MEtop
User guide

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1 Introduction

MEtop is a parton level generator of single top FCNC events for pp or $p\bar{p}$ collision, optionally at leading order (LO) or next-to-leading order (NLO) approximation. FCNC interactions were introduced using effective formalism where a total of nine 6-dimension operators are implemented. MEtop generate events following the *Les Houches Accord* format and therefore can be be easly interfaced with PYTHIA or Herwig. To generate NLO events MEtop uses a matching procedure, where the phase-space is divided in two regions according to the top quark transverse momentum.

2 Installation

MEtop is written in C and python. In order to compile it, you must have a C compiler [1] and python version 2.6 or higher. To run the package you must additionaly install:

- Cuba Library version 3.0
- LHAPDF: tests were done with version 5.8.6
- Numpy: tests were done with version 1.3.0

Note: Cuba and LHAPDF library must be available through the library environment variable (for example).

To install MEtop you just have to execute "make" in the main directory.

[1] There is one file written in fortran and therefore you also need a fortran compiler.

Mx	Particle's masses (x=u,d,c,s,b,top,e,μ,τ,W,Z,H)
wx	Particle's Widths (x=W,top,Z,H)
sx	Values for CKM matrice elements (x=12,23,13)
SW	$\sin\theta_W$ (θ_W is the Weinberg angle)
EE	Electromagnetic coupling constant
cox	coupings of the x operator (x=1,2,...,9)
fx,hx	Chirality parameters from operator co1 and co2
Q	Factorization scale
miuR	Renormalization scale for Direct top at NLO
L	Energy scale
ECM	Centre of mass Energy
PTmatch	PT for matching
PTmin	Cut in PT for LO $2 \to 2$ processes
NEvnts	Number of events to generate
pdf	PDF name according to LHAPDF
pp	Type of collider: 1 for pp and -1 for $p\bar{p}$
DecMod	Turn on/off W decay modes
SpCorr	Turn on/off Spin Correlations
ttbar	t, $\bar{t}$ channel. 0-t only;1-$\bar{t}$ only;2-t and $\bar{t}$
seed	Turn Radom number seed

Table 1: Summary description of "param.dat" file.

3 The generator

3.1 param.dat

In MEtop all parameters are set in one file: "param.dat" . Table 1 summarizes the definitions of each parameter.

3.2 Cross Section and Event Production

In addition to the parameters from Table 1 there are two more flags in "param.dat" file: "cs" and "Process". The first one dictates whether or not to calculated cross sections and/or generate events. The second sets which physical process should be taken into account. If "cs" is set to 0, the cross sections for all sub-processes defined by the "Process" flag will be calculated and no generation will be performed. The result will be stored in the CS folder, in a csX.txt file, where X can be "Dtop","Gtop" and "Lqtop". If "cs" is set to 1, only the event generation will be performed. In this case events are produced according to the calculated cross sections. Therefore cross ections must have been calculated before generation can take place. After generation the *LHE* files will be stored in the Events folder as well as a file named "runinfo.txt" which keeps all event production information.

4 Physical Processes

MEtop introduce top quark FCNC interactions through nine different effective operators. Two for strong FCNC, five to electroweak and two four-fermion interaction. As a consequence, depending which operators are "turned on", different physics will be generated. Two different topologies are available in MEtop: $2 \to 1 \to 3$ and $2 \to 2 \to 4$. The first one concerns "Direct top" production, and the second "top+gluon" and "top+ light quark". All cross section and events are calculated and generated for t and $\bar{t}$.

Note: If parameter "SpCorr" is set to 0 the top quark decay will not performed in MEtop, which means the generated events will have the topology $2 \to 1$ and $2 \to 2$. In this case the spin correlations are lost and the decay is expected to be done by PYTHIA, Herwig, etc.

4.1 Process 1: "Direct top" (LO)

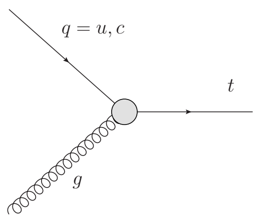

Figure 1: Direct top production (LO).

Strong FCNC top interaction is included in MEtop through two equivalent effective operators. One for top and u quark interaction, and a second for top and c quark. The constants which parametrize these operators are co1 and co2, respectively. In order to generate events at LO through "Direct top production", represented in Figure 1, you must set the flag "Process" in the 'param.dat' file to 1.

Note: In this case the parameters co3-co9 , constants like EE and SW, and PTmatch and PTmin, are irrelevant.

4.2 Process 2: "Top+Gluon" (LO)

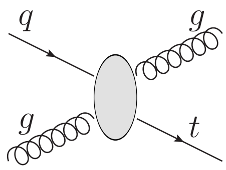

Figure 2: top+gluon production (LO).

