MadGraph Tutorial

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Plan

Help and Instructions

- This presentation should be self-contained
- See https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Milan for some lectures
- See https://arxiv.org/pdf/1106.0522.pdf including appendices for useful information

Tutorial

- MG5aMC Basics
- Heavily based off Olivier Mattelaer and Marco Zaro's previous tutorials!!

Aim of MadGraph5_aMC@NLO

- Calculate hard matrix element and/or cross section for any process in any model at (N)LO
- Aims to be as generic and user friendly as possible
- Can export results to your favourite parton shower program
- Can import your favourite model to calculate the process

Flow of MadGraph5_aMC@NLO

1. Choose model
   - ➡ Stored as UFO file (see https://arxiv.org/pdf/1108.2040.pdf)
   - ➡ 4 prebuilt models
   - ➡ Otherwise use FeynRules to output new model from Lagrangian
2. Choose process to study
   - ➡ MadGraph generates, writes, and builds a program on the fly to study this process
3. Run the program/calculate the process

Tutorial map

Learning MG5

1. Download MG5, follow the built-in tutorial
2. Cards meaning
3. Meaning of QCD/QED
4. Details of syntax ($/)
5. tt~ processes
   - ➡ Scripting
   - ➡ Decay
6. Other models

Where to find help?

- Ask us
- Use the command "help" / "help XXX"
  - ➡ "help" tell you the next command that you need to do.
- Launchpad:
  - ➡ https://answers.launchpad.net/madgraph5
  - ➡ FAQ: https://answers.launchpad.net/madgraph5/+faqs

Exercise 1: Download MG5 & Built-in tutorial

- Download from https://launchpad.net/mg5amcnlo/3.0/3.4.x/+download/MG5_aMC_v3.4.0.tar.gz
  - ➡Unpack with tar xvzf MG5_aMC_v3.4.0.tar.gz
- Launch the code
  - ➡./bin/mg5_aMC
- Type tutorial
  - ➡ Follow instructions

Exercise 2: What are those cards?

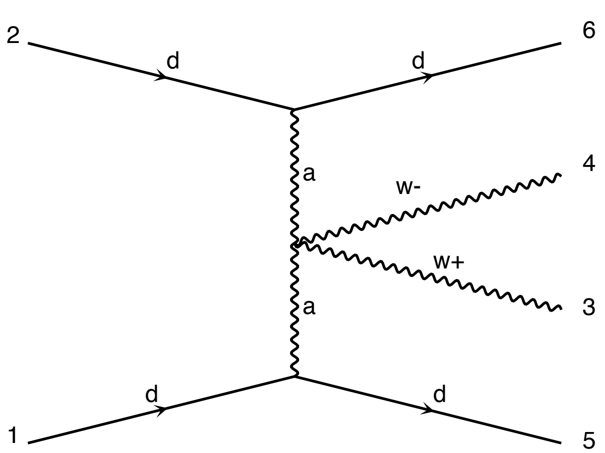
- Run a new process. In the launch step, read the cards and identify what they do
  - ➡ param_card: model parameters
  - ➡ run_card: beam/run parameters and cuts
    - https://answers.launchpad.net/madgraph5/+faq/2014

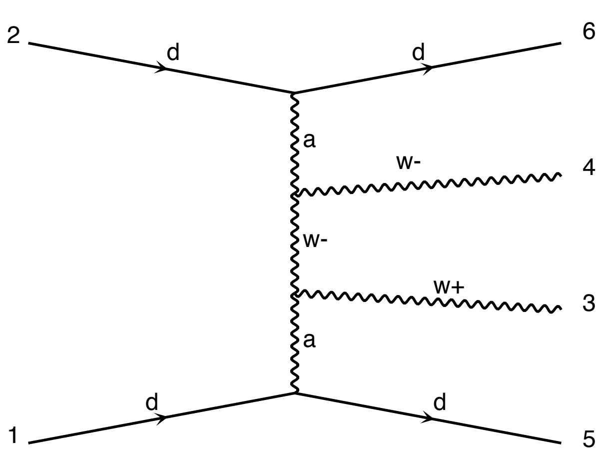
Exercise 2: Cards Meaning

- How do you change?
  - ➡ top mass
  - ➡ top width
  - ➡ W mass
  - ➡ beam energy
  - ➡ pt cut on the lepton
- Change some of these variables and observe their effect

Exercise 3 : QED/QCD Syntax

- What's the meaning of the order QED/QCD?
- What's the difference between
  - ➡ p p > t t~
  - ➡ p p > t t~ QED=2
  - ➡ p p > t t~ QED=0
  - ➡ p p > t t~ QCD=0
  - ➡ p p > t t~ QED<=2
  - ➡ p p > t t~ QCD^2==2
- Compute the cross-section for each of those and check the diagrams created
- Generate VBF processes





Exercise 4: Syntax ($/)

- Generate the cross-section and the distribution (invariant mass) for
  - ➡ p p > e+ e-
  - ➡ p p > z, z > e+ e-
  - ➡ p p > e+ e- $ z (note: in run_card must set sde_strategy=1)
  - ➡ p p > e+ e- / z

Hint :To plot automatically distributions:

mg5> install MadAnalysis5

- Use the invariant mass distribution to determine the meaning of each syntax.

