CMS measurements of EFT parameters with top quarks.

Nicolas TONON on behalf of the CMS Collaboration

TOP2020

17th September 2020
INTRODUCTION

- No clear sign of new physics (BSM) at LHC so far…
  - … and future accelerators in coming decades will increase $\int L$, not $\sqrt{s}$

- Many BSM theories predict sizeable deviations of top quark’s couplings w.r.t. SM predictions

- Most of canonical top quark processes at LHC have reached precision era (systematics-limited)

Motivates ambitious top physics programme to reveal new physics indirectly through precision measurements
SM Effective Field Theory (SMEFT) framework allows for systematic & comprehensive interpretation of potential deviations in interactions between SM fields.

- Assume new physics is characterized by (unknown) energy scale $\Lambda \gg E_{\text{LHC}}$.
- Expand SM Lagrangian with higher-order operators.
- Model-independent → Can map experimental constraints to ~ any UV-complete model.
- Predicts well-defined deviation patterns, correlated in different observables/processes.

Famous EFT example: Fermi theory of beta decay ($W$ boson → 4-fermions interaction).

Well-motivated, global approach to maximize discovery potential of massive BSM states at (HL)LHC.
TOP EFT OPERATORS

- Outcomes from fruitful EXP/TH collaboration within LHCTopWG summarized in EFT note
  - Provides extremely useful guiding principles, discusses assumptions, etc. → Guideline for Top-EFT@LHC
  - Use convenient Warsaw basis (complete, minimal set of operators)

- Restrict analysis to leading dimension-6
  - # operators grows exponentially with mass dimension → $\mathcal{O}(60)$ non-redundant operators involving top quark!

- May further restrict huge param. space by making assumptions
  - Ex: Minimal Flavour Violation (MFV) hypothesis
    ↔ flavour/CP-violation only originates from SM-like Yukawa couplings
Outcomes from fruitful EXP/TH collaboration within LHCTopWG summarized in EFT note
➢ Provides extremely useful guiding principles, discusses assumptions, etc. → Guideline for Top-EFT@LHC
➢ Use convenient Warsaw basis (complete, minimal set of operators)

 Restrict analysis to leading dimension-6
➢ # operators grows exponentially with mass dimension → $\mathcal{O}(60)$ non-redundant operators involving top quark!

 May further restrict huge param. space by making assumptions

 Top quark operators enter in numerous final states
➢ Calls for global combinations of results

 Large ongoing effort by theorists to refine EFT predictions
{ Complete dim-8 operator basis [arXiv:2005.00008]
{ NLO simulation models
{ Study correlations/interferences, etc.

 Quadratic EFT parameterization:

$$\mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{EFT} = \mathcal{M}_{SM} + \sum_{i} c_i \cdot \mathcal{M}_i$$

$$\sigma \propto |\mathcal{M}|^2 \propto \sum_{i,j=0}^{N} S_{ij} \cdot C_i \cdot C_j$$
EFT APPROACHES IN CMS-TOP

- Good scalability
- Easily combinable in global fits beyond LHC
- Decouples experiment / theory
- Treat all backgrounds SM-like
- Many assumptions, overestimate uncertainties, missing all correlations, ...

Post-measurement interpretation

Direct measurement at detector-level

- Optimal sensitivity to Wilson coefficients
- Minimal assumptions
- Can probe EFT in all sensitive processes
- In-situ constraint of systematics considering correlations
- Novel approach, less experience with combination
Reinterpret inclusive measurement

- Wilson coeff. constrained using straightforward EFT parameterization
- Scalable & combinable
- No MC EFT sample required
- Maximal assumptions

