KIT-Fakultät für Physik
Institut für Experimentelle Teilchenphysik
Prof. Dr. Ulrich Husemann
Dr. Matthias Schröder
Denise Müller
Michael Waßmer

Übungen zu Teilchenphysik I

Wintersemester 2017/18

Übungsblatt Nr. 4 Bearbeitung bis 16. November 2017

MadGraph5aMC@NLO/MadEvent

MadGraph5aMC@NLO/MadEvent is a program suite to calculate cross sections and generate events in high energy physics at parton level. It has evolved a lot over the past years and includes a lot of additional features, way beyond this exercise, but it is all centred around one core, the MadGraph5aMC@NLO (MG5aMC) package.

MadGraph5aMC@NLO is a tool that starts with a set of particles and their interactions and finds all the Feynman graphs contributing to a given initial and final state configuration. The contributing particles and their interactions are given by the Lagrangian of the theory and are used in the MG5aMC program as a "model". A model is just a special way of listing the various possible particles and their couplings. From this, MG5aMC starts for a given initial-state configuration (e.g. incoming electrons, quarks, gluons, photons, protons) and adds possible couplings and particles until the desired final state is reached. In this way, all possible Feynman graphs are constructed and stored.

From the generated graphs, MG5aMC produces `FORTRAN` code that can be used to calculate the corresponding cross sections. This is done in a clever way, by means of helicity amplitudes, the so-called `HELAS` formalism: all the lines in the Feynman diagrams are identified with either helicity amplitudes or currents and plugged together. That way, the spin of the particles is already taken into account during the calculation. The obtained amplitudes are the matrix elements of the considered process, so MG5aMC does the complete quantum-field theoretical calculation for you.

The subprogram MadEvent now takes these matrix elements and calculates the cross section. **Question:**

- Recall Fermi's Golden Rule. Which factors contribute to the cross section of a certain process?

For this purpose, a phase-space generator is used, which computes the phase-space integral. This integration cannot be performed analytically in almost all of the considered processes. Therefore, programs like MG5aMC/MadEvent have to rely on Monte Carlo integration, and are thus called Monte Carlo event generators.

The matrix element can be computed either at leading order **(LO)** perturbation theory **(MadGraph operation mode**) or at next-to-leading order **(NLO)** perturbation theory (**aMC@NLO operation mode**). Therefore, Monte Carlo event generators like MadGraph5aMC@NLO are more precisely called 'matrix-element generators'.

From the output of MadEvent, you can obtain the cross section of the process of interest. In addition, one can apply different cuts – that is, requirements on the kinematic properties of the outgoing particles or energies of the incoming particles – and study how the cross section changes etc. Furthermore, you can write lists of the incoming and outgoing particles ('events'). The events can be analysed further by investigating specific observables or by feeding the events into so-called general-purpose event generators like Pythia8, Herwig7, or Sherpa, which simulate also showering and hadronisation in addition to the hard-scattering process.

Now, let's put all of that into practice!

General Instructions

To install the MadGraph5aMC@NLO package, copy `MG5_aMC_v2.4.3.tar.gz` from ILIAS to your local directory[1]. First, you have to unpack the archive:

```
tar xvf MG5_aMC_v2.4.3.tar.gz
```

Navigate into the created MG5aMC working directory

```
cd MG5_aMC_v2_4_3
```

and start the MG5aMC program with the command

```
./bin/mg5_aMC
```

[1]Alternatively, you can also download the tarball from the official MadGraph5aMC@NLO webpage: `https://launchpad.net/mg5amcnlo/2.0/2.4.x/+download/MG5_aMC_v2.4.3.tar.gz`

This will open the MG5aMC command line.

Since we will need the MadAnalysis package later, we will install it now via

```
MG5_aMC> install MadAnalysis
```

In the following, some introductory examples are provided on how to work with MG5aMC. The actual exercises are presented in later sections.

