MadGraph5_aMC@NLO tutorial

Pavia

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Part 1:
getting familiar with

What is MadGraph5_aMC@NLO?

- It is an automatic meta-code that write the code for computing the cross-section and generating events for any process at colliders
- All the details are in arXiv:1405.0301
- NLO QCD corrections can be included
- Matrix elements of different multiplicities can be combined
  - at LO (CKKW or MLM)
  - at NLO (FxFx or UNLOPS)

Software prerequisites:

- Python 2.6 or 2.7
- Fortran compiler supporting quadruple precision (needed for NLO)
  - gfortran v4.6+ OK
- Optional:
  - gnuplot
  - FastJet (FJcore is included in the tarball)
  - LHAPDF
  - Herwig++ / Pythia8

Where do I get it?

- On LaunchPad: https://launchpad.net/mg5amcnlo

marco zaro (marco-zaro) • Log Out

MadGraph5_aMC@NLO Generator

Overview | Code | Bugs | Blueprints | Translations | Answers

Registered 2009-09-15 by Michel Herquet

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

MadGraph5_aMC@NLO is the new version of both MadGraph5 and aMC@NLO that unifies the LO and NLO lines of development of automated tools within the MadGraph family. It therefore supersedes all the MadGraph5 1.5.x versions and all the beta versions of aMC@NLO.

The standard reference for the use of the code is: J. Alwall et al, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", arXiv:1405.0301 [hep-ph]. A more complete list of references can be found here: http://amcatnlo.web.cern.ch/amcatnlo/list_refs.htm

Download:

The latest stable release can downloaded as a tar.gz package (see the right of this page), or through the Bazaar versioning system, using bzr branch lp:madgraph5

Installation:

MadGraph5_aMC@NLO needs Python version 2.6 or 2.7 ; gfortran/gcc 4.6 or higher is required for NLO calculations/simulations.

Getting started:

Run bin/mg5_aMC and type "help" to learn how to run MadGraph5_aMC@NLO using the command interface, or run the interactive quick-start tutorial by typing "tutorial". Some third-party packages can be installed using the MG5_aMC shell command "install". LO generation can also be done

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Configuration Progress

Configuration options

Downloads

Latest version is 2.2.0

MG5_aMC_v2....beta.tar.gz

MG5_aMC_v2.2.3.tar.gz

Where do I get it?

- On LaunchPad: https://launchpad.net/mg5amcnlo
- `tar -xzf MG5_aMC_v2.3.0.tar.gz`
- `cd MG5_aMC_v2_3_0`
- `./bin/mg5_aMC`

Let’s start the tutorial

- On LaunchPad: https://launchpad.net/mg5amcnlo
- `tar -xzf MG5_aMC_v2.3.0.tar.gz`
- `cd MG5_aMC_v2_3_0`
- `./bin/mg5_aMC`
- `> tutorial`

Exercise 1: Top pair production at LO

- Basic questions:
  - Generate the process (following the tutorial)
  - Which partonic subprocesses contribute?
  - How many Feynman diagrams has each subprocess?
  - Output the code
  - Compute the cross-section at the LHC (8 TeV) for m_t=170 GeV
- Extra questions:
  - Are b-quarks included in the initial state? If not, how can I include them?
  - Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change? What is that 'WEIGHTED'?
  - Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV

Exercise 1: solution

- Generate the process (following the tutorial)
  - > generate p p > t t~

```
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED=2
INFO: Trying process: g g > t t~ WEIGHTED=2
INFO: Process has 3 diagrams
INFO: Trying process: u u~ > t t~ WEIGHTED=2
INFO: Process has 1 diagrams
INFO: Trying process: u c~ > t t~ WEIGHTED=2
INFO: Trying process: c u~ > t t~ WEIGHTED=2
INFO: Trying process: c c~ > t t~ WEIGHTED=2
INFO: Process has 1 diagrams
INFO: Trying process: d d~ > t t~ WEIGHTED=2
INFO: Process has 1 diagrams
INFO: Trying process: d s~ > t t~ WEIGHTED=2
INFO: Trying process: s d~ > t t~ WEIGHTED=2
INFO: Trying process: s s~ > t t~ WEIGHTED=2
INFO: Process has 1 diagrams
INFO: Process u~ u > t t~ added to mirror process u u~ > t t~
INFO: Process c~ c > t t~ added to mirror process c c~ > t t~
INFO: Process d~ d > t t~ added to mirror process d d~ > t t~
INFO: Process s~ s > t t~ added to mirror process s s~ > t t~
5 processes with 7 diagrams generated in 0.075 s
Total: 5 processes with 7 diagrams
```

Exercise 1: solution

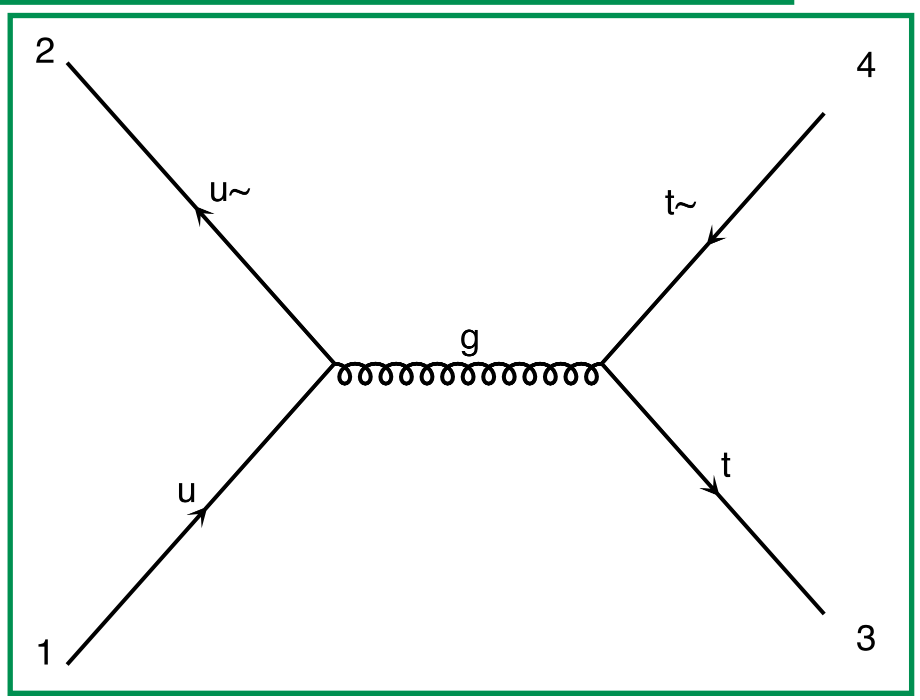
- Which partonic subprocesses contribute?
  - `> display processes`

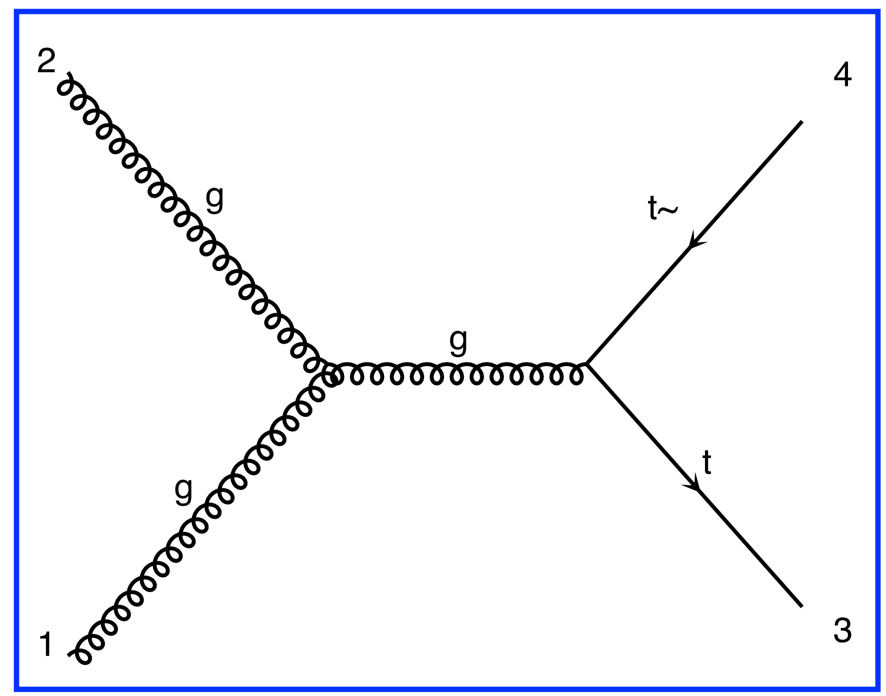
```
Process: g g > t t~ WEIGHTED=2
Process: u u~ > t t~ WEIGHTED=2
Process: c c~ > t t~ WEIGHTED=2
Process: d d~ > t t~ WEIGHTED=2
Process: s s~ > t t~ WEIGHTED=2
```

Exercise 1: solution

- Which partonic subprocesses contribute?
  - > display processes

```
Process: g g > t t~ WEIGHTED=2
Process: u u~ > t t~ WEIGHTED=2
Process: c c~ > t t~ WEIGHTED=2
Process: d d~ > t t~ WEIGHTED=2
Process: s s~ > t t~ WEIGHTED=2
```





Exercise 1: solution

- Which partonic subprocesses contribute?
  - > `display processes`

```
Process: g g > t t~ WEIGHTED=2
Process: u u~ > t t~ WEIGHTED=2
Process: c c~ > t t~ WEIGHTED=2
Process: d d~ > t t~ WEIGHTED=2
Process: s s~ > t t~ WEIGHTED=2
```

QCD master formula:

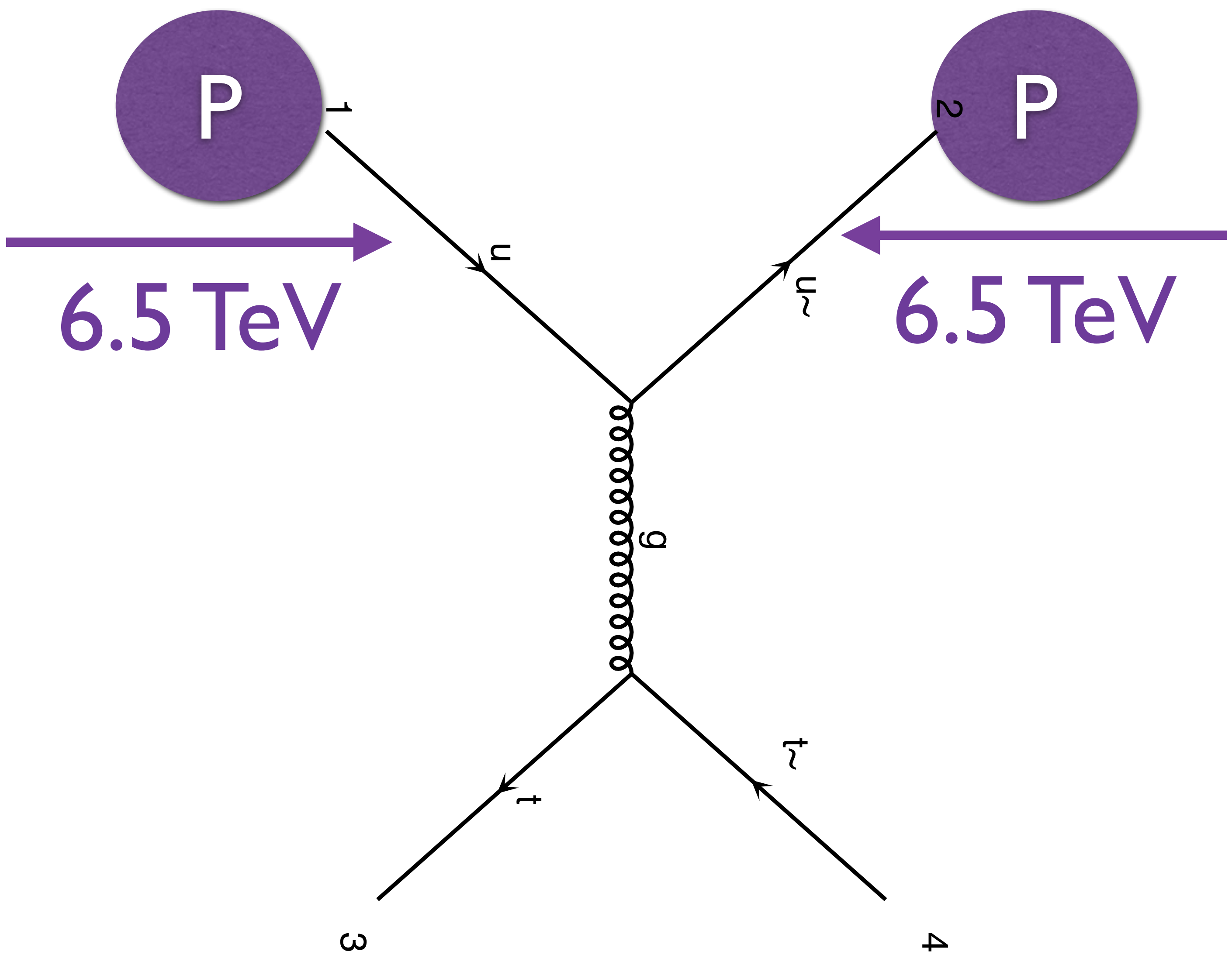
$$\sigma(pp \to t\bar{t}) = \sum_{ab} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \times \hat{\sigma}(ab \to t\bar{t})$$

What does it mean?

$$\sigma(pp \to t\bar{t}) = \sum_{ab} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \times \hat{\sigma}(ab \to t\bar{t})$$

