Monte Carlo event generation

The tutorial

Benjamin Fuks

LPTHE / Sorbonne Université

Lectures and tutorials on Monte Carlo event generation

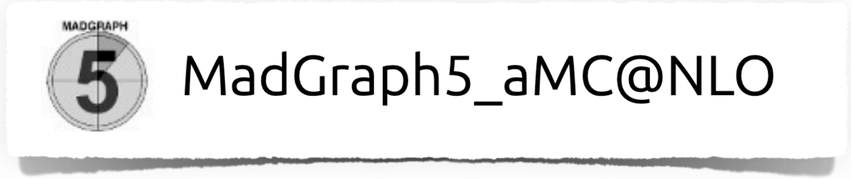
The 14th IDPASC school

15 – 25 July 2025

The MG5aMC - let's get started

Requirements

- Computer (with internet connection)
- Terminal (for shell operations)
- Basic knowledge of shell commands (*pwd, mkdir, cd, cp, mv, rm, tar, less, more*, …)
- Python 3.9 (or higher)
- gfortran/gcc 4.6 (or higher)
- matplotlib [for MadAnalysis5 and plots]



First step with MG5aMC

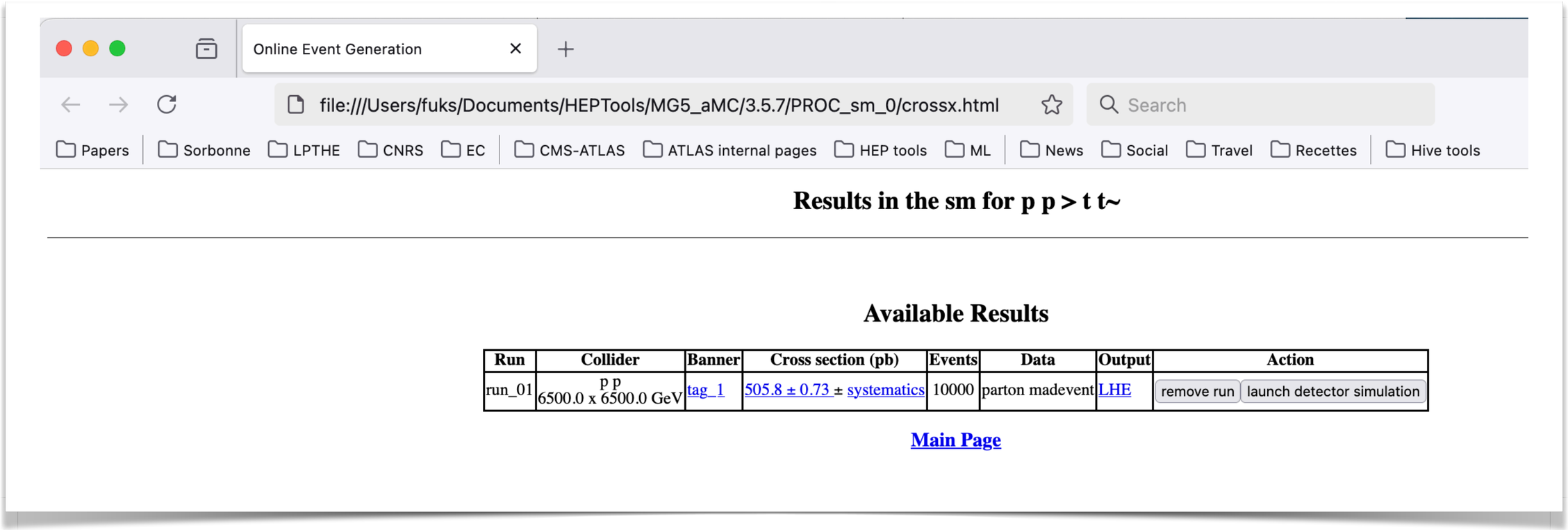
- Download MG5_aMC_vX.Y.Z.tar.gz (v3.5.9 for instance) from launchpad:
  https://launchpad.net/mg5amcnlo
- From the working directory, unpack the tarball
  $ tar xzvf MG5_aMC_X.Y.Z.tar.gz
- Go the the MG5 directory
  $ cd MG5_aMC_vX_Y_Z
- Start MG5aMC:
  $ ./bin/mg5_aMC

Top-antitop at the LHC

A first process

- From the MG5_aMC> prompt:
  - MG5_aMC> generate p p > t t~
  - MG5_aMC> output
  - MG5_aMC> launch
- Ignore all questions from MG5aMC (press "enter")
- Webpage in the browser automatically displayed

Ready to handle LHC simulations!