A new process is initialised with the command `generate`. A process is specified by entering the initial state particles (there should be two, since we are simulating collider physics) and the final state particles, separated by a `>`. For example, for Bhabha scattering, you would enter

```
MG5_aMC>generate e+ e- > e+ e-
```

Quarks are denoted by their first letter: `u, d, c, s, t, b`, charged leptons by their first two (except electrons and positrons, which are specified by `e`) and sign: `e-, mu-, ta-`, the corresponding neutrinos by `ve, vm, vt`. Bosons go by their first letter `g, z, w-,w+, h`, except for the photon, which is specified with `a`. If a particle carries integer elementary charge, it has a minus sign, the corresponding charge conjugate state carries a plus sign. All other antiparticles just get a tilde `~` after their name, e.g. `u~`.

So far, we invoked the so-called MG5aMC5 operation mode, which allows cross-section calculation and event generation only at LO. In order to calculate cross sections at NLO, you have to invoke the aMC@NLO operation mode of the Madgraph5aMC@NLO event generator by adding the keyword "[QCD]" during the generate step, e.g.

```
MG5_aMC>generate p p > t t~ [QCD]
```

One can also limit the couplings and diagrams to be considered in the calculation, which can help to speed up the calculation (at the cost of lower precision). For example,

```
MG5_aMC>generate e+ e- > e+ e- /z QED=2
```

will exclude the Feynman diagrams with Z boson exchange (indicated by the `/z`) and keep only the processes with a photon exchange. In addition, `QED=2` sets the maximum number of QED vertices to consider to 2 (which has of course no influence in this case).

In case you generate an internal resonance, you can specify its decay in the same way, and in case of several resonances, you can specify separate decays by using commas, for example

```
e+ e- > z > mu+ mu-
p p > w+ w-, w+ > j j, w- > l- vl~
```

In the second line, we use the feature of 'multiparticle templates' available in MadGraph5aMC@NLO, which allows specifying several objects with one symbol. The following multiparticle templates exist: `p` for protons, `j` for jets (short for all `u, d, s, c, u∼, d∼, s∼, c∼, g` initiated jets), `l` for charged leptons and `vl` for neutrinos.

If you collide protons, these do not enter in the Feynman diagrams, only their constituent partons do. You can specify what partons you want to include into the proton and MadGraph5aMC@NLO will create all the possible contributions automatically. Analogously, you can specify the quark contributions to jets lepton and lepton-neutrino contributions. The specifications can be displayed with the command

```
MG5_aMC>display multiparticles
```

To define new multiparticles, you can use the `define` command. For instance, you can include b quarks into the jet composition via

```
MG5_aMC>define j = g u c d s u~ c~ d~ s~ b b~
```

In case of proton collisions, the momenta of the incoming partons depend on the momenta of the colliding protons. The probability to probe a parton with a specific momentum is parametrised in the parton distribution functions ('PDFs'), which are convoluted with the cross section of the parton scattering process to obtain the full cross section. This is already done in MadGraph5aMC@NLO, where a particular PDF set (CTEQ6L) is used per default. However, it is possible to use different PDF sets, which can be accessed for example via the LHAPDF library that contains many of the available PDF sets[2].

Usually, the `generate` command overwrites previously created diagrams. To generate more than one process at once, you can specify further processes with `add process`.

After having defined all processes you want to analyse, you should save the MadGraph5aMC@NLO results. This is done with the command

```
MG5_aMC>output <NAME>
```

where `<NAME>` is the name of a directory that will be created. In this directory, there will be several sub-directories:

- `bin`: contains the scripts used to run the programs.
- `Cards`: stores the input files, which can be used to change the run parameters
- `Events`: will contain the created events.

[2]See `http://projects.hepforge.org/lhapdf/` for details

- `HTML`: contains HTML files that are created during the event generation and contain information about the process and the status of your running calculation. You can open the `index.html` file in the main directory with a web browser to have a look on the provided output.
- `lib`: contains linked libraries.
- `Source`: contains the FORTRAN code for the different programs.
- `SubProcesses`: contains the code for the generated amplitudes.

