Top quark pair production as a laboratory for probing anomalous top-quark couplings through electroweak loops

based on [JHEP 04 (2020) 017] & [PRD 104 (2021) 055045]

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PHYSICS AT THE TERA SCALE Helmholtz Alliance

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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!

Deviations from the SM parametrised within EFT

Wilson coefficient · dimension-six operator · Scale of New Physics

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

Focus on anomalous electroweak top quark interactions

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

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

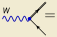
$$Ztt, Wtb, \chi tt, \phi tb: \; Q^{\varphi q3}_{33} = (\varphi^\dagger \mathrm{i}\tau^I \overleftrightarrow{D}_\mu \varphi)(\bar{q}'_{3\,\mathrm{L}}\, \tau^I \gamma^\mu\, q'_{3\,\mathrm{L}}) \leftrightarrow C^{\varphi q3}_{33},$$

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

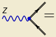
$$Htt: \; Q^{u\varphi}_{33} = (\varphi^\dagger \varphi)(\bar{q}'_{3\,\mathrm{L}}\, t'_{\mathrm{R}} \tilde{\varphi}) \leftrightarrow C^{u\varphi}_{33}$$

Top quark coupling to $W^{\pm}, Z, H$

Modified Feynman rules I: $W^{\pm}, Z$



$= \frac{-ie}{\sqrt{2}s_w}\gamma^\mu\left(d_L^W P_L + d_R^{W,SM} P_R\right)$ &



$= \frac{-ie}{s_w c_w}\gamma^\mu\left(d_L^Z P_L + d_R^Z P_R\right)$

with $P_{R/L} = \frac{1}{2}(1 \pm \gamma_5)$, $d_L^W = d_L^{W,SM} + \frac{v^2}{\Lambda^2} C_{33}^{\varphi q3}$

& $d_L^Z = d_L^{Z,SM} + \frac{v^2}{\Lambda^2} C_{33}^{\varphi q3}$, $d_R^Z = d_R^{Z,SM} - \frac{1}{2}\frac{v^2}{\Lambda^2} C_{33}^{\varphi u}$

SMEFT $\Rightarrow$ simple coupling replacement

Modified Feynman rules II: $\phi^{\pm}, \chi$

$= \frac{-ie}{\sqrt{2}s_w c_w}\left(d_L^\phi P_L + d_R^{\phi,SM} P_R\right)$ &

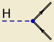
$= \frac{-e}{2 s_w c_w}\left(d_L^\chi P_L + d_R^\chi P_R\right)$

with $d_L^{\phi^+} = d_L^{\phi^+,SM} - \frac{v^2}{\Lambda^2}\frac{\not{p}_\phi}{M_Z} C_{33}^{\varphi q3}$, $d_L^{\phi^-} = d_L^{\phi^-,SM} + \frac{v^2}{\Lambda^2}\frac{\not{p}_\phi}{M_Z} C_{33}^{\varphi q3}$

& $d_L^\chi = d_L^{\chi,SM} - \frac{v^2}{\Lambda^2}\frac{\not{p}_\chi}{M_Z} 2\, C_{33}^{\varphi q3}$, $d_R^\chi = d_R^{\chi,SM} + \frac{v^2}{\Lambda^2}\frac{\not{p}_\chi}{M_Z} C_{33}^{\varphi u}$

SMEFT $\Rightarrow$ new coupling structure ($\propto \not{p}_{\chi/\phi}$)

Modified Feynman rules III: H



$= \frac{-im_t}{v} + \frac{iv^2}{\sqrt{2}\Lambda^2}\left(P_L {C_{33}^{u\varphi}}^* + P_R C_{33}^{u\varphi}\right) = \frac{-im_t}{v}(\underbrace{\kappa}_{\text{CP even}} + \underbrace{i\gamma_5\tilde{\kappa}}_{\text{CP odd}})$ with $\kappa = 1 - \frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Re}(C_{33}^{u\varphi})$ & $\tilde{\kappa} = -\frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Im}(C_{33}^{u\varphi})$

- CP-odd states inherent to, e.g., SUSY or two-Higgs-doublet models
- Arbitrary CP-mixing possible via κ, $\tilde{\kappa}$
- SM recovered for $\kappa = 1$ and $\tilde{\kappa} = 0$

On-shell vs. loop sensitivity

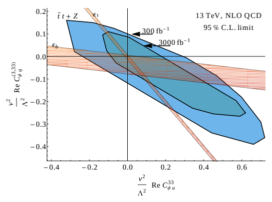
$C_{33}^{\varphi q3}$ and $C_{33}^{\varphi u}$ can be probed in $pp \to t\bar{t} + Z$

- **On-shell sensitivity** to couplings between t and Z
- Production rate low due to coupling suppression, high production threshold and branching fractions

$$\sigma_{t\bar{t}Z} \times \mathcal{B}_{Z\to\ell\ell} \times \mathcal{B}_{t\bar{t}\to\ell\nu+\text{jets}} \approx 1\ \text{pb} \times 6\% \times 33\% \approx 20\ \text{fb}$$

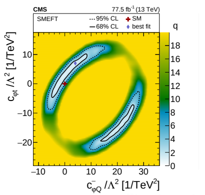
- Process known to NLO QCD ($\approx \pm 15\%$ scale unc.)

