

November 30, 2018

Dimension six effective operators in t -channel single top production and decay at NLO in QCD

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I summarize phenomenological LHC13 studies of the effect of dimension six effective operators on the inclusive cross section and differential distributions for the t -channel single top process at NLO in QCD [1].

PRESENTED AT

11th International Workshop on Top Quark Physics
Bad Neuenahr, Germany, September 16–21, 2018

arXiv:1811.12123v1 [hep-ph] 29 Nov 2018

1 Standard Model effective theory and single top quark production

With the large amounts of data that the LHC is delivering we are well inside the era of precision physics. This makes it possible to not only stress-test the Standard Model, but also to measure or constrain new physics. The framework of Standard Model Effective Field Theory allows us to describe these unknown effects in a model independent way, while being able to incorporate the symmetries of the SM.

Since top quarks are singly produced via the weak charged current interaction, the relevant production and decay vertex are the same, as can be seen in Figure 1. This narrows down the number of effective operators that can enter in the process. It also means that the width of the top quark can be affected. Moreover, an interference between effective operators in the production and the decay vertex can occur. Finally, single top quarks produced in this way are polarized which makes the study of additional angular observables interesting.

We extend the SM Lagrangian by including the relevant dimension-6 operators \mathcal{O}_i , with their associated coefficient C_i . The scale of new physics Λ is set to 1 TeV.

$$\mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^{[6]} + \text{hermitian conjugate} \quad (1)$$

Only the following three operators can enter our process at tree level at $\mathcal{O}(1/\Lambda^2)$

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi \right) (\overline{Q} \gamma^\mu \tau^I Q) \quad (2)$$

$$O_{tW} = y_t g_w (\overline{Q} \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I \quad (3)$$

$$O_{qQ,rs}^{(3)} = (\overline{q}_r \gamma^\mu \tau^I q_s) (\overline{Q} \gamma_\mu \tau^I Q) \quad (4)$$

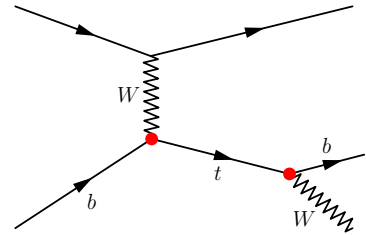


Figure 1: Diagram for the t -channel single top production and decay process.

where we use the same notation as in Ref. [2].

2 Cross-section results

We consider the process $pp \rightarrow Wbj$ (decayed top) for which the computation is performed using MADGRAPH5_AMC@NLO [3]. The NLO EFT implementation of Ref. [2] makes use of the 5 flavour scheme (b quarks are massless). The W boson is decayed leptonically through MADSPIN [4], and PYTHIA8 [5] is used for parton showering and hadronisation. Since we also generate the irreducible backgrounds, a loose invariant mass cut is imposed on the Wb system, centred on the top mass $100 \text{ GeV} < M_{Wb\text{-jet}} < 250 \text{ GeV}$ [6].

The choice for our benchmark coefficients of the effective operators can be found in Table 1, together with the corresponding cross section and width of the top quark. The predicted deviations from the SM lie within the uncertainty of recent single top measurements: $\sigma = 156 \pm 35 \text{ pb}$ and $0.6 \leq \Gamma_{\text{top}} \leq 2.5 \text{ GeV}$ [7, 8]

Operator	Coupling value	LO		NLO	
		$\sigma[\text{pb}] \pm \text{scale} \pm \text{PDF}$	$\Gamma_{\text{top}} [\text{GeV}]$	$\sigma[\text{pb}] \pm \text{scale} \pm \text{PDF}$	$\Gamma_{\text{top}} [\text{GeV}]$
SM	-	$123^{+9.3\%}_{-11.4\%} \pm 8.9\%$	1.49	$137^{+2.7\%}_{-2.6\%} \pm 1.2\%$	1.36
$O_{qQ,rs}^{(3)}$	-0.4	$172^{+8.7\%}_{-10.8\%} \pm 8.9\%$	1.49	$190^{+2.4\%}_{-1.8\%} \pm 1.1\%$	1.35
$O_{\varphi Q}^{(3)}$	1	$137^{+9.3\%}_{-11.4\%} \pm 8.9\%$	1.67	$154^{+2.3\%}_{-2.3\%} \pm 1.2\%$	1.52
$O_{tW} (\text{Re})$	2	$132^{+9.3\%}_{-11.4\%} \pm 8.8\%$	1.83	$148^{+2.3\%}_{-2.5\%} \pm 1.2\%$	1.68
$O_{tW} (\text{Im})$	1.75i	$125^{+9.2\%}_{-11.4\%} \pm 8.8\%$	1.51	$140^{+2.3\%}_{-2.5\%} \pm 1.2\%$	1.38

Table 1: The benchmark choices for the coefficients of the effective operators, together with the corresponding t -channel single top cross section and the width of the top quark. The scale and PDF uncertainties of the cross sections are also shown.

