A handle on anomalous top-Higgs couplings in top quark pair production through EW loops

based on [arXiv:2104.04277]

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Motivation

The LHC is a top quark factory:

- Top quark produced $\approx 240 \times 10^6$ times in Run-2 ($\approx 160\ \mathrm{fb}^{-1}$) (1000$\times$ more than at Tevatron)

Main top quark dynamics predictable at percent level:

- NNLO+NNLL QCD predictions for single and pair production
  [Czakon,Fiedler,Heymes,Mitov],[Brucherseifer,Caola,Melnikov],[Berger,Gao,Yuan,Zhu], [Czakon,Mitov,Sterman],[Beneke,Czakon,Falgari,Mitov,Schwinn],[Beneke,Falgari,Klein,Schwinn],[Kidonakis], [Ferroglia,Pecjak,Yang],[Ferroglia,Marzani,Pecjak,Yang],[Czakon,Ferroglia,Heymes,Mitov,Pecjak,Scott]
- Decay known to NNLO QCD ($\leftrightarrow$ prod. via NWA and beyond)
  [Gao,Li,Zhu],[Brucherseifer, Caola, Melnikov],[Bevilacqua,Czakon,v.Hameren,Papadopoulos,Worek], [Denner,Dittmaier,Kallweit,Pozzorini],[Heinrich,Maier,Nisius,Schlenk,Winter], [Frederix,Frixione,Papanastasiou,Prestel,Torrielli],[Denner,Pellen]
- EW corrections known for production and width
  [Beenakker,Denner,Hollik,Mertig,Sack,Wackeroth],[Kühn,Scharf,Uwer],[Bernreuther,Fücker,Si], [Moretti,Nolten,Ross],[Groote,Körner,Mauser],[Basso,Dittmaier,Huss,Toggero]

Top quark sector ideal lab for New Physics searches!

Dimension-six operators in SMEFT

Deviations from the SM parametrised within EFT

Wilson coefficient

Dimension-six operator

$$\mathcal{L}^{\mathrm{EFT}} = \mathcal{L}^{(4)}_{\mathrm{SM}} + \sum_X \frac{C^X}{\Lambda^2} Q^{(6)}_X + \mathcal{O}\left(\frac{Q^{(8)}}{\Lambda^4}\right)$$

Scale of New Physics

Focus on electroweak top quark interactions

E.g. (SMEFT in Warsaw basis [Dedes,Materkowska,Paraskevas,Rosiek,Suxho'17]):

$$Ztt: \; Q^{\varphi q1}_{33} = (\varphi^\dagger \mathrm{i} \overleftrightarrow{D}_\mu \varphi)(\bar{q}'_{3\,\mathrm{L}} \gamma^\mu \, q'_{3\,\mathrm{L}}) \leftrightarrow C^{\varphi q1}_{33},$$

$$Ztt, Wtb, \chi tt, \phi tb: \; Q^{\varphi q3}_{33} = (\varphi^\dagger \mathrm{i} \tau^I \overleftrightarrow{D}_\mu \varphi)(\bar{q}'_{3\,\mathrm{L}} \tau^I \gamma^\mu \, q'_{3\,\mathrm{L}}) \leftrightarrow C^{\varphi q3}_{33},$$

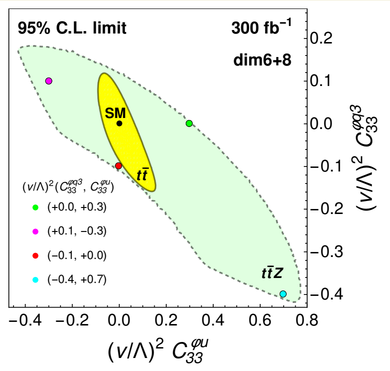
$$Ztt, \chi tt: \; Q^{\varphi u}_{33} = (\varphi^\dagger \mathrm{i} \overleftrightarrow{D}_\mu \varphi)\,(\bar{t}'_{\mathrm{R}} \gamma^\mu t'_{\mathrm{R}}) \leftrightarrow C^{\varphi u}_{33},$$

$$Htt: \; Q^{u\varphi}_{33} = (\varphi^\dagger \varphi)(\bar{q}'_{3\,\mathrm{L}} \, t'_{\mathrm{R}} \tilde{\varphi}) \leftrightarrow C^{u\varphi}_{33}$$

On-shell vs. loop sensitivity [Schulze,TM'20]

Previous study: Focus on anomalous Ztt: $C_{33}^{\varphi u}$ & $C_{33}^{\varphi q3}$

- Sensitivity in $t\bar{t}Z$: low rate (coupling, threshold, BR), known to NLO QCD ($\approx \pm 15\%$ scale unc.)
- $t\bar{t}$ sensitive via EW loops: $\approx 100\times$ more events, QCD background known to NNLO+NNLL ($\approx \pm 5\%$ scale unc.), Sudakov enhancement in diff. distrib., requires EW NLO calculation within SMEFT



Promising way to constrain New Physics!