For process represented in Figure 2 you must "turn on" the parameters co1 and/or co2 and set the "Process" flag to 2. At LO there is an infrared divergence (only cured by the NLO calculation) and in order to avoid it you must set a minimum top quark transverse momentum, through the variable "PTmin", in the "param.dat" file. Just like in the Direct top production, parameters co3 to co9 and electroweak constants are irrelevant.

4.3 Process 3: "Top+Light quark" (LO)

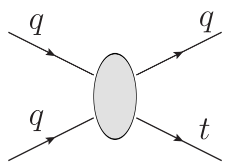

Figure 3: top+Light quark production (LO).

Production of a top and one light quark $(u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s}, b, \bar{b})$ (Fig. 3) can be done by setting "Process" to 3. In this case all operators included in MEtop contribute and therefore you must pay attention which parameter cox (x=1-9) should be different from zero. MEtop is configured to calculate sub-processes for which the amplitude depends on the effective operators parameters. The sub-processes that result only from Standard Model (SM), and SM only, are not included. This means that sub-processes that interfere with SM are included but not the SM alone.

4.4 Process 21: Inclusive Direct Top at NLO

In order to calculate the cross section and generate events of *inclusive FCNC Direct Top events at NLO approximation*, partly represented in figure 4 (not

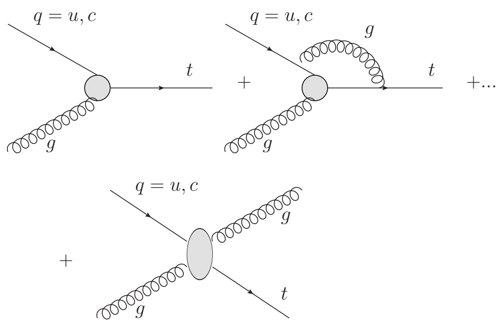

Figure 4: Inclusive FCNC Direct top at NLO precision.

all virtual diagrams are shown), you must set "Process" to 21. The relevant operators here are co1 and co2, since the remaining do not contribute to the NLO calculation. The NLO result is obtained by a matching procedure which depends of one variable: "PTmatch". The cross section results are divided in three files: "csDtopLO.txt", "csDtopNLO.txt" and "csGtop.txt". The first file informs the LO calculation. The second keeps information on the NLO increment in respect to the LO result ($\sigma_{NLO}^{Total} - \sigma_{LO}^{Total}$). The third file gives the LO cross section for "top+gluon" process with a top quark transverse momentum above "PTmatch". "PTmin" variable became irrelevant for this process. After the generation there will one file, "DtopNLO.lhe", in the Events folder containing $2 \to 1 \to 3$ and $2 \to 2 \to 4$ configurations. These two samples represent the Direct top inclusive NLO approximated event generation, and must subsequently be showered by PYTHIA using the PT-ordered scheme, in order to complete the matching.

4.5 Process 22: Inclusive Direct Top at NLO + "Top + Light quark"

With "Process" set to 22, MEtop calculates the cross section for Figure 5, the sum of Process = 21 and the LO "Top+Light quark" (Process = 3). The "PTmacth" variable plays the same role as in Process 21 and "PTmin" will be the top transverse momentum cut, for the "Top + Light quark" subprocesses.

5 Running MEtop

To run the package you just have to execute the command "./run.py" in the main directory. Care should be taken when changing the values of the

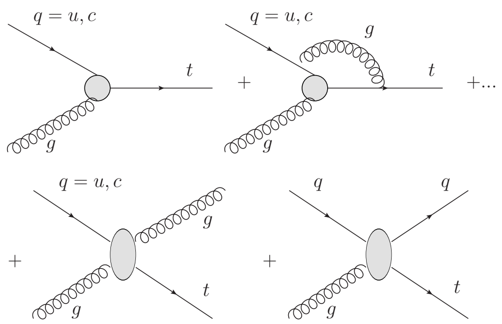

Figure 5: Inclusive FCNC Direct top at NLO precision.

physical parameters and/or the process you wish to calculate. For such cases you must always recalculate the cross section. In addition, if you change the process used for generation you must be sure that all cross sections for the new process are calculated beforehand . This is mandatory once the generation is done using the cs*.txt files saved in the CS folder.

6 Effective operators

There are three different packages available, where each one has a different set of effective operators. The first one is a light version where it was only included two operators from the strong sector. The second is a set builded with the same strong sector together with FCNC electroweak operators and finally, the third is equivalent to the second one where the electroweak sector was substituted by four-fermion operators.