Post-measurement interpretation

Direct measurement at detector-level
**4 TOPS**

- **Very rare process**, not yet observed
  - $\sigma(\text{SM}) = 9.2 \, \text{fb}$, $\mathcal{O}(10^5)$ smaller than $t \bar{t}$ background
- Target 1$\ell$ and 2$\ell$ OS final states with jets ($35.9 \, \text{fb}^{-1}$)
- BDTs to assign jets & isolate signal
- Results combined with same-sign 2$\ell$ + 3$\ell$ analysis
  - **Observed limit** = $3.6 \, \sigma(\text{SM})$ / **Observed significance** = 1.4 s.d
- **Highly sensitive to 4-heavy-quark operators**
- Parameterization derived at gen-level:
  \[
  \sigma_{t \bar{t}t \bar{t}} = \sigma_{t \bar{t}t \bar{t}}^{\text{SM}} + \frac{1}{\Lambda^2} \sum_k C_k \sigma_k^{(1)} + \frac{1}{\Lambda^4} \sum_{j,k} C_j C_k \sigma_{j,k}^{(2)}
  \]
- 95 % CL upper limits derived on individual operators, marginalizing other operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expected $C_k/\Lambda^2$ (TeV$^{-2}$)</th>
<th>Observed (TeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}_{t t}^1$</td>
<td>$[-2.0, 1.9]$</td>
<td>$[-2.2, 2.1]$</td>
</tr>
<tr>
<td>$\mathcal{O}_{QQ}^1$</td>
<td>$[-2.0, 1.9]$</td>
<td>$[-2.2, 2.0]$</td>
</tr>
<tr>
<td>$\mathcal{O}_{Qt}^1$</td>
<td>$[-3.4, 3.3]$</td>
<td>$[-3.7, 3.5]$</td>
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<tr>
<td>$\mathcal{O}_{Qt}^8$</td>
<td>$[-7.4, 6.3]$</td>
<td>$[-8.0, 6.8]$</td>
</tr>
</tbody>
</table>
EFT APPROACHES IN CMS-TOP

Reinterpret inclusive measurement

- Wilson coeff. constrained using straightforward EFT parameterization
- Scalable & combinable
- No MC EFT sample required
- Maximal assumptions

Post-measurement interpretation

Reinterpret unfolded differential measurement

- Quantity(ies) sensitive to EFT are measured at particle/parton-level
- Need differential MC EFT at gen-level
- Combinable if bin correlations are provided
- Ignore EFT effects on acceptance/efficiency

Direct measurement at detector-level
Unfolded differential $tt\to 2l$ final states

- $2\ell$ OS + b-jets final states
  - $(35.9 \text{ fb}^{-1})$

- Differential $tt\to 2l$ cross section measurement as a function of kinematics of top quark, decay products, $tt$, njets
  - Unfolded at parton- (full PS) & particle-level (fiducial PS)
  - Extract $tt$ and leptonic charge asymmetries

- Small top chromomagnetic dipole moment (CMDM) predicted by SM, modified in 2HDM/SUSY/technicolor/…
  - Related to $c_{tG}$ operator → Modifies yield, kinematics, spin structure

- EFT parameterized at gen-level at NLO QCD
  - Calculate $\Delta \Phi(\ell\ell) \leftrightarrow$ RIVET
  - LO → NLO : $+$ctG effect, $-$ scale uncert.
  - Assume SM-like acceptance, $k$-factors ($NLO \to NNLO+NNLL$), etc.
Unfolded diff.

**TT POLARIZATION & SPIN CORREL.**

- 2ℓ OS + b-jets final states (35.9 fb⁻¹)

- Differential $t\bar{t}$ cross section measurement as a function of polarization and spin correl. observables
  - Unfolded at parton-level, consistent with SM

Similar parameterization & assumptions as previous analysis

- 95% CL limit on $c_tG$ obtained from simultaneous $\chi^2$ fit to several differential spin distributions
  - Stat./syst. correlation matrices determined for all bins
  - Sensitivity improved by ~ 30 % w.r.t. previous analysis

→ See talk by M. Kareem

10.1103/PhysRevD.100.072002
EFT APPROACHES IN CMS-TOP

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**Hybrid measurement at detector-level**
- a) Parameterize yields with SMEFT at gen-level, translate to detector-level assuming SM shapes

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**Post-measurement interpretation**

**Reinterpret unfolded differential measurement**
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**Direct measurement at detector-level**

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DESY. | TOP2020 | Nicolas Tonon, September 17th 2020
- 2ℓ channel (35.9 fb⁻¹)

- Event categorized by:
  - lepton channel
  - jet/bjet multiplicities

- Train dedicated **neural networks** to:
  - Isolate the tW process (+ sensitivity)
  - Distinguish FCNC signatures from SM

- EFT contributions estimated at gen-level, and extrapolated to detector-level

- Extract individual limits from simultaneous fit to yields or NN distributions in all categories

- First step towards more global fits
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**Hybrid measurement at detector-level**
- a) Parameterize yields with SMEFT at gen-level, translate to detector-level assuming SM shapes
- b) Reweight distributions as SMEFT/SM at gen-level, translate to detector-level under SM assumption

