Rare and new top quark interactions in CMS

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On behalf of the CMS Collaboration

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Top-quark production can be used to look for **New Physics**:

- Effective Field Theory frameworks (EFT)
- Searches for Flavour Changing Neutral currents
- CP-violation
- ...

**Introduction**

September 2019

CMS Preliminary

7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 137 fb⁻¹)
Theory prediction

CMS 95%CL limits at 7, 8 and 13 TeV

All results at: http://cern.ch/go/pNj7
Introduction: EFT

- No clear sign of New Physics @LHC from direct searches
- Allows to search for BSM effects in a model independent way, using precision measurements
- SM Effective Field Theory (SMEFT) parametrize the effect of physics up to an energy scale ($\Lambda$).
- The Lagrangian can be expressed as an expansion in higher dimensional (d) operators ($\mathcal{O}$) consisting on SM fields

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_{i}^d$$

Suppressed by $1/\Lambda$, computation up to dim 6
Introduction: EFT

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} Q_i^d \]

 Wilson coefficients

- 59 non-redundant dim-6 operators
- Depending on CP/flavour assumptions

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} Q_i^d \]

Suppressed by 1/\(\Lambda\), computation up to dim 6

\[ \Box \]

CERN-LPCC-2018-01

<table>
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<th>(Q_{ij}^{(LL)})</th>
<th>(Q_{ij}^{(RR)})</th>
<th>(Q_{ij}^{(LR)})</th>
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</tr>
</tbody>
</table>

Suppressed by 1/\(\Lambda\), computation up to dim 6

| Table 3: Four-fermion operators. |

\[ \Box \]

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} Q_i^d \]

Suppressed by 1/\(\Lambda\), computation up to dim 6

| Table 2: Dimension-six operators other than the four-fermion ones. |
Baseline Selection (Inclusive Measurement):
- 3 or 4 leptons
- $N_{\text{Jet}} > 0$

**EFT interpretation:**
- SMEFT in the Warsaw basis is used
- 4 relevant coefficients used for the parametrization: $C_{tZ}, C_{tZ}^{[l]}, C_{\phi t}, C_{\phi Q}$
- Expressed using Warsaw basis:

$$
\begin{align*}
 c_{tZ} &= \text{Re} \left( -\sin \theta_W C_{uB}^{(33)} + \cos \theta_W C_{uW}^{(33)} \right) \\
 c_{tZ}^{[l]} &= \text{Im} \left( -\sin \theta_W C_{uB}^{(33)} + \cos \theta_W C_{uW}^{(33)} \right) \\
 c_{\phi t} &= C_{\phi t} = C_{\phi u}^{(33)} \\
 c_{\phi Q} &= C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)}
\end{align*}
$$

$\theta_W$ : weak mixing angle
To assume Wtb vertex to be the SM one $\rightarrow [\ ] = 0$
Classification to enhance sensitivity:

Events are further classified in bins of $p_T(Z)$ and bins of $\cos(\theta^*_Z)$ (cosine of the angle between the negative charged lepton and the Z candidate in the Z rest frame.)

Procedure:

- gen-level samples for SM and SMEFT (LO) produced with grid in the parameter space
- Weight SMEFT/SM applied to detector-level SM sample
- Simultaneous fit using all $N_{\text{Lep}}$ categories split in $N_{\text{Jet}}, N_{\text{B-tag}}, p_T(Z), \cos(\theta^*_Z)$
Results:

- Most stringent direct constraints on top quark EW dipole moments and top-Z vector couplings
- Good agreement with SM
Baseline Selection: 2ℓOS and single lepton final states

Strategy:
BDT used to identify hadronic top decays. A second BDT is used to discriminate tttt from tt. This takes as input the first BDT, event topology, event activity, N_{B-tag}

EFT Interpretation:
- Sensitive to 4-fermion interactions
- SMEFT in the Warsaw basis is used
- Four operators relevant at LO production

Very low cross section process \(\sigma(\text{NLO}) \approx 9 \text{ fb}\) (not yet observed)
**Procedure:**

- Cross section is parametrized at LO in terms of WC
  \[ \sigma_{t\bar{t}t\bar{t}} = \sigma_{t\bar{t}t\bar{t}}^{\text{SM}} + \frac{1}{\Lambda^2} \sum_k C_k \sigma_k^{(1)} + \frac{1}{\Lambda^4} \sum_{j \leq k} C_j C_k \sigma_{j,k}^{(2)}, \]
- Simulation of EFT effects implemented using FeynRules and MadGraph_aMC@NLO
- In the limit setting kinematics of $t\bar{t}t\bar{t}$ assumed to be the SM one.