Exercise 5:
Top pair production at LO

- Basic questions:
  - Generate the process
  - Which partonic subprocesses contribute?
  - How many Feynman diagrams does each each subprocess have?
  - Output the code
  - Are b-quarks included in the initial state? If not, how can I include them?

- Extra questions:
  - Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
  - Add the top decay and redo the mass scan. Anything strange?

Exercise 5a: Automation

- Compute the cross-section for the top pair production for m_t=170, 172, 174 … 180 GeV.
  - ➡ Do NOT use the interactive interface
    - hint: you can edit the param_card/run_card via the "set" command [After the launch]
    - hint: All commands [including answer to question] can be put in a file. (run ./bin/mg5 PATH_TO_FILE)

Examples

File:

```
import model EWDim6
generate p p > t t~
output TUTO_DIM6
launch
  set nevents 5000
  set MT 170
```

How to Run:

```
./bin/mg5_amc PATH
```

Exercise 5b: Decay Chain

- Generate p p > t t~ , and decay the tops (no need to decay the W's)
  - ➡ Use the decay-chain formalism
  - ➡ Do the same mass scan as in Ex. 5a & compare cross-sections
    - Do you notice something wrong? If so, what did you forget to also update?
    - Update the missing piece and confirm that the issue is fixed

Exercise 5b: Decay Chain and MadSpin

- Generate p p > t t~ , fully decayed (fully leptonic decay for the top)
  - ➡ Using the decay-chain formalism
  - ➡ Using MadSpin
- Compare cross-sections
  - ➡ which one is the correct one?
  - ➡ Why are they different?
- Compare the shape.

Exercise 6: Other Models

- Calculate cross-section and event shapes for p p > j j h
    - ➡ Note how many/which diagrams/subprocesses exist
- Now run the same calculation except this time in the Higgs effective theory
    - ➡ Hint: different models can be loaded with import model <model_name>
- Which model has the greater cross section?
    - ➡ Can you see which process contribute the most to the cross section?

Solutions

- I of course encourage you to try and do the exercises yourself first, but if needed or wanted, the following slides contain the solutions to the exercises

Solution 2: Cards Meaning

- How do you change
  - ➡ top mass
  - ➡ top width
  - ➡ W mass
  - ➡ beam energy
  - ➡ pt cut on the lepton

Param_card

Run_card

- top mass

```
###################################
## INFORMATION FOR MASS
###################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000 # d : 0.0
  2 0.000000 # u : 0.0
  3 0.000000 # s : 0.0
  4 0.000000 # c : 0.0
  11 0.000000 # e- : 0.0
  12 0.000000 # ve : 0.0
  13 0.000000 # mu- : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  21 0.000000 # g : 0.0
  22 0.000000 # a : 0.0
  24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```

```
###################################
## INFORMATION FOR MASS
###################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000 # d : 0.0
  2 0.000000 # u : 0.0
  3 0.000000 # s : 0.0
  4 0.000000 # c : 0.0
  11 0.000000 # e- : 0.0
  12 0.000000 # ve : 0.0
  13 0.000000 # mu- : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  21 0.000000 # g : 0.0
  22 0.000000 #
  24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```

W Mass is an internal parameter!

MG5 didn't use this value!

So you need to change MZ or Gf or alpha_EW

Solution 3: QED/QCD Syntax

- What's the meaning of the order QED/QCD
- What's the difference between
  - ➡ p p > t t~
  - ➡ p p > t t~ QED=2
  - ➡ p p > t t~ QED==2
  - ➡ p p > t t~ QCD=0
  - ➡ p p > t t~ QED<=2
  - ➡ p p > t t~ QCD^2==2

Solution 3 : QED/QCD Syntax

- What's the meaning of the order QED/QCD
  - ➡ This is the number of QED/QCD vertices in diagram
  - ➡ By default MG5 takes the lowest order in QED!
  - ➡ p p > t t~ => p p > t t~ QED=0
  - ➡ p p > t t~ QED=2
    - additional diagrams (photon/z exchange)

p p > t t~

Cross section (pb)
555 ± 0.84

p p > t t~ QED=2

Cross section (pb)
555.8 ± 0.91

No significant QED contribution

Solution 3: QED/QCD Syntax

- QED<=2 is the SAME as QED=2
  - ➡ Quite often source of confusion since most of the people use the = syntax
- QED==2
  - ➡ Only include diagrams with exactly 2 QED vertices
- QCD^2==2
  - ➡ Exactly 2 factors of g_s in squared amplitude
  - ➡ Returns the interference between the QCD and the QED diagrams

Cross section (pb)
-2.985e-16 ± 1.3e-18

Solution 3: QED/QCD Syntax

- generate p p > w+ w- j j
  - ➡ 76 processes
  - ➡ 1432 diagrams
  - ➡ None of them are VBF

- generate p p > w+ w- j j QED = 2
  - ➡ 76 processes
  - ➡ 1432 diagrams
  - ➡ None of them are VBF

- generate p p > w+ w- j j QED = 4
  - ➡ 76 processes
  - ➡ 5332 diagrams
  - ➡ VBF present! + those not VBF

- generate p p > w+ w- j j QCD = 0
  - ➡ 60 processes
  - ➡ 3900 diagrams
  - ➡ VBF present!