Parametrizing CP-scenarios of the top Yukawa coupling

Next step: Focus on anomalous *Htt*: $C_{33}^{u\varphi}$

Including $Q_{33}^{u\varphi}$ in the Lagrangian yields modified Feynman rules:

$$\Gamma_{Htt}^{\mathrm{EFT}} = \frac{-\mathrm{i}m_t}{v} + \frac{\mathrm{i}v^2}{\sqrt{2}\Lambda^2}\left(P_{\mathrm{L}}\, {C_{33}^{u\varphi}}^{*} + P_{\mathrm{R}}\, C_{33}^{u\varphi}\right) \quad /\mathrm{w} \quad P_{\mathrm{R/L}} = \tfrac{1}{2}(1 \pm \gamma_5)$$

Definitions: $\boxed{\kappa = 1 - \frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Re}(C_{33}^{u\varphi})}$, $\boxed{\tilde{\kappa} = -\frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Im}(C_{33}^{u\varphi})}$

$$\Rightarrow \boxed{\Gamma_{Htt}^{\kappa,\tilde{\kappa}} = \frac{-\mathrm{i}m_t}{v}\left(\kappa \quad + \quad \mathrm{i}\gamma_5\tilde{\kappa}\right)}$$

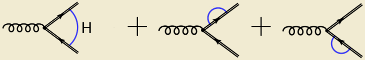
CP even   CP odd

- 0^- states inherent to, e.g., SUSY or two-Higgs-doublet models (CP violation required to explain baryon asymm. [Sakharov'91])
- Arbitrary CP-mixing possible via $\kappa, \tilde{\kappa}$
- SM recovered for $\kappa = 1$ and $\tilde{\kappa} = 0$

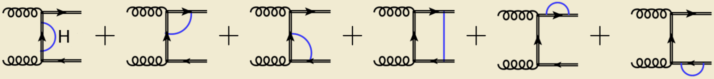
Loop sensitivity on $\kappa, \tilde{\kappa}$ in $t\bar{t}$ production

Calculational details — modified amplitudes

- Final state corrections depending on $\kappa, \tilde{\kappa}$ in *s*-channel *gg* and $q\bar{q}$:



- Loop diagrams depending on $\kappa, \tilde{\kappa}$ in *t*-channel *gg*:



Due to coupling structure in $\Gamma^{\kappa,\tilde{\kappa}}_{Htt}$, interference of diagrams with Higgs loops and Born level either $\propto (\kappa^2 + \tilde{\kappa}^2)$ or $\propto (\kappa^2 - \tilde{\kappa}^2)$.

$\Rightarrow$ **No sensitivity on signs of $\kappa, \tilde{\kappa}$**

Loop diagrams involving the Higgs boson are IR finite but contain UV poles $\Rightarrow$ Renormalization necessary within SMEFT

One-loop amplitude is UV finite after renormalization! ✓

Loop sensitivity on $\kappa, \tilde{\kappa}$ in $t\bar{t}$ production

Calculational details — numerical evaluation

We build upon the existing SM implementation of $t\bar{t}$-production at NLO EW in `MCFM` and allow for arbitrary top Yukawa couplings

- Analytic results of our calculation available as external add-on: https://github.com/TOPAZdevelop/MCFM-8.3_EWSMEFT_ADDON
- `MCFM` results reproduced when setting $\kappa = 1, \tilde{\kappa} = 0$
- `MCFM` established framework able to produce multi-dim. kinematic distributions together with EW correction factor

$$\delta_{\rm wk}^{\kappa,\tilde{\kappa}} = \frac{d\sigma_{\kappa,\tilde{\kappa}}^{\rm NLO\ EW} - d\sigma^{LO}}{d\sigma^{\rm LO}}$$

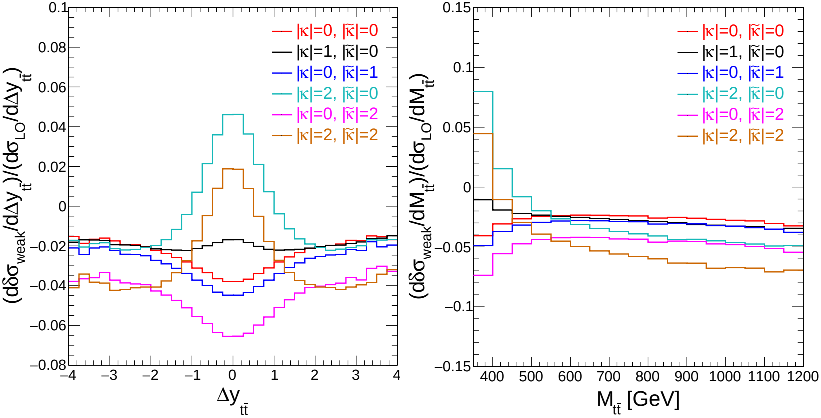
- $\delta_{\rm wk}^{\kappa,\tilde{\kappa}}$ can be used to reweight distributions generated by LO+PS+DetectorSim. generators

Note: Higgs loops with scalable κ (CP even only) available in `HATHORv2.1` and resp. study done by CMS [Phys.Rev.D100 7,(2019)072007]