**Results:**

- Limits are set on $C_k/\Lambda$ using the rate from the combination with **EPJC 78 (2018) 140**
- Marginalized constraints are set at 95% CL
- Improved constraints with respect to previous measurement **Chin. Phys. C42 (2018) 023104**
Targeting $t\bar{t}H$, $tH$, $t\bar{t}ll$, $t\bar{t}lv$, $t\bar{t}lq$

**Baseline Selection:**
- MVA to select prompt leptons
- 2 same sign, 3 and 4 leptons categories
- Jet and b-tag multiplicity, charge OSSF mass used to categorize
- **35 signal regions**

**Strategy:**
Signal samples modelled at LO including EFT

Using detector-level observables

Yields are parametrized as function of WC

**2017 data**

Event weights parametrized as function of WC
t(\bar{t}) + leptons

Operators:
- Dim-6 in the Warsaw basis
- Operators involved in interaction with at least one top
- 16 Operators used:

Operators involving two quarks and one or more bosons

<table>
<thead>
<tr>
<th>Operator</th>
<th>Definition</th>
<th>WC</th>
<th>Lead processes affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O^{(ij)}_{u\nu}$</td>
<td>$\bar{u}_i u_j \varphi^T (\varphi^T \varphi)$</td>
<td>$c_{ij} + i c_{ij}$</td>
<td>$t\bar{t}H, tHq$</td>
</tr>
<tr>
<td>$O^{(ij)}_{e\nu}$</td>
<td>$(\varphi^T \bar{D}_{\mu \nu}^s)(\bar{q}_i \gamma^\mu q_j)$</td>
<td>$c_{ij} + i c_{ij}$</td>
<td>$t\bar{t}H, t\bar{t}v, t\bar{t}l, tHq, tllq$</td>
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</tr>
<tr>
<td>$O^{(ij)}_{u\nu W}$</td>
<td>$(\bar{u}<em>i \sigma^{\mu \nu} T^A u_j) \varphi W^\mu</em>{\mu}$</td>
<td>$c_{ij} + i c_{ij}$</td>
<td>$t\bar{t}H, t\bar{t}v, t\bar{t}l, tllq$</td>
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<td>$O^{(ij)}_{d\nu W}$</td>
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<td>$O^{(ij)}_{u\nu B}$</td>
<td>$(\bar{u}<em>i \sigma^{\mu \nu} T^A u_j) \varphi B</em>{\mu \nu}$</td>
<td>$(c_{ij}c_{ij} - c_{ij})/s_{W} + i(c_{ij}c_{ij} - c_{ij})/s_{W}$</td>
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Operators involving two quarks and two leptons

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<td>$O^{(ij)}_{e\nu q}$</td>
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</tr>
</tbody>
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Results:

- Simultaneous fit to the 16 WC and nuisance parameters using all 35 SR
- Post fit plot: increase in $tHq$ is due to the low sensitivity to this process added to the fact that it receives large enhancements from the EFT operators considered
t(\bar{t}) + leptons

Results:
- Simultaneous fit to the 16 WC and nuisance parameters using all 35 SR
- One dim CL for all considered WC
- 2-d CL with other WC treated as unconstrained
- Results in agreement with SM
Baseline Selection:
- Two leptons OS
- At least 1 jet
- Categorization in flavour, jet and b-tag multiplicity

Operators Involved:
\[ O^{(3)}_{\phi q} = (\phi^+ \tau^i D_\mu \phi)(\bar{q} \gamma^\mu \tau^i q) \]
\[ O_{tW} = (\bar{q} \sigma^{\mu\nu} \tau^i \bar{t}) \tilde{W}^i_{\mu\nu} \]
\[ O_{tG} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \tilde{G}^a_{\mu\nu} \]
\[ O_{G} = f_{abc} G^a_{\mu} G^b_{\nu} G^c_{\rho} \]
\[ O_{u(c)G} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \tilde{G}^a_{\mu\nu} \]
Discriminant variable
Total Yield to constrain $C_G$
Dedicated Neural Networks to

a) Separate tW vs. $\bar{t}t$ → used in tW sensitive categories 

b) Spilt FCNC from SM bkg → used to constrain $C_{uG}, C_{cG}$ in 2 jets,1 tag categories
**Results**