[arXiv:1404.1005v2]



$\frac{v^2}{\Lambda^2} C_{33}^{\varphi q3} \in [-0.40, 0.16]$, $\frac{v^2}{\Lambda^2} C_{33}^{\varphi u} \in [-0.35, 0.73]$ at 300/fb

[arXiv:1907.11270]



$\frac{v^2}{\Lambda^2} C_{33}^{\varphi q3} \in [-0.46, 0.21]$, $\frac{v^2}{\Lambda^2} C_{33}^{\varphi u} \in [-0.55, 0.79]$ at 78/fb

Question:

Can we exploit the **abundance of top quark pairs** and the **good perturbative control** of their theoretical description to constrain anomalous EW top quark interactions?

Idea: Sensitivity to NP from EW loops in $pp \to t\bar{t}$

Estimate:

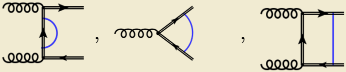
$$\sigma_{t\bar{t}} \times \alpha \times \mathcal{B}_{t\bar{t}\to\ell\nu+\text{jets}} \approx 840\ \text{pb} \times \frac{1}{128} \times 33\% \approx 1800\ \text{fb}$$

- anomalous EW top-quark couplings enter through $Z, W^{\pm}, \chi, \phi^{\pm}, H$ running in loops
- Irred. BG: QCD $\mathcal{O}(\alpha_s^2)$ (dom. prod. mech.), known to NNLO+NNLL ($\approx \pm 5\%$ scale unc.)
- EW corrections dominated by $\mathcal{O}(\alpha\alpha_s^2)\log^2(\hat{s}/M_W^2)$ $\Rightarrow$ sensitivity enhancement
- SM EW corrections to $t\bar{t}$ production known for a long time and already implemented in, e.g., MCFM

Calculational details

UV divergencies

- EW loop corrections yield bubble, triangle and box diagrams,

  e.g. : 

- Loop amplitudes with $\chi, \phi^{\pm}$ increase the integral tensor rank by up to 2 due to additional $\not{p}$ terms in the EFT contributions

→ Higher-rank tensor integrals → add. divergencies

- Interf. of diagrams /w Higgs loops and Born level either $\propto (\kappa^2 + \tilde{\kappa}^2)$ or $\propto (\kappa^2 - \tilde{\kappa}^2)$.

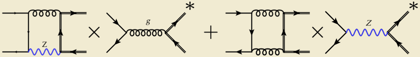
  (No sensitivity on signs of $\kappa, \tilde{\kappa}$)

→ **Wave function and mass renormalization within SMEFT required**

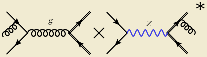
Squared amplitude is UV finite after renormalization!

IR divergencies

- UV finite box diagrams contain additional IR poles from soft and coll. gluons in the loop:



- Canceled by mixed QCD-EW amplitudes with real gluon emission (also sensitive to EFT operators):



- Loop diagrams involving Higgs boson are IR finite

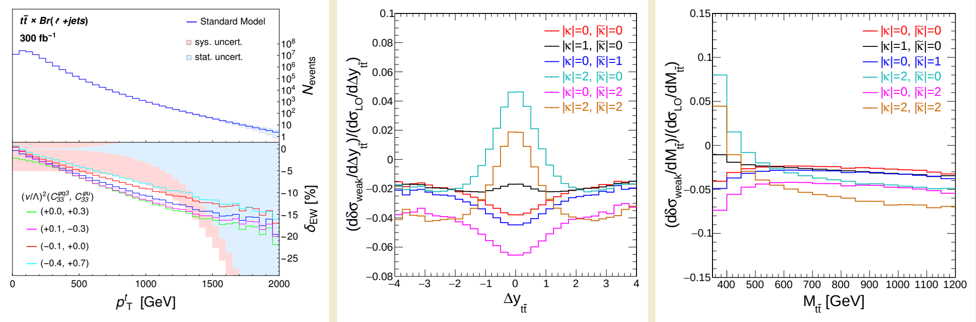
Cancellation of all IR poles for modified EW top couplings!

