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MadGraph5_AMC@NLO and top pair production at a Linear Collider

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Summary. — In these proceedings, we will present the latest update on the madgraph5_aMC@NLO via a short tutorial both for production at leading and next-to-leading order. Finally, we will present some preliminary study of the top quark pair production at next-to-leading order.

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1. – Introduction

Since the discovery of the Higss boson particle [1-4] the High Energy physics community has started to push to have a linear collider which could perform extremely sensitive measurements on the mass and on the couplings of the Higgs Boson. In the current preparatory stage, it is important to assess the sensitivity to new physics and to have a reliable estimate of the expected significance for key processes. We will present, in sect. **2** a tutorial of the MadGraph5_aMC@NLO [5,6] framework, a Monte Carlo tool for Leading and Next Leading Order simulations. While in sect. **3**, we will discuss a preliminary example of study that can be done at Linear Collider and its main technical point: the complex mass scheme.

2. – MadGraph5_aMC@NLO

MadGraph5_aMC@NLO is a framework to create a code for the evaluation of the matrix-element based on Helicity amplitude formalism [7, 8]. The interest stands in the various output formats available. MadEvent [9] allows the computation of the cross-section at leading-order (LO) accuracy as well as the generation of events. aMC@NLO [5] allows the same at next-to-leading order (NLO) accuracy in QCD. Other specific modules like MadSpin [10], MadDarkMatter [11], MadWeight [12], MadLoop [13], MadWidth [14] allows respectively to decay unstable particles will full spin

correlation, to compute the relic density, to estimate the weights of the matrix element method [15,16] and finally to automatically evaluate the width of all particles for a given benchmark point. In this section, we will first review how the code can be installed, and the various steps to generate a process and to generate events.

2˙1. *Installation and first step with the code.* – MadGraph5_aMC@NLO is a Python program which runs with Python 2.6 and Python 2.7. Most of the LINUX distribution and all MacOS X version (since 10.6) are distributed with one of those two versions. Additionally, each of the output format (*i.e.* MadEvent, aMC@NLO, MadSpin, ...) can, on top of that, require some specific programs. Those programs are gmake, gcc and root. **gmake** is present by default on any Linux distributions but not on Mac OS X, in that case, the easiest way to install this program is via Xcode. The standard version of **gcc** on most distribution is currently gcc4.4, which is perfectly compatible with all the LO computation. However, aMC@NLO and MadLoop packages require at least gcc4.6. **root** is only required for some external package like SysCalc [17] and MadAnalysis [18,19].

The code is available at the following address: https://launchpad.net/madgraph5 and the latest version of the code is currently 2.0.1. The code does not need any compilation and can be directly executed via the executable "mg5_amc" present in the "bin" directory.

A series of external tools can be downloaded/installed by MadGraph5_aMC@NLO with the command "install PACKAGE" that can be type inside the MadGraph5_aMC@NLO shell initiated by the executable. The currently supported packages are Delphes2 [20], Delphes3 [21], ExRootAnalysis [22], MadAnalysis, SysCalc and Pythia-PGS [23,24].

A basic tutorial on how this framework works is built-in inside the code via the command "tutorial". In that case, a series of instruction will be prompted on the screen allowing you to learn the basic functionalities of the code. More exactly this will teach you how to: load a model, generate a process, create output for MadEvent and run it (*i.e.* obtain the cross-section and a given number of event), define a multi-particle label, store a history of the commands in a session, execute shell commands from the interface, use the various built-in help commands and display information about the model (*e.g.* particle, interaction).

In addition to this basic tutorial, some dedicated tutorials are also available for aMC@NLO (type "tutorial aMCatNLO" in the shell) for all generation/computation at NLO accuracy and for MadLoop ("tutorial MadLoop") for learning how to evaluate the loop contribution for a given phase-space point.

Here, we will only stress that the full generation can be done by using four simple commands, *e.g.* the following allows to generate events for VBF and to compute the cross-section at LO accuracy:

```
import model sm
generate p p > j j w+ w+ QCD=0, w+ > l+ vl
output PATH
launch
```

The various syntax allowed for the "generate" command are explained in the following subsection.

