

Implementation of the top effective-field theory for MG5

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1 Introduction

This MadGraph5 [1] model is the implementation of the top effective field theory described in [2]. All the four-fermion operators are flavor diagonal and universal for the two lightest generations. The model has not been used so far for a full study and can thus not be considered as fully tested. However, we have performed some strong tests first on the FeynRules [3] model from which this UFO[4] model has been automatically extracted. We have computed with FeynArts [5] and FormCalc [6] the analytic amplitudes squared for the top decay and both the single top and the top pair productions and found them in agreement with the results in ref. [2]. We have also checked the gauge and Lorentz invariance for all these processes in MG5 using ALOHA[7]. We have also compared the MG5 results (from the `madevent5` branch) for the top pair production cross-section with those obtained in [8] with MG4. For the remaining operators and processes, we have only checked that qualitatively the shapes for the new physics contributions compared with the SM one are consistent with the expectations from [2].

The four-fermion operators have been implemented using heavy vectors since they are not yet available in MadGraph5. In consequence, the model should not be used for other processes than the top decay and single top and top pair productions because it can contain extra operators. For example, a heavy vector coupled to $t\bar{t}$ and $d\bar{d}$ will induce a $t\bar{t}d\bar{d}$ vertex as well as a 4-top one.

MadGraph5 is only able to compute squared amplitude so far. We can only compute

$$|\mathcal{M}_{SM} + \mathcal{M}_{\Lambda^{-2}}|^2 = |\mathcal{M}_{SM}|^2 + 2\Re(\mathcal{M}_{SM}\mathcal{M}_{\Lambda^{-2}}^*) + |\mathcal{M}_{\Lambda^{-2}}|^2 \quad (1)$$

where \mathcal{M}_{SM} is the SM amplitude and $\mathcal{M}_{\Lambda^{-2}}$ is the $\mathcal{O}(\Lambda^{-2})$ amplitude of all the diagrams with one new vertex. It contains also partially the $\mathcal{O}(\Lambda^{-4})$ contribution in addition to the SM amplitude squared and the interference (that were computed in [2]). In principle, it should not make a huge difference since Λ should be large enough such that the expansion in $\frac{1}{\Lambda}$ remains valid, i.e. the $\mathcal{O}(\Lambda^{-4})$ contributions are much smaller than the $\mathcal{O}(\Lambda^{-2})$ ones. This condition can be checked by computing those $\mathcal{O}(\Lambda^{-4})$ contributions ($|\mathcal{M}_{\Lambda^{-2}}|^2$) and $|\mathcal{M}_{SM}|^2$ to get the interference. It should be noted that this condition depends also on the cuts. The expansion makes sense only if the energy of the process is small compared to Λ .

2 In practice

The TopEffTh directory should be put into the models directory of MadGraph. The model can then be loaded in MG5 using the command `import model TopEffTh`. The only particularity to generate

a process is the possibility to specify the order NP (which stand for New Physics) in addition to the usual QED and QCD order. NP is the maximum order in $\frac{1}{\Lambda}$, so in our case NP=2. It should be noted that the new vertices can also have an order in QCD or in QED. Our rule is that the vertex with the lowest number of legs is NP=2 QED=0 QCD=0 for each operator. Then, consistently, QED or QCD are increased by one unit each time an additional leg is added. For example, the $\bar{t}t g$ vertex coming from the operator \mathcal{O}_{tG} is NP=2 QED=0 QCD=0, the $\bar{t}t gh$ vertex is NP=2 QED=1 QCD=0, the $\bar{t}t gg$ vertex is NP=2 QED=0 QCD=1 and $\bar{t}t ggh$ vertex is NP=2 QED=1 QCD=1. This rule allows to remove the SM contribution if needed.

The param_card contains three blocks related to the new physics:

- APPROX contains the parameters that controle the approximation for the four-fermion operators. The mass of each heavy vector is given by one of the parameters of this block times Λ . The mass of the vector for $\mathcal{O}_{qq}^{(1,3)}$ is given by $K \Lambda$, for $\mathcal{O}_{qq}^{(8,3)}$ by $K1 \Lambda$, for all the operators involving the right-handed top by $K2 \Lambda$ and for all the remaining operators involving the left-handed top by $K3 \Lambda$.
- DIM6 contains Λ and all the coefficients of the operators that are not four-fermion operators. The coefficients are named similarly than in [2]: C followed by the numbers in exponent and by the letters in indices. The coefficient is split into its real (starting with an "R") and imaginary part (starting with a "I") if the coefficient is complex. For example, $C_{\phi q}^{(3)} \equiv \text{RC3phiq} + i \text{IC3phiq}$.
- FOURFERMION contains all the coefficients of the four-fermion operators. The couplings of the heavy vectors to the fermions are computed internally such that they give the right coefficients for the operators whatever the values in the block APPROX are. These values can thus be used to check that the vector are heavy enough to be approximated by four-fermion operators.