- What is the probability to find parton a inside the proton with momentum fraction x? $f_a(x)$
- μ_F is a scale which separates low energy from high energy dynamics
- The partonic scattering occurs at a reduced energy:

$$\hat{s} = x_1 x_2 S = x_1 x_2 (13\text{TeV})^2$$



Exercise 1: solution

- How many Feynman diagrams has each subprocess?
  - > display diagrams

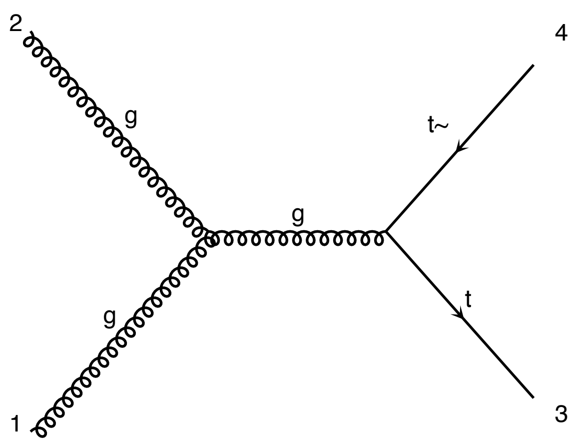


diagram 1 QCD=2, QED=0

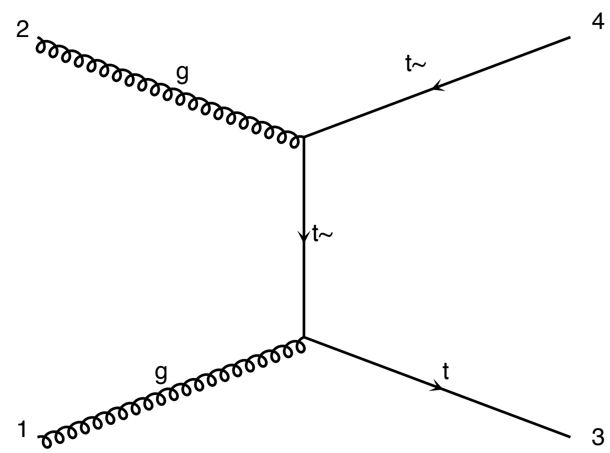


diagram 2 QCD=2, QED=0

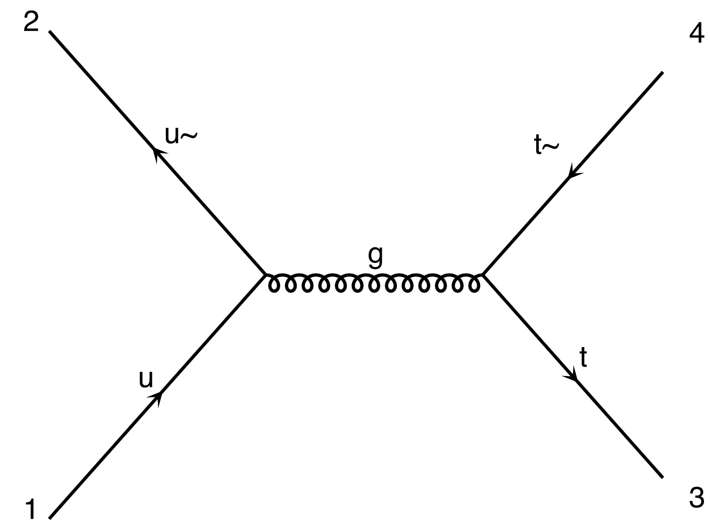


diagram 1 QCD=2, QED=0

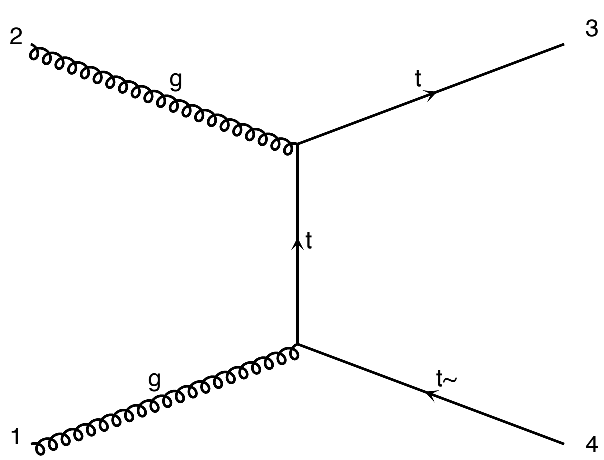


diagram 3 QCD=2, QED=0

gg: 3 diagrams

$q\bar{q}$: 1 diagram

Exercise 1: solution

- Output the code
  - > output mytestdir

```
INFO: initialize a new directory: mytestdir
INFO: remove old information in mytestdir
INFO: Creating files in directory P0_gg_ttx
INFO: Generating Feynman diagrams for Process: g g > t t~ WEIGHTED=2
INFO: Finding symmetric diagrams for subprocess group gg_ttx
INFO: Creating files in directory P0_qq_ttx
INFO: Generating Feynman diagrams for Process: u u~ > t t~ WEIGHTED=2
INFO: Finding symmetric diagrams for subprocess group qq_ttx
History written to /Users/marcozaro/Physics/MadGraph/MG5_aMC_v2_2_2/mytestdir/Cards/proc_card_mg5.dat
Generated helas calls for 2 subprocesses (0 diagrams) in 0.000 s
Wrote files for 16 helas calls in 0.102 s
Export UFO model to MG4 format
ALOHA: aloha creates FFV1 routines
ALOHA: aloha creates VVV1 set of routines with options: P0
save configuration file to /Users/marcozaro/Physics/MadGraph/MG5_aMC_v2_2_2/mytestdir/Cards/me5_configuration.txt
INFO: Use Fortran compiler gfortran
INFO: Generate jpeg diagrams
INFO: Generate web pages
Output to directory /Users/marcozaro/Physics/MadGraph/MG5_aMC_v2_2_2/mytestdir done.
```

Exercise 1: solution

- Compute the cross-section at the LHC (8 TeV) for m_t=170 GeV
  - > launch

```
The following switches determine which programs are run:
 1 Run the pythia shower/hadronization:                   pythia=NOT INSTALLED
 2 Run PGS as detector simulator:                            pgs=NOT INSTALLED
 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, 4, 5, auto, done, madspin=ON, madspin=OFF, madspin, reweight=ON, ... ][60s to answer]
```

  - > 0 (let's keep it simple ;-)

```
Do you want to edit a card (press enter to bypass editing)?
  1 / param      : param_card.dat
  2 / run        : run_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.
   - call an external program (ASperGE/MadWidth/...).
     Type 'help' for the list of available command
 [0, done, 1, param, 2, run, enter path][60s to answer]
```

  - edit the cards

Exercise 1: solution

- Compute the cross-section at the LHC (8 TeV) for m_t=170 GeV

run_card

```
#*********************
# Running parameters
#*********************
#
#*********************************************************************
# Tag name for the run (one word)                                    *
#*********************************************************************
  tag_1     = run_tag ! name of the run
#*********************************************************************
# Run to generate the grid pack                                      *
#*********************************************************************
  .false.     = gridpack  !True = setting up the grid pack
#*********************************************************************
# Number of events and rnd seed                                      *
# Warning: Do not generate more than 1M events in a single run       *
# If you want to run Pythia, avoid more than 50k events in a run.    *
#*********************************************************************
  10000 = nevents ! Number of unweighted events requested
      0       = iseed   ! rnd seed (0=assigned automatically=default))
#*********************************************************************
# Collider type and energy                                           *
# lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton,      *
#                                         3=photon from electron     *
#*********************************************************************
       1      = lpp1    ! beam 1 type
       1      = lpp2    ! beam 2 type
    6500      = ebeam1  ! beam 1 total energy in GeV
    6500      = ebeam2  ! beam 2 total energy in GeV
#*********************************************************************
# Beam polarization from -100 (left-handed) to 100 (right-handed)    *
#*********************************************************************
       0      = polbeam1 ! beam polarization for beam 1
       0      = polbeam2 ! beam polarization for beam 2
#*********************************************************************
# PDF CHOICE: this automatically fixes also alpha_s and its evol.    *
#*********************************************************************
                                                        47,1          5%
```

param_card

```
###################################
## 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 1.250000e+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)))
<_v2_2_2/mytestdir/Cards/param_card.dat" 78L, 2770C 1,1          Top
```

Exercise 1: solution

- Compute the cross-section at the LHC (8 TeV) for m_t=172 GeV
  - One can also set the parameters without editing the cards (useful for scripting)
  - `> set ebeam1 4000`
  - `> set ebeam2 4000`
  - `> set MT 172.`
  - `> done`

Exercise 1: solution

- Compute the cross-section at the LHC (8 TeV) for m_t=172 GeV
  - One can also set the parameters without editing the cards (useful for scripting)
  - > set ebeam1 4000
  - > set ebeam2 4000
  - > set MT 172.
  - > done

```
. . .
Working on SubProcesses
    P0_gg_ttx
    P0_qq_ttx
INFO:  Idle: 0,  Running: 1,  Completed: 1 [ current time: 15h13 ]
INFO: End survey
refine 10000
Creating Jobs
INFO: Refine results to 10000
    P0_gg_ttx
    P0_qq_ttx
INFO:  Idle: 6,  Running: 4,  Completed: 3 [  3.2s  ]
INFO:  Idle: 2,  Running: 4,  Completed: 7 [  6.6s  ]
INFO:  Idle: 0,  Running: 1,  Completed: 12 [  9.7s  ]
INFO: Combining runs
INFO: finish refine
refine 10000
Creating Jobs
INFO: Refine results to 10000
    P0_gg_ttx
    P0_qq_ttx
INFO: Combining runs
INFO: finish refine
combine_events
INFO: Combining Events
  === Results Summary for run: run_01 tag: tag_1 ===

     Cross-section :   160.1 +- 0.2302 pb
     Nb of events :  10000
```

Monitor via the web interface

Results in the sm for p p > t t~

Currently Running

Run Name	Tag Name	Cards	Results	Status/Jobs		
				Queued	Running	Done
run_01	tag_1	param_card run_card plot_card	160.1 ± 0.2302 (pb)	Combining Events		

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 4000 x 4000 GeV	tag_1	160.1 ± 0.23	No events yet		banner only	remove run / re-run from the banner

Main Page

Exercise 1: solution

- Script it:
  - open a text file (`mymg5amc.txt`) and put the commands inside:

```
generate p p > t t~
output mytestdir
launch
set ebeam1 4000
set ebeam2 4000
set MT 172
```

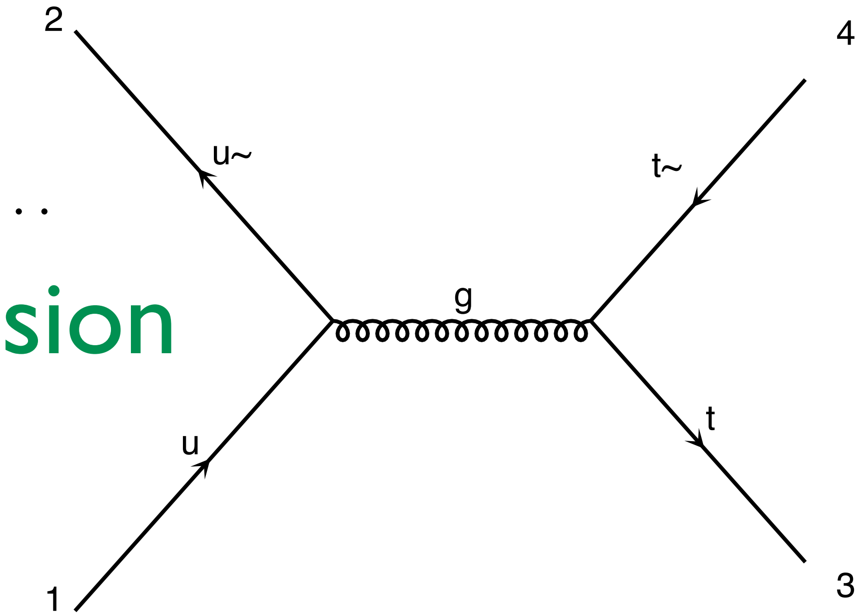
  - launch MG5_aMC@NLO with that file
  - `./bin/mg5_amc mymg5amc.txt`

Intermezzo:
From Feynman diagrams to the amplitude

- What is the amplitude for $u\bar{u} \to t\bar{t}$?
  - Peskin & Schroeder answer:

$$|M|^2 = Tr[\not{p}_2 \gamma^\mu \not{p}_1 \gamma^\nu] \frac{g^4}{(p_1 \cdot p_2)^2} Tr[(\not{p}_3 + m)\gamma^\mu (\not{p}_4 - m)\gamma^\nu] = \dots$$

  - Gives a clean and compact expression (for simple processes)
  - Number of terms ~ N_{diag}^2
  - OK for simple processes, not for complex ones!

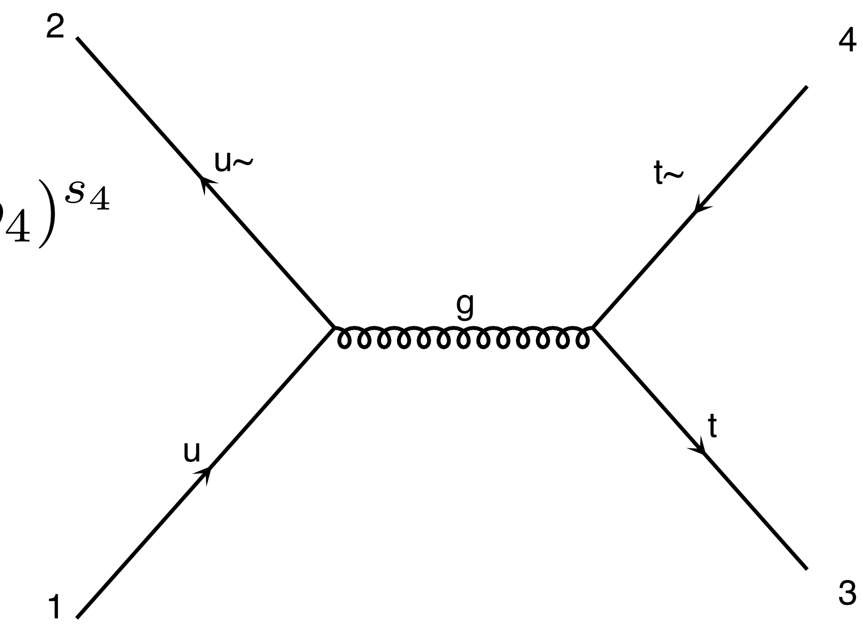


Intermezzo:
From Feynman diagrams to the amplitude

- What is the amplitude for $u\bar{u} \to t\bar{t}$?
  - Helicity-based formula

$$|M|^{s_1 s_2 s_3 s_4} = g^2 \bar{v}(p_2)^{s_2} \gamma_\mu u(p_1)^{s_1} \frac{g^{\mu\nu}}{p_1 \cdot p_2} \bar{u}(p_3)^{s_3} \gamma_\nu u(p_4)^{s_4}$$

$$|M|^2 = \sum_{s_1 s_2 s_3 s_4} (|M|^{s_1 s_2 s_3 s_4})^2$$



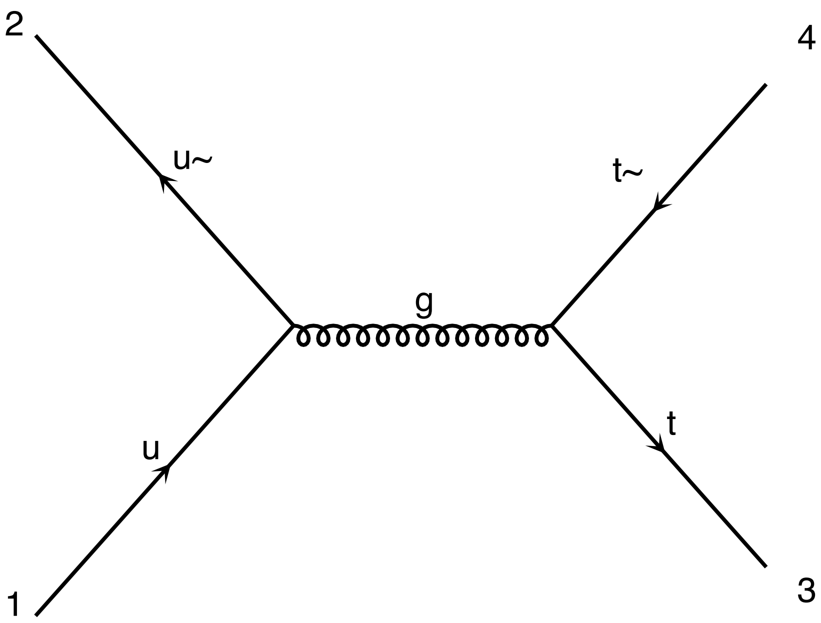
  - Much simpler expression
  - Number of terms ~ N_{diag}
  - Suitable for numeric codes!

