MadGraph tutorial

Dark Tool workshop

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Outline of the tutorial

- Outline:
  1. Compute LO cross section
  2. Modify model and run parameters
  3. Understand process syntax and plot distributions
  4. Load and check BSM model
  5. Test BSM process
  6. Compute BSM mass scan and branching ratio

Where to find help

- Command ‘help’ or ‘help COMMAND’
- Launchpad
  - https://answers.launchpad.net/madgraph5
  - https://answers.launchpad.net/madgraph5/+faqs
- Ask
  - luca.beccatini@uclouvain.be

Exercise 1: built-in tutorial

- Launch MadGraph:
  - ‘cd MG5_aMC_v3_6_2’
  - ‘./bin/mg5_aMC’

- Start the built-in tutorial:
  - ‘tutorial’
  - Follow the instructions

MadGraph base commands

- Base commands:
  - To check the model:
    - ‘display particles’: display all the model particles
    - ‘display interactions’: display all the model interactions
  - To compute a cross section:
    - ‘generate p p > z g’: generate the process
    - ‘display diagrams’: display all the Feynman diagrams of the generated process
    - ‘output dir_name’: create a directory dir_name to evaluate the process
    - ‘launch dir_name’: evaluate the process
  - To quit:
    - ‘exit’

Exercise 2: MadGraph Cards

- Compute LO cross section for p p > z jet:
  - ‘generate p p > z j’
  - ‘output; launch’
  - Press Enter
  - Check param_card: ‘1’
  - Check run_card: ‘2’
  - Press Enter

- Questions:
  - What is the default value for the Z mass?
  - What about the W mass?
  - What is the beam energy?
  - Are there any cuts?

Exercise 2: Solution

- Cards:
  - param_card: model parameters
  - run_card: beam/run and cuts parameters

- Questions:

- Z mass

```
#*********************************************************************
## PARAM_CARD AUTOMATICALLY GENERATED BY MG5 FOLLOWING UFO MODEL    ####
#*********************************************************************
##                                                                   ##
##  Width set on Auto will be computed following the information     ##
##        present in the decay.py files of the model.                ##
##        See  arXiv:1402.1178 for more details.                     ##
##                                                                   ##
#*********************************************************************

#####################################
## INFORMATION FOR MASS
#####################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   23 9.118800e+01 # MZ
   25 1.250000e+02 # MH
```

- Beam energy

```
#*********************************************************************
# Collider type and energy                                           *
# lpp: 0=No PDF, 1=proton, -1=antiproton,                            *
#               2=elastic photon of proton/ion beam                  *
#            +/-3=PDF of electron/positron beam                      *
#            +/-4=PDF of muon/antimuon beam                          *
#*********************************************************************
    1       = lpp1    ! beam 1 type
    1       = lpp2    ! beam 2 type
  6500.0    = ebeam1  ! beam 1 total energy in GeV
  6500.0    = ebeam2  ! beam 2 total energy in GeV
```