In order to generate Monte Carlo events with MadEvent from the processes, type in the following command

```
MG5_aMC>launch <NAME>
```

where `<NAME>` is the name of the process you have created before. The `launch` command will first ask if you want to execute

- a showering and hadronisation process with the PYTHIA general-purpose event generator, which is directly interfaced to the MadEvent generation process
- a simplistic detector simulation with the PGS package
- a simplistic detector simulation with the Delphes package
- a decay considering spin-correlations with the MadSpin package
- adding additional weights useful for systematic studies of model parameters

You can safely use the choices provided as default. (Please note that MadGraph5aMC will proceed with the default choices if you do not give an answer within 60 seconds.)

No matter what you answered in the previous question, you will be asked if you want to edit the files `param_card.dat` and `run_card.dat` which are located in the `<NAME>/Cards/` directory[3]. The file `param_card.dat` includes all parameters as masses, coupling strengths, and decay widths of the model. In `run_card.dat`, the configuration of the matrix-element event generation are defined: you can specify the number of events to be produced, the energy of the colliding particles, and you can define kinematic constraints (cuts) for produced particles. After defining the run parameters, the Monte Carlo event generation is started.

In the file `<NAME>/HTML/crossx.html`, the status of the event generation is documented and updated. A web browser will open automatically and display the status.

[3]By default, the text files will be opened automatically with the text editor `vi`. If you want to use a different editor, you can specify this in the file `input/mg5_configuration.txt`.

(If not, open the file manually with a browser.) When finished, the total cross section of the process will be shown. Clicking on `results` will show you the cross sections of all subprocesses. The `banner` link opens a file including all parameter settings which have been used in this run. Furthermore, you can find the generated events when clicking on `LHE`, which opens a list of all generated events given in the 'Les Houches Event' (LHE) data format. In `plots`, you can find diagrams of basic kinematic quantities of the produced particles. If you click on `Main Page` and then on `Process Information`, you can find all leading order Feynman diagrams of the produced events.

You can exit the MadGraph command line via `MG5_aMC>exit` or `MG5_aMC>quit`.

Short Version

1. Open terminal
2. Navigate into the directory: `cd MG5_aMC_v2_4_3`
3. Start MadGraph5aMC@NLO: `./bin/mg5`
4. Install the MadAnalysis package which is required later: `MG5_aMC> install MadAnalysis`.
5. Define the process you want to simulate: `MG5_aMC>generate p p > ...`
6. Specify the name of directory to which the output files will be written: `MG5_aMC>output <NAME>` (`<NAME>` can be for example `Exercise_1`)
7. Start the event generation: `MG5_aMC>launch <NAME>`
8. Answer the question whether you want to run additional packages
9. Edit `param_card.dat` or `run_card.dat`: adjust for example the beam energy or switch from proton-proton to proton-antiproton in `run_card.dat`
10. After the event generation has started, a web browser opens displaying the status (if not, open `index.html` manually)
11. The resulting cross section can be viewed under "results" in your web browser, and are displayed on the terminal
12. Quit the Madgraph5aMC@NLO terminal: `MG5_aMC>quit`
13. Navigate into the output directory: `cd <NAME>`

14. Now you can adjust `nano Cards/plot_card.dat` in the `Cards` directory and plot histograms by executing
    ```
    cd Events
    ../bin/madevent
    MG5_aMC> plot run_XX
    ```
    where `run_XX` is the run you want to plot (e.g. `run_01`)