Intermezzo: From Feynman diagrams to the amplitude

- What is the amplitude for $u\bar{u} \to t\bar{t}$?
  - Helicity-based formula

$$|M|^{s_1 s_2 s_3 s_4} = g^2 \bar{v}(p_2)^{s_2} \gamma_\mu u(p_1)^{s_1} \frac{g^{\mu\nu}}{p_1 \cdot p_2} \bar{u}(p_3)^{s_3} \gamma_\nu u(p_4)^{s_4}$$

$$|M|^2 = \sum_{s_1 s_2 s_3 s_4} \left(|M|^{s_1 s_2 s_3 s_4}\right)^2$$



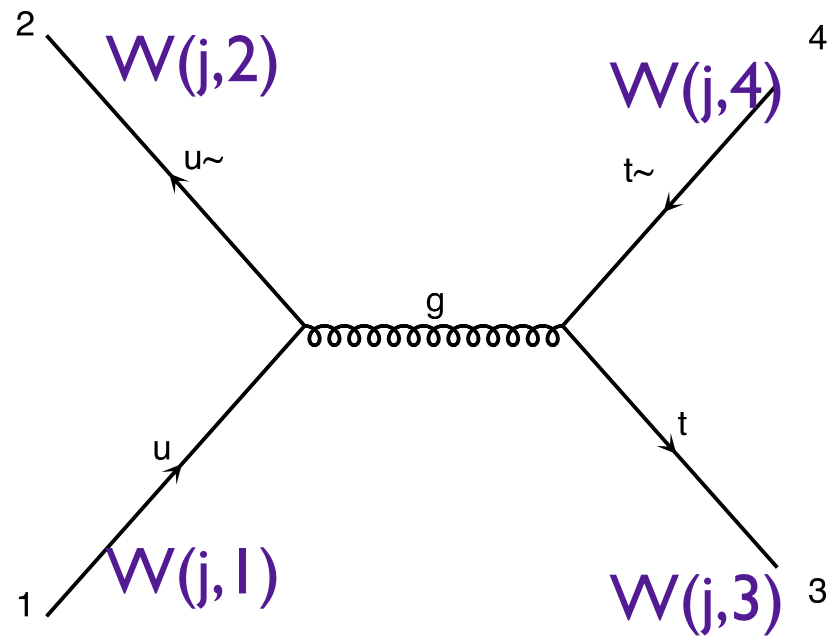

```
----------
BEGIN CODE
----------
CALL IXXXXX(P(0,1),ZERO,NHEL(1),+1*IC(1),W(1,1))
CALL OXXXXX(P(0,2),ZERO,NHEL(2),-1*IC(2),W(1,2))
CALL OXXXXX(P(0,3),MDL_MT,NHEL(3),+1*IC(3),W(1,3))
CALL IXXXXX(P(0,4),MDL_MT,NHEL(4),-1*IC(4),W(1,4))
CALL FFV1P0_3(W(1,1),W(1,2),GC_11,ZERO,ZERO,W(1,5))
Amplitude(s) for diagram number 1
CALL FFV1_0(W(1,4),W(1,3),W(1,5),GC_11,AMP(1))
```

Intermezzo:
From Feynman diagrams to the amplitude

- What is the amplitude for $u\bar{u} \to t\bar{t}$?
  - Helicity-based formula

$$|M|^{s_1 s_2 s_3 s_4} = g^2 \boxed{\bar{v}(p_2)^{s_2}} \gamma_\mu \boxed{u(p_1)^{s_1}} \frac{g^{\mu\nu}}{p_1 \cdot p_2} \boxed{\bar{u}(p_3)^{s_3}} \gamma_\nu \boxed{u(p_4)^{s_4}}$$

$$|M|^2 = \sum_{s_1 s_2 s_3 s_4} \left(|M|^{s_1 s_2 s_3 s_4}\right)^2$$



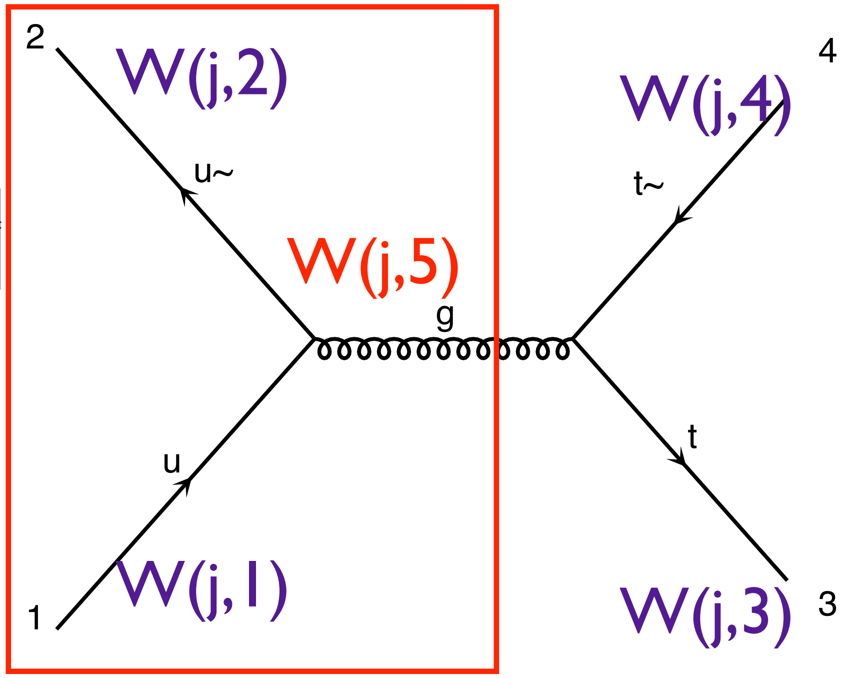

```
----------
BEGIN CODE
----------
CALL IXXXXX(P(0,1),ZERO,NHEL(1),+1*IC(1),W(1,1))
CALL OXXXXX(P(0,2),ZERO,NHEL(2),-1*IC(2),W(1,2))
CALL OXXXXX(P(0,3),MDL_MT,NHEL(3),+1*IC(3),W(1,3))
CALL IXXXXX(P(0,4),MDL_MT,NHEL(4),-1*IC(4),W(1,4))
CALL FFV1P0_3(W(1,1),W(1,2),GC_11,ZERO,ZERO,W(1,5))
Amplitude(s) for diagram number 1
CALL FFV1_0(W(1,4),W(1,3),W(1,5),GC_11,AMP(1))
```

Intermezzo:
From Feynman diagrams to the amplitude

- What is the amplitude for $u\bar{u} \to t\bar{t}$?
  - Helicity-based formula

$$|M|^{s_1 s_2 s_3 s_4} = g^2 \bar{v}(p_2)^{s_2} \gamma_\mu u(p_1)^{s_1} \frac{g^{\mu\nu}}{p_1 \cdot p_2} \bar{u}(p_3)^{s_3} \gamma_\nu u(p_4)^{s_4}$$

$$|M|^2 = \sum_{s_1 s_2 s_3 s_4} \left(|M|^{s_1 s_2 s_3 s_4}\right)^2$$



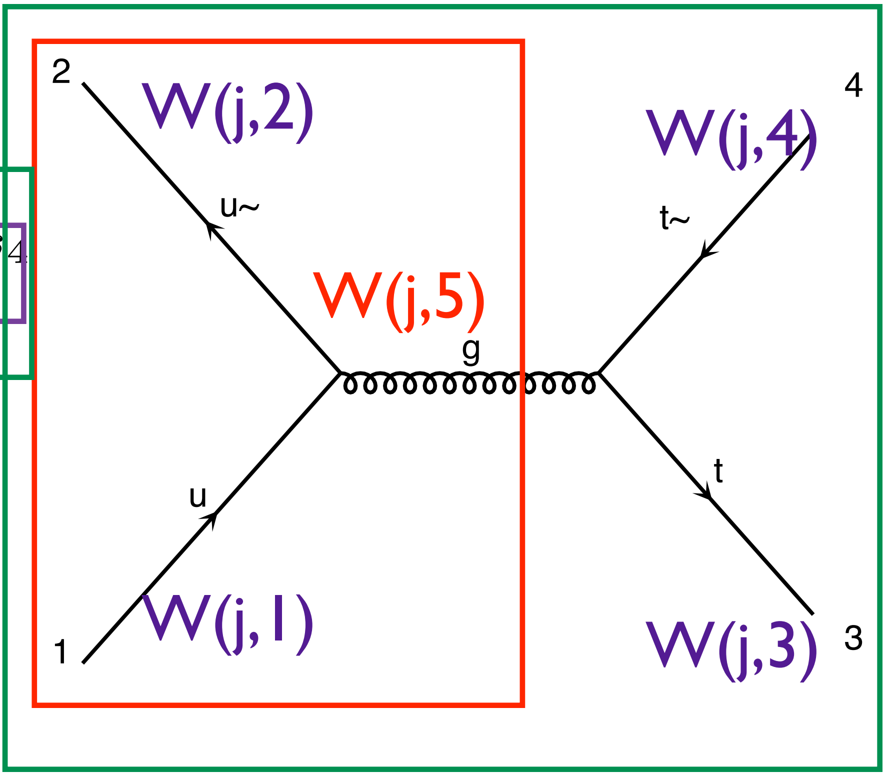

```
----------
BEGIN CODE
----------
CALL IXXXXX(P(0,1),ZERO,NHEL(1),+1*IC(1),W(1,1))
CALL OXXXXX(P(0,2),ZERO,NHEL(2),-1*IC(2),W(1,2))
CALL OXXXXX(P(0,3),MDL_MT,NHEL(3),+1*IC(3),W(1,3))
CALL IXXXXX(P(0,4),MDL_MT,NHEL(4),-1*IC(4),W(1,4))
CALL FFV1P0_3(W(1,1),W(1,2),GC_11,ZERO,ZERO,W(1,5))
Amplitude(s) for diagram number 1
CALL FFV1_0(W(1,4),W(1,3),W(1,5),GC_11,AMP(1))
```

Intermezzo:
From Feynman diagrams to the amplitude

- What is the amplitude for u$\bar{\text{u}}$→t$\bar{\text{t}}$?
  - Helicity-based formula

$$|M|^{s_1 s_2 s_3 s_4} = g^2 \bar{v}(p_2)^{s_2} \gamma_\mu u(p_1)^{s_1} \frac{g^{\mu\nu}}{p_1 \cdot p_2} \bar{u}(p_3)^{s_3} \gamma_\nu u(p_4)^{s_4}$$

$$|M|^2 = \sum_{s_1 s_2 s_3 s_4} (|M|^{s_1 s_2 s_3 s_4})^2$$



AMP(1)

```
----------
BEGIN CODE
----------
CALL IXXXXX(P(0,1),ZERO,NHEL(1),+1*IC(1),W(1,1))
CALL OXXXXX(P(0,2),ZERO,NHEL(2),-1*IC(2),W(1,2))
CALL OXXXXX(P(0,3),MDL_MT,NHEL(3),+1*IC(3),W(1,3))
CALL IXXXXX(P(0,4),MDL_MT,NHEL(4),-1*IC(4),W(1,4))
CALL FFV1P0_3(W(1,1),W(1,2),GC_11,ZERO,ZERO,W(1,5))
Amplitude(s) for diagram number 1
CALL FFV1_0(W(1,4),W(1,3),W(1,5),GC_11,AMP(1))
```

Exercise 1: Extra questions:

- Are b-quarks included in the initial state? If not, how can I include them?
- `> display processes`

```
Process: g g > t t~ WEIGHTED=2
Process: u u~ > t t~ WEIGHTED=2
Process: c c~ > t t~ WEIGHTED=2
Process: d d~ > t t~ WEIGHTED=2
Process: s s~ > t t~ WEIGHTED=2
```

- No b-quark appears. Note that at the startup you have

```
Defined multiparticle p = g u c d s u~ c~ d~ s~
Defined multiparticle j = g u c d s u~ c~ d~ s~
```

- You can add the b/$\bar{b}$ to the multiparticle labels
- `> define p = p b b~`

```
Defined multiparticle p = g u c d s u~ c~ d~ s~ b b~
```

- `> display multiparticles`
- For consistency one should use a model with $m_b=0$
- `> import model sm-no_b_mass`

Exercise 1:
Extra questions:

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- Are b-quarks included in the initial state? If not, how can I include them?

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- Are b-quarks included in the initial state? If not, how can I include them?
- Regenerate the process
  - > generate p p > t t~
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Process: g g > t t~ WEIGHTED=2
Process: u u~ > t t~ WEIGHTED=2
Process: c c~ > t t~ WEIGHTED=2
Process: d d~ > t t~ WEIGHTED=2
Process: s s~ > t t~ WEIGHTED=2
Process: b b~ > t t~ WEIGHTED=2
```

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- Are b-quarks included in the initial state? If not, how can I include them?
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Process: c c~ > t t~ WEIGHTED=2
Process: d d~ > t t~ WEIGHTED=2
Process: s s~ > t t~ WEIGHTED=2
Process: b b~ > t t~ WEIGHTED=2
```

- Does it make a big difference?
  - > output
  - > launch
  - > set ebeam1 4000
  - > set ebeam2 4000
  - > set MT 172

Exercise 1: Extra questions:

- Are b-quarks included in the initial state? If not, how can I include them?
- Regenerate the process
  - `> generate p p > t t~`
  - `> display processes`

```
Process: g g > t t~ WEIGHTED=2
Process: u u~ > t t~ WEIGHTED=2
Process: c c~ > t t~ WEIGHTED=2
Process: d d~ > t t~ WEIGHTED=2
Process: s s~ > t t~ WEIGHTED=2
Process: b b~ > t t~ WEIGHTED=2
```

- Does it make a big difference?
  - `> output`
  - `> launch`
  - `> set ebeam1 4000`
  - `> set ebeam2 4000`
  - `> set MT 172`

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

Without b

```
Cross-section :   160.1 +- 0.2302 pb
Nb of events :  10000
```

Exercise 1:
Extra questions:

Exercise 1: Extra questions:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change? What is that 'WEIGHTED'?

Exercise 1: Extra questions:

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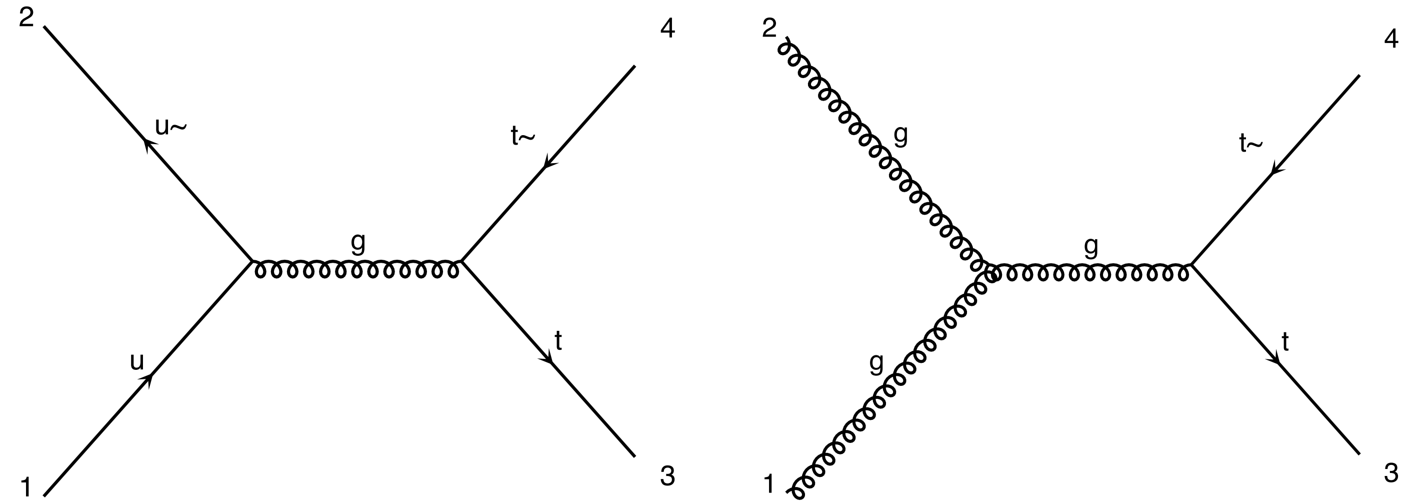
  - > display diagrams



- No photon/z appear.
- Are we missing anything important?