- Cuts

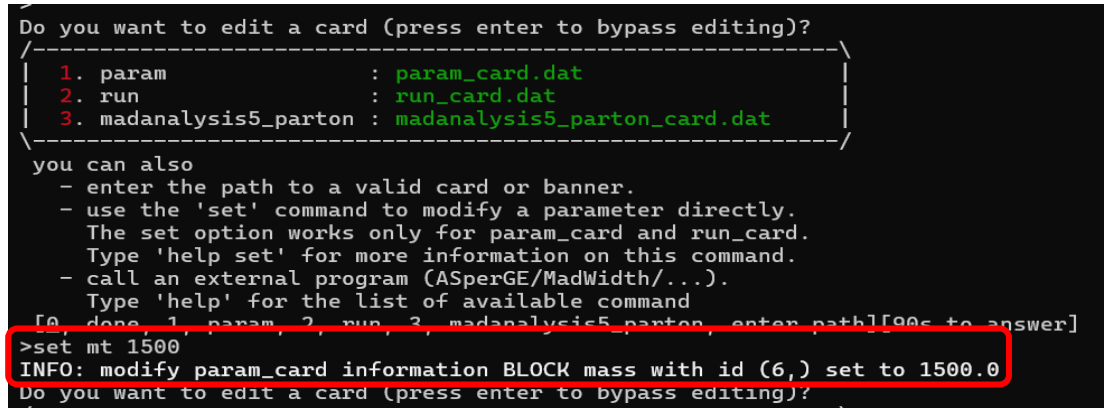
```
#*********************************************************************
# Standard Cuts                                                      *
#*********************************************************************
# Minimum and maximum pt's (for max, -1 means no cut)                *
#*********************************************************************
 20.0  = ptj       ! minimum pt for the jets
 -1.0  = ptjmax    ! maximum pt for the jets
 {}    = pt_min_pdg ! pt cut for other particles (use pdg code). Applied on particle and anti-particle
 {}    = pt_max_pdg ! pt cut for other particles (syntax e.g. {6: 100, 25: 50})
#
# For display option for energy cut in the partonic center of mass frame type 'update ecut'
#
#*********************************************************************
# Maximum and minimum absolute rapidity (for max, -1 means no cut)   *
#*********************************************************************
 5.0 = etaj    ! max rap for the jets
```

- W mass

```
14 0.000000e+00 # vm : 0.0
16 0.000000e+00 # vt : 0.0
21 0.000000e+00 # g : 0.0
22 0.000000e+00 # a : 0.0
24 8.041900e+01 # w+ : cmath.sqrt(mz__exp__2/2. + cmath.sqrt(mz__exp__4/4. - (aew*cmath.pi*mz__exp__2)/(gf*sqrt__2)))
```

MadGraph Cards

- How to modify model, beam or cuts parameters:
  - You can edit the card
  - Shortcut:
    instead of open the parameter or run card, you can use:
    ‘set parameter value’
    - example:



Exercise 3: MadAnalysis and Syntax

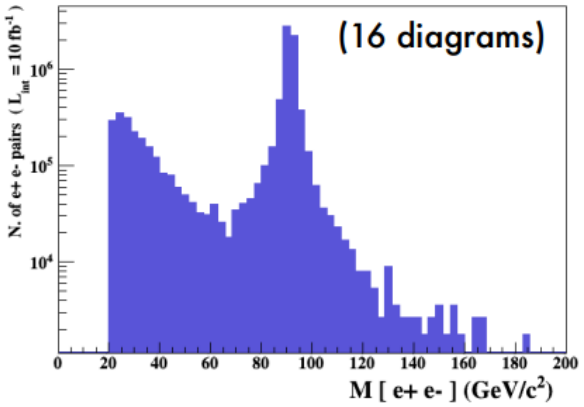
- Compute the LO cross section and analysis for p p > mu+ mu-:
  - ‘generate p p > mu+ mu- ; output ; launch’
  - Activate MadAnalysis:
    if “analysis = off’’ => ‘3’
    if “analysis = MadAnalysis5’’ => ok
  - Open the crossx.html generated in the process directory
  - Click on “MA5_report_analysis1’’
  - Find the invariant mass plot

- Additional, repeat for the processes:
  - ‘p p > z, z > mu+ mu-’
  - ‘p p > mu+ mu- $ z’ (in the run_card, check that sde_strategy=1)
  - ‘p p > mu+ mu- / z’