**Post-measurement interpretation**

**Reinterpret unfolded differential measurement**
- Quantity(ies) sensitive to EFT are measured at particle/parton-level
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- Ignore EFT effects on acceptance/efficiency

**Direct measurement at detector-level**
- 3\ell + 4\ell channels (77.5 fb\(^{-1}\))
- Event categorized by:
  - # of leptons
  - jet/bjet multiplicities

**Procedure:**

a) **Produce gen-level samples** for SM & SMEFT (LO), in fine grid of EFT parameter space

b) **Calculate weights SMEFT/SM** in bins of both observables, before event selection

c) **Apply weights to detector-level** (NLO) SM sample to emulate EFT contributions + verify closure

- Inclusive and differential measurements of \(\sigma(\ttZ)\) found in good agreement with SM
- \(pt(Z)\) and \(\cos(\theta_Z^*)\) are sensitive to BSM
  - Almost uncorrelated
- Extract 1D/2D limits on 4 independent top-Z operators
- Anomalous coupling interpretation: most stringent direct constraints on EWK dipole moment & top-Z vector couplings
- ~20% improvement due to shape information
EFT APPROACHES IN CMS-TOP

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a) Parameterize yields with SMEFT at gen-level, translate to detector-level assuming SM shapes
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Direct EFT measurement
- ~ no SM assumption
- Consider EFT in all sensitive processes
  ➔ Need full SMEFT sample for each
- Simultaneous fit to multiple regions
Constraints on anomalous Higgs couplings to bosons & fermions in $H \rightarrow 4\ell$ events (137 fb$^{-1}$)

- Consider both production and decay
- Simultaneous measurement of up to 9 couplings ($5\ HVV + 2\ Hgg + 2\ Htt$)
  - Requires arbitrary assumptions about their relationships
- Results interpreted within EFT framework in terms of corresponding operators (Higgs basis)

Full detector simulation of all kinematic effects from BSM (event weights from JHUGen, LO & NLO)

Enhance analysis sensitivity using discriminants from Matrix Element Method (MELA package)

Constrain top-H coupling in ttH process

- Combination with $H \rightarrow \gamma\gamma$, assuming no BSM particles enter the loop
Direct Fit to Multiple T(T)X Processes

- Targets [ttll, ttlv, tllq, ttH, tHq] processes at once in the [2l SS, 3l, 4l + bjets] channels (41.5 fb⁻¹)

- Full detector simulation of SMEFT samples
  - Per-event weights parameterized on all relevant WCs

- Categories based on lepton, jet and bjet multiplicities
  → Enhance sensitivity in different processes / operators

- Constrain 16 relevant EFT operators
  - For each WC, either profile the others or set them to 0

Important step towards direct measurements accounting for EFT in all sensitive processes
Top physics @ LHC has entered **precision differential era** for good
- EFT measurements represent a key part of future physics programme & LHC legacy

CMS Top-EFT group is building upon its expertise to **continuously improve its strategies**
- Already numerous publications employing **different approaches** with pros/cons

Discussion with community and theorists is key!
- **Guidelines** from theorists within LHCTopWG well received by the collaborations
  - CMS has taken its first step towards global analysis
  - Floor is open for **further exchanges of ideas** in view of future developments

Exciting developments and innovative analyses are forthcoming!
BACKUP
CMS TOP EFT SUMMARY PLOTS

September 2020

CMS Preliminary
EFT from top quark production $\sqrt{s} = 13$ TeV

Four-fermion operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Marginalized</th>
<th>Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{T}$</td>
<td>$\times 0.1$</td>
<td></td>
</tr>
<tr>
<td>$C_{S}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{I}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{W}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{Z}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{Q}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

95% CL limit [TeV$^2$]

September 2020

CMS Preliminary
EFT from top quark production $\sqrt{s} = 13$ TeV

(Top) quark - vector boson operators

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<tr>
<td>$C_{Z}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{Q}$</td>
<td></td>
<td></td>
</tr>
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</table>

95% CL limit [TeV$^2$]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures
Within restricted scenario (→ LHCTopWG note), assuming BSM physics couples predominantly to LH doublet and RH up-type quark singlet of 3rd generation, only 4 top operators are expected to contribute:

\[
\begin{align*}
\mathcal{O}_{tt}^1 &= (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R), \\
\mathcal{O}_{QQ}^1 &= (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma_\mu Q_L), \\
\mathcal{O}_{Qt}^1 &= (\bar{Q}_L \gamma^\mu Q_L)(\bar{t}_R \gamma_\mu t_R), \\
\mathcal{O}_{Qt}^8 &= (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{t}_R \gamma_\mu T^A t_R),
\end{align*}
\]

\[Q_L \leftrightarrow \text{left-handed 3rd generation quark doublet}\]

\[t_R \leftrightarrow \text{top quark singlet}\]