- generate p p > w+ w- j j QCD = 2
  - ➡ 76 processes
  - ➡ 5332 diagrams

- generate p p > w+ w- j j QCD = 4
  - ➡ 76 processes
  - ➡ 5332 diagrams

Solution 4: Syntax ($/)

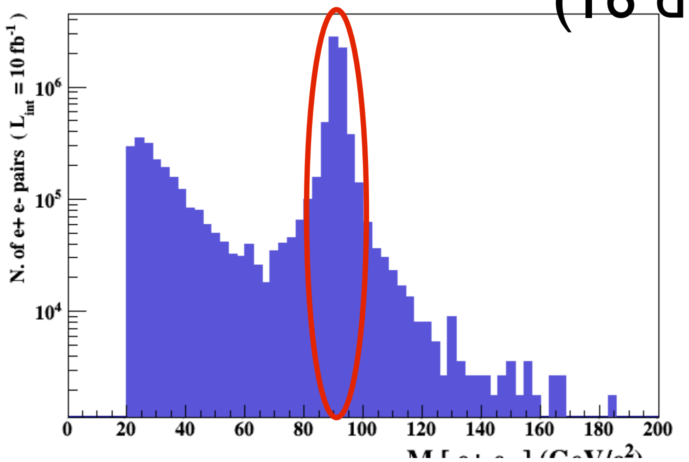
- Generate the cross-section and the distribution (invariant mass) for
  - ➡ p p > e+ e-
  - ➡ p p > z, z > e+ e-
  - ➡ p p > e+ e- $ z (note: in run_card must set sde_strategy=1)
  - ➡ p p > e+ e- / z

Hint :To have automatic distributions:

mg5> install MadAnalysis

p p > e+ e-

(16 diagrams)

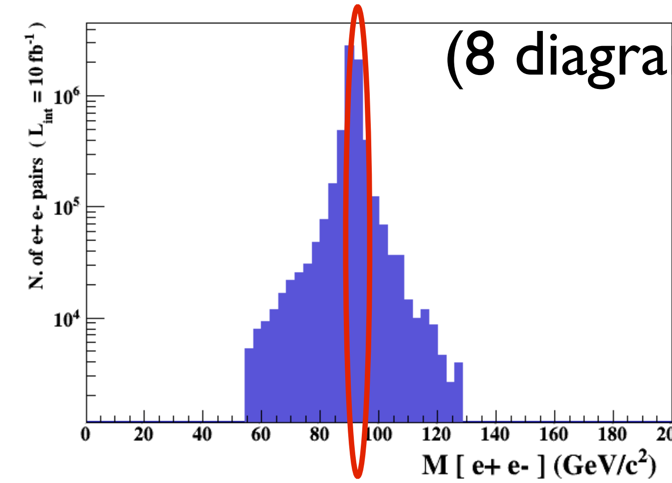


Correct Distribution

Z Peak

p p >z , z > e+ e-

(8 diagrams)



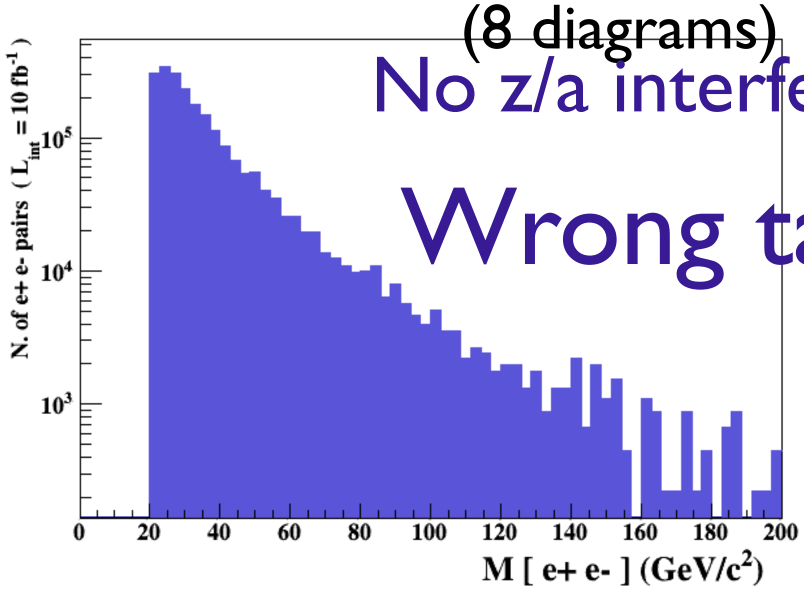
p p > e+ e- /z

(8 diagrams)