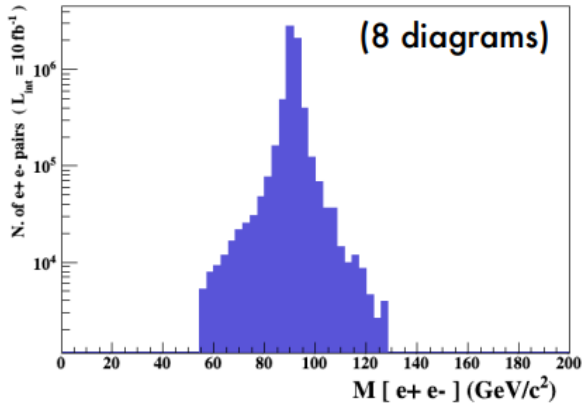
Exercise 3: Solution

- Standard process

p p > mu+ mu-



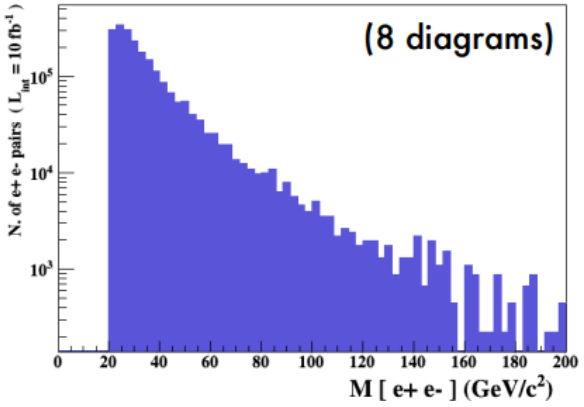
p p >z , z > mu+ mu-



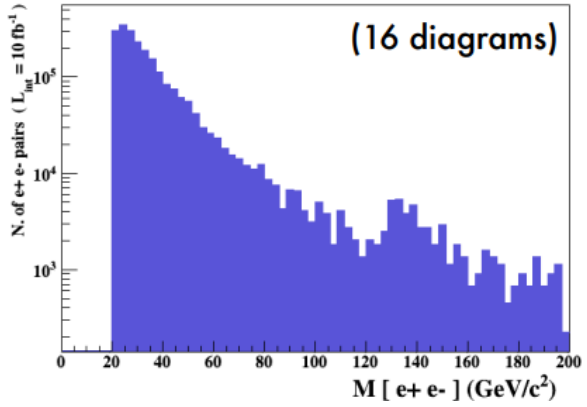
- Z on-shell decay

- Z veto

p p > mu+ mu- /z



p p > mu+ mu- $ z

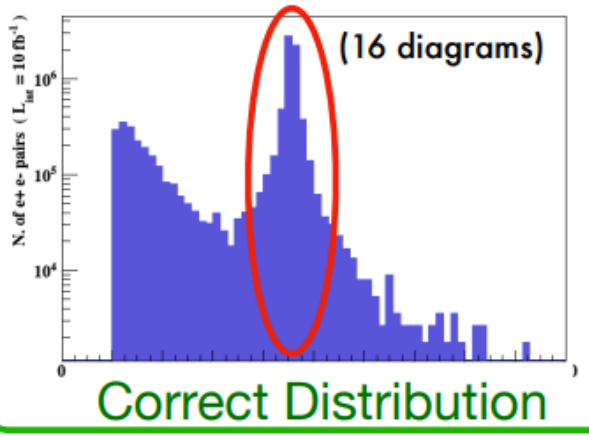


- Z on-shell veto

Exercise 3: Solution

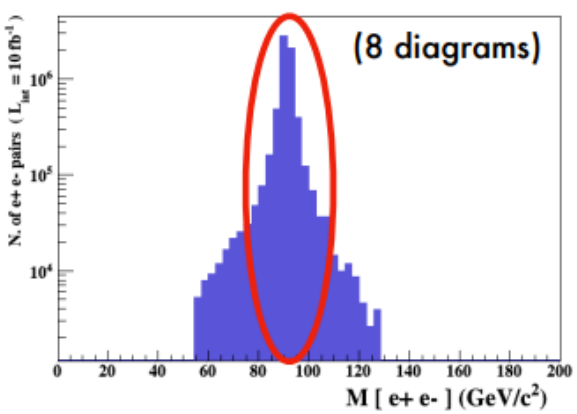
- Standard process

p p > mu+ mu-



Z Peak

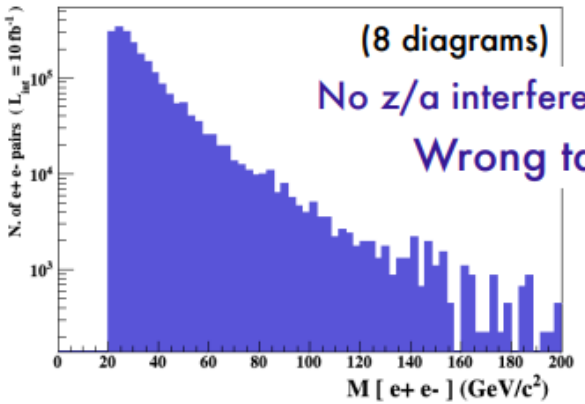
p p >z , z > mu+ mu-



- Z on-shell decay

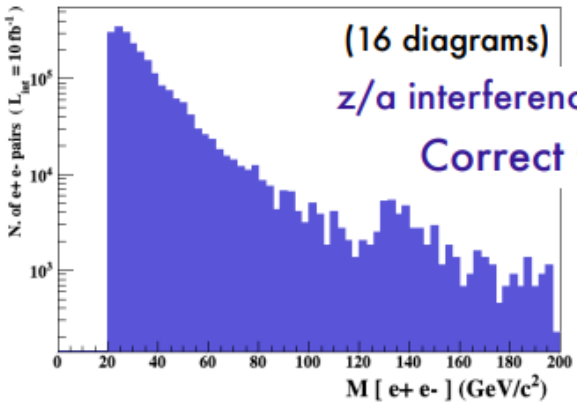
- Z veto

p p > mu+ mu- /z



No Z Peak

p p > mu+ mu- $ z



- Z on-shell veto

Syntax advices

- Preferred syntax:
  - On-shell decay
    ‘p p > z , z > mu+ mu-’
  - Forbid on-shell s-channel
    ‘p p > mu+ mu- $z’

- Syntax to avoid:
  - Single s channel
    ‘p p > z > mu+ mu-’
  - Forbid particle
    ‘p p > mu+ mu- /z’

  - Not gauge invariant