Exercise 1: Extra questions:

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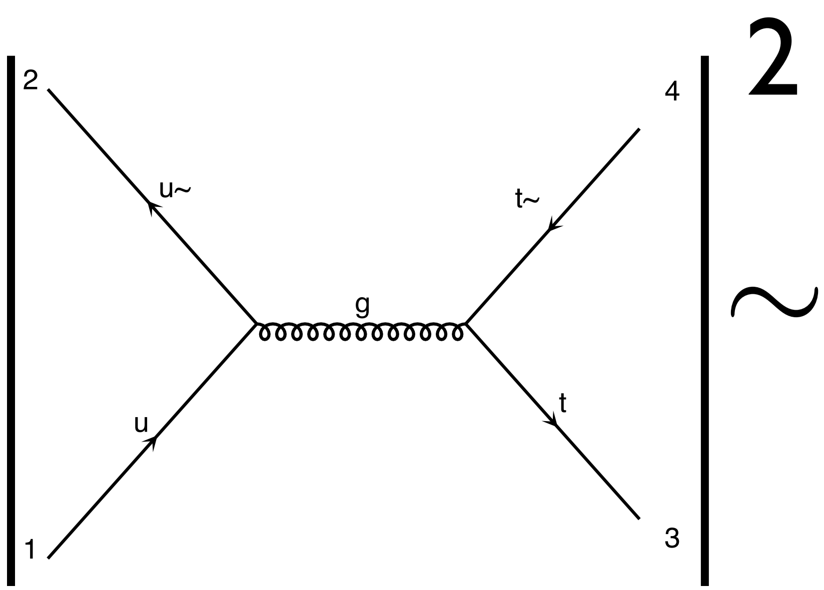
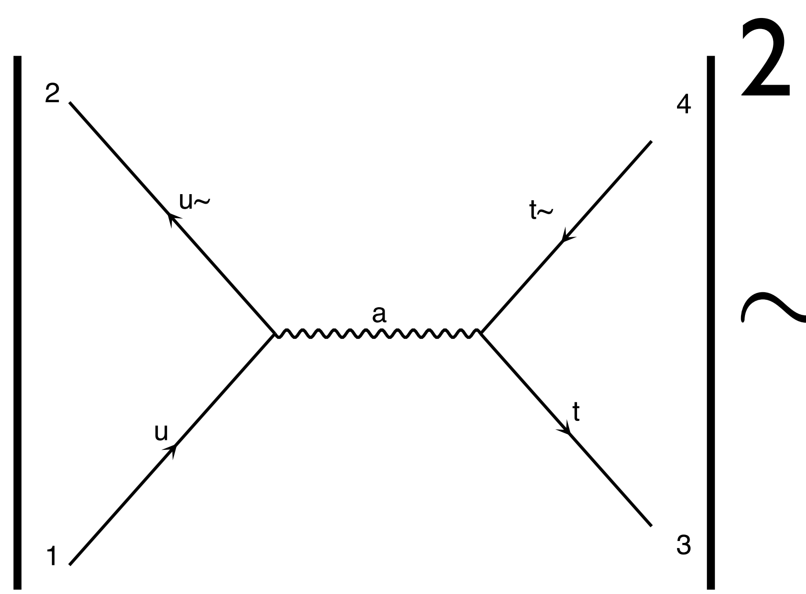


$\sim \alpha_s^2$



$\sim \alpha_e^2$

Exercise 1: Extra questions:

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  - `> display diagrams`
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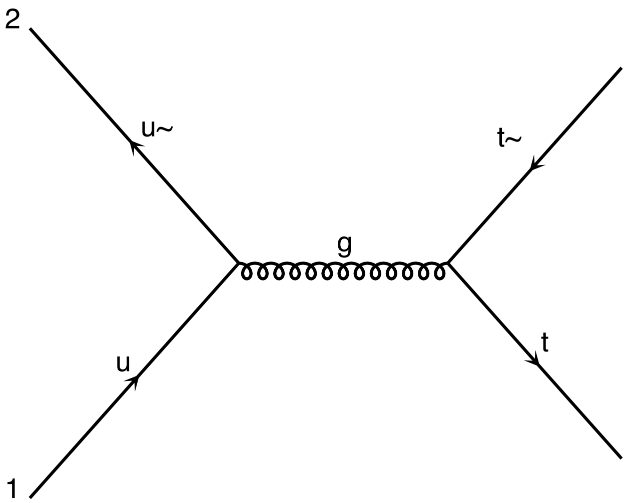
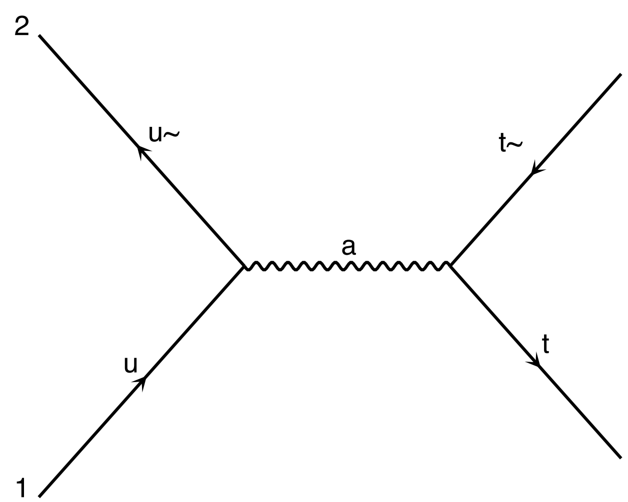


$\Big|\ \cdot\ \Big|^2 \sim \alpha_s^2$



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

Exercise 1:
Extra questions:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change?
  What is that 'WEIGHTED'?
  - > display diagrams
  - No photon/z appear.
  - Are we missing anything important? Does not seem the case
  - How to have them anyway?
  - MG5 exploits the hierarchy between QCD and QED couplings in order to give the leading (i.e. with most QCD) contribution to the cross-section by default
  - It assign WEIGHTED order =1(=2) to QCD (QED) vertices and generates the process with minimum WEIGHTED order

Exercise 1: Extra questions:

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Exercise 1:
Extra questions:

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Extra questions:

- 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~ WEIGHTED=4`
  - > `display diagrams`

Exercise 1: Extra questions:

- 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~ WEIGHTED=4`
  - `> display diagrams`

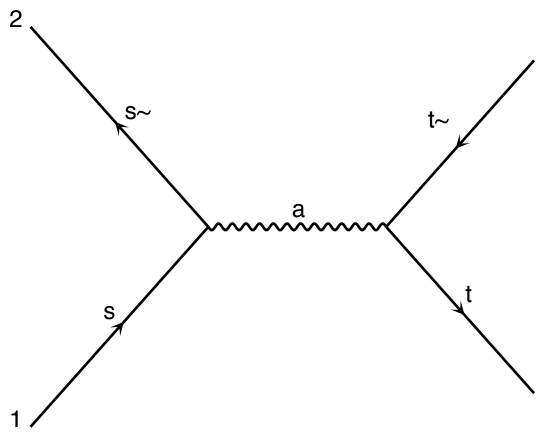


diagram 1 QCD=0, QED=2

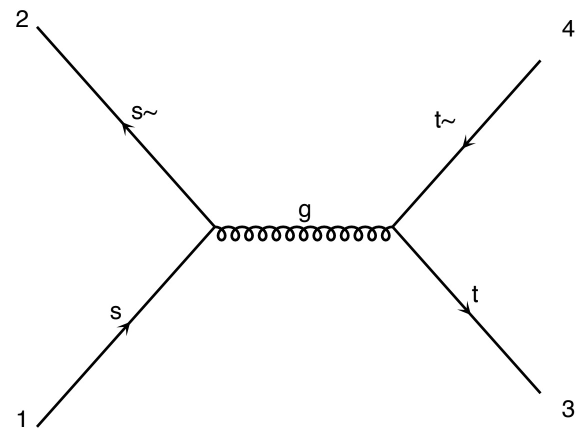


diagram 2 QCD=2, QED=0

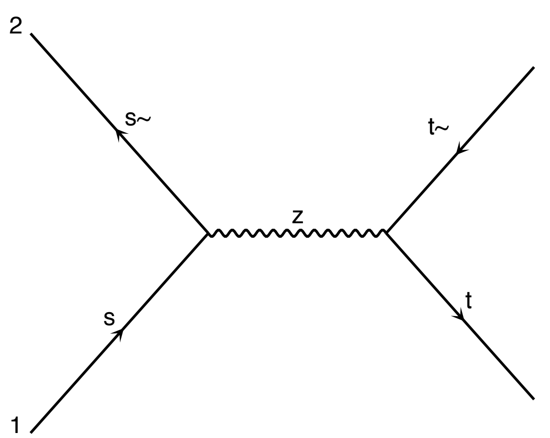
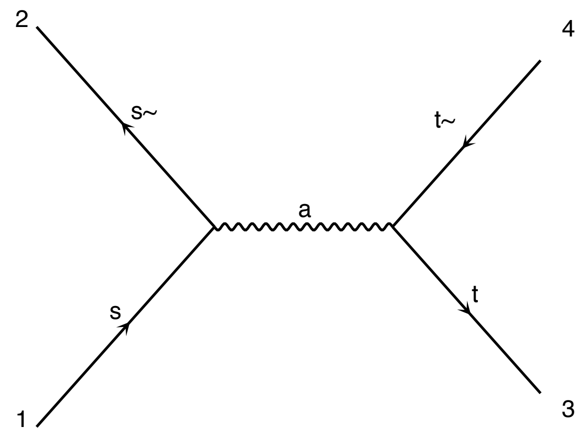
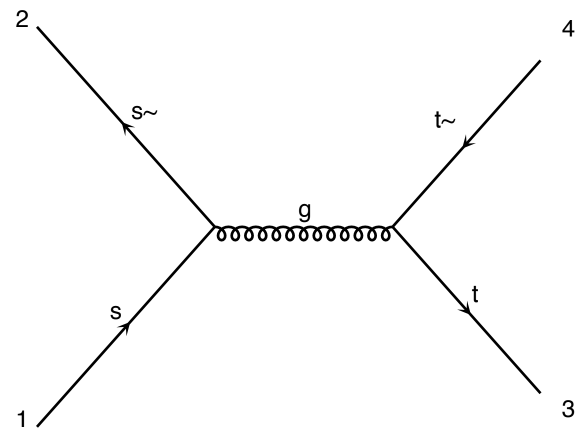


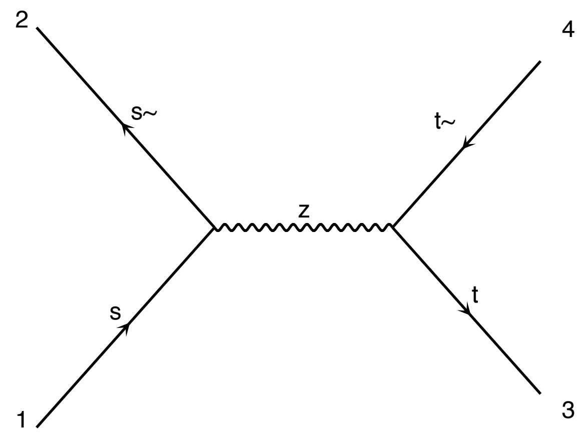
diagram 3 QCD=0, QED=2

Exercise 1: Extra questions:

- 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~ WEIGHTED=4
  - > display diagrams
  - > output ...
  - > launch
  - > ...







Exercise 1: Extra questions:

- 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~ WEIGHTED=4
  - > display diagrams
  - > output …
  - > launch
  - > …

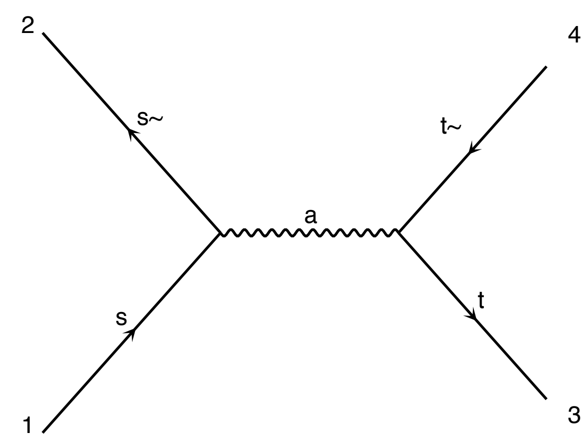


diagram 1 QCD=0, QED=2

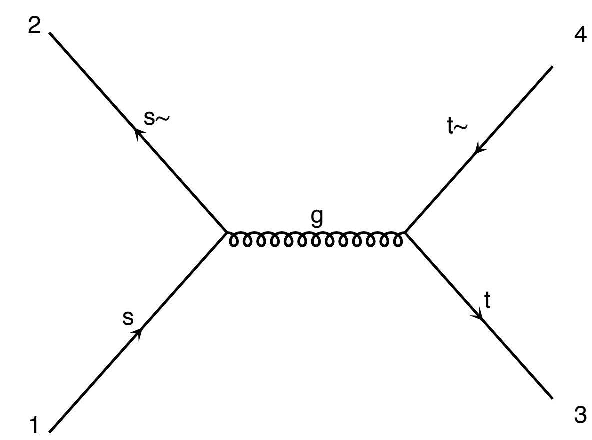


diagram 2 QCD=2, QED=0

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

WEIGHTED=2

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

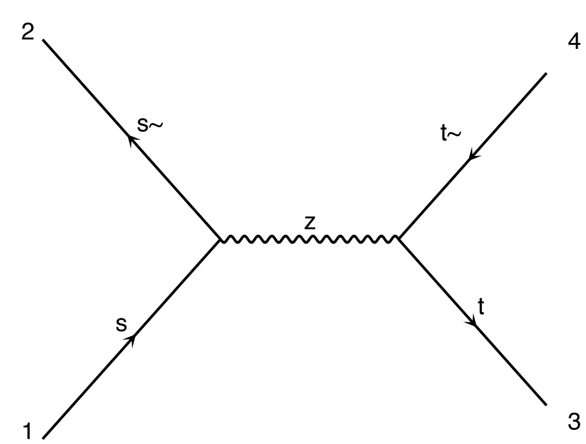


diagram 3 QCD=0, QED=2

Exercise 1:
Extra questions:

Exercise 1: Extra questions:

- Alternatively, one can specify the coupling powers
  - `> generate p p > t t~ QED=2`
  - orders which are not specified are unconstrained

Exercise 1:
Extra questions:

- Alternatively, one can specify the coupling powers
  - `> generate p p > t t~ QED=2`
  - orders which are not specified are unconstrained
- In order to have only the QED contribution
  - `> generate p p > t t~ QED=2 QCD=0`

Exercise 1:
Extra questions:

- 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`

Exercise 1: Extra questions:

- 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
```

Exercise 1:
Extra questions:

- 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

Exercise 1: Extra questions:

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

Results in the sm for p p > t t~

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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 what?

Exercise 1: Extra questions:

- 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
```

Exercise 1: Extra questions:

- 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
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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

Intermezzo: The Standalone output mode

- Suppose you want just the matrix element for a given process
- Why shall I need it?
  - You want to cross-check one computation you did
  - You have your own integrator, and you need to plug the matrix element in
  - The Standalone output mode is what you need
  - > `generate u u~ > t t~`
  - > `output standalone my_uux_ttx_SA`
  - > `launch`