SM kinematics assumed, only rate information used to set constraints

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected limit ( \times \sigma_{\text{HT}}^{\text{SM}} )</th>
<th>Observed limit ( \times \sigma_{\text{HT}}^{\text{SM}} )</th>
<th>Expected limit (fb)</th>
<th>Observed limit (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton</td>
<td>9.4^{+4.4}_{-2.9}</td>
<td>10.6</td>
<td>86^{+40}_{-25}</td>
<td>97</td>
</tr>
<tr>
<td>Dilepton</td>
<td>7.3^{+4.5}_{-2.5}</td>
<td>6.9</td>
<td>67^{+41}_{-23}</td>
<td>64</td>
</tr>
<tr>
<td>Combined (this analysis)</td>
<td>5.7^{+2.9}_{-1.8}</td>
<td>5.2</td>
<td>52^{+26}_{-17}</td>
<td>48</td>
</tr>
<tr>
<td>Multilepton [25]</td>
<td>2.5^{+1.4}_{-0.8}</td>
<td>4.6</td>
<td>23^{+12}_{-8}</td>
<td>42</td>
</tr>
<tr>
<td>Combined (this analysis + multilepton)</td>
<td>2.2^{+1.1}_{-0.7}</td>
<td>3.6</td>
<td>20^{+10}_{-6}</td>
<td>33</td>
</tr>
</tbody>
</table>

**Parameterization coefficients:**

\[
\begin{array}{c|c|c|c|c|c}
\text{Operator} & \sigma_k^{(1)} & \mathcal{O}_{tt}^1 & \mathcal{O}_{QQ}^1 & \mathcal{O}_{Qt}^1 & \mathcal{O}_{Qt}^8 \\
\hline
\mathcal{O}_{tt}^1 & 0.39 & 5.59 & 0.36 & -0.39 & 0.3 \\
\mathcal{O}_{QQ}^1 & 0.47 & 5.49 & -0.45 & 0.13 & \\
\mathcal{O}_{Qt}^1 & 0.03 & 1.9 & -0.08 & \\
\mathcal{O}_{Qt}^8 & 0.28 & 0.45 & \\
\end{array}
\]

*Table 4.* Linear (left) and quadratic (right) parameterization coefficients, \( \sigma_k^{(1)} \) and \( \sigma_k^{(2)} \), of eq. (6.3). The coefficients \( \sigma_k^{(1)} \) are in units (fb TeV^2), while the coefficients \( \sigma_k^{(2)} \) are in units (fb TeV^4).
- 15 coefficients completely characterize the spin dependence of $t\bar{t}$ production
  - Probed by measuring 22 normalized angular distributions, unfolded at parton-level
- Imaginary part of $c_G$ (top CEDM) assumed to be 0
- RIVET framework used to apply object definitions and calculate spin density matrix observables
- 4 independent observables chosen to constrain $c_G$

Data strongly favor spin-correlated (SM) scenario

Systematic correlation matrix for all measured bins of the norm. differential xsecs.
- 6 WCs probed separately (in production, not decay)
- tW interferes with tt at NLO QCD
  - tW sample simulated with DR,
    difference with DS taken as systematic
- 4-fermion / CP-odd / … operators not considered
- NLO EFT parameterization (except for unavailable CtG)

\[
O^{(3)}_{\phi q} = (\phi^+ \tau^i D_\mu \phi)(\bar{q} \gamma^\mu \tau^i q)
\]
\[
O_{tW} = (\bar{q} \sigma^{\mu\nu} \tau^i t) \tilde{\phi} W^i_{\mu\nu},
\]
\[
O_{tG} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \tilde{\phi} G^a_{\mu\nu},
\]
\[
O_G = f_{abc} G^a_\mu G^b_\nu G^c_\rho
\]
\[
O_{u(c)G} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \tilde{\phi} G^a_{\mu\nu},
\]

