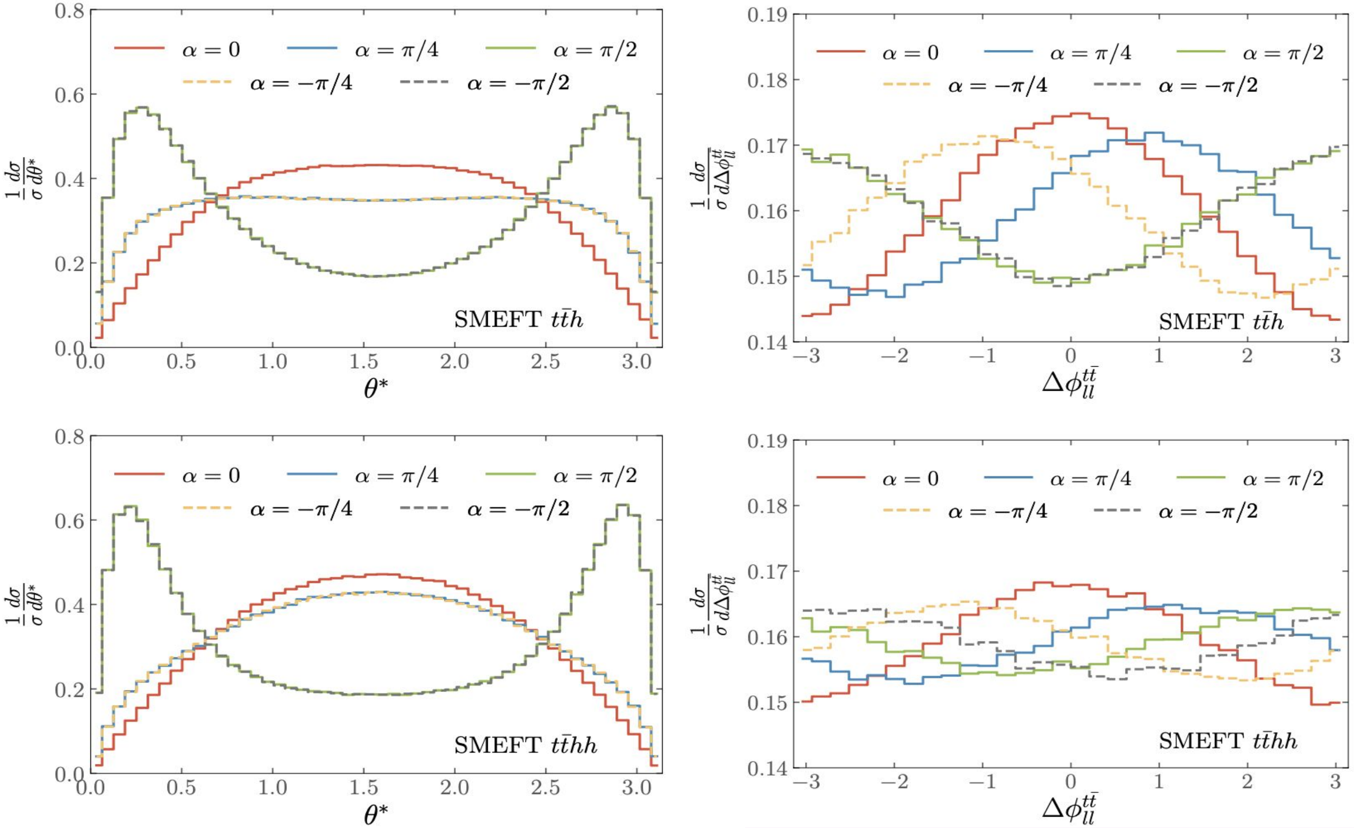


Collins-Soper angle θ* for the tthh process in HEFT framework.

CP-odd observables

tth

tthh



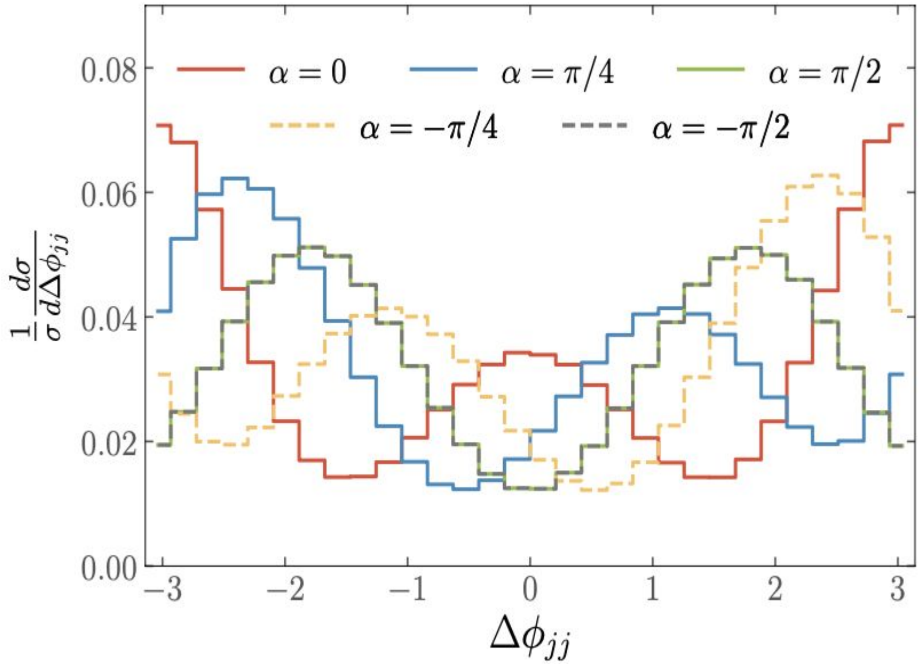
Collins-Soper Angle

Azimuthal angle distribution

Gluon fusion h + 2j production

- ❑ Rapidity ordered jets : $\eta_{j1} > \eta_{j2}$
- ❑ Azimuthal angular difference

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



Distribution for the azimuthal angle difference between the two tagging jets in h+2j production