3 Polarization angles

The polarisation angle θ_i^z is the angle between the direction of decay product i and the spectator jet, as viewed in the top rest frame. The angular distribution of any top decay product in this frame can be parametrised as

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_i^z} = \frac{1}{2} (1 + a_i P \cos \theta_i^z) \quad (5)$$

where P denotes the top quark polarisation and a_i encodes how much spin information is transferred to each decay product. For the charged lepton a_l is close to 1, indicating nearly 100% correlation.

We use the same reference system as in [9] to construct a new set of coordinates:

$$\hat{z} = \frac{\vec{p}_j}{|\vec{p}_j|}, \quad \hat{y} = \frac{\vec{p}_j \times \vec{p}_q}{|\vec{p}_j \times \vec{p}_q|}, \quad \hat{x} = \hat{y} \times \hat{z}. \quad (6)$$

The vectors \vec{p}_j and \vec{p}_q represent the direction of the spectator- and of the initial quark, respectively, both in the top quark rest-frame. Since the initial quark cannot be known with certainty, the beam axis is used.

We investigate the distributions of the angles between the directions of the top quark decay products and these new directions. The angle of the charged lepton with respect to the three axes defined above is affected mostly by the polarisation of the top [10].

It should be noted that we have exclusively studied Monte Carlo distributions. No background processes are taken into account, apart from the SM contributions to Wb_j production and only minimal selection criteria that resemble the ATLAS detector acceptance are applied: leptons must have a p_T of at least 10 GeV and lie in the region $|\eta| < 2.47$, whereas jets must have a p_T bigger than 20 GeV and that lie inside $|\eta| < 4.5$.

4 Sensitivity

Figure 2 shows that different distributions are sensitive to different operators, which makes it possible to distinguish between operators. The 4-fermion operator ($O_{qQ^{(3)},rs}$) leads to harder leptons (left). The lepton p_T is a good observable to measure in experiments. Angles are also an accessible observable in measurements, especially since one could increase the sensitivity by measuring the asymmetry between forward and backward scattering. In the plot on the right we show that one can also probe the imaginary part of the dipole operator (O_{tW}), which reveals the presence of CP violation.

It is important to notice that the ratios of the NLO over LO predictions (K -factors) are rather large, and that the distributions show that there is a difference in shape for the lepton p_T between LO and NLO, it is not just a normalization.

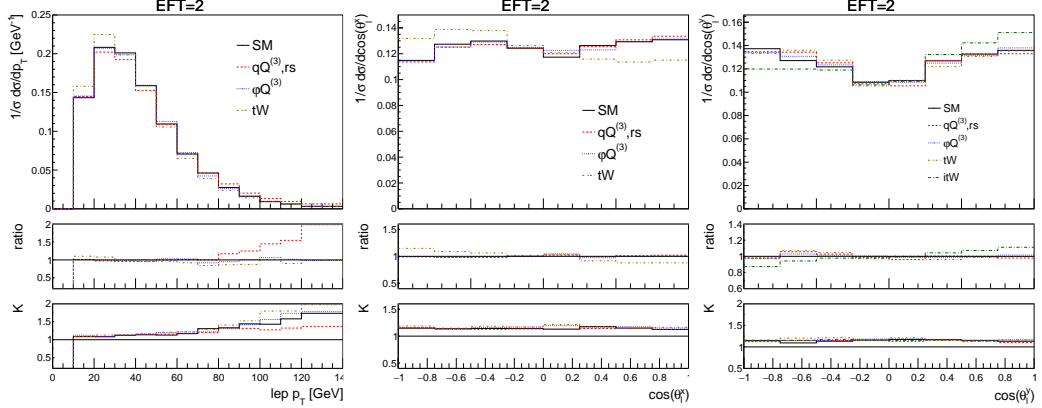


Figure 2: The NLO distributions of the lepton transverse momentum (left) and two of the three polarization angles, the θ_i^x (middle) and θ_i^y (right). The coefficients of the effective operators can be found in Table 1. The ratio shown in the first inset is defined as the effect of the operator over the SM, the second inset shows the K -factor which is defined as the ratio of the NLO over the LO predictions.

5 Conclusion

In this work we computed for the first time single top production and decay at NLO in QCD, in the presence of dimension-6 operators. QCD corrections are found to affect both the total rates and the differential distributions in a non-trivial way.

We find that different distributions are sensitive to different operators and that an angular distribution can be used to identify CP-violating effects coming from the imaginary part of the dipole operator coefficient.

This work has been done in collaboration with Eleni Vryonidou, Eric Laenen and Marcel Vreeswijk. The full study can be found at [1].

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