The Standalone output mode

```
mdl_lam =   0.12886910601690263
mdl_yb =    2.6995554250465490E-002
mdl_yt =   0.99366614581500623
mdl_ytau =    1.0206617000654717E-002
mdl_muH =    88.388347648318430
mdl_I1x33 =  (  2.6995554250465490E-002,  0.0000000000000000     )
mdl_I2x33 =  ( 0.99366614581500623     ,  0.0000000000000000     )
mdl_I3x33 =  ( 0.99366614581500623     ,  0.0000000000000000     )
mdl_I4x33 =  (  2.6995554250465490E-002,  0.0000000000000000     )
mdl_ee__exp__2 =    9.4835522759998875E-002
mdl_sw__exp__2 =   0.22224648578577769
mdl_cw__exp__2 =   0.77775351421422245
 Internal Params evaluated point by point
 ----------------------------------------

mdl_sqrt__aS =   0.34351128074635334
mdl_G__exp__2 =    1.4828317324943823
 Couplings of sm
 ---------------------------------

      GC_11 =   0.00000E+00   0.12177E+01
  1000.0000000000000        500.00000000000000

 Phase space point:

 -----------------------------------------------------------------------------
 n        E             px             py              pz               m
 1   0.5000000E+03  0.0000000E+00  0.0000000E+00  0.5000000E+03  0.0000000E+00
 2   0.5000000E+03  0.0000000E+00  0.0000000E+00 -0.5000000E+03  0.0000000E+00
 3   0.5000000E+03  0.1040730E+03  0.4173556E+03 -0.1872274E+03  0.1730000E+03
 4   0.5000000E+03 -0.1040730E+03 -0.4173556E+03  0.1872274E+03  0.1730000E+03
 -----------------------------------------------------------------------------
 Matrix element =   0.61562818665255248       GeV^          0
 -----------------------------------------------------------------------------
```

Momenta and masses

Matrix element value

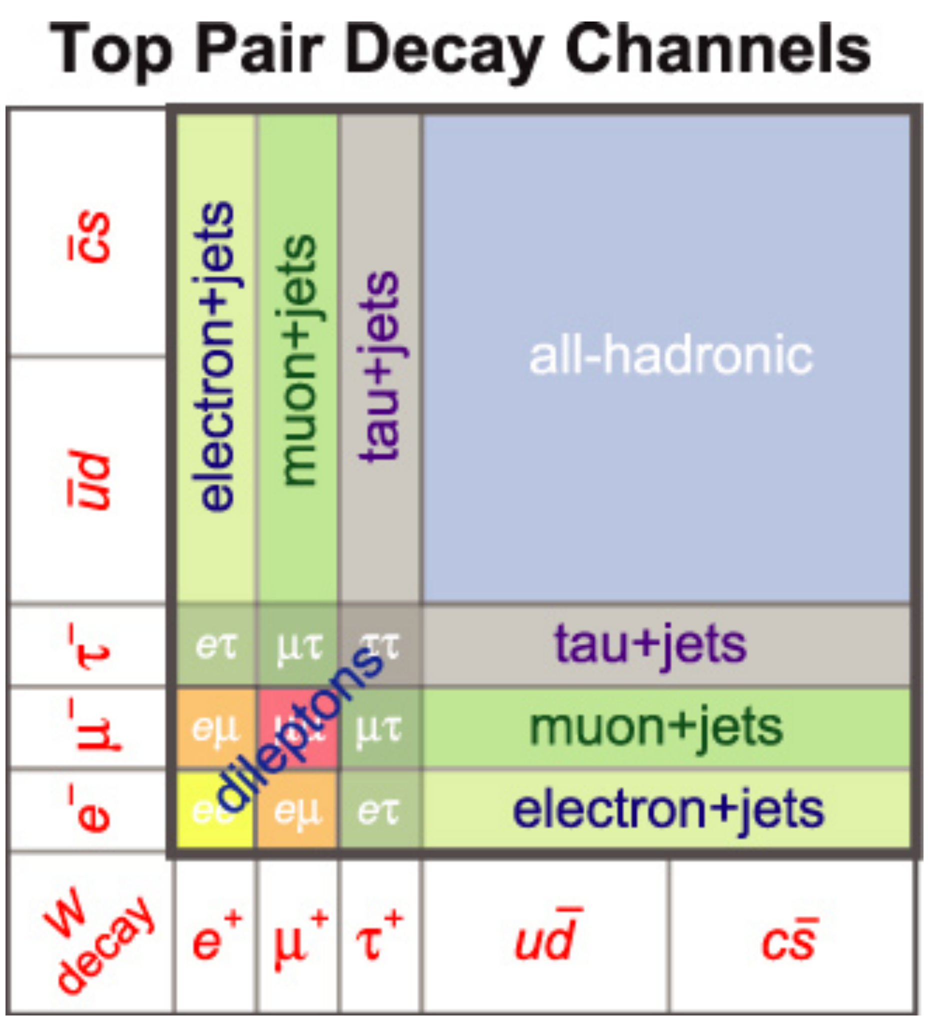
Exercise 2:
decay chains

- Theory: the top quark is an unstable particle:
  - It decays: ~100% of times into b W
  - The W boson decays too:
    - 67% (2/3) of times into hadrons
    - 22% (2/9) of times into "leptons" (e-ν_e or μ-ν_μ)
    - 11% (1/9) of times into τ-ν_τ
- A decayed pair of top quarks can be classified as:
  - hadronic (both tops to hadrons)
  - semileptonic (one top to hadrons, the other to leptons)
  - dileptonic (both quarks to leptons)

Exercise 2: decay chains

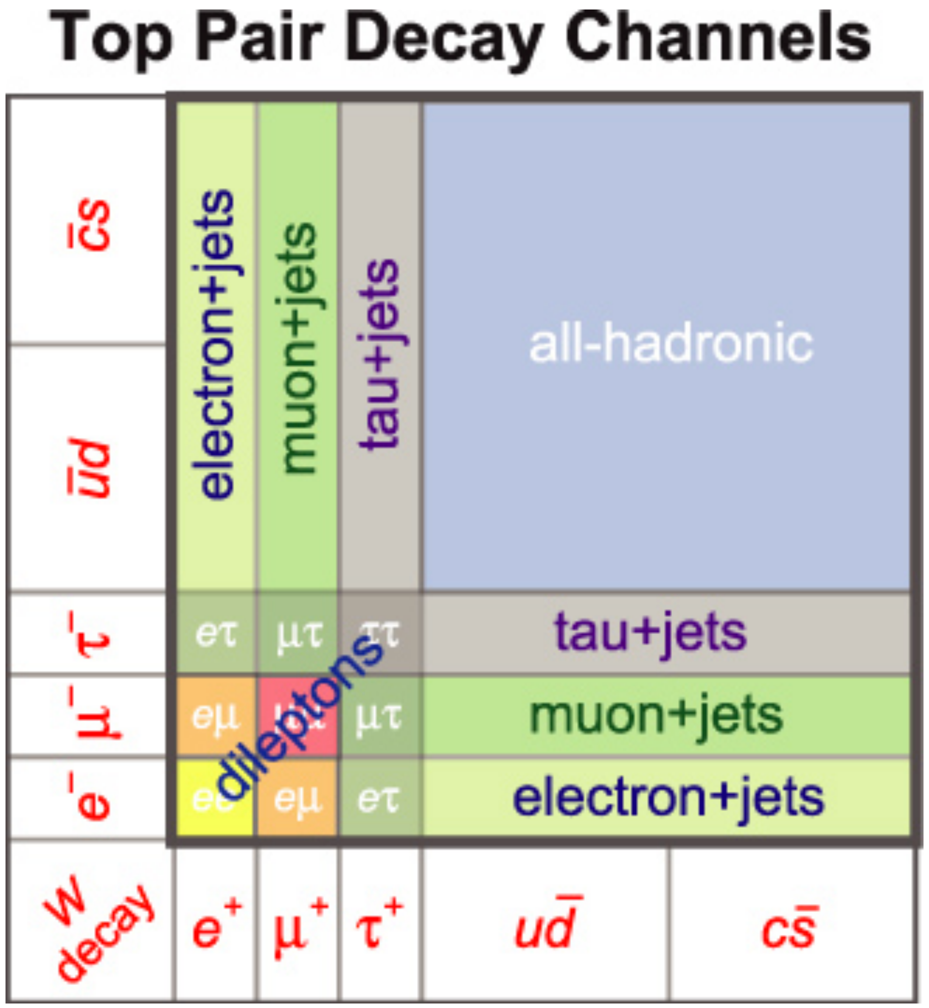
- Questions:
  - How often a top pair decays hadronically/semi-leptonically/di-leptonically?
  - Learn the syntax to specify decay chains
  - Generate the code for dileptonic top decay and compute the cross-section. Compare with what computed in Ex.1
  - What is the difference with `p p > l+ l- vl vl~ b b~`?

Exercise 2: Solution



Exercise 2: Solution

- Questions:
  - How often a top pair decays hadronically/semi-leptonically/di-leptonically?
    - Since the top always decays to Wb, look at how a pair of W decays (b's are stable)



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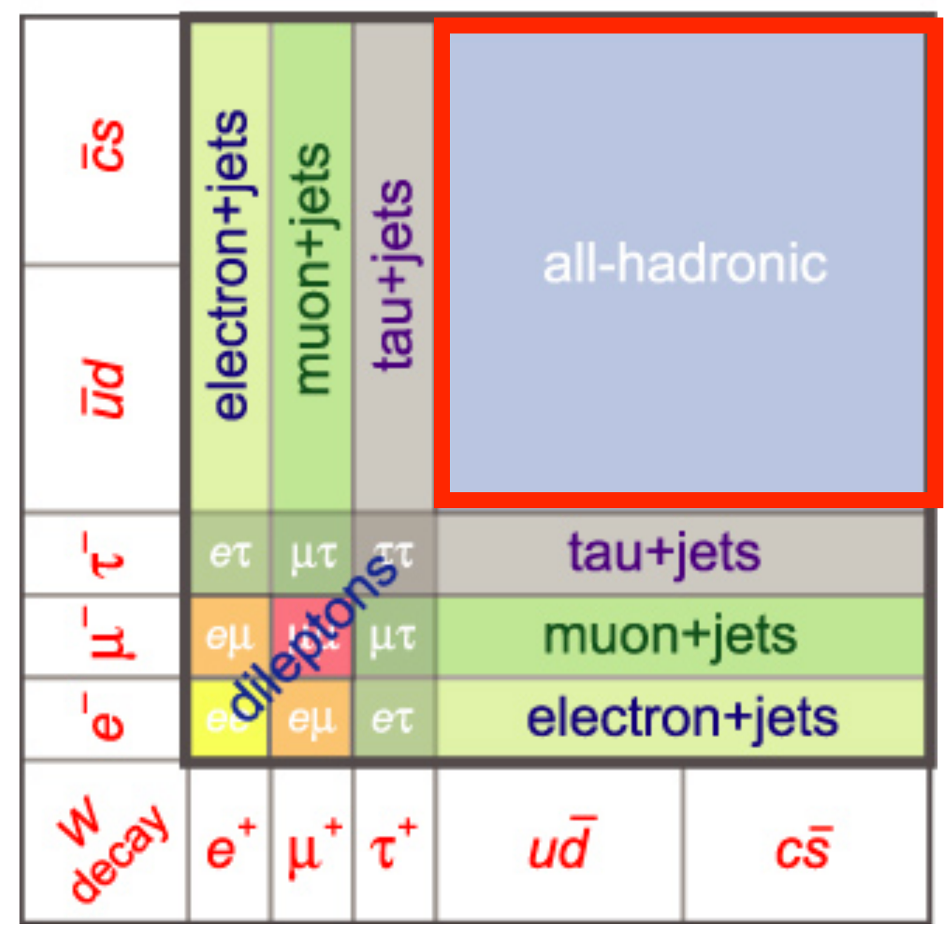
    - Hadronically: 2/3 * 2/3 = 4/9

Top Pair Decay Channels



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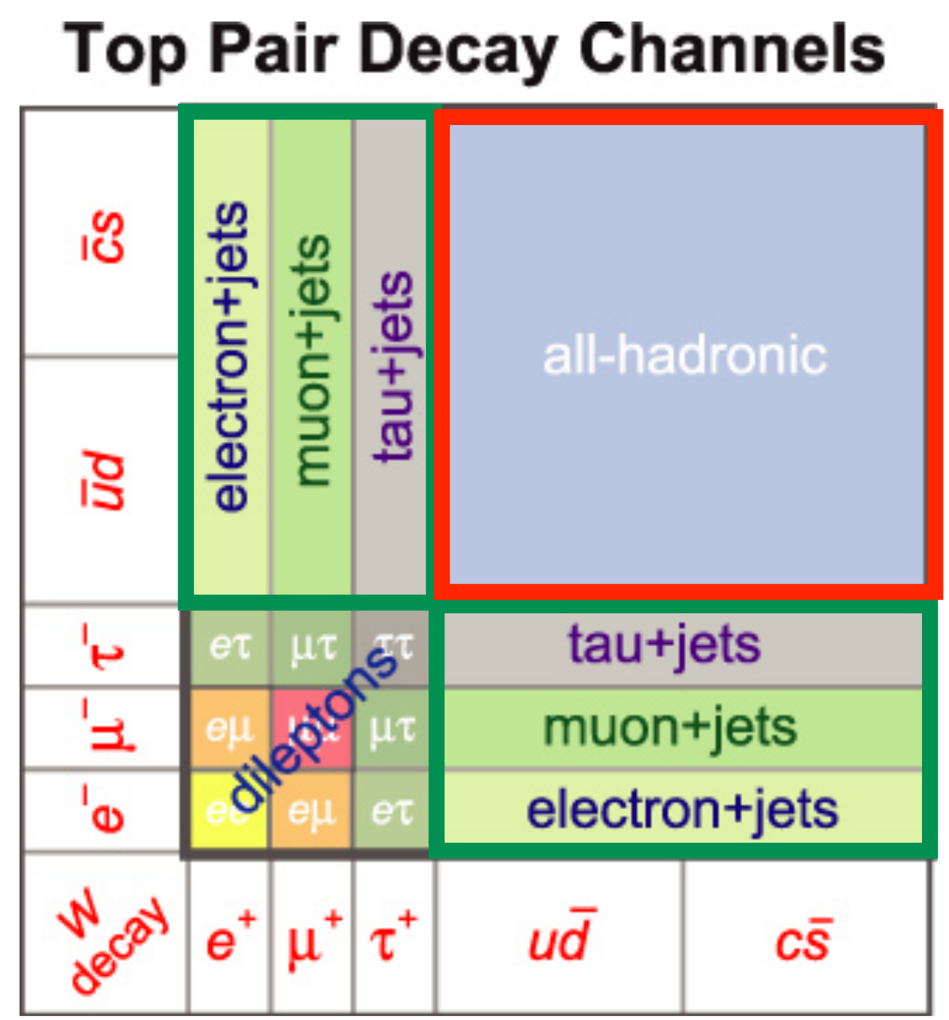