2˙2. *Generation of the code.* – The syntax associate to the generate command is the following one:

TABLE I. – *Special syntax of process generation and their meaning.*

Symbol	Meaning	Example
X, X >	Forcing X to be on shell and then decay it in a given channel The decay keeps full spin correlation and off-shell effects ([1]).	p p > h j, h > b b~
$ X	Forbidding the particle to be on-shell ([1]).	p p > e+ e- $ Z
/ X	Forbidding the particle to appear in the diagram ([2]).	p p > e+ e- / Z
> X >	Forcing to have at least one particle X in S-channel ([2]).	p p > z > e+ e-
$$ X	Forbidding that particle to be in S-channel ([2]).	e+ e- > e+ e- $$ z

```
INITIAL_STATE > FINAL_STATE SPECIAL_TAG PERTURBATION_ORDER_TAG
```

where INITIAL_STATE/FINAL_STATE are respectively the list of initial/final states particles. The list of SPECIAL_TAG and their meaning are presented in table I, with each time an example of the above syntax. Those tags allow to filter the diagram generated. We provide two versions of the selection: the first one based on the notion of on-shell/off-shell particles([1]), the second one corresponding to just throw away some diagram([2]).

The PERTURBATION_ORDER_TAG specifies the maximal power in the perturbative theory to consider. For example the following syntax.

```
generate p p > j j w+ w+ QCD=0 QED=4
generate p p > j j w+ w+ QCD=2 QED=2
```

generates respectively the pure electroweak VBF process and the associated QCD background. If some of the couplings are missing([3]), then the associate value is set to infinity. Therefore the following syntax is equivalent to the one above:

```
generate p p > j j w+ w+ QCD=0 # VBF electroweak
generate p p > j j w+ w+ QED=2 # QCD background
```

Finally, if this information is simply missing, then the code generates the most important contribution according to the information present in the model (see sect. 6.1.7 of ref. [25]). For most of the models, this means that we maximize the QCD contribution and minimize the rest.

The syntax for the generation of the NLO processes follows the exact same logic/syntax as the difference that requires an additional tag: the perturbative coupling that needs to be evaluated at NLO accuracy has to be placed between brackets at the end of the line (*e.g.* generate p p > j j w+ w+ QCD=0 [QCD]). At current stage, only QCD is allowed to be estimated at NLO.

Once the diagrams are generated, the next command tells MADGRAPH5_AMC@NLO which kind of code is expected to be created. The command "output" or "output PATH"

([1]) The definition of on-shell/off-shell is related to a kinematical cut on the invariant mass which is allowed (respectively forbidden) to differ from the pole mass by a given number of times the width of the particles. This number (call bw_cuttof) is by default set to 15, and can be changed in the run_card.dat

([2]) Removing diagrams can lead to unphysical distributions either due to the missing interference or due to a violation of the gauge/Lorentz invariance.

([3]) The list of such couplings can be obtained for a given model by the command "display couplings_order".

generates the MadEvent/aMC@NLO code. The other output mode need to specify the output type via the command "output FORMAT PATH", where "FORMAT" is either pythia8, madweight, standalone, standalone_cpp, madevent.

2˙3. *Running the code.* – In MadGraph5_aMC@NLO v.2.0.0 (and later), the command to generate events is either *"./bin/generate_events"*, starting from the process directory, or "launch PROCESS_DIRECTORY_PATH" from the MadGraph5_aMC@NLO shell interface. In both cases, the code starts by an interactive question:

```
The following switches determine which programs are run:
1 Run the pythia shower/hadronization:  pythia=ON
2 Run PGS as detector simulator:  pgs=OFF
3 Run Delphes as detector simulator: delphes=NOT INSTALLED
4 Decay particles with the MadSpin module: madspin=OFF
5 Add weight to events based on coupling parameters: reweight=OFF
Either type the switch number (1 to 5) to change its default setting,
or set any switch explicitly (e.g. type 'madspin=ON'
at the prompt)
Type '0', 'auto', 'done' or just press enter when you are done.
[0, 1, 2, 4, 5, auto, done, pythia=ON, pythia=OFF, ... ][60s to answer]
```

This question indicates if some external modules are detected or not ([4]). After entering a number of an assignment for a flag (*e.g.* "pgs=ON"), the question will be re-asked with that flag flipped (respectively set to the associated value). The code automatically checks that all the flags are set in a consistent way and fixes them automatically if needed (*i.e.* if one user types "pgs=ON", then the pythia flag is always set on "ON"). We advise not to use the switch number when you script([5]), since their meaning can be ambiguous and might change over time.

Compared to version 1.5.x, we introduce the possibility to run two additional built-in packages: MadSpin and the reweighing module. MadSpin allows to decay particles generated on-shell with full spin correlations([6]). The reweighing module allows to associate to a given event additional weights corresponding to those which would have been associated to this event if it were associated to a different theory. Those weights are

$$W_{new} = \frac{|M_{new}|^2}{|M_{old}|^2} * W_{old}, \tag{1}$$

Those weights are then written inside the output file following the LHEF v3 convention [26].