  - Ignores diagram interference
  - Can provide unphysical distributions

Exercize 4: Load and check model

Simplified DM model with vector mediator

$$\mathcal{L}_{DM}^{Y_1} = \bar{\chi}\gamma_\mu(g_{DM}^V + g_{DM}^A\gamma^5)\chi\, Y_1^\mu,$$
$$\mathcal{L}_{SM}^{Y_1} = \bar{t}\gamma_\mu(g_t^V + g_t^A\gamma^5)t\, Y_1^\mu + \bar{b}\gamma_\mu(-g_t^A\gamma^5)b\, Y_1^\mu$$

- Load model:
  - List available models: ‘display modellist’
  - Load model: ‘import model DMsimp_s_spin1’
- Check model:
  - ‘display particles’
  - ‘display interactions’
  - Check process validity: ‘check d d~ > xd xd~ ’

Exercize 4: Load and check model

- Check model:
  - ‘display particles’

```
MG5_aMC>display particles
Current model contains 26 particles:
w+/w- gha/gha~ ghz/ghz~ ghwp/ghwp~ ghwm/ghwm~ ghg/ghg~ ve/ve~ vm/vm~ vt/vt~ e-/e+ mu-/mu+ ta-/ta+ u/u~ c/c~ t/t~ d/d~ s/s~ b/b~ xc/xc~ xd/xd~
a z g h xr y1
MG5_aMC>
```