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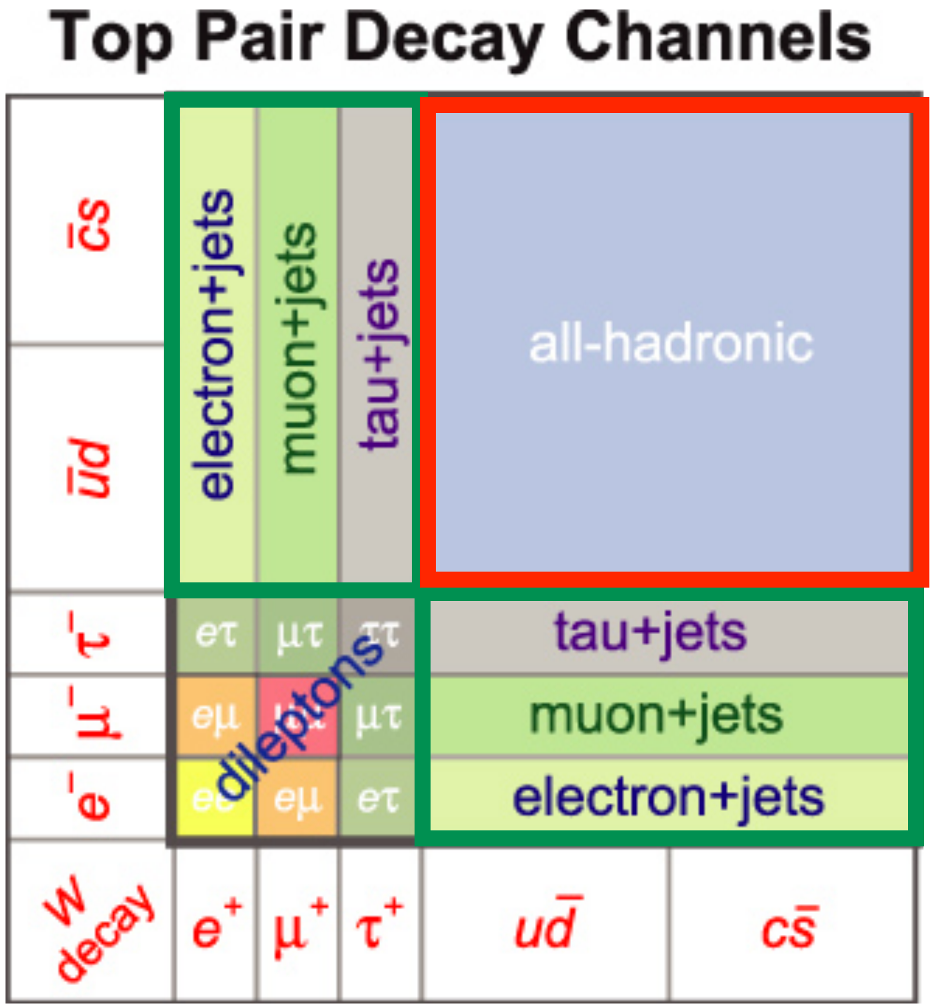
    - Semi-lep. (incl. τ): 2 * 1/3 * 2/3 = 4/9



Exercise 2: Solution

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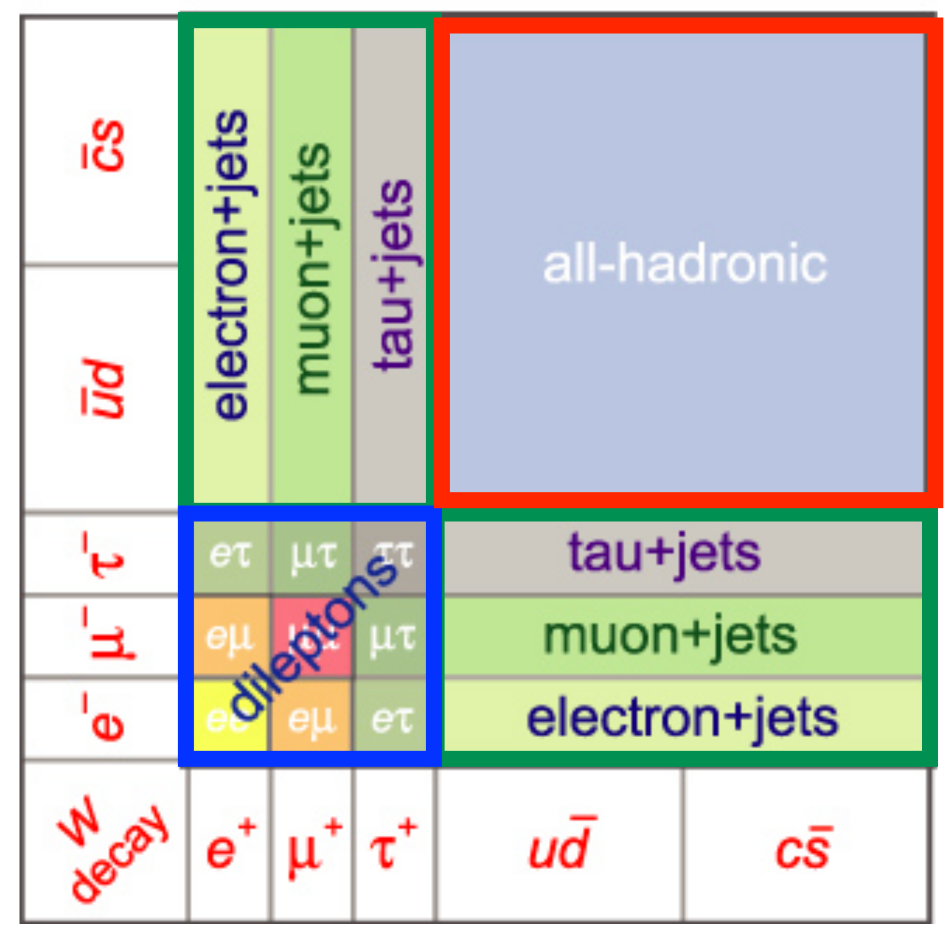
  - How often a top pair decays hadronically/semi-leptonically/di-leptonically?
    - Since the top always decays to Wb, look at how a pair of W decays (b's are stable)
    - Hadronically: 2/3 * 2/3 = 4/9
    - Semi-lep. (incl. τ): 2 * 1/3 * 2/3 = 4/9
    - Di-lep. (incl. τ): 1/3 * 1/3 = 1/9

Top Pair Decay Channels



Exercise 2: Solution

- Questions:
  - Learn the syntax to specify decay chains
  - > help generate

```
-- generate diagrams for a given process
General leading-order syntax:
 o generate INITIAL STATE > REQ S-CHANNEL > FINAL STATE $ EXCL S-CHANNEL / FORBIDDEN PARTICLES COUP1=ORDER1 COUP2^2=ORDER2
@N
 o Example: generate l+ vl > w+ > l+ vl a $ z / a h QED=3 QCD=0 @1
 > Alternative required s-channels can be separated by "|":
   b b~ > W+ W- | H+ H- > ta+ vt ta- vt~
 > If no coupling orders are given, MG5 will try to determine
   orders to ensure maximum number of QCD vertices.
 > Desired coupling orders combination can be specified directly for
   the squared matrix element by appending '^2' to the coupling name.
   For example, 'p p > j j QED^2==2 QCD^==2' selects the QED-QCD
   interference terms only. The other two operators '<=' and '>' are
   supported. Finally, a negative value COUP^2==-I refers to the
   N^(-I+1)LO term in the expansion of the COUP order.
 > To generate a second process use the "add process" command
Decay chain syntax:
 o core process, decay1, (decay2, (decay2', ...)), ...  etc
 o Example: generate p p > t~ t QED=0, (t~ > W- b~, W- > l- vl~), t > j j b @2
 > Note that identical particles will all be decayed
```

Something like this!

  - > generate p p > t t~, (t > w+ b, w+ > l+ vl), (t~ > w- b~, w- > l- vl~)

Exercise 2: Solution

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  - Generate the code for dileptonic top decay and compute the cross-section. Compare with what computed in Ex.1

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    - `> set ebeam1 4000`
    - `> set ebeam2 4000`
    - `> set MT 172`

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Cross-section :   5.65 +- 0.01823 pb
Nb of events :  10000
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  - Wait: what is `l+/l-`?
    - `> display multi particles`

```
Multiparticle labels:
all = g u c d s u~ c~ d~ s~ a ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ t
l- = e- mu-
j = g u c d s u~ c~ d~ s~
vl = ve vm vt
l+ = e+ mu+
p = g u c d s u~ c~ d~ s~
vl~ = ve~ vm~ vt~
```

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  - What do we expect? 4/81 = 7.9
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  - Check the run_card…

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```

Exercise 2:

MG5_aMC_v2_2_2 — vim — 72×58

bash | mzar...-real | mzar...alisi | bash | bash

```
 20     =  ptj          ! minimum pt for the jets
 0      =  ptb          ! minimum pt for the b
 10     =  pta          ! minimum pt for the photons
 10     =  ptl          ! minimum pt for the charged leptons
 0      =  misset       ! minimum missing Et (sum of neutrino's momenta)
 0      =  ptheavy      ! minimum pt for one heavy final state
 1.0    =  ptonium      ! minimum pt for the quarkonium states
 -1     =  ptjmax       ! maximum pt for the jets
 -1     =  ptbmax       ! maximum pt for the b
 -1     =  ptamax       ! maximum pt for the photons
 -1     =  ptlmax       ! maximum pt for the charged leptons
 -1     =  missetmax    ! maximum missing Et (sum of neutrino's momenta)
#*********************************************************************
# Minimum and maximum E's (in the center of mass frame)              *
#*********************************************************************
 0      =  ej        ! minimum E for the jets
 0      =  eb        ! minimum E for the b
 0      =  ea        ! minimum E for the photons
 0      =  el        ! minimum E for the charged leptons
 -1     =  ejmax   ! maximum E for the jets
 -1     =  ebmax   ! maximum E for the b
 -1     =  eamax   ! maximum E for the photons
 -1     =  elmax   ! maximum E for the charged leptons
#*********************************************************************
# Maximum and minimum absolute rapidity (for max, -1 means no cut)   *
#*********************************************************************
 5      =  etaj       ! max rap for the jets
 -1     =  etab       ! max rap for the b
 2.5    =  etaa       ! max rap for the photons
 2.5    =  etal       ! max rap for the charged leptons
 0.6    =  etaonium    ! max rap for the quarkonium states
 0      =  etajmin    ! min rap for the jets
 0      =  etabmin    ! min rap for the b
 0      =  etaamin    ! min rap for the photons
 0      =  etalmin    ! main rap for the charged leptons
#*********************************************************************
# Minimum and maximum DeltaR distance                                *
#*********************************************************************
 0.4    =  drjj       ! min distance between jets
 0      =  drbb       ! min distance between b's
 0.4    =  drll       ! min distance between leptons
 0.4    =  draa       ! min distance between gammas
 0      =  drbj       ! min distance between b and jet
 0.4    =  draj       ! min distance between gamma and jet
 0.4    =  drjl       ! min distance between jet and lepton
```

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  - C ... p decay and compute the c ... omputed in Ex. 1

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Marco Zarc

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    -
    -
    -
    -
    -
  - V
    -
- V
  -
- C

```
Cross-section :   6.936 +- 0.01553 pb
Nb of events :  10000
```

last 1pb of discrepancy comes from more subtle things (scales, widths, ...)

```
le labels:
 d s u~ c~ d~ s~ a ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ t

 d s u~ c~ d~ s~
 vt

 d s u~ c~ d~ s~
 vm~ vt~
```

Marco Zarc

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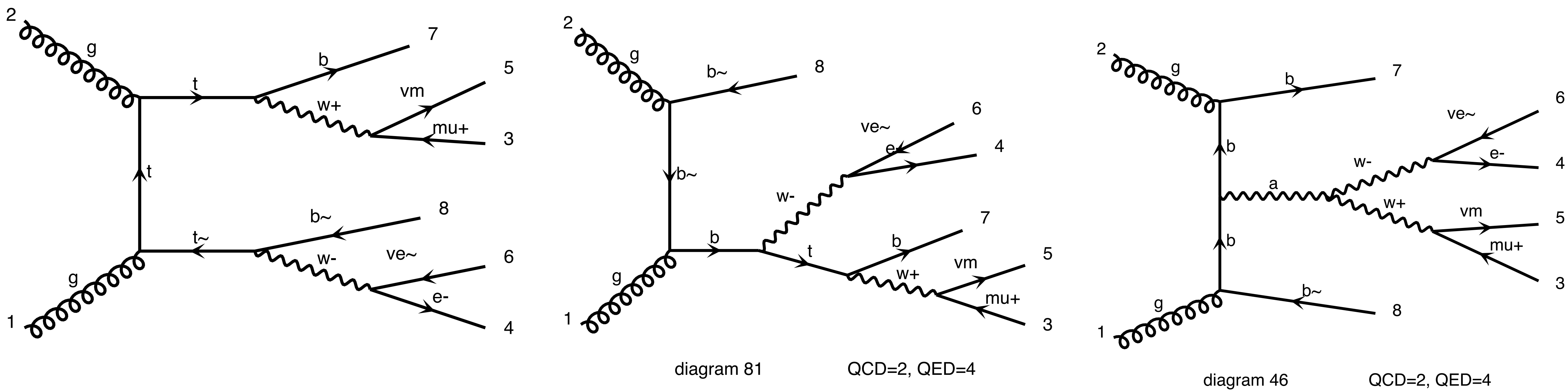

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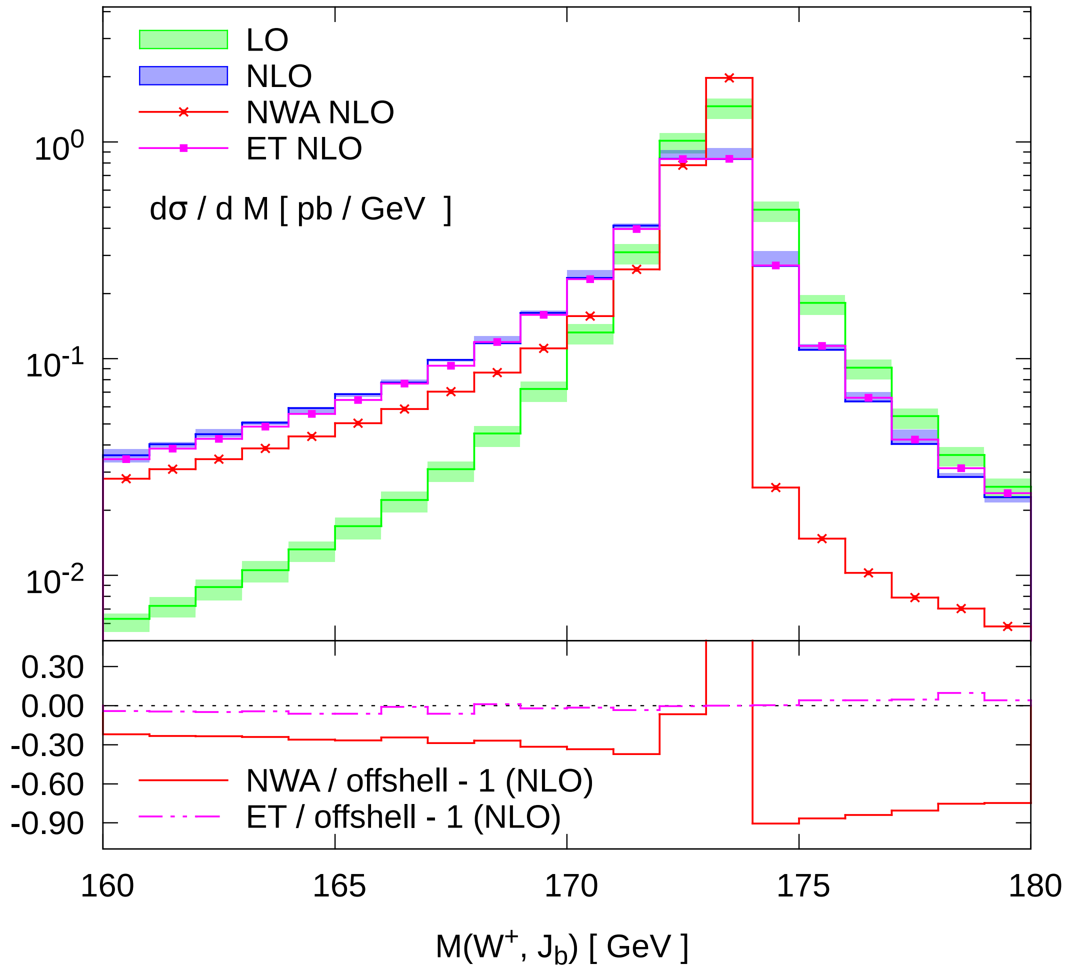
  - Which one is correct?
    - Strictly speaking $t\bar{t}$ decayed, is correct only in the limit Γ_t=0 i.e. when tops are on-shell
    - If one searches for (on-shell) top-pair production (e.g.imposing cuts on l, v, b mass), the full process will give little extra contribution
    - If one wants to look away from the resonant region, then the full process must be used

Exercise 2: Solution

- Questions:
  - What is the difference with `p p > l+ l- vl vl~ b b~`?
  - Have a look at single-top production (Papanastasiou et al. arXiv:1305.7088)



Part 2:
NLO

Why should I care?