Once the first question is answered (*i.e.* by just pressing enter or "0" or "done" to the previous question), a second question allows you to modify the parameter of the run:

([4]) The default value for the current run is given by the previous run performed in the same output directory.

([5]) For instruction on how to script a call to MadGraph5_aMC@NLO, please read: `https://answers.launchpad.net/madgraph5/+faq/2186`

([6]) This module is actually designed for NLO processes since it has only a small interest at LO. Indeed, the decay syntax of the "generate" command –only allowed for LO processes– produces samples of events within the same approximation (but for the estimation of the cross-section which did not rely on the Narrow-Width Approximation) but in a safer and faster way.

```
Do you want to edit a card (press enter to bypass editing)?
1 / param : param_card.dat
2 / run : run_card.dat
3 / pythia : pythia_card.dat
9 / plot : plot_card.dat
you can also
- enter the path to a valid card or banner.
- use the 'set' command to modify a parameter directly.
The set option works only for param_card and run_card.
Type 'help set' for more information on this command.
[0, done, 1, param, 2, run, 3, pythia, 9, enter path, ... ]
```

The param_card contains all the model parameters and follows the Les Houches convention, while the run_card contains the definition of the collider parameters and the cuts to apply at parton level. We emphasize that you can use the "set" command in order to edit your file. The "compute_widths" command allows to use MadWidth for the automatic computation of the width. A command to directly call ASperGE [27] for the mass diagonalization is currently in development.

After this stage, the code is going to run without any need of interaction. A report of the main result is available on a html web page "PROCESS_DIR/crossx.html".

3. – Complex-mass scheme

The presence of unstable particles in perturbative calculations demands the inclusion of higher order terms to describe the Breit-Wigner shape of resonances. This mixing of different perturbative orders can spoil gauge invariance if not implemented with caution, leading to unreliable results. A simple and powerful approach to handle this problem is the complex-mass scheme [28, 29]. It has been widely and successfully used in several calculations at tree-level and for EW and QCD radiative corrections. In this Section we describe the implementation of the complex-mass scheme in the MadGraph5_aMC@NLO framework.

In order to run in the complex mass scheme, a single command is required (before the command to generate the diagram):

```
set complex_mass_scheme
```

In addition to modify various Template, it makes three conceptual modifications to the model:

- It promotes all masses to a complex parameter define by $\sqrt{m^2 + im\Gamma}$.
- It fixes the Yukawa masses to the value of the associated (complex) mass.
- Since all the masses are promoted to complex numbers, it's important for consistency that the both masses and widths are free parameters of the model. However most of the UFO models [30,25] uses an electroweak scheme which computes the W mass. We therefore change automatically the gauge scheme for such model in order to promote the W mass as a free parameter and fix α_{EW} to an internal (complex) parameter fixed by gauge invariance.

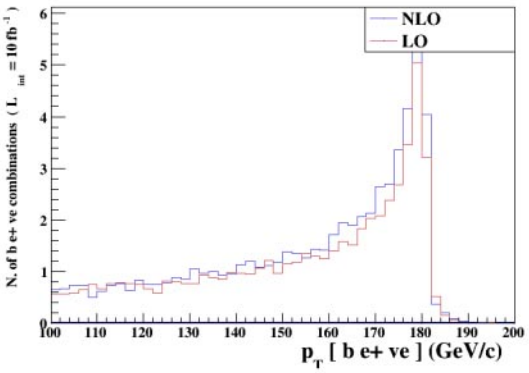

Fig. 1. – Transvers momentum of the top both at LO and NLO (in complex mass scheme).

At NLO, the counter-term have to be computed accordingly. At current stage the only model officially supported at NLO in MadGraph5_aMC@NLO is the Standard Model. In that case, the complex mass scheme needs only one additional counter term that we have added by hand [31]. In fig. 1 we plot the transverse momentum p_T of the top both at LO and at NLO using the complex mass-scheme for a Linear Collider at a centre-of-mass energy of 500 GeV.

3˙1. *Conclusion.* – In these proceedings, we have presented a short tutorial of the MadGraph5_aMC@NLO package, explaining the main technical points required to use MadGraph5_aMC@NLO in a fully professional way. We also present some results for the top-quark pair production computed at NLO accuracy for a Linear Collider at 500 GeV and discussed the most technical points to have the full NLO computation: the complex-mass scheme.

* * *

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