No z/a interference

Wrong tail

NO Z Peak



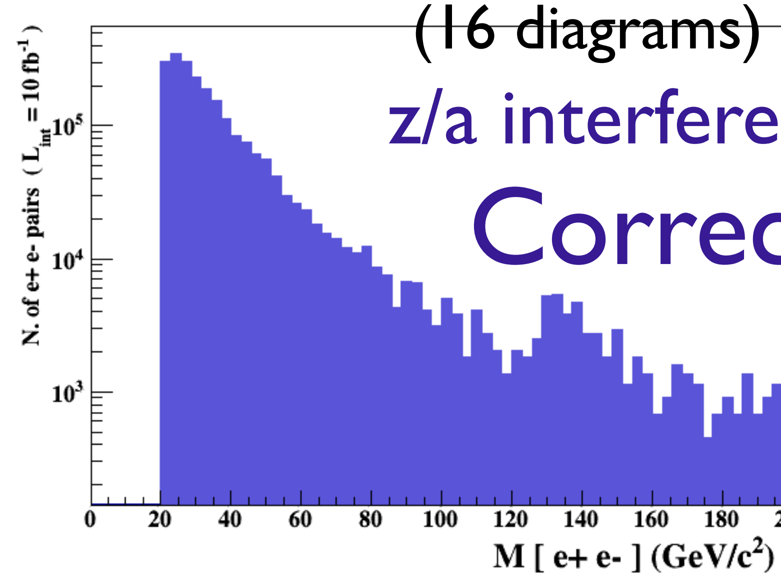
No Z

p p > e+ e- $ z

(16 diagrams)

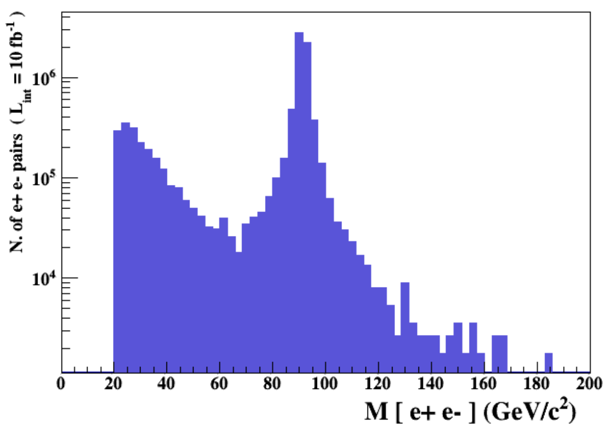
z/a interference

Correct tail



Z- onshell veto

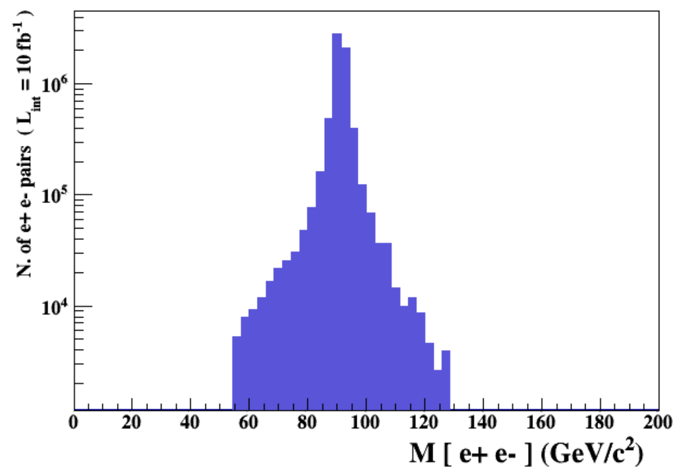
p p > e+ e-



(16 diagrams)

=

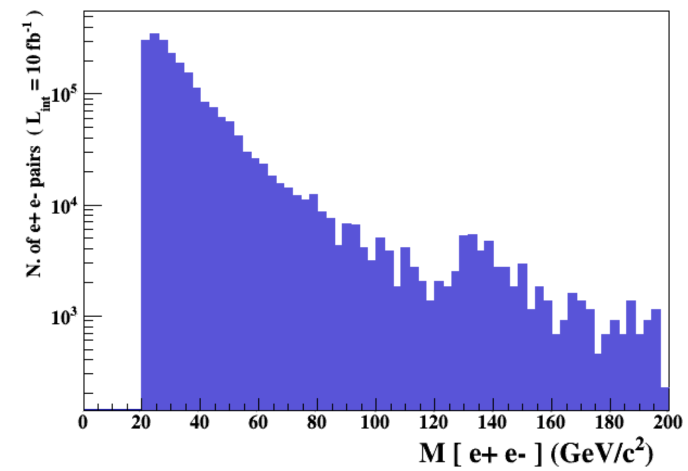
p p >z , z > e+ e-



(8 diagrams)

+

p p > e+ e- $ z



(16 diagrams)