- Reliable predictions of rates and shapes
- Reliable estimate of uncertainties (scale & PDF)
- Better theoretical accuracy, less need of fine tuning
- Realistic description of the final state
- Better understanding of data
- Steep increase in complexity (in particular for higher multiplicities)

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Ask a computer to do the hard job
Automation!

NLO: How to?

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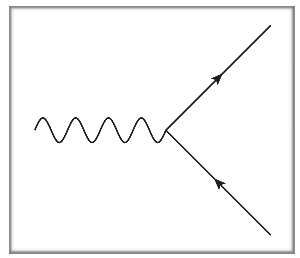
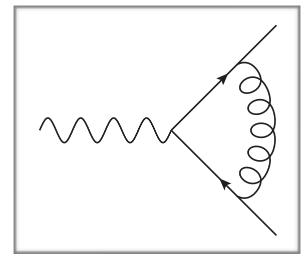
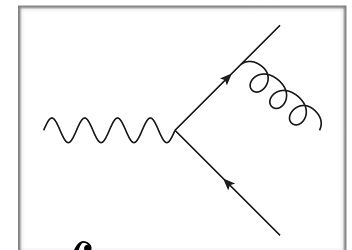
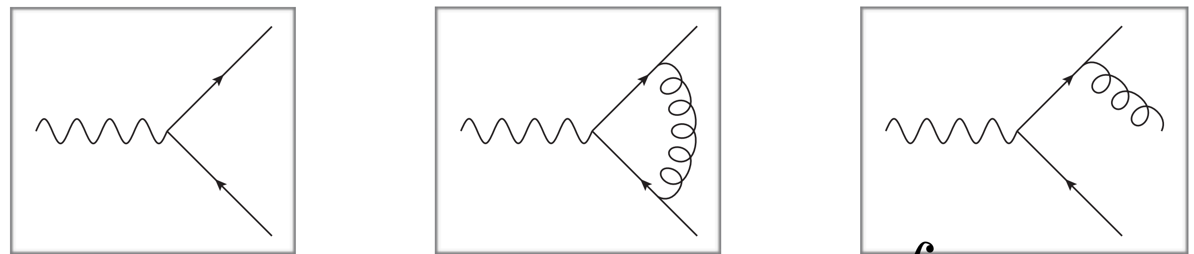




$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

NLO: How to?



$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

- Virtual and real emission not finite if taken alone
  - Infra-red divergences occur

$$\sigma_R^{q\bar{q}g} = \sigma_{LO} H(\epsilon) C_F \frac{\alpha_s}{2\pi} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} \right)$$

$$\sigma_V^{q\bar{q}(g)} = \sigma_{LO} H(\epsilon) C_F \frac{\alpha_s}{2\pi} \left(-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 \right)$$

- Need to include both in order to have a finite result

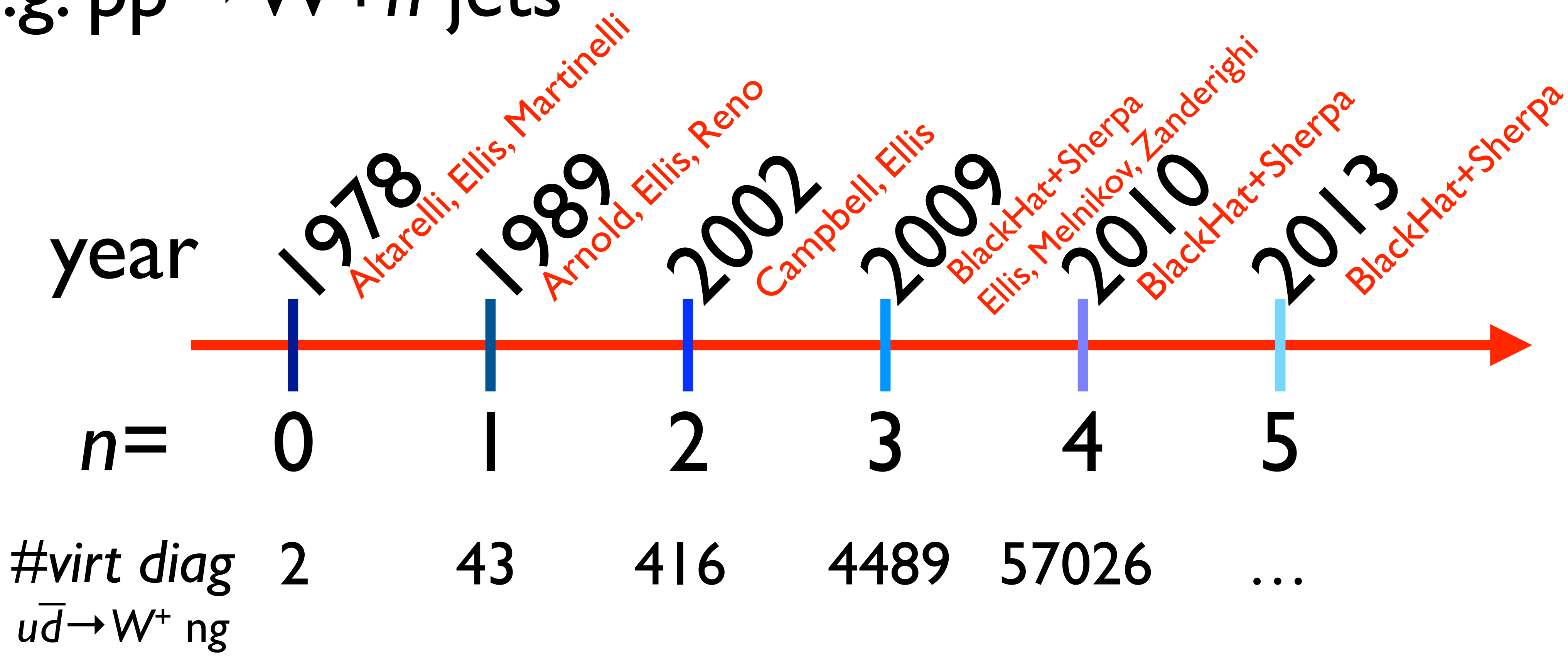
$$\sigma_{NLO} = \sigma_{LO} \left(1 + C_F \frac{\alpha_s}{2\pi} \frac{3}{2} \right)$$

Challenges at NLO:

- Compute (renormalized) one-loop diagrams for any choice of external particles
- Subtract singularities before doing the integration (numerically) in d=4
- If showering events, avoid double counting radiation from the shower and from real emissions

A revolution has just happened

- NLO evolution:
  - e.g. pp→W+*n* jets



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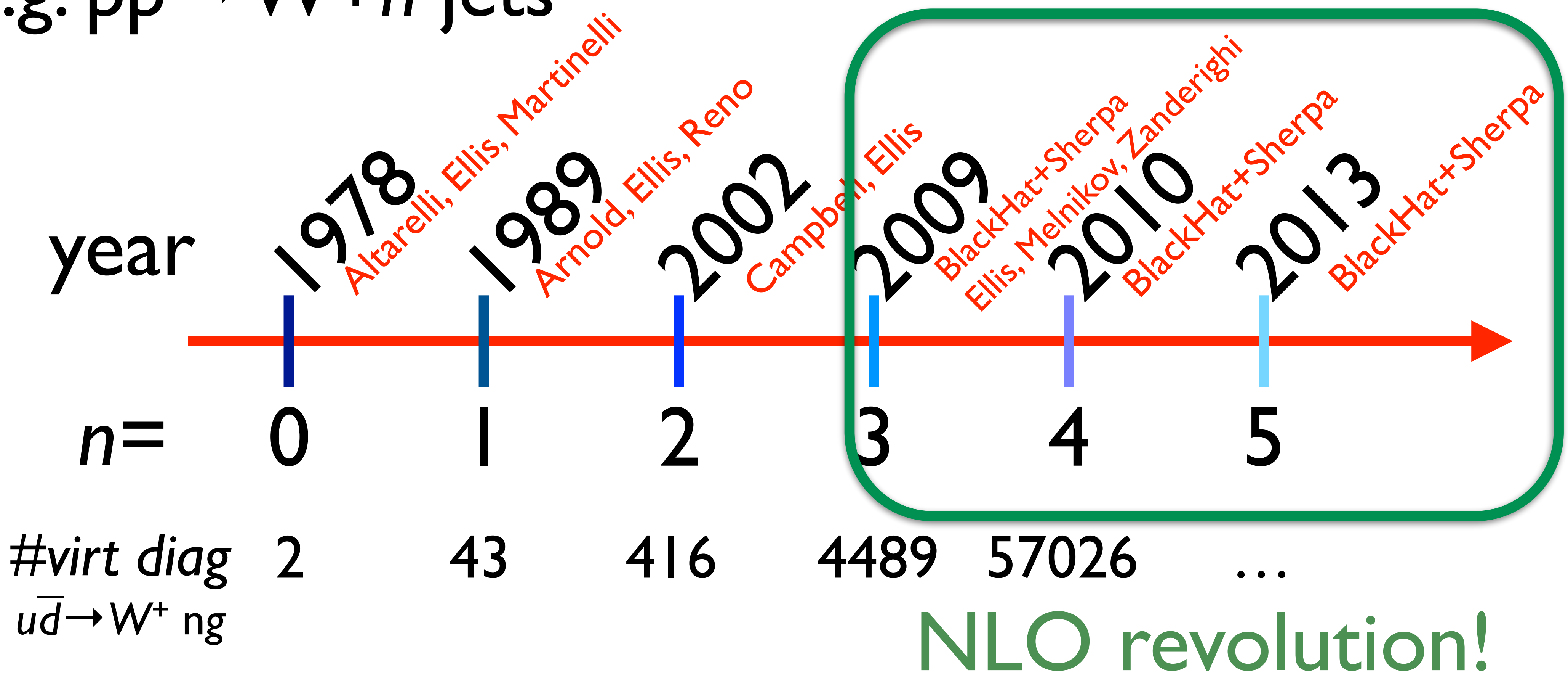


Process		Syntax	Cross section (pb)			
Vector boson +jets			LO 13 TeV		NLO 13 TeV	
a.1	$pp \to W^\pm$	`p p > wpm`	$1.375 \pm 0.002 \cdot 10^5$	$^{+15.4\%}_{-16.6\%}$ $^{+2.0\%}_{-1.6\%}$	$1.773 \pm 0.007 \cdot 10^5$	$^{+5.2\%}_{-9.4\%}$ $^{+1.9\%}_{-1.6\%}$
a.2	$pp \to W^\pm j$	`p p > wpm j`	$2.045 \pm 0.001 \cdot 10^4$	$^{+19.7\%}_{-17.2\%}$ $^{+1.4\%}_{-1.1\%}$	$2.843 \pm 0.010 \cdot 10^4$	$^{+5.9\%}_{-8.0\%}$ $^{+1.3\%}_{-1.1\%}$
a.3	$pp \to W^\pm jj$	`p p > wpm j j`	$6.805 \pm 0.015 \cdot 10^3$	$^{+24.5\%}_{-18.6\%}$ $^{+0.8\%}_{-0.7\%}$	$7.786 \pm 0.030 \cdot 10^3$	$^{+2.4\%}_{-6.0\%}$ $^{+0.9\%}_{-0.8\%}$
a.4	$pp \to W^\pm jjj$	`p p > wpm j j j`	$1.821 \pm 0.002 \cdot 10^3$	$^{+41.0\%}_{-27.1\%}$ $^{+0.5\%}_{-0.5\%}$	$2.005 \pm 0.008 \cdot 10^3$	$^{+0.9\%}_{-6.7\%}$ $^{+0.6\%}_{-0.5\%}$
a.5	$pp \to Z$	`p p > z`	$4.248 \pm 0.005 \cdot 10^4$	$^{+14.6\%}_{-15.8\%}$ $^{+2.0\%}_{-1.6\%}$	$5.410 \pm 0.022 \cdot 10^4$	$^{+4.6\%}_{-8.6\%}$ $^{+1.9\%}_{-1.5\%}$
a.6	$pp \to Zj$	`p p > z j`	$7.209 \pm 0.005 \cdot 10^3$	$^{+19.3\%}_{-17.0\%}$ $^{+1.2\%}_{-1.0\%}$	$9.742 \pm 0.035 \cdot 10^3$	$^{+5.8\%}_{-7.8\%}$ $^{+1.2\%}_{-1.0\%}$
a.7	$pp \to Zjj$	`p p > z j j`	$2.348 \pm 0.006 \cdot 10^3$	$^{+24.3\%}_{-18.5\%}$ $^{+0.6\%}_{-0.6\%}$	$2.665 \pm 0.010 \cdot 10^3$	$^{+2.5\%}_{-6.0\%}$ $^{+0.7\%}_{-0.7\%}$
a.8	$pp \to Zjjj$	`p p > z j j j`	$6.314 \pm 0.008 \cdot 10^2$	$^{+40.8\%}_{-27.0\%}$ $^{+0.5\%}_{-0.5\%}$	$6.996 \pm 0.028 \cdot 10^2$	$^{+1.1\%}_{-6.8\%}$ $^{+0.5\%}_{-0.5\%}$
a.9	$pp \to \gamma j$	`p p > a j`	$1.964 \pm 0.001 \cdot 10^4$	$^{+31.2\%}_{-26.0\%}$ $^{+1.7\%}_{-1.8\%}$	$5.218 \pm 0.025 \cdot 10^4$	$^{+24.5\%}_{-21.4\%}$ $^{+1.4\%}_{-1.6\%}$
a.10	$pp \to \gamma jj$	`p p > a j j`	$7.815 \pm 0.008 \cdot 10^3$	$^{+32.8\%}_{-24.2\%}$ $^{+0.9\%}_{-1.2\%}$	$1.004 \pm 0.004 \cdot 10^4$	$^{+5.9\%}_{-10.9\%}$ $^{+0.8\%}_{-1.2\%}$