1 Calculate a standard model process

- Generate 1000 events of the process $pp \to e^- \bar{\nu}_e$ at a centre-of-mass energy of 13 TeV (i.e. 6.5 TeV per beam) at the LHC. Change the file `run_card.dat` accordingly. Do not run the Pythia shower or any other additional package for this process.
- What is the LO cross section of this process?
- What are the primary Feynman diagrams of this process? Also, have a look into the generated LHE file in the `Events` directory (for example using the program `less`) and try to understand the listed particles for a few events.

```
5   0  0.1019000E+01  0.8232092E+02  0.7957747E-01  0.1321443E+00
      1   -1    0    0  501    0  0.00000000000E+00  0.00000000000E+00  0.81108158319E+02  0.81108158319E+02  0.00000000000E+00 0. -1.
     -2   -1    0    0    0  501  0.00000000000E+00  0.00000000000E+00 -0.20887951627E+02  0.20887951627E+02  0.00000000000E+00 0.  1.
    -24    2    1    2    0    0  0.00000000000E+00  0.00000000000E+00  0.60220206692E+02  0.10199610995E+03  0.82320915630E+02 0.  0.
     11    1    3    3    0    0  0.17252447165E+02  0.92092617408E+01  0.74984121070E+02  0.77492424453E+02  0.00000000000E+00 0. -1.
    -12    1    3    3    0    0 -0.17252447165E+02 -0.92092617408E+01 -0.14763914378E+02  0.24503685493E+02  0.00000000000E+00 0.  1.
```

  Each event starts with the statement `<event>` followed by the list of particles of this particular event. The first row contains information on the total number of particles in the event, the process ID, the weight of the event, and the values of the factorisation scale Q, coupling constants of the electroweak interaction, α, and the strong interaction, α_s. The subsequent rows contain information on the particles in the event:

  - the first column lists the particle's PDG code[4];
  - the second column lists the 'status' of the particle (-1: initial-state particle; 2: intermediate particle; 1: final-state particle);
  - the third and fourth columns list information about the particle's mothers;
  - the fifth and sixth columns list information about the colour-flow in the event; and
  - the further columns list the components of the particle's four-momentum, the mass of the particle and its spin.

- Calculate the LO cross section as a function of the centre-of-mass energy (1 TeV to 14 TeV) and compare this with the cross section at the Tevatron ($p\bar{p}$ collider, 1.96 TeV centre-of-mass energy). Edit the beam parameters in `run_card.dat` to perform this task. To change from pp collisions to $p\bar{p}$ collisions change the parameter `lpp2` from 1 to -1.

[4] Have a look at `http://pdg.lbl.gov/2016/reviews/rpp2016-rev-monte-carlo-numbering.pdf` for a list of PDG-IDs.

- Compare the LO cross sections of $pp \to e^- \bar{\nu}_e$ and $pp \to e^+ \nu_e$ for a centre-of-mass energy of 13 TeV at the LHC. Is there a difference? Why?

- Calculate the NLO cross section for the process $pp \to e^- \bar{\nu}_e$ at a centre-of-mass energy of 13 TeV. To do so, you have to generate the process again but you have to add the keyword "[QCD]" during the generate step; for example

  ```
  generate p p > ... [QCD]
  ```

  In this way, the aMC@NLO operation mode is invoked, which will allow you to calculate the cross section at NLO. Make sure, that the fixed_order, shower, madspin, and reweight option are switched off.

  NB: At first usage of the aMC@NLO operation mode, it is common that MG5aMC has to install some additional packages required for the calculation of higher-order Feynman diagrams containing loops: please stay patient.

  What differences between the LO and NLO Feynman diagrams and cross sections occur? Can you explain these differences by considering the available phase space?

Now we want to study some of the kinematic distributions of the generated particles. The plotting routine is called **MadAnalysis** and is steered by the parameters in `Cards/plot_card.dat`. MadAnalysis is a little bit involved at first because of the very compact way it works. The basic principle is: there are predefined kinematic quantities which can be calculated from one or more 4-vectors, like for example the rapidity or the transverse momentum as well as the invariant mass of a dijet pair. Do not hesitate to contact your tutor in case of questions!