Onshell cut: BW_cut

$$|M^* - M| < BW_{cut} * \Gamma$$

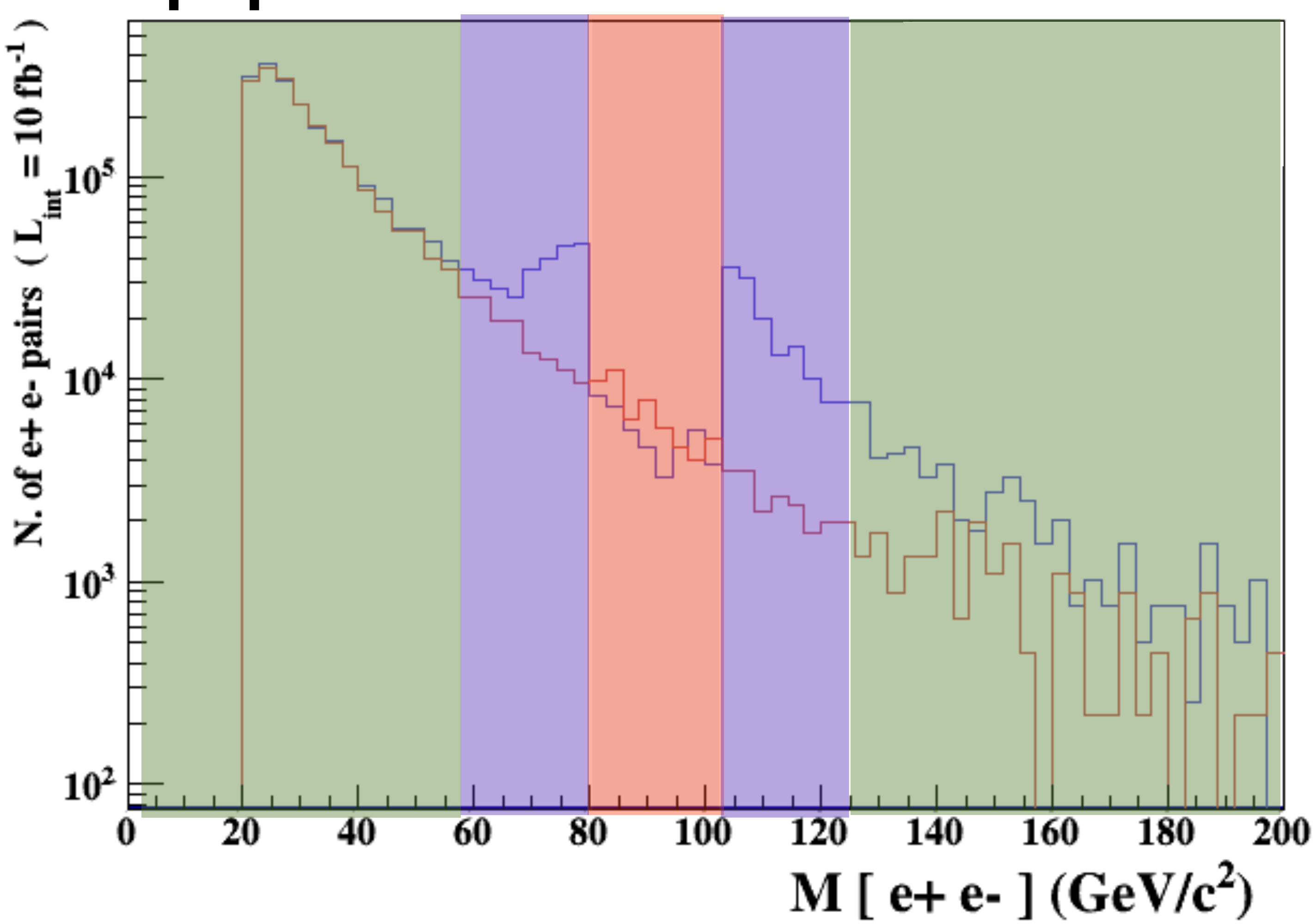
- The Physical distribution is (very close to) exact sum of the two other one.
- The "$" forbids the Z to be on shell but the photon invariant mass can be at MZ (i.e. on shell subtraction).
- The "/" is to be avoided if possible since this leads to violation of gauge invariance.

WARNING

- NEXT SLIDE is generated with bw_cut =5
- This is TOO SMALL to have a physical meaning (15 the default value used in previous plot is better)
- This was done to illustrate more in detail how the "$" syntax works.

$ explanation

p p > e+ e- / Z (red curve) adding p p > e+ e- $ Z (blue curve)



- Z on-shell veto
- In veto area only photon contribution
- area sensitive to z-peak
- Very off-shell Z: the difference between the curves is due to interference which need to be KEPT in simulation.

5 times width area

15 times width area

>15 times width area

The "$" can be use to split the sample in BG/SG area

WARNING!! Bad Syntax!

- Syntax Like
  - p p > z > e+ e- (ask one S-channel z)
  - p p > e+ e- / z (forbids any z)
  - p p > e+ e- $$ z (forbids any z in s-channel)
- ARE NOT GAUGE INVARIANT !
- forgets diagram interference.
- can provides un-physical distributions.