Modify Wtb

CMDM

Triple-gluon field strength

FCNC

<table>
<thead>
<tr>
<th>Eff. coupling</th>
<th>Channel</th>
<th>1-jet, 0-tag</th>
<th>1-jet, 1-tag</th>
<th>2-jets, 1-tag</th>
<th>&gt;2-jets, 1-tag</th>
<th>&gt;2-jets, 2-tags</th>
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<tr>
<td>C_G</td>
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<td>—</td>
<td>Yield</td>
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<td>Yield</td>
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<td>e\mu</td>
<td>—</td>
<td>Yield</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>\mu\mu</td>
<td>—</td>
<td>Yield</td>
<td>Yield</td>
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<tr>
<td>C^{(3)}<em>{\phi q}, C</em>{tW}, C_{tG}</td>
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<td>NN_{10}</td>
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<td>NN_{21}</td>
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<td>C_{uG}, C_{cG}</td>
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<td>—</td>
<td>NN_{FCNC}</td>
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<td></td>
<td>\mu\mu</td>
<td>—</td>
<td>—</td>
<td>NN_{FCNC}</td>
<td>—</td>
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</table>
Probes operators defined as linear combinations of Warsaw basis operators:

- **Region definitions:**

<table>
<thead>
<tr>
<th>$N_1$</th>
<th>$N_2$</th>
<th>$p_T(Z)$ (GeV)</th>
<th>$-1 \leq \cos \theta_Z &lt; 0$</th>
<th>$-0.6 \leq \cos \theta_Z &lt; 0.6$</th>
<th>$0.6 \leq \cos \theta_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$\geq 1$</td>
<td>$\geq 3$</td>
<td>1</td>
<td>0–100</td>
<td>SR1</td>
</tr>
<tr>
<td>4</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>1</td>
<td>100–200</td>
<td>SR7</td>
</tr>
<tr>
<td></td>
<td>$\geq 1$</td>
<td>$\geq 0$</td>
<td>2</td>
<td>$\geq 200$</td>
<td>SR10</td>
</tr>
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</table>

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<th>$N_1$</th>
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<th>$p_T(Z)$ (GeV)</th>
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<th>$0.6 \leq \cos \theta_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0</td>
<td>$\geq 1$</td>
<td>1</td>
<td>0–100</td>
<td>CR1</td>
</tr>
<tr>
<td>5</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>1</td>
<td>100–200</td>
<td>CR4</td>
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<td>$\geq 2$</td>
<td>2</td>
<td>$\geq 400$</td>
<td>CR7</td>
</tr>
</tbody>
</table>

Table 5. Definition of the signal regions (SRs) and control regions (CRs). For signal regions SR13, SR14, and SR15 and control regions CR13, CR14, and CR15, there is no requirement on $\cos \theta_Z$.

**HL-LHC projection**

**Measurement (2016+2017 data)**

$$c_{tZ} = \text{Re} \left( -\sin \theta_W C_{uB}^{(33)} + \cos \theta_W C_{uW}^{(33)} \right)$$

$$c_{tZ}^{[\ell]} = \text{Im} \left( -\sin \theta_W C_{uB}^{(33)} + \cos \theta_W C_{uW}^{(33)} \right)$$

$$c_{\phi t} = C_{\phi t} = C_{\phi u}^{(33)}$$

$$c_{\phi Q} = C_{\phi Q}^{(33)} = C_{\phi u}^{(13)} - C_{\phi Q}^{(33)}$$
Follow same formalism used in other Run-1 and Run-2 Higgs AC studies

Results presented in model-independent way → Possible EFT or PO re-interpretation

Observables designed with MEM (MELA FW)
  - Optimal sensitivity, exploiting both production and decay kinematics
  - Requires full set of observables describing LO kinematics for ggH, VBF, VH, ttH topologies

Anomalous H-fermion couplings (e.g. in ttH or bbH) parameterized as:

\[ A(H_{ff}) = -\frac{m_t}{v} \bar{\psi}_t (\kappa_f + i \tilde{\kappa}_f \gamma_5) \psi_f \]

- CP-even and CP-odd parts \( \kappa_f \) and \( \tilde{\kappa}_f \) (1 and 0 in SM) can be treated as EFT parameters

- Effective fractional xsec for Hff coupling:
  \[ f_{CP}^{H_{ff}} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} \text{sign} \left( \frac{\tilde{\kappa}_f}{\kappa_f} \right) \]

Define 2 categorization schemes to enhance sensitivity to specific couplings
  - Target either Htt/Hgg or HVV couplings