Numerical evaluation

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

- Analytic results of calculation available as external add-on: `github.com/TOPAZdevelop/MCFM-8.3_EWSMEFT_ADDON`
- `MCFM` reproduced for $\kappa = 1, \ \tilde{\kappa} = C_{33}^{\varphi u} = C_{33}^{\varphi q3} = 0$

Dependence of the shapes on $C_{33}^{\varphi u}, C_{33}^{\varphi q3}, \kappa, \tilde{\kappa}$

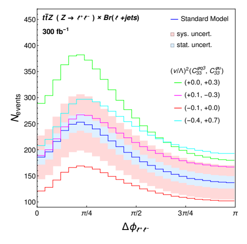


- State-of-the-art QCD predictions included in approx. way:
  - NNLO QCD K-factor of 1.67, scale uncertainty $\approx \pm 5\%$
- p_T^t sensitive to anom. coupling of the top to the EW gauge bosons
- $\Delta y_{t\bar{t}}$ and $M_{t\bar{t}}$ sensitive to CP structure of top Yukawa coupling

On-shell benchmark processes

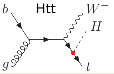
Benchmark $t\bar{t} + Z$

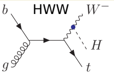
- Sensitive to anom. coupling of the top to the EW gauge bosons
- Calculation from `TOPAZ` framework (`github.com/TOPAZdevelop/TOPAZ`)
- NLO QCD K-factor of 1.23
- Scale uncertainty $\approx \pm 15\%$
- Z decaying into e^+e^- or $\mu^+\mu^-$



Benchmarks $t\bar{t} + H$, tHq, tHW

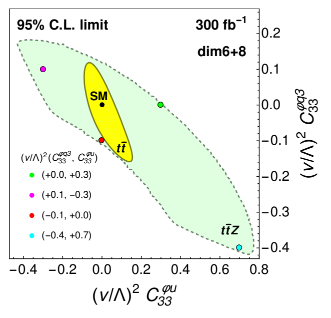
- Sensitive to anomalous top Yukawa coupling
  - Single top + Higgs sensitive to relative sign of coupling of Higgs boson to top and W

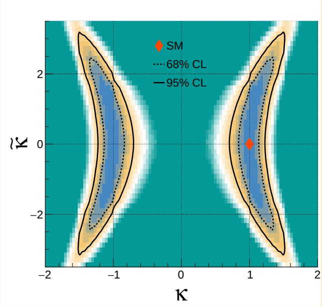


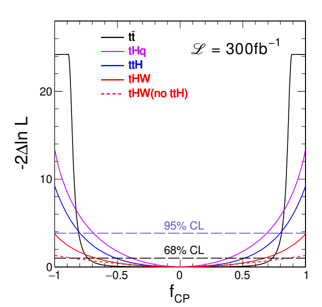


- Theoretical predictions with anomalous Htt coupling available [Demartin,Maltoni,Mawatari,Zaro'15], [Gritsan,Röntsch,Schulze,Xiao'16], [Kraus,TM,Peitzsch,Uwer'19] and implemented in the `JHU Generator` framework
- `JHU Generator` generates unweighted events which can be passed to PS+DetectorSim.
- `JHU Generator` website: `spin.pha.jhu.edu`

Exclusion limits







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

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

Conclusions

Probing New Physics through EW loops

- Calculation of EW correction to $pp \to t\bar{t}$
- NP included via SMEFT parametrisation of Ztt, Wtb, Htt couplings

Comparison to direct on-shell probes

- **Anomalous coupling of top to EW gauge bosons**
  - $t\bar{t}$ at $\mathcal{O}(\alpha\alpha_s^2)$ significantly more sensitive to NP than $t\bar{t}+Z$
  - Promising new way for EW studies in $t\bar{t}$ production at LHC
- **Anomalous top Yukawa coupling**
  - $t\bar{t}$ expected to exclude $|f_{CP}| > 0.81$ for 300 fb^{-1} and $|f_{CP}| > 0.67$ for 3 ab^{-1} at 95% CL
  - pure pseudo-scalar model excluded by tHW at 2σ for 300 fb^{-1} and $|f_{CP}| > 0.48$ for 3 ab^{-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 3 ab^{-1}
  - $t\bar{t}$ best probe to exclude purely CP-odd top Yukawa coupling

$t\bar{t}$ and respective on-shell processes with anomalous EW top couplings available as add-on to `MCFM` or via `TOPAZ` & `JHU Generator` respectively