In equation 1 it is shown the Lagrangian introduced in the strong sector package, included in the file named "MEtop_S_vxx.tar.gz":

$$\mathcal{L}_S = co_1\mathcal{O}_{uG} + co_2\mathcal{O}_{cG} + h.c. \tag{1}$$

with

$$\mathcal{O}_{uG} = i\frac{g_s}{\Lambda}\bar{u}\lambda^a\sigma^{\mu\nu}(f_u + h_u\gamma_5)tG^a_{\mu\nu} \quad , \quad \mathcal{O}_{cG} = i\frac{g_s}{\Lambda}\bar{c}\lambda^a\sigma^{\mu\nu}(f_c + h_c\gamma_5)tG^a_{\mu\nu}$$

The file named "MEtop_SEW_vxx.tar.gz" contains the strong and electroweak sector. The Lagrangian introduced in this package and a dictionary to the co_i format of the coupling parameters, are shown in equation 2 and table 2 respectively.

$$\begin{aligned}\mathcal{L}_{SEW} &= \mathcal{L}_S + \sum_{\substack{i,j=1,3\\ i\neq j}} \Big(\alpha_{uW}^{ij} \mathcal{O}_{uW}^{ij} + \alpha_{uB\phi}^{ij}\, \mathcal{O}_{uB\phi}^{ij} + \alpha_{\phi u}^{ij}\, \mathcal{O}_{\phi u}^{ij} + \alpha_{\phi q}^{(3,ij)}\, \mathcal{O}_{\phi q}^{(3,ij)} \\ &\quad + \alpha_{\phi q}^{(1,ij)}\, \mathcal{O}_{\phi q}^{(1,ij)} + \alpha_{u\phi}\, \mathcal{O}_{u\phi}^{ij} \Big) \end{aligned} \tag{2}$$

where the electroweak operators are:

$$\begin{aligned}\mathcal{O}_{u\phi}^{ij} &= (\phi^\dagger \phi)\,(\bar{q}_{Li}\, u_{Rj}\, \tilde{\phi}) \quad , \quad \mathcal{O}_{\phi q}^{(1,ij)} = i\,(\phi^\dagger\, D_\mu\, \phi)\,(\bar{q}_{Li}\,\gamma^\mu\, q_{Lj}) \\ \mathcal{O}_{\phi q}^{(3,ij)} &= i\,(\phi^\dagger\, D_\mu\, \tau^I\, \phi)\,(\bar{q}_{Li}\,\gamma^\mu\,\tau^I\, q_{Lj}) \quad , \quad \mathcal{O}_{\phi u}^{ij} = i\,(\phi^\dagger\, D_\mu\, \phi)\,(\bar{u}_{Ri}\,\gamma^\mu\, u_{Rj}) \\ \mathcal{O}_{uW}^{ij} &= (\bar{q}_{Li}\,\sigma_{\mu\nu}\,\tau_I\, u_{Rj})\,\tilde{\phi}\, W_{\mu\nu}^I \quad , \quad \mathcal{O}_{uB\phi}^{ij} = (\bar{q}_{Li}\,\sigma_{\mu\nu}\, u_{Rj})\,\tilde{\phi}\, B_{\mu\nu}\end{aligned}$$

$co3 \to \alpha_{uW}^{ut}$	$co7 \to \alpha_{\phi u}^{ut}$	$co11 \to \alpha_{\phi q}^{(1,ut)}$
$co4 \to \alpha_{uW}^{tu}$	$co8 \to \alpha_{\phi u}^{tu}$	$co12 \to \alpha_{\phi q}^{(1,tu)}$
$co5 \to \alpha_{uB\phi}^{ut}$	$co9 \to \alpha_{\phi q}^{(3,ut)}$	$co13 \to \alpha_{u\phi}^{ut}$
$co6 \to \alpha_{uB\phi}^{tu}$	$co10 \to \alpha_{\phi q}^{(3,tu)}$	$co14 \to \alpha_{u\phi}^{tu}$

Table 2: Coefficient dictionary for $\mathcal{L}_{SEW}$

The file named "MEtop_S4F_vxx.tar.gz" contains the strong and four-fermion sector. Equation 3 shows explicitly the operators introduced:

$$\mathcal{L}_{S4F} = \mathcal{L}_S + \mathcal{L}_{4fu} + \mathcal{L}_{4fc} \tag{3}$$

where the four-fermion Lagragians are give by

$$\begin{aligned}\mathcal{L}_{4fu} &= \frac{1}{2}(\alpha_{qq}^{1113} + \alpha_{qq'}^{1113})(\bar{u}_L\,\gamma^\mu u_L)(\bar{u}_L\gamma_\mu t_L) \\ &\quad -\frac{1}{2}(\alpha_{qu'}^{1311} + \frac{1}{3}\alpha_{qu}^{1311})(\bar{u}_L\gamma^\mu u_L)(\bar{u}_R\gamma_\mu t_R) \\ &\quad -\frac{1}{2}(\alpha_{qu'}^{1113} + \frac{1}{3}\alpha_{qu}^{1113})(\bar{u}_R\gamma^\mu u_R)(\bar{u}_L\gamma_\mu t_L) \\ &\quad +\frac{1}{2}\alpha_{uu}^{1113}(\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma_\mu t_R) \\ &\quad -\frac{1}{4}\alpha_{qu}^{1311}(\bar{u}_L\gamma^\mu\lambda^a u_L)(\bar{u}_R\gamma_\mu\lambda^a t_R) \\ &\quad -\frac{1}{4}\alpha_{qu}^{1113}(\bar{u}_R\gamma^\mu\lambda^a u_R)(\bar{u}_L\gamma_\mu\lambda^a t_L)\end{aligned}$$