Try to understand the various options to plot different observables by playing around with the possible settings. All the predefined observables are listed with their names and possible applications in `Cards/plot_card.dat`. (Some of them are commented out, however.) You can define sets of particles you want to treat the same ('particle classes') and examine their distributions. This is done at the beginning, after the introduction section, between the `Classes` tags.

To plot quantities of the $pp \to e^- \bar{\nu}_e$ process, you should specify two classes: one class containing the electron and one class containing the neutrino. Go to the `Classes` tag in `plot_card.dat` and define the two classes. All particles in a class are identified with their PDG code. For example, the electron has the code 11, the electron anti-neutrino has the code -12. For the plot and cut statements, these classes will be referred to not by their name but by their ordering — first defined class, second class etc.

NB: a special entry `mET`, which denotes the missing transverse momentum in the event, is automatically inserted into this list. It is treated in a special way and does *not* increment the index of subsequent classes. For example, if the class before `mET` has index 2, the one after `mET` will have index 3.

Where does the missing transverse momentum in the event stem from?

Usually, MadAnalysis is executed directly with the `launch` command, but you can also produce new plots for a previously produced run. To do so, open a terminal and navigate to the `Events` directory of your process. Then, run MadAnalysis with the command

```
../bin/madevent or
MG5_aMC> plot run_XX
```

where `run_XX` is the name of a previously produced set of Monte Carlo events.

NB: Plots for the NLO aMC@NLO operation mode can only be produced if you have applied the parton shower. Thus, you have to use the events from your LO event generation.

- Have a look at the distribution of the transverse momentum p_{T} of the electron at a centre-of-mass energy of 13 TeV. How does the differential production cross section change as a function of p_{T}?
- Plot the invariant mass of the (e^-, $\bar{\nu}_e$) pair and their angular difference `dRij`. Adjust the plot range of the invariant mass to $[0, 200]$GeV and decrease the bin size. Each distribution will have unique features: what are they and what is their origin?

2 Calculate $pp \to Z/\gamma^* \to \mu^+\mu^-$ production

- Generate the process $pp \to \mu^+\mu^-$. Do not run the Pythia shower or any additional package for this process.
- Set the beam energy to 6500 GeV each and apply cuts on the transverse momentum of both muons: $p_{\mathrm{T},\mu} > 30$ GeV (this corresponds to a typical selection applied by the LHC experiments) and remove the cut on the maximum pseudorapidity η_μ (parameters `ptl` and `etal` in `run_card.dat`).
- Plot the muon transverse momentum and the di-muon invariant mass distribution. Explain the features observed and the difference with respect to W^- production studied in the previous example.
- Have a look at the muon pseudorapidity distributions. Perform a new run with a cut of $|\eta_\mu| < 2.5$ applied (this is the typical geometric *acceptance* of an LHC muon detector) by editing `run_card.dat` and try to understand the effect on the pseudorapidity distributions.

- Apply an additional cut of $80\,\mathrm{GeV} < M_{\mu^+\mu^-} < 100\,\mathrm{GeV}$, calculate the corresponding cross section. Estimate the number of events expected in a dataset corresponding to an integrated luminosity of $L_{\mathrm{int}} = 5\,\mathrm{fb}^{-1}$, given a selection and reconstruction efficiency of 80 % per muon.

- (Optional) Compare the contributions from the photon and Z boson by excluding one of them. Exclusion of a particle/resonance can be done by appending "`/ name`" at the end of the line with the process definition. What can you conclude about the size of the interference term?

- (Optional) Calculate the cross sections for all possible Z boson decays in the mass window $80\,\mathrm{GeV} < M_{\mu^+\mu^-} < 100\,\mathrm{GeV}$. If you add each possible decay channel as an extra subprocess, you can derive the partial decay widths of the Z boson from the ratio of the different cross sections. Determine the partial widths and compare your results with the literature values.