Loop sensitivity on $\kappa, \tilde{\kappa}$ in $t\bar{t}$ production

Dependence of the shapes on $\kappa, \tilde{\kappa}$

$\Delta y_{t\bar{t}}$ and $M_{t\bar{t}}$ sensitive to CP structure of top Yukawa coupling



Event simulation and analyses

Loop sensitivity: $t\bar{t}$ (semileptonic channel)

- Top quark pair events simulated by `MadGraph5_v2.6.4+Pythia8.1+Delphes3` (CMS setting)
- Simulated events are normalized to $\sigma_{t\bar{t}}^{\mathrm{NNLO\ QCD}} = 832^{+40}_{-46}$ pb
- 2-dim distribution of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ filled with events
- 2-dim distrib. can be reweighted with $\delta_{\mathrm{wk}}^{\kappa,\tilde{\kappa}}$ from modified `MCFM`
- Main background: single top, V+jets and QCD multijets

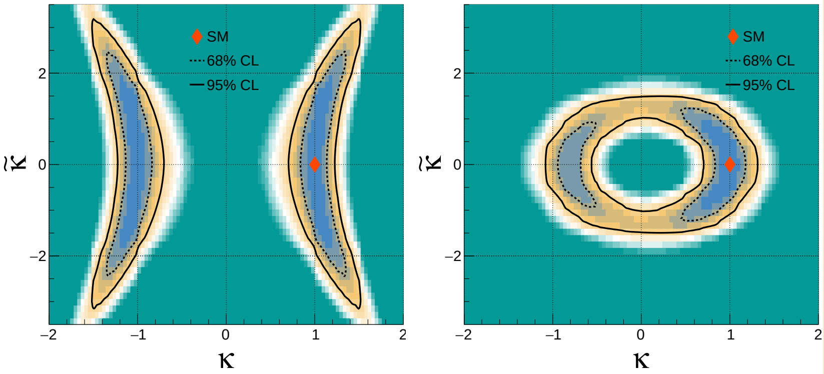
On-shell benchmark: e.g. tHW (full hadr. channel and $H \to \gamma\gamma$)

- Events with top and antitop quarks simulated by `JHU Generator+Pythia8.1+Delphes3` (CMS setting)
- Differential cross sections for different hypotheses implemented in `JHU Generator`
- MELA (matrix element likelihood approach): 3 discriminants
- Main background: $t\bar{t}H$

Results

Two dimensional likelihood scans of κ and $\tilde{\kappa}$

Loop sensitivity **On-shell benchmark**



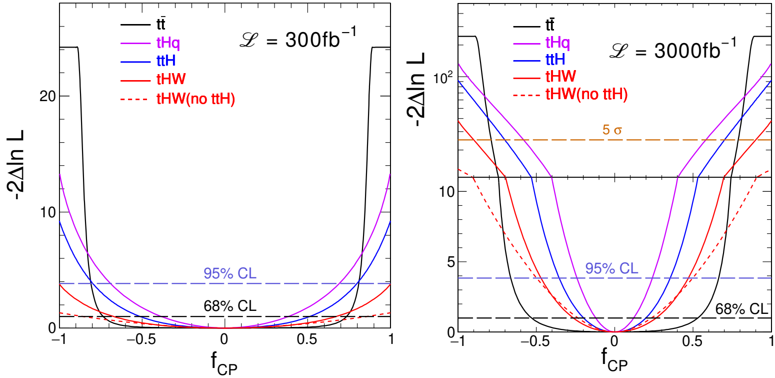
$t\bar{t}$ at 300 fb^{-1} tHW at 300 fb^{-1}

Results

Fractional contribution of the CP-odd component

$$f_{CP} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2+|\tilde{\kappa}|^2}\mathrm{sign}\left(\frac{\tilde{\kappa}}{\kappa}\right)$$

Likelihood scans of f_{CP}



$t\bar{t}H$ and tHq results taken from [Gritsan,Röntsch,Schulze,Xiao'16]

Conclusions

- **Probing CP structure of top Yukawa coupling through EW loops**
  - Calculation of EW correction to $pp \to t\bar{t}$
  - NP included via SMEFT parametrisation of Htt coupling
- **Comparison to direct on-shell probes, e.g.,** $pp \to tHW$ with full-fledged simulation chain
  - $t\bar{t}$ expected to exclude $|f_{CP}| > 0.81$ for 300 fb^{-1} and $|f_{CP}| > 0.67$ for 3000 fb^{-1} at 95% CL
  - tHW can exclude pure pseudo-scalar model at 2σ for 300 fb^{-1} and $|f_{CP}| > 0.48$ for 3000 fb^{-1} at 95% CL
  - tHq gives most stringent 95% CL exclusion: $|f_{CP}| > 0.68$ for 300 fb^{-1} and $|f_{CP}| > 0.22$ for 3000 fb^{-1}
  - $t\bar{t}$ best probe to exclude purely CP-odd top Yukawa coupling
- $t\bar{t}$ and tHW with anomalous top Yukawa couplings available as add-on to `MCFM` or via `JHU Generator` respectively