Avoid Those as much as possible!

check physical meaning and gauge/Lorentz invariance if you do.

Better Syntax Examples

- Syntax like
  - p p > z, z > e+ e- (on-shell z decaying)
  - p p > e+ e- $ z (forbids s-channel z to be on-shell)

$$|M^* - M| < BW_{cut} * \Gamma$$

- Are linked to cuts
- Are safer to use

Use the above syntax instead of those on the previous slide!!

Exercise 5:
Top pair production at LO

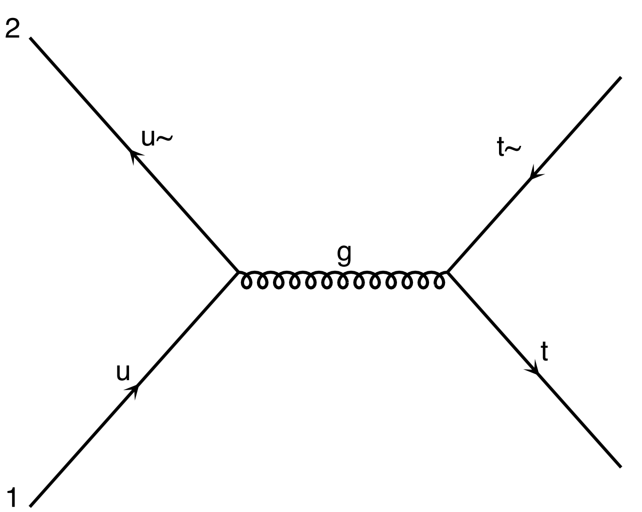
- Basic questions:
  - Generate the process
  - Which partonic subprocesses contribute?
  - How many Feynman diagrams does each each subprocess have?
  - Output the code
  - Are b-quarks included in the initial state? If not, how can I include them?

Solution 5:
Top pair production at LO

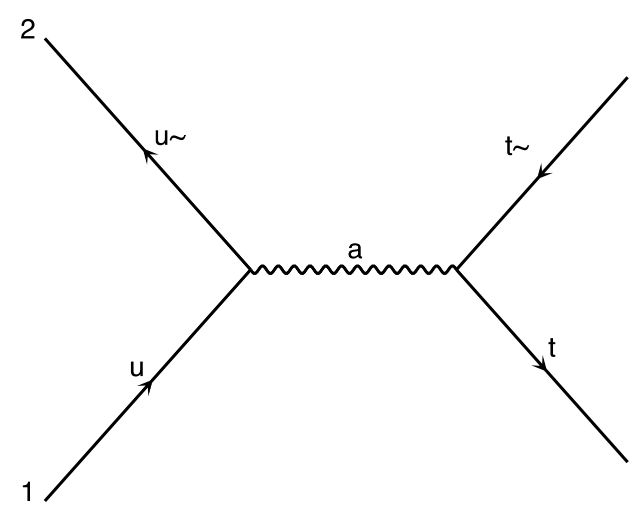
- Basic questions:
  - Which partonic subprocesses contribute?
  - How many Feynman diagrams does each each subprocess have?
    - g g > t t~ (3 diagrams)
    - u u~ > t t~ (1 diagram)
    - d d~ > t t~ (1 diagram)
    - c c~ > t t~ (1 diagram)
    - s s~ > t t~ (1 diagram)
  - Are b-quarks included in the initial state? If not, how can I include them?
    - define p = g u u~ c c~ d d~ s s~ b b~

Solutions 5:
Old extra question:

- Are diagrams with photons/z included?If not, how can I include them? How much does the cross-section change?
  - > display diagrams
  - No photon/z appear.
  - Are we missing anything important?
    - Expect only small effects

$\Big|$ 

$\Big|^2 \sim \alpha_s^2$

$\Big|$ 

$\Big|^2 \sim \alpha_e^2 \quad \frac{\alpha_e}{\alpha_s} \lesssim 0.1$

Solution 5:
Old extra question:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change?
  - > `generate p p > t t~ QED=2`
  - > `display diagrams`
  - > `output …`
  - > `launch`
  - > `…`

