

# Complete study of four top quark production at the LHC in the SMEFT

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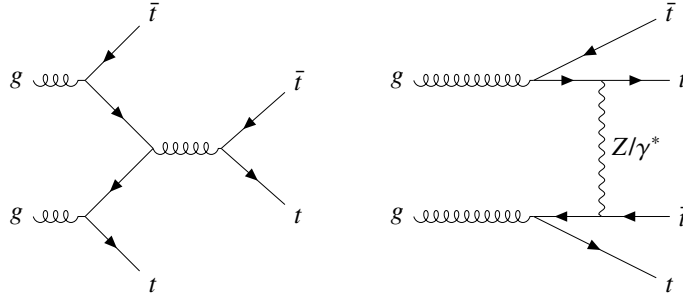
We present a study of four top quark production at the LHC in the Standard Model Effective Field Theory (SMEFT). The analysis is performed at the tree-level, including all terms from the mixed QCD-EW-coupling cross-section expansion and all the relevant dimension-six SMEFT operators. We find several cases in which formally subleading terms give rise to significant contributions. Moreover, we obtain limits on the SMEFT Wilson coefficients (WCs), including different collider setups, FCC-hh and HL-LHC, using a simplified chi-square fit. Through the latter, we also assessed the importance of including differential information in the fit.

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## 1. Introduction

The four top quark production at the LHC is characterised by a tiny SM cross-section at 13 TeV of about 12 fb. Despite this,  $t\bar{t}t\bar{t}$  signatures are distinctive, leading to an affluent and energetic final state rendering four top signatures a remarkable opportunity for probing new physics.

The complete NLO predictions, including all possible QCD and electroweak (EW) orders, have been calculated in Ref. [1]. The latter's results show a peculiar and unforeseen interplay between EW and QCD contributions, with significant contributions arising from formally subleading terms. In the SM, representative diagrams of purely QCD-induced four-top production and through the inclusion of EW vertices are shown in fig. 1. QCD-induced diagrams typically provide the leading contribution. However, Ref. [1] shows that in the SM at  $\sqrt{s} = 13$  TeV, the contributions arising from



**Figure 1:** Representative diagrams of four top production at  $\mathcal{O}(\alpha_s^2)$  (left) and at  $\mathcal{O}(\alpha_s\alpha_w)$  (right), at the LHC.

the non-purely-QCD diagrams are significant, reaching more than a third of the leading tree-level QCD contributions. Such a peculiar cross-section behaviour motivates a detailed study of new physics effects, particularly in the SMEFT framework.

## 2. Four-fermion operators and cross-section expansion

This work considers all possible contributions from the SM and SMEFT, including all dimension-six operators of the latter [2]. We follow the notation and operator conventions of Refs. [3, 4] and consider all possible dimension-six SMEFT operators contributing to four top quark production. However, in this note, we mainly focus on the 4-heavy four-fermion operators (we refer the interested reader to Ref. [2] for the detailed study):

$$\{O_{QQ}^1, O_{QQ}^8, O_{tt}^1, O_{Qt}^1, O_{Qt}^8\}. \quad (1)$$

The decomposition of the partonic differential cross-section up to  $\mathcal{O}(\Lambda^{-4})$  in SMEFT reads

$$d\sigma = d\sigma_{\text{SM}} + \frac{1}{\Lambda^2} d\sigma_{\text{int}} + \frac{1}{\Lambda^4} (d\sigma_{\text{quad}} + d\sigma_{\text{dbl}} + d\sigma_{\text{d8}}), \quad (2)$$

where the leading SMEFT contribution,  $d\sigma_{\text{int}}$ , is the linear interference between the SM amplitudes and ones with a single insertion of a dimension-six operator. The  $d\sigma_{\text{quad}}$  and  $d\sigma_{\text{dbl}}$  are the squared single-insertion and double-insertion contributions, respectively. The interference cross-section

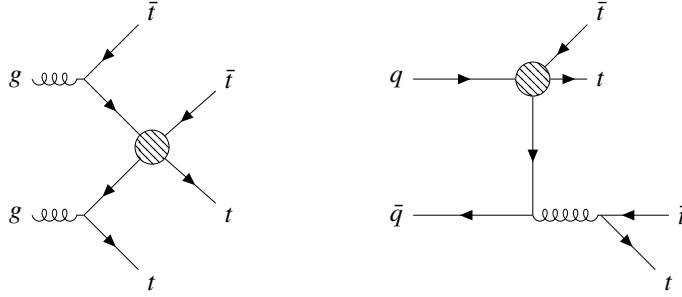
expansion for the  $gg$ -initiated four top quark production in the presence of four-fermion SMEFT operators can therefore be written as follows:

$$d\sigma_{\text{int},gg,[4F]} = \alpha_s^3 d\sigma_{\text{int},gg}^{(3,0,0)} + \alpha_s^2 \left( \alpha d\sigma_{\text{int},gg}^{(2,1,0)} + \alpha_t d\sigma_{\text{int},gg}^{(2,0,1)} \right), \quad (3)$$

with  $\alpha_s$ ,  $\alpha$  and  $\alpha_t$  denoting the strong, gauge and top-Yukawa couplings, respectively.