NN outputs in each category or Yields (if no NN needed) used to perform a Likelihood fit
Each parameter is fit at a time

First time $t\bar{t}$ and $tW$ used in this kind of search
Top polarization and $t\bar{t}$ spin correlations

BSM predictions modify top chromomagnetic and chromoelectric dipole moment (CEDM and CMDM)

**2016 data**

**Baseline Selection:**
- Two leptons OS
- At least 2 jets (at least 1 b-tag)

**Strategy:**
Kinematic reconstruction of $t\bar{t}$ system
- All combinations of lep. and jets
- Constrains: $m_W$, MET from neutrinos, $m_{top}$
- Four momentum reconstructed
Allows to use reconstruct angular observables

Unfolding to parton level to measure diff. cross-section using 22 observables
Top polarization and $t\bar{t}$ spin correlations

This measurement of the spin correlations is sensitive to 11 dim-6 operators. Limits are set on this operators by using simultaneous fits to measured norm. diff. x-sections.

**Constrain CMDM**

The operator responsible for anomalous CMDM is:

$$O_{\text{tg}} = y_t g_s (\bar{Q} \sigma^\mu_{\nu} T^a \phi G^a_{\mu\nu}).$$

**Constraints on Anomalous couplings**

Limits on each coupling setting the others to 0:

CEDM: $-0.33 < C_{1G}/\Lambda^2 < 0.20 \text{ TeV}^{-2}$
CP violating top coupling

Top interaction with chromo electric dipole moment (CEDM) is a potential source of CP violation

$$\mathcal{L} = \frac{g_S}{2} T^a \sigma^{\mu \nu} (d_t^a) + i \gamma_5 (d_t^a) t G^{\mu \nu}$$

2016 data

Baseline Selection:
- Two leptons OS
- At least 2 Jets
- At least 1 b-tag

Strategy:
Kinematic reconstruction of $t\bar{t}$ system
- All combinations of lep. and Jets
- Constrains: $m_W$, MET from neutrions, $m_{top}$
- Four momentum reconstructed

Observables: Levi-civita of leptons, reconstructed (anti-)top ($\phi_1$) and (anti-)b jets ($\phi_3$)
$\mathcal{O}_i$ are odd under CP transformations:

$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}.$$ 

The asymmetry (A) and the cross-section are simultaneously extracted from the fit.

This allows to measure the CEDM, in agreement with SM.
• LHC is now capable of measuring **rare SM processes with top quarks**.

• EFT measurements are key in the search for new physics @LHC.

• Precision measurements are needed for these BSM searches.

• Most of the analyses are not using the full Run 2 data yet.

• **Many new analysis coming, so stay tuned!**


**Thank You!**
Back up
**t\bar{t}Z - EFT Interpretation**

- Regions defined using $p_T(Z)$ and $\cos(\theta^*_Z)$

![Graph showing data and regions](image)

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<th>$N_b$</th>
<th>$N_J$</th>
<th>$N_Z$</th>
<th>$p_T(Z)$ (GeV)</th>
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<th>$-0.6 \leq \cos(\theta^*_Z) &lt; 0.6$</th>
<th>$0.6 \leq \cos(\theta^*_Z)$</th>
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<td>SR2</td>
<td>SR3</td>
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<td>SR4</td>
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<th>Coefficient</th>
<th>Expected 68% CL</th>
<th>95% CL</th>
<th>Observed 68% CL</th>
<th>95% CL</th>
<th>Previous CMS constraints</th>
<th>Indirect constraints 68% CL</th>
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<td>[−2.0, 2.0]</td>
<td>[−2.6, 2.6]</td>
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<td>[−1.1, 1.1]</td>
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<td>$c_{q}/\Lambda^2$</td>
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<td>[−3.4, 2.8]</td>
<td>[1.7, 4.2]</td>
<td>[0.3, 5.4]</td>
<td>[−20.2, 4.0]</td>
<td>[−3.2, −6.0]</td>
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<td>[−3.0, −1.0]</td>
<td>[−4.0, 0.0]</td>
<td></td>
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2016 data
Baseline Selection:

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<tr>
<td>ee</td>
</tr>
<tr>
<td>m_{ℓℓ}</td>
</tr>
<tr>
<td>N_{jet}</td>
</tr>
<tr>
<td>N_{B-tag}</td>
</tr>
</tbody>
</table>

Strategy:
BDT used to identify hadronic top decays. A second BDT is used to discriminate tttt from tt. This takes as input the first BDT, event topology, event activity, N_{B-tag}

Combination with EPJC 78 (2018) 140 (2016 multilepton):

σ = 13^{+11}_{-9} fb

Observed (expected) significance = 1.4 (1.1)
Baseline Selection:

- 2 same sign, 3 and 4 leptons categories
- Jet and b-tag multiplicity used to categorize
- 35 signal regions
**Discriminant variable**

Total Yield to constrain $C_G$

Dedicated Neural Networks to

a) Separate tW vs. $t\bar{t}$ → used in tW sensitive categories

b) Spilt FCNC from SM bkg → used to constrain $C_{uG}, C_{cG}$ in 2 jets, 1 tag categories

### Table 3

Summary of the observables used to probe the effective couplings in various ($n$-jets,$m$-tags) categories in the ee, $e\mu$, and $\mu\mu$ channels

<table>
<thead>
<tr>
<th>Eff. coupling</th>
<th>Channel</th>
<th>Categories</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>
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<td>$C_G$</td>
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<td>--</td>
<td>Yield</td>
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<tr>
<td></td>
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<td>Yield</td>
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<td>Yield</td>
<td>Yield</td>
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<td>$C^{(3)}<em>{q\phi}, C</em>{tW}, C_{tG}$</td>
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<td>--</td>
<td>NN_{11}</td>
<td>NN_{21}</td>
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<td>NN_{10}</td>
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<td>$\mu\mu$</td>
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<td>NN_{11}</td>
<td>NN_{21}</td>
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<tr>
<td>$C_{uG}, C_{cG}$</td>
<td>ee</td>
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<td>NN_{FCNC}</td>
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Discriminant variable

Total Yield to constrain $C_G$

Dedicated Neural Networks to

a) Separate $tW$ vs. $t\bar{t}$ → used in $tW$ sensitive categories

b) Spilt FCNC from SM bkg → used to constrain $C_{uG}$, $C_{cG}$ in 2 jets, 1 tag categories

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$C_G$ (%)</th>
<th>$C_{\phi q}^{(3)}$ (%)</th>
<th>$C_{tW}$ (%)</th>
<th>$C_{tG}$ (%)</th>
<th>$C_{uG}$ (%)</th>
<th>$C_{cG}$ (%)</th>
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<tbody>
<tr>
<td>Trigger</td>
<td>10.2</td>
<td>2.3</td>
<td>7.0</td>
<td>2.9</td>
<td>1.7</td>
<td>2.5</td>
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<td>Lepton ident./isolation</td>
<td>7.4</td>
<td>1.1</td>
<td>1.2</td>
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<td>&lt;1</td>
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<td>4.9</td>
<td>$&lt;1$</td>
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<td>$tW$ DS/DR</td>
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<td>4.4</td>
<td>3.0</td>
<td>7.6</td>
<td>7.8</td>
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<tr>
<td>ME/PS matching</td>
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<td>9.9</td>
<td>1.2</td>
<td>$&lt;1$</td>
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<td>FSR scale</td>
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<td>4.0</td>
<td>10.2</td>
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<td>DY background</td>
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<td>Nonprompt background</td>
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<td>5.8</td>
<td>$&lt;1$</td>
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<td>$&lt;1$</td>
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<td>1.1</td>
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<td>Statistical</td>
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<td>72.6</td>
<td>73.6</td>
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<td>5.2</td>
<td>2.9</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Constrain on Anomalous couplings