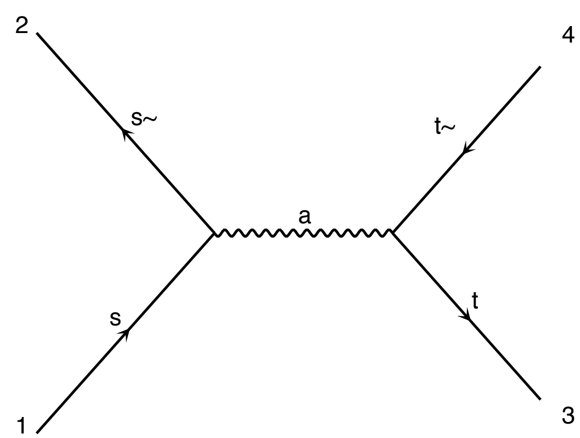


diagram 1 QCD=0, QED=2

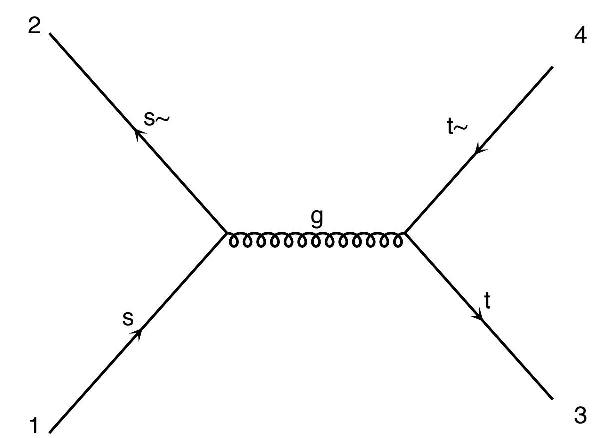


diagram 2 QCD=2, QED=0

```
Cross-section :   160.8 +- 0.1999 pb
Nb of events :  10000
```

WEIGHTED=2

```
Cross-section :   160.4 +- 0.231 pb
Nb of events :  10000
```

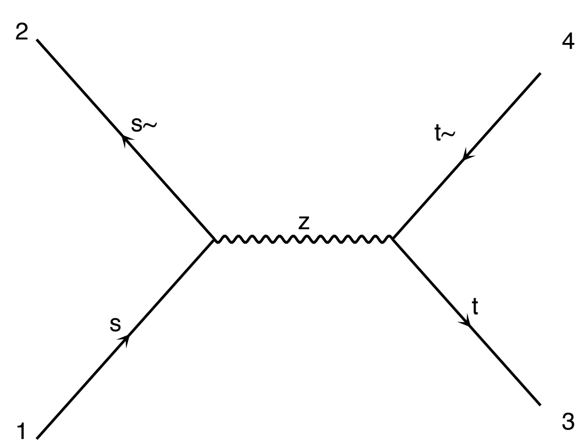


diagram 3 QCD=0, QED=2

Exercise 5a: Automation

- Compute the cross-section for the top pair production for m_t=170, 172, 174 … 180 GeV.
  - ➡ Do NOT use the interactive interface
    - hint: you can edit the param_card/run_card via the "set" command [After the launch]
    - hint: All commands [including answer to question] can be put in a file. (run ./bin/mg5 PATH_TO_FILE)

Examples

File:

```
import model EWDim6
generate p p > t t~
output TUTO_DIM6
launch
  set nevents 5000
  set MT 170
```

How to Run:

```
./bin/mg5_amc PATH
```

Solutions 5a: Automation

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
- Be smart! Script it!
- Create a txt file `myttbar_scan.txt`

```
generate p p > t t~
output mytestdir2
launch
set ebeam1 4000
set ebeam2 4000
set MT 170
launch
set MT 172
launch
set MT 174
launch
set MT 176
launch
set MT 178
launch
set MT 180
```

- `./bin/mg5_aMC myttbar_scan.txt`

Solutions 5a: Automation

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
- Be smart! Script it!
- You can also launch an existing folder, without regenerating the code

```
launch mytestdir2
set ebeam1 4000
set ebeam2 4000
set MT 170
launch
set MT 172
launch
set MT 174
launch
set MT 176
launch
set MT 178
launch
set MT 180
```

Solutions 5a: Automation

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV

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 4000 x 4000 GeV	tag_1	169.8 ± 0.24	10000	parton madevent	LHE	remove run / launch detector simulation
run_02	p p 4000 x 4000 GeV	tag_1	160.1 ± 0.28	10000	parton madevent	LHE	remove run / launch detector simulation
run_03	p p 4000 x 4000 GeV	tag_1	151.1 ± 0.2	10000	parton madevent	LHE	remove run / launch detector simulation
run_04	p p 4000 x 4000 GeV	tag_1	142.9 ± 0.18	10000	parton madevent	LHE	remove run / launch detector simulation
run_05	p p 4000 x 4000 GeV	tag_1	134.7 ± 0.19	10000	parton madevent	LHE	remove run / launch detector simulation
run_06	p p 4000 x 4000 GeV	tag_1	127.3 ± 0.16	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

which folder is which?