How to survive to MG5aMC

A few steps further (optional)

- For plots:
  MG5_aMC> install MadAnalysis5
- For parton-showering and hadronisation:
  MG5_aMC> install pythia8
- LHAPDF (parton densities)
  MG5_aMC> install lhapdf6
- Failure: install the package externally

MG5aMC in a nutshell

- From the MG5_aMC> prompt:
  MG5_aMC> import model MODEL
  (e.g. 2HDM, MSSM)
  MG5_aMC> generate PROCESS
  (e.g. p p > t t~)
  MG5_aMC> output NAME
  (e.g. any folder name)
  MG5_aMC> launch

MG5aMC tips

- Auto-completion by "tab"
- The internal helper
  MG5_aMC> help
  MG5_aMC> help COMMAND
  (e.g. generate)
- The MG5 tutorial:
  MG5_aMC> tutorial

Exercise 1 – top-antitop at the LHC

Feynman diagrams

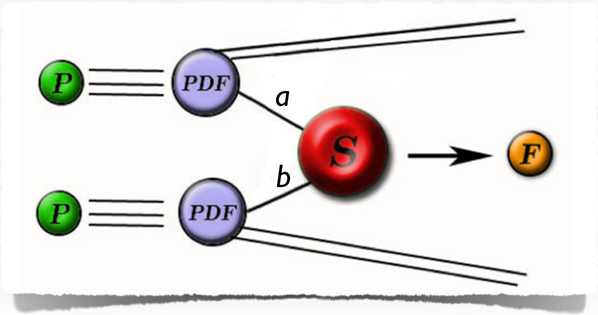
- From the MG5_aMC> prompt:
  MG5_aMC> generate p p > t t~
- Question 1: Feynman diagrams
  - ⋆ Which partonic subprocesses contribute ?
  - ⋆ What do the Feynman diagrams look like ?

Answer:

MG5_aMC>display diagrams

Reminder: predictions at the LHC

Distribution of an observable ω: the QCD factorisation theorem



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \sum_{a,b} \int \mathrm{d}x_a \, \mathrm{d}x_b \, \mathrm{d}\Phi_n \; f_{a/p}(x_a;\mu_F) \; f_{b/p}(x_b;\mu_F) \; \frac{1}{2s} \overline{|\mathcal{M}|}^2 (s;\mu_F,\mu_R) \; \mathcal{O}_\omega(\Phi_n)$$

- Long distance physics: the parton densities
  - ⋆ Content of the proton
  - ⋆ Dominating processes at colliders (LHC *vs.* Tevatron)
- Short distance physics: the differential parton cross section $\mathrm{d}\sigma_{ab}$
  - ⋆ Leading order: OK for shapes
  - ⋆ Higher-order: reduction of uncertainties

Exercise 2 – top-antitop production in 2010, 2015 and 2025

Cross section as a function of $\sqrt{s}$

- Same process as before:

  MG5_aMC> generate p p > t t~
- Question 2: cross sections @ the LHC
  - ⋆ Cross section @ 7 TeV (Run-1, 2010)
  - ⋆ Cross section @ 13 TeV (Run-2, 2015−2018)
  - ⋆ Cross section @ 13.6 TeV (Run-3, 2022−2025)

Answer 1:

MG5_aMC> output NAME
MG5_aMC> open index.html
(check the diagrams)
MG5_aMC> launch
(modify run_card)

Answer 2:

MG5_aMC> output NAME
MG5_aMC> open index.html
(check the diagrams)
MG5_aMC> launch -n run1
> set LHC 7
(for LHC @ 7 TeV)

Scripting is good!

Exercise 2 – top-antitop production in 2010, 2015 and 2025

Cross section as a function of $\sqrt{s}$

- Same process as before:

  MG5_aMC> generate p p > t t~

- Question 2: cross sections @ the LHC
  - ⋆ Cross section @ 7 TeV (Run-1, 2010)
  - ⋆ Cross section @ 13 TeV (Run-2, 2015−2018)
  - ⋆ Cross section @ 13.6 TeV (Run-3, 2022−2025)

Results in the sm for p p > t t~

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	505.8 ± 0.73 ± systematics	10000	parton madevent	LHE	remove run launch detector simulation
run1	p p 3500.0 x 3500.0 GeV	tag_1	109.5 ± 0.15 ± systematics	10000	parton madevent	LHE	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	504.1 ± 0.61 ± systematics	10000	parton madevent	LHE	remove run launch detector simulation
run_03	p p 6800.0 x 6800.0 GeV	tag_1	559.3 ± 0.71 ± systematics	10000	parton madevent	LHE	remove run launch detector simulation

Main Page

Exercise 3 – 4FNS vs 5FNS

Quark content of the proton

- Question 3a: What about initial *b*-quarks?
  - ⋆ Check the diagrams
- Question 3b: How much do *b* quarks contribute?
  - ⋆ Cross section contribution?

Answer 1:

```
MG5_aMC> display multiparticles
MG5_aMC> define p = p b b~
MG5_aMC> generate ...; output ...; launch
```

Answer 2 (best!):

```
MG5_aMC> import model sm-no_b_mass
```
(SM with $m_b = 0$)
```
MG5_aMC> display multiparticles
MG5_aMC> generate ...; output ...; launch
```

Exercise 3 – 4FNS vs 5FNS

Quark content of the proton

- Question 3a: What about initial *b*-quarks?
  - ⋆ Check the diagrams
- Question 3b: How much do *b* quarks contribute?
  - ⋆ Cross section contribution?