3 Some results and comments

Here are some results for the three processes mentioned earlier at the Tevatron with a factorization and renormalization scale fixed at $m_t = 174.3$ GeV. For top the decay, all the outputs from ME are written as if they were in pb but we think it is due only to a display problem and that pb should simply be replaced by GeV. If such is the case,

$$\Gamma(t \rightarrow b e^+ v_e) = 165 \text{ MeV} + \left(27 \text{ MeV } C_{tW} + 20 \text{ MeV } C_{\phi q}^{(3)} \right) \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2. \quad (2)$$

The higher order corrections are quite small for $\Lambda \sim 1$ TeV and $C_i \sim 1$: the squared amplitude for the diagram with a new vertex coming from \mathcal{O}_{tW} ($\mathcal{O}_{\phi q}^{(3)}$) are $1.9 \text{ MeV } C_{tW}^2 \left(\frac{1 \text{ TeV}}{\Lambda} \right)^4$ ($0.6 \text{ MeV } C_{\phi q}^{(3)2} \left(\frac{1 \text{ TeV}}{\Lambda} \right)^4$ respectively). For the single top production in the s-channel, the hierarchy between the Λ^{-2} and Λ^{-4} is clearly smaller. The $\mathcal{O}(\Lambda^{-2})$ cross-section is

$$\sigma(u\bar{d} \rightarrow t\bar{b}) = 274 \text{ fb} + \left(129 \text{ fb } C_{tW} + 33 \text{ fb } C_{\phi q}^{(3)} + 467 \text{ fb } C_{qq}^{(1,3)} \right) \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2 \quad (3)$$

and the squared amplitudes of the new physics diagrams are $21 \text{ fb } C_{tW}^2 \left(\frac{1 \text{ TeV}}{\Lambda} \right)^4$, $1 \text{ fb } C_{\phi q}^{(3)2} \left(\frac{1 \text{ TeV}}{\Lambda} \right)^4$ and $323 \text{ fb } C_{qq}^{(1,3)2} \left(\frac{1 \text{ TeV}}{\Lambda} \right)^4$. It suggests clearly that $C_{qq}^{(1,3)}$ should be taken well below one. The cross-section

for the tW associated production is

$$\sigma(gb \rightarrow tW) = 20 \text{ fb} + \left(2.73 \text{ fb } C_{tG} - 1.7 \text{ fb } C_{tW} + 2.34 \text{ fb } C_{\phi q}^{(3)}\right) \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2 \quad (4)$$

and the squared amplitudes of the new physics diagrams are $0.52 \text{ fb } C_{tG}^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$, $0.31 \text{ fb } C_{tW}^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$ and $0.073 \text{ fb } C_{\phi q}^{(3)2} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$. Finally, the cross-section for the top pair production is

$$\begin{aligned} \sigma(pp \rightarrow t\bar{t}) = & 6.15 \text{ pb} + \left\{ 3.05 \text{ pb } C_{tG} + 0.45 \text{ pb} \left(C_{qq}^{(8,1)} + C_{qt}^{(1)} + \frac{C_{ut}^{(8)} + C_{dt}^{(8)}}{2} + \frac{C_{qu}^{(8)} + C_{qd}^{(8)}}{2} \right) \right. \\ & + 0.32 \text{ fb} \left(C_{qq}^{(8,3)} + \frac{C_{ut}^{(8)} - C_{dt}^{(8)}}{2} + \frac{C_{qu}^{(8)} - C_{qd}^{(8)}}{2} \right) + 0.019 \text{ pb } C_G + 0.0050 \text{ pb } C_{\phi G} \left. \right\} \\ & \times \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2 \quad (5) \end{aligned}$$

where $m_h = 120 \text{ GeV}$. The squared amplitudes of the new physics diagrams are $404 \text{ fb } C_{tG}^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$, $29.5 \text{ fb} \left(C_{qq}^{(8,1)2} + C_{qt}^{(1)2} + C_{qq}^{(8,3)2} \right) \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$, $25.9 \text{ fb} \left(C_{ut}^{(8)2} + C_{qu}^{(8)2} \right) \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$, $3.6 \text{ fb} \left(C_{dt}^{(8)2} + C_{qd}^{(8)2} \right) \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$, $49.3 \text{ fb } C_G^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$ and $0.493 \text{ fb } C_{\phi G}^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4$. The effect of \mathcal{O}_G is dominated by its $\mathcal{O}(\Lambda^{-4})$ contribution for $\Lambda \sim 1 \text{ TeV}$. However, the effect of this operator is quite small. The contribution of $\mathcal{O}_{\phi G}$ depends on the Higgs mass. For example, it is $5.6 \text{ fb } C_{\phi G}^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2$ if $m_h = 180 \text{ GeV}$.

All the $\mathcal{O}(\Lambda^{-4})$ corrections have been computed for one operator at a time. Consequently, the interferences between the different operators do not appear.

References

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