  - ‘display interactions’

```
Current model contains 292 interactions
1:h h h QED=2 base
2:h h QED=1 base
3:gha ghwm~ w- QED=1 base
4:gha ghwp~ w+ QED=1 base
5:ghwm gha~ w+ QED=1 base
6:ghwm ghwm~ h QED=1 base
7:ghwm ghwm~ a QED=1 base
8:ghwm ghwm~ z QED=1 base
9:ghwm ghz~ w+ QED=1 base
10:ghwp gha~ w- QED=1 base
11:ghwp ghwp~ h QED=1 base
12:ghwp ghwp~ a QED=1 base
13:ghwp ghwp~ z QED=1 base
14:ghwp ghz~ w- QED=1 base
15:ghz ghwm~ w- QED=1 base
16:ghz ghwp~ w+ QED=1 base
17:ghz ghz~ h QED=1 base
18:ghg ghg~ g QCD=1 base
19:g g g QCD=1 base
20:g g g g QCD=2 base
21:ta+ ta- h QED=1 base
22:t~ t h QED=1 base
23:a w- w+ QED=1 base
24:w- w+ h h QED=2 base
25:w- w+ h QED=1 base
26:a a w- w+ QED=2 base
27:w- w+ z QED=1 base
28:w- w- w+ w+ QED=2 base
30:b~ b y1 DMV=1 base
31:d~ b y1 DMV=1 base
32:c~ c y1 DMV=1 base
33:b~ d y1 DMV=1 base
35:e+ e- y1 DMV=1 base
```

  - Check process validity

```
Lorentz invariance results:
Process          Min element       Max element       Relative diff.    Result
d d~ > xd xd~    6.9029061781e-02  6.9029061781e-02  4.0208536665e-15  Passed
Summary: 1/1 passed, 0/1 failed
Gauge results (switching between Unitary/Feynman/axial gauge):
Process          Unitary           Feynman           Relative diff.    Result
d d~ > xd xd~    3.7041735880e-02  3.7041735880e-02  0.0000000000e+00  Passed
Summary: 1/1 passed, 0/1 failed
Process permutation results:
Process          Min element       Max element       Relative diff.    Result
d d~ > xd xd~    5.1416961704e-02  5.1416961704e-02  6.8826235035e-15  Passed
Summary: 1/1 passed, 0/1 failed
```

- If the model has a resonance at 1TeV you can get «ZeroDivisionError». Recheck with ‘check d d~ > xd xd~ --energy=2000’

Exercize 5: Test DM process

- Compute d d~ into g + y1, that decays on-shell into xd xd~

- Questions:
  - Which are the Feynman diagrams?
  - How much is the cross section?
  - How is the distribution of the g pT?

Exercise 5: Solution

- Compute d d~ into g + y1, that decays on-shell into xd xd~:
  - ‘generate d d~ > g y1 , y1 > xd xd~’

- Questions:

- How much is the cross section?

```
refine 10000
Creating Jobs
INFO: Refine results to 10000
INFO: Generating 10000.0 unweighted events.
sum of cpu time of last step: 1 seconds
INFO: Effective Luminosity 2838.3556459624388 pb^-1
INFO: need to improve 2 channels
- Current estimate of cross-section: 4.2278 +- 0.04327505032926016
    P1_qq_gy1_y1_xdxdx
INFO:  Idle: 1,  Running: 12,  Completed: 0 [ current time: 16h02 ]
INFO:  Idle: 0,  Running: 0,  Completed: 13 [  0.75s  ]
INFO: Combining runs
sum of cpu time of last step: 13 seconds
INFO: finish refine
refine 10000 --treshold=0.9
No need for second refine due to stability of cross-section
INFO: Combining Events
combination of events done in 1.2777745723724365 s
  === Results Summary for run: run_01 tag: tag_1 ===

    Cross-section :   4.232 +- 0.01512 pb
    Nb of events :  10000
```

- Which are the Feynman diagrams?