Results in the sm-no_b_mass for p p > t t~

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 3500.0 x 3500.0 GeV	tag_1	110 ± 0.2 ± systematics	10000	parton madevent	LHE	remove run / launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	505.2 ± 0.6 ± systematics	10000	parton madevent	LHE	remove run / launch detector simulation
run_03	p p 6800.0 x 6800.0 GeV	tag_1	559.8 ± 0.65 ± systematics	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

How is the impact?

Exercise 4 – LHC *vs* Tevatron

Proton-proton *vs* proton-antiproton collisions

- Question 4a: How to calculate Tevatron cross sections ($p\bar{p}$ machine)?
- Question 4b: Compare LHC and Tevatron rates at 2 TeV
  - ⋆ Where the difference is coming from?
    (explore the contributing subprocesses)

run_04	p p 1000.0 x 1000.0 GeV	tag_1	1.55 ± 0.0024 ± systematics	10000	parton madevent	LHE	remove run launch detector simulation
run_05	p p~ 1000.0 x 1000.0 GeV	tag_1	6.343 ± 0.009 ± systematics	10000	parton madevent	LHE	remove run launch detector simulation

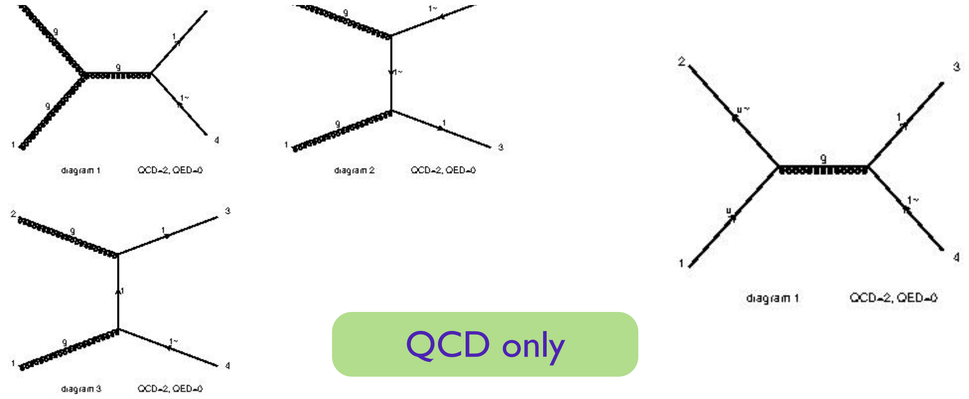
Exercise 5 – Electroweak diagrams

More diagrams?!

- Question 5.a: Compare LHC rates obtained with the following commands
  - ⋆ MG5_aMC> generate p p > t t~
  - ⋆ MG5_aMC> generate p p > t t~ QCD=0
  - ⋆ MG5_aMC> generate p p > t t~ QED=0
  - ⋆ MG5_aMC> generate p p > t t~ QED=99
- Question 5.b: Explain the differences

s= 504.09 ± 0.611 (pb)

Graph	Cross-Section ↓
/Users/fuks/Documents/HEPTools/MG5_aMC/3.5.7/PROC_sm_0/SubProcesses/P1_gg_ttx	439.8
/Users/fuks/Documents/HEPTools/MG5_aMC/3.5.7/PROC_sm_0/SubProcesses/P1_qq_ttx	64.28

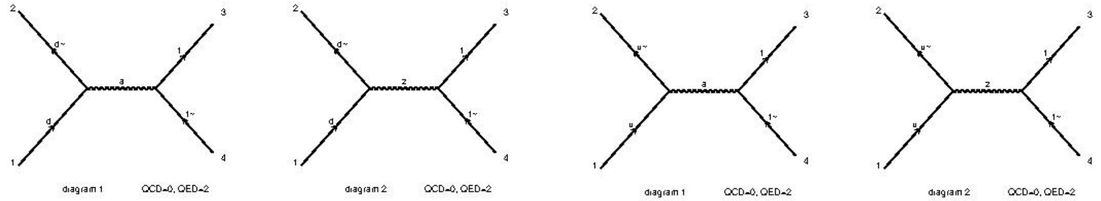


QCD only

s= 0.36128 ± 0.000415 (pb)

Graph	Cross-Section ↓
/Users/fuks/Documents/HEPTools/MG5_aMC/3.5.7/PROC_sm_1/SubProcesses/P1_qq_ttx	0.3613

EW only



Test – Final exercise

Final questions

- Question 6a: Determine the energy dependence of the cross section for $\sqrt{s} \in [1,100]$TeV
  - ⋆ Put the MG5aMC commands inside a text file
    ./bin/mg5_aMC TEXT FILE
- Question 6b: Compare with data
  - ⋆ Find measurements online
- Question 6c: Determine the top mass dependence of the cross section for $m_t \in [170,180]$ GeV
- Question 6d: Compare with data
  - ⋆ Find measurements online