Solutions 5a: Automation

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
- Be smart! Script it!
- You can specify the name (instead of `run_01...`) with `-n NAME`

```
launch mytestdir2 -n run_MT170
set ebeam1 4000
set ebeam2 4000
set MT 170
launch -n run_MT172
set MT 172
launch -n run_MT174
set MT 174
launch -n run_MT176
set MT 176
launch -n run_MT178
set MT 178
launch -n run_MT180
set MT 180
```

Solutions 5a: Automation

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 4000 x 4000 GeV	tag_1	169.8 ± 0.24	10000	parton madevent	LHE	remove run launch detector simulation
run_02	p p 4000 x 4000 GeV	tag_1	160.1 ± 0.28	10000	parton madevent	LHE	remove run launch detector simulation
run_03	p p 4000 x 4000 GeV	tag_1	151.1 ± 0.2	10000	parton madevent	LHE	remove run launch detector simulation
run_04	p p 4000 x 4000 GeV	tag_1	142.9 ± 0.18	10000	parton madevent	LHE	remove run launch detector simulation
run_05	p p 4000 x 4000 GeV	tag_1	134.7 ± 0.19	10000	parton madevent	LHE	remove run launch detector simulation
run_06	p p 4000 x 4000 GeV	tag_1	127.3 ± 0.16	10000	parton madevent	LHE	remove run launch detector simulation
run_MT170	p p 4000 x 4000 GeV	tag_1	170 ± 0.22	10000	parton madevent	LHE	remove run launch detector simulation
run_MT172	p p 4000 x 4000 GeV	tag_1	159.6 ± 0.22	10000	parton madevent	LHE	remove run launch detector simulation
run_MT174	p p 4000 x 4000 GeV	tag_1	151.1 ± 0.22	10000	parton madevent	LHE	remove run launch detector simulation
run_MT176	p p 4000 x 4000 GeV	tag_1	142.6 ± 0.19	10000	parton madevent	LHE	remove run launch detector simulation
run_MT178	p p 4000 x 4000 GeV	tag_1	134.7 ± 0.18	10000	parton madevent	LHE	remove run launch detector simulation
run_MT180	p p 4000 x 4000 GeV	tag_1	127.2 ± 0.24	10000	parton madevent	LHE	remove run launch detector simulation

Main Page

Solutions 5a: Automation

- Since recently, multiple values can be specified for parameters. Just set in the `param_card`, instead of the top mass
  `6 scan:[170,172,174,176,178]`

Exercise 5b: Decay Chain

- Generate p p > t t~ , and decay the tops (no need to decay the W's)
  - ➡ Use the decay-chain formalism
  - ➡ Do the same mass scan as in Ex. 5a & compare cross-sections
    - Do you notice something wrong? If so, what did you forget to also update?
    - Update the missing piece and confirm that the issue is fixed

Exercise 5b: Decay Chain

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_MT170	p p 4000.0 x 4000.0 GeV	tag_1	143.6 ± 0.23 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT172	p p 4000.0 x 4000.0 GeV	tag_1	146.9 ± 0.27 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT174	p p 4000.0 x 4000.0 GeV	tag_1	150.5 ± 0.24 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT176	p p 4000.0 x 4000.0 GeV	tag_1	153.7 ± 0.27 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT178	p p 4000.0 x 4000.0 GeV	tag_1	157 ± 0.29 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT180	p p 4000.0 x 4000.0 GeV	tag_1	160.1 ± 0.33 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation

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- generate p p > t t~, t > w+ b, t~ > w- b~
- What's wrong?
  - ➡ The cross-section now increases with mass

Exercise 5b: Decay Chain

- What's wrong?
  - ➡The width was not updated. Let's fix it:

```
launch mytestdir2 -n run_MT170
set ebeam1 4000
set ebeam2 4000
set MT 170
set WT auto
launch -n run_MT172
set MT 172
set WT auto
launch -n run_MT174
set MT 174
set WT auto
launch -n run_MT176
set MT 176
set WT auto
launch -n run_MT178
set MT 178
set WT auto
launch -n run_MT180
set MT 180
set WT auto
```

Exercise 5b: Decay Chain

- After updating the widths

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_MT170	p p 4000.0 x 4000.0 GeV	tag_1	162.3 ± 0.3 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT172	p p 4000.0 x 4000.0 GeV	tag_1	153 ± 0.28 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT174	p p 4000.0 x 4000.0 GeV	tag_1	144.7 ± 0.26 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT176	p p 4000.0 x 4000.0 GeV	tag_1	136.2 ± 0.24 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT178	p p 4000.0 x 4000.0 GeV	tag_1	128.4 ± 0.23 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
					hadron MA5		
run_MT180	p p 4000.0 x 4000.0 GeV	tag_1	121.5 ± 0.21 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation

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Exercise 6: Other Models

- Calculate cross-section and event shapes for p p > j j h
  - ➡ Note how many/which diagrams/subprocesses exist
- Now run the same calculation except this time in the Higgs effective theory
  - ➡ Hint: different models can be loaded with import model <model_name>
- Which model has the greater cross section?
  - ➡ Can you see which process contribute the most to the cross section?

Solution 6: Other Models

- Calculate cross-section and event shapes for p p > j j h
  - ➡ Note how many/which diagrams/subprocesses exist
    - Cross section: 3.351 +- 0.009 (pb), 60 processes, 84 diagrams
- Now run the same calculation except this time in the Higgs effective theory
  - ➡ Hint: different models can be loaded with import model <model_name>
    - At beginning of run card or in program write "import model heft", then proceed as normal
    - Cross section: 7.863 +- 0.025 (pb), 65 processes, 214 diagrams
      - gluon-gluon fusion included and is dominant