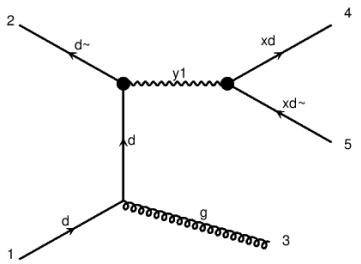


diagram 1 DMV=2, QCD=1, QED=0

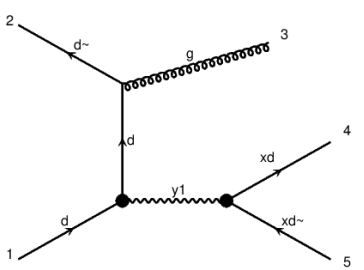
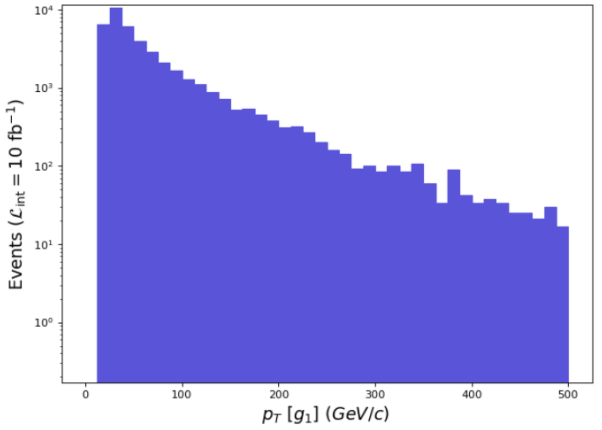


diagram 2 DMV=2, QCD=1, QED=0

- How is the distribution of the g pT?



Exercise 6: DM Scan mass

- ‘scan’ command:
  - compute cross section over model parameters scans (like couplings, masses, ..)
  - How to use it:
    substitute the select parameter with
    - ‘scan:[x_1, x_2, x_3, ..] ’ (in the parameter card)
    - ‘scan:range(x_i, x_f, x_step)’ (in the parameter card)

- Compute the cross section for d d~ into y1 with scan:[500, 1000, 1500]
- Additonal:
  - Repeat for d d~ > y1 , y1 > xd xd~
  - Compute the branching ratio
  - Repeat for d d~ > y1 , y1 > xd xd~, with y1 width ‘Auto’

Exercise 6: Solution without Auto

- Cross section for d d~ > y1 with my1=scan:[500, 1000, 1500]

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	43.74 ± 0.043	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	3.054 ± 0.003	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	0.5022 ± 0.00045	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation

- Cross section for d d~ > y1, y1 > xd xd~ with my1=scan:[500, 1000, 1500]

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	56.95 ± 0.058	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	7.926 ± 0.0084	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	1.956 ± 0.0021	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation

- Braching ratio: [1.3, 2.6, 3.9] WRONG!!

Exercise 6: Solution with Auto

- Cross section for d d~ > y1 with my1=scan:[500, 1000, 1500]

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	43.74 ± 0.043	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	3.054 ± 0.003	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	0.5022 ± 0.00045	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation

- Cross section for d d~ > y1, y1 > xd xd~ with my1=scan:[500, 1000, 1500] and wy1='auto'

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	20.8 ± 0.021	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	1.466 ± 0.0018	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	0.249 ± 0.00049	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation

- Braching ratio: [0.47, 0.48, 0.49] CORRECT

- Changing a particle's mass without updating its width can lead to unphysical results, enabling 'auto' ensures the width is recalculated consistently.

What else?

- What else you can do with MadGraph?
  - Compute NLO cross secction
    including QCD and QED corrections
  - Generate events with parton shower and hadronization
    with Pythia, Herwig, or Sherpa
  - Full simulation of DM signals
    From production to decay at colliders, including detector-level studiesInterface with Delphes
  - Use custom UFO model for for exclusion plots and sensitivity studies

THANKS FOR YOUR ATTENTION!