Limits on each coupling setting the others to 0:

\[
\begin{array}{cccc}
\text{Coupling} & \text{Operator type} & \text{Symmetry properties} \\
\tilde{\mu}_t & 2 \text{ quarks plus gluon(s)} & P\text{-even, CP-even} \\
\tilde{d}_t & 2 \text{ quarks plus gluon(s)} & P\text{-odd, CP-odd} \\
\tilde{c}_- & 2 \text{ quarks plus gluon(s)} & P\text{-odd, CP-even} \\
\tilde{c}_+ & 2 \text{ quarks plus gluon(s)} & P\text{-even, CP-odd} \\
\tilde{c}_{VV} & 4 \text{ quarks (weak isospin 0)} & P\text{-even, CP-even} \\
\tilde{c}_{VA} & 4 \text{ quarks (weak isospin 0)} & P\text{-odd, CP-even} \\
\tilde{c}_{AV} & 4 \text{ quarks (weak isospin 0)} & P\text{-even, CP-odd} \\
\tilde{c}_{AA} & 4 \text{ quarks (weak isospin 0)} & P\text{-odd, CP-odd} \\
\tilde{c}_1 & 4 \text{ quarks (weak isospin 1)} & \text{CP-even} \\
\tilde{c}_2 & 4 \text{ quarks (weak isospin 1)} & \text{CP-even} \\
\tilde{c}_3 & 4 \text{ quarks (weak isospin 1)} & \text{CP-even} \\
\end{array}
\]

95% C.L. \[ \begin{align*}
\hat{\mu}_t & \lesssim 0.014 < \hat{\mu}_t < 0.004 \\
\hat{d}_t & \lesssim 0.020 < \hat{d}_t < 0.012 \\
\hat{c}_- & \lesssim 0.040 < \hat{c}_- < 0.006 \\
\hat{c}_+ & \lesssim 0.009 < \hat{c}_+ < 0.005 \\
\hat{c}_{VV} & \lesssim 0.011 < \hat{c}_{VV} < 0.042 \\
\hat{c}_{VA} & \lesssim 0.044 < \hat{c}_{VA} < 0.027 \\
\hat{c}_{AV} & \lesssim 0.035 < \hat{c}_{AV} < 0.032 \\
\hat{c}_1 & \lesssim 0.09 < \hat{c}_1 < 0.34 \\
\hat{c}_3 & \lesssim 0.35 < \hat{c}_3 < 0.21 \\
\hat{c}_1 - \hat{c}_2 + \hat{c}_3 & \lesssim 0.17 < \hat{c}_1 - \hat{c}_2 + \hat{c}_3 < 0.15
\end{align*} \]

Theoretical unc. \[ \frac{\hat{C}_i}{\text{coefficients}} \]

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\mu}_t$</td>
<td>$C_{kk}, C_{nn}, C_{rk} + C_{kr}, D$</td>
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<tr>
<td>$\tilde{d}_t$</td>
<td>$B_2^* + B_2^{<strong>}, B_1^*, B_1^{</strong>}, C_{nr} - C_{rn}$</td>
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<tr>
<td>$\tilde{c}_-$</td>
<td>$B_2^* + B_2^{**}, C_{nr} - C_{rn}, C_{nb} - C_{bn}$</td>
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<tr>
<td>$\tilde{c}_+$</td>
<td>$B_2^* + B_2^{**}, C_{nr} - C_{rn}$</td>
</tr>
<tr>
<td>$\tilde{c}_{VV}$</td>
<td>$B_2^<em>, B_2^{**}, B_1^</em>, C_{nk} + C_{kn}$</td>
</tr>
<tr>
<td>$\tilde{c}_{VA}$</td>
<td>$C_{kk}, C_{nn}, C_{rk} + C_{kr}, D$</td>
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<tr>
<td>$\tilde{c}_{AV}$</td>
<td>$B_2^<em>, B_2^{**}, B_1^</em>, B_1^{**}, B_2^*$</td>
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<tr>
<td>$\tilde{c}_{AA}$</td>
<td>$B_2^*, B_2^{**}, C_{kk}, C_{nr} + C_{rn}$</td>
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<td>$\tilde{c}_1$</td>
<td>$C_{kk}, C_{nn}, C_{rk} + C_{kr}, D$</td>
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<tr>
<td>$\tilde{c}_2$</td>
<td>$B_2^*, B_2^{**}, C_{kk}, C_{nr} + C_{rn}$</td>
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<tr>
<td>$\tilde{c}_3$</td>
<td>$B_2^<em>, B_2^{**}, B_1^</em>, B_1^{**}, B_2^*$</td>
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