$$
\begin{aligned}
\mathcal{L}_{4fc} \;=\;& \frac{1}{2}(\alpha^{1123}_{qq} + \alpha^{2113}_{qq'} + \frac{1}{3}\alpha^{2113}_{qq} + \frac{1}{3}\alpha^{1123}_{qq'})(\bar{u}_L\,\gamma^\mu u_L)(\bar{c}_L\gamma_\mu t_L) \\
& -\frac{1}{2}(\alpha^{1321}_{qu'} + \frac{1}{3}\alpha^{1321}_{qu})(\bar{u}_L\gamma^\mu u_L)(\bar{c}_R\gamma_\mu t_R) \\
& -\frac{1}{2}(\alpha^{2113}_{qu'} + \frac{1}{3}\alpha^{2113}_{qu})(\bar{u}_R\gamma^\mu u_R)(\bar{c}_L\gamma_\mu t_L) \\
& +\frac{1}{2}(\alpha^{1123}_{uu} + \frac{1}{3}\alpha^{2113}_{uu})(\bar{u}_R\gamma^\mu u_R)(\bar{c}_R\gamma_\mu t_R) \\
& -\frac{1}{4}\alpha^{1321}_{qu}(\bar{u}_L\gamma^\mu\lambda^a u_L)(\bar{c}_R\gamma_\mu\lambda^a t_R) \\
& -\frac{1}{4}\alpha^{2113}_{qu}(\bar{u}_R\gamma^\mu\lambda^a u_R)(\bar{c}_L\gamma_\mu\lambda^a t_L) \\
& +\frac{1}{4}(\alpha^{2113}_{qq} + \alpha^{1123}_{qq'})(\bar{c}_L\gamma^\mu\lambda^a t_L)(\bar{u}_L\gamma^\mu\lambda^a u_L) \\
& +\frac{1}{4}\alpha^{2113}_{uu}(\bar{c}_R\gamma^\mu\lambda^a t_R)(\bar{u}_R\gamma^\mu\lambda^a u_R) \\
& +(\frac{1}{3}\alpha^{2311}_{qu'} + \alpha^{2311}_{qu})(\bar{c}_L t_R)(\bar{u}_R u_L) + \frac{1}{2}\alpha^{2311}_{qu'}(\bar{c}_L\lambda^a t_R)(\bar{u}_R\lambda^a u_L) \\
& +(\frac{1}{3}\alpha^{1123}_{qu'} + \alpha^{1123}_{qu})(\bar{c}_R t_L)(\bar{u}_L u_R)) + \frac{1}{2}\alpha^{1123}_{qu'}(\bar{c}_R\lambda^a t_L)(\bar{u}_L\lambda^a u_R).
\end{aligned}
$$

The correspondent co_i parameters dictionary is shown in table 3:

$co27 \rightarrow \alpha^{1113}_{qq} + \alpha^{1113}_{qq'}$	$co33 \rightarrow \alpha^{1123}_{qq} + \alpha^{2113}_{qq'}$	$co39 \rightarrow \alpha^{1123}_{uu}$
$co28 \rightarrow \alpha^{1311}_{qu'}$	$co34 \rightarrow \alpha^{2113}_{qq} + \alpha^{1123}_{qq'}$	$co40 \rightarrow \alpha^{2113}_{uu}$
$co29 \rightarrow \alpha^{1113}_{qu'}$	$co35 \rightarrow \alpha^{1321}_{qu'}$	$co41 \rightarrow \alpha^{2311}_{qu'}$
$co30 \rightarrow \alpha^{1113}_{uu}$	$co36 \rightarrow \alpha^{1321}_{qu}$	$co42 \rightarrow \alpha^{1123}_{qu'}$
$co31 \rightarrow \alpha^{1311}_{qu}$	$co37 \rightarrow \alpha^{2113}_{qu'}$	$co43 \rightarrow \alpha^{2311}_{qu}$
$co32 \rightarrow \alpha^{1113}_{qu}$	$co38 \rightarrow \alpha^{2113}_{qu}$	$co44 \rightarrow \alpha^{1123}_{qu}$

Table 3: Coefficient dictionary for $\mathcal{L}_{S4F}$