### 3. Inclusive predictions

This section presents the complete LO SMEFT inclusive predictions for  $t\bar{t}t\bar{t}$  production at  $\sqrt{s} = 13$  TeV at the LHC. Predictions are shown for the 4-heavy four-fermion operators, ones connecting four heavy quark lines, as displayed in the *left* diagram of fig. 2 where the shaded blob depicts the SMEFT insertion. For more results on the 2-heavy 2-light four-fermion operators (depicted in the *right* diagram of fig. 2), as well as the two-fermion and purely bosonic operators, we remind the reader to consult Ref. [2], where also the differential predictions are presented.

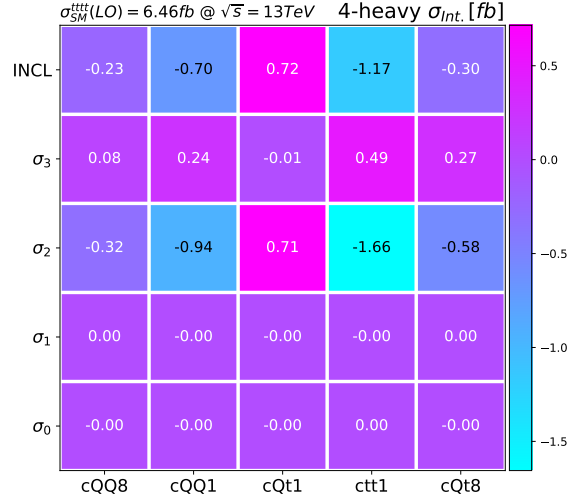


**Figure 2:** Representative diagrams of four top quark production with blobs representing the one dimension-six EFT insertion, in the  $gg$ -initiated production mode (*left*) and in the  $q\bar{q}$ -initiated production mode (*right*).

The computations were performed via MadGraph5\_aMC@NLO [5, 6] with the use of the SMEFTatNLO model [4]. The interference cross-section of the 4-heavy four-fermion operators is presented in fig. 3 where the total inclusive interference cross-section,  $\sigma_{\text{incl.}/\text{INCL}}$ , is split as follows:  $\sigma_{\text{incl.}} = \sigma_3 + \sigma_2 + \sigma_1 + \sigma_0$ , with  $\sigma_i$  with  $i = 3, 2, 1, 0$  denoting the different contributions arising from terms with order  $\alpha_s^i$  in line with eq. (3). For *all* 4-heavy operators, the dominant interference arises from formally subleading orders,  $\sigma_2$ . This observation conflicts with the “naive” expectation that purely QCD-induced terms deliver the highest contribution to the cross-section (through  $\sigma_3$ ). Such conflict emphasises the significance of the EW  $tt \rightarrow tt$  scattering present in  $t\bar{t}t\bar{t}$  production at LO.

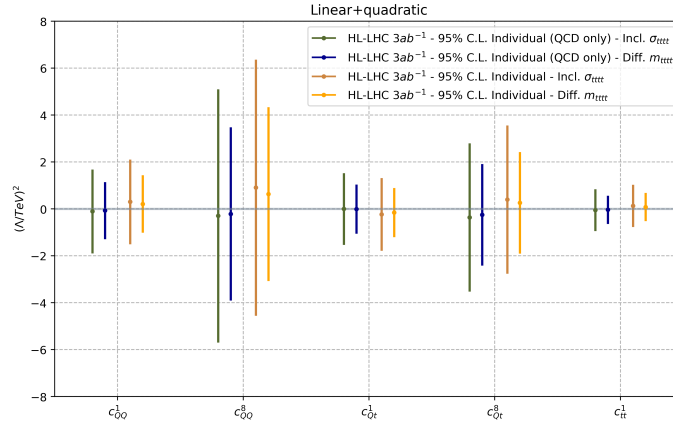
### 4. Toy fits

This section presents limits on the WCs from a simplified  $\chi^2$  individual fit in different collider scenarios: LHC, FCC-hh and HL-LHC. Through such exercise, we explored the effects of differential information and the different collider energies on the WCs bounds.



**Figure 3:** Depiction of the interference strength of the 4-heavy operators. The columns denote the WCs in their UFO notation. The SM LO cross-section at  $\sqrt{s} = 13$  TeV is presented for reference. WCs were individually set to unity, and the scale of new physics  $\Lambda$  is fixed to 1 TeV.

**Impact of differential information** Figure 4 displays the individual limits presented (I) when only QCD-induced (leading) terms are considered and (II) when contributions to the cross-section from all tree-level terms in the mixed QCD-EW expansion are included. Furthermore, it compares the use of only inclusive information from  $\sigma_{t\bar{t}t}$  to when also adding differential information in the fit from  $m_{t\bar{t}t}$ . The exercise is performed for the HL-LHC at  $\sqrt{s} = 14$  TeV with  $3 \text{ ab}^{-1}$  of integrated luminosity. The SM prediction calculated at LO is  $\sigma_{t\bar{t}t}^{\text{HL}} = 9.0 \text{ fb}$ , with a 20% theoretical uncertainty. Experimental measurement is assumed to be that of SM within the expected 28% experimental total uncertainty [7]. Our results indicate that differential information improves the



**Figure 4:** 95%CL limits on the 4-heavy operators' coefficients at the HL-LHC scenario from a  $\chi^2$  fit. The limits are shown for when using inclusive and differential information from  $\sigma_{t\bar{t}t}$  and  $m_{t\bar{t}t}$ , respectively.

sensitivity and should be used whenever possible.



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