Process		Syntax	Cross section (pb)			
Vector-boson pair +jets			LO 13 TeV		NLO 13 TeV	
b.1	$pp \to W^+W^-$ (4f)	`p p > w+ w-`	$7.355 \pm 0.005 \cdot 10^1$	$^{+5.0\%}_{-6.1\%}$ $^{+2.0\%}_{-1.5\%}$	$1.028 \pm 0.003 \cdot 10^2$	$^{+4.0\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$
b.2	$pp \to ZZ$	`p p > z z`	$1.097 \pm 0.002 \cdot 10^1$	$^{+4.5\%}_{-5.6\%}$ $^{+1.9\%}_{-1.5\%}$	$1.415 \pm 0.005 \cdot 10^1$	$^{+3.1\%}_{-3.7\%}$ $^{+1.8\%}_{-1.4\%}$
b.3	$pp \to ZW^\pm$	`p p > z wpm`	$2.777 \pm 0.003 \cdot 10^1$	$^{+3.6\%}_{-4.7\%}$ $^{+2.0\%}_{-1.5\%}$	$4.487 \pm 0.013 \cdot 10^1$	$^{+4.4\%}_{-4.4\%}$ $^{+1.7\%}_{-1.3\%}$
b.4	$pp \to \gamma\gamma$	`p p > a a`	$2.510 \pm 0.002 \cdot 10^1$	$^{+22.1\%}_{-22.4\%}$ $^{+2.4\%}_{-2.1\%}$	$6.593 \pm 0.021 \cdot 10^1$	$^{+17.6\%}_{-18.8\%}$ $^{+2.0\%}_{-1.9\%}$
b.5	$pp \to \gamma Z$	`p p > a z`	$2.523 \pm 0.004 \cdot 10^1$	$^{+9.9\%}_{-11.2\%}$ $^{+2.0\%}_{-1.6\%}$	$3.695 \pm 0.013 \cdot 10^1$	$^{+5.4\%}_{-7.1\%}$ $^{+1.8\%}_{-1.4\%}$
b.6	$pp \to \gamma W^\pm$	`p p > a wpm`	$2.954 \pm 0.005 \cdot 10^1$	$^{+9.5\%}_{-11.0\%}$ $^{+2.0\%}_{-1.7\%}$	$7.124 \pm 0.026 \cdot 10^1$	$^{+9.7\%}_{-9.9\%}$ $^{+1.5\%}_{-1.3\%}$
b.7	$pp \to W^+W^-j$ (4f)	`p p > w+ w- j`	$2.865 \pm 0.003 \cdot 10^1$	$^{+11.6\%}_{-10.0\%}$ $^{+1.0\%}_{-0.8\%}$	$3.730 \pm 0.013 \cdot 10^1$	$^{+4.9\%}_{-4.9\%}$ $^{+1.1\%}_{-0.8\%}$
b.8	$pp \to ZZj$	`p p > z z j`	$3.662 \pm 0.003 \cdot 10^0$	$^{+10.9\%}_{-9.3\%}$ $^{+1.0\%}_{-0.8\%}$	$4.830 \pm 0.016 \cdot 10^0$	$^{+5.0\%}_{-4.8\%}$ $^{+1.1\%}_{-0.9\%}$
b.9	$pp \to ZW^\pm j$	`p p > z wpm j`	$1.605 \pm 0.005 \cdot 10^1$	$^{+11.6\%}_{-10.0\%}$ $^{+0.9\%}_{-0.7\%}$	$2.086 \pm 0.007 \cdot 10^1$	$^{+4.9\%}_{-4.8\%}$ $^{+0.9\%}_{-0.7\%}$
b.10	$pp \to \gamma\gamma j$	`p p > a a j`	$1.022 \pm 0.001 \cdot 10^1$	$^{+20.3\%}_{-17.7\%}$ $^{+1.2\%}_{-1.5\%}$	$2.292 \pm 0.010 \cdot 10^1$	$^{+17.2\%}_{-15.1\%}$ $^{+1.0\%}_{-1.4\%}$
b.11*	$pp \to \gamma Zj$	`p p > a z j`	$8.310 \pm 0.017 \cdot 10^0$	$^{+14.5\%}_{-12.8\%}$ $^{+1.0\%}_{-1.0\%}$	$1.220 \pm 0.005 \cdot 10^1$	$^{+7.3\%}_{-7.4\%}$ $^{+0.9\%}_{-0.9\%}$
b.12*	$pp \to \gamma W^\pm j$	`p p > a wpm j`	$2.546 \pm 0.010 \cdot 10^1$	$^{+13.7\%}_{-12.1\%}$ $^{+0.9\%}_{-1.0\%}$	$3.713 \pm 0.015 \cdot 10^1$	$^{+7.2\%}_{-7.1\%}$ $^{+0.9\%}_{-1.0\%}$
b.13	$pp \to W^+W^+jj$	`p p > w+ w+ j j`	$1.484 \pm 0.006 \cdot 10^{-1}$	$^{+25.4\%}_{-18.9\%}$ $^{+2.1\%}_{-1.5\%}$	$2.251 \pm 0.011 \cdot 10^{-1}$	$^{+10.5\%}_{-10.6\%}$ $^{+2.2\%}_{-1.6\%}$
b.14	$pp \to W^-W^-jj$	`p p > w- w- j j`	$6.752 \pm 0.007 \cdot 10^{-2}$	$^{+25.4\%}_{-18.9\%}$ $^{+2.4\%}_{-1.7\%}$	$1.003 \pm 0.003 \cdot 10^{-1}$	$^{+10.1\%}_{-10.4\%}$ $^{+2.5\%}_{-1.8\%}$
b.15	$pp \to W^+W^-jj$ (4f)	`p p > w+ w- j j`	$1.144 \pm 0.002 \cdot 10^1$	$^{+27.2\%}_{-19.9\%}$ $^{+0.7\%}_{-0.5\%}$	$1.396 \pm 0.005 \cdot 10^1$	$^{+5.0\%}_{-6.8\%}$ $^{+0.7\%}_{-0.6\%}$
b.16	$pp \to ZZjj$	`p p > z z j j`	$1.344 \pm 0.002 \cdot 10^0$	$^{+26.6\%}_{-19.6\%}$ $^{+0.7\%}_{-0.6\%}$	$1.706 \pm 0.011 \cdot 10^0$	$^{+5.8\%}_{-7.2\%}$ $^{+0.8\%}_{-0.6\%}$
b.17	$pp \to ZW^\pm jj$	`p p > z wpm j j`	$8.038 \pm 0.009 \cdot 10^0$	$^{+26.7\%}_{-19.7\%}$ $^{+0.7\%}_{-0.5\%}$	$9.139 \pm 0.031 \cdot 10^0$	$^{+3.1\%}_{-5.1\%}$ $^{+0.7\%}_{-0.5\%}$
b.18	$pp \to \gamma\gamma jj$	`p p > a a j j`	$5.377 \pm 0.029 \cdot 10^0$	$^{+26.2\%}_{-19.8\%}$ $^{+0.6\%}_{-1.0\%}$	$7.501 \pm 0.032 \cdot 10^0$	$^{+8.8\%}_{-10.1\%}$ $^{+0.6\%}_{-1.0\%}$
b.19*	$pp \to \gamma Zjj$	`p p > a z j j`	$3.260 \pm 0.009 \cdot 10^0$	$^{+24.3\%}_{-18.4\%}$ $^{+0.6\%}_{-0.6\%}$	$4.242 \pm 0.016 \cdot 10^0$	$^{+6.5\%}_{-7.3\%}$ $^{+0.6\%}_{-0.6\%}$
b.20*	$pp \to \gamma W^\pm jj$	`p p > a wpm j j`	$1.233 \pm 0.002 \cdot 10^1$	$^{+24.7\%}_{-18.6\%}$ $^{+0.6\%}_{-0.6\%}$	$1.448 \pm 0.005 \cdot 10^1$	$^{+3.6\%}_{-5.4\%}$ $^{+0.6\%}_{-0.7\%}$

Process		Syntax	Cross section (pb)			
Three vector bosons +jet			LO 13 TeV		NLO 13 TeV	
c.1	$pp \to W^+W^-W^\pm$ (4f)	`p p > w+ w- wpm`	$1.307 \pm 0.003 \cdot 10^{-1}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.5\%}$	$2.109 \pm 0.006 \cdot 10^{-1}$	$^{+5.1\%}_{-4.1\%}$ $^{+1.6\%}_{-1.2\%}$
c.2	$pp \to ZW^+W^-$ (4f)	`p p > z w+ w-`	$9.658 \pm 0.065 \cdot 10^{-2}$	$^{+0.8\%}_{-1.1\%}$ $^{+2.1\%}_{-1.6\%}$	$1.679 \pm 0.005 \cdot 10^{-1}$	$^{+6.3\%}_{-5.1\%}$ $^{+1.6\%}_{-1.2\%}$
c.3	$pp \to ZZW^\pm$	`p p > z z wpm`	$2.996 \pm 0.016 \cdot 10^{-2}$	$^{+1.0\%}_{-1.4\%}$ $^{+2.0\%}_{-1.6\%}$	$5.550 \pm 0.020 \cdot 10^{-2}$	$^{+6.8\%}_{-5.5\%}$ $^{+1.5\%}_{-1.1\%}$
c.4	$pp \to ZZZ$	`p p > z z z`	$1.085 \pm 0.002 \cdot 10^{-2}$	$^{+0.0\%}_{-0.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.417 \pm 0.005 \cdot 10^{-2}$	$^{+2.7\%}_{-2.1\%}$ $^{+1.9\%}_{-1.5\%}$
c.5	$pp \to \gamma W^+W^-$ (4f)	`p p > a w+ w-`	$1.427 \pm 0.011 \cdot 10^{-1}$	$^{+1.9\%}_{-2.6\%}$ $^{+2.0\%}_{-1.5\%}$	$2.581 \pm 0.008 \cdot 10^{-1}$	$^{+5.4\%}_{-4.3\%}$ $^{+1.4\%}_{-1.1\%}$
c.6	$pp \to \gamma\gamma W^\pm$	`p p > a a wpm`	$2.681 \pm 0.007 \cdot 10^{-2}$	$^{+4.4\%}_{-5.6\%}$ $^{+1.9\%}_{-1.6\%}$	$8.251 \pm 0.032 \cdot 10^{-2}$	$^{+7.6\%}_{-7.0\%}$ $^{+1.0\%}_{-1.0\%}$
c.7	$pp \to \gamma ZW^\pm$	`p p > a z wpm`	$4.994 \pm 0.011 \cdot 10^{-2}$	$^{+0.8\%}_{-1.4\%}$ $^{+1.9\%}_{-1.6\%}$	$1.117 \pm 0.004 \cdot 10^{-1}$	$^{+7.2\%}_{-5.9\%}$ $^{+1.2\%}_{-0.9\%}$
c.8	$pp \to \gamma ZZ$	`p p > a z z`	$2.320 \pm 0.005 \cdot 10^{-2}$	$^{+2.0\%}_{-2.9\%}$ $^{+1.9\%}_{-1.5\%}$	$3.118 \pm 0.012 \cdot 10^{-2}$	$^{+2.8\%}_{-2.7\%}$ $^{+1.8\%}_{-1.4\%}$
c.9	$pp \to \gamma\gamma Z$	`p p > a a z`	$3.078 \pm 0.007 \cdot 10^{-2}$	$^{+5.6\%}_{-6.8\%}$ $^{+1.9\%}_{-1.6\%}$	$4.634 \pm 0.020 \cdot 10^{-2}$	$^{+4.5\%}_{-5.0\%}$ $^{+1.7\%}_{-1.3\%}$
c.10	$pp \to \gamma\gamma\gamma$	`p p > a a a`	$1.269 \pm 0.003 \cdot 10^{-2}$	$^{+9.8\%}_{-11.0\%}$ $^{+2.0\%}_{-1.8\%}$	$3.441 \pm 0.012 \cdot 10^{-2}$	$^{+11.8\%}_{-11.6\%}$ $^{+1.4\%}_{-1.5\%}$
c.11	$pp \to W^+W^-W^\pm j$ (4f)	`p p > w+ w- wpm j`	$9.167 \pm 0.010 \cdot 10^{-2}$	$^{+15.0\%}_{-12.2\%}$ $^{+1.0\%}_{-0.7\%}$	$1.197 \pm 0.004 \cdot 10^{-1}$	$^{+5.2\%}_{-5.6\%}$ $^{+1.0\%}_{-0.8\%}$
c.12*	$pp \to ZW^+W^-j$ (4f)	`p p > z w+ w- j`	$8.340 \pm 0.010 \cdot 10^{-2}$	$^{+15.6\%}_{-12.6\%}$ $^{+1.0\%}_{-0.7\%}$	$1.066 \pm 0.003 \cdot 10^{-1}$	$^{+4.5\%}_{-5.3\%}$ $^{+1.0\%}_{-0.7\%}$
c.13*	$pp \to ZZW^\pm j$	`p p > z z wpm j`	$2.810 \pm 0.004 \cdot 10^{-2}$	$^{+16.1\%}_{-13.0\%}$ $^{+1.0\%}_{-0.7\%}$	$3.660 \pm 0.013 \cdot 10^{-2}$	$^{+4.8\%}_{-5.6\%}$ $^{+1.0\%}_{-0.7\%}$
c.14*	$pp \to ZZZj$	`p p > z z z j`	$4.823 \pm 0.011 \cdot 10^{-3}$	$^{+14.3\%}_{-11.8\%}$ $^{+1.4\%}_{-1.0\%}$	$6.341 \pm 0.025 \cdot 10^{-3}$	$^{+4.9\%}_{-5.4\%}$ $^{+1.4\%}_{-1.0\%}$
c.15*	$pp \to \gamma W^+W^-j$ (4f)	`p p > a w+ w- j`	$1.182 \pm 0.004 \cdot 10^{-1}$	$^{+13.4\%}_{-11.2\%}$ $^{+0.8\%}_{-0.7\%}$	$1.233 \pm 0.004 \cdot 10^3$	$^{+18.9\%}_{-19.9\%}$ $^{+1.0\%}_{-1.5\%}$
c.16	$pp \to \gamma\gamma W^\pm j$	`p p > a a wpm j`	$4.107 \pm 0.015 \cdot 10^{-2}$	$^{+11.8\%}_{-10.2\%}$ $^{+0.6\%}_{-0.8\%}$	$5.807 \pm 0.023 \cdot 10^{-2}$	$^{+5.8\%}_{-5.5\%}$ $^{+0.7\%}_{-0.7\%}$
c.17*	$pp \to \gamma ZW^\pm j$	`p p > a z wpm j`	$5.833 \pm 0.023 \cdot 10^{-2}$	$^{+14.4\%}_{-12.0\%}$ $^{+0.7\%}_{-0.6\%}$	$7.764 \pm 0.025 \cdot 10^{-2}$	$^{+5.1\%}_{-5.5\%}$ $^{+0.8\%}_{-0.6\%}$
c.18*	[illegible]	[illegible]	$9.995 \pm 0.013 \cdot 10^{-3}$	$^{+12.5\%}_{-10.6\%}$ $^{+1.2\%}_{-0.9\%}$	$1.371 \pm 0.005 \cdot 10^{-2}$	$^{+5.6\%}_{-5.5\%}$ $^{+1.2\%}_{-0.9\%}$
c.19*	$pp \to \gamma\gamma Zj$	`p p > a a z j`	$1.372 \pm 0.003 \cdot 10^{-2}$	$^{+10.9\%}_{-9.4\%}$ $^{+1.0\%}_{-0.9\%}$	$2.051 \pm 0.011 \cdot 10^{-2}$	$^{+7.0\%}_{-6.3\%}$ $^{+1.0\%}_{-0.9\%}$

Process		Syntax	Cross section (pb)			
Four vector bosons			LO 13 TeV		NLO 13 TeV	
c.21*	$pp \to W^+W^-W^+W^-$ (4f)	`p p > w+ w- w+ w-`	$5.721 \pm 0.014 \cdot 10^{-4}$	$^{+3.7\%}_{-3.5\%}$ $^{+2.3\%}_{-1.7\%}$	$9.959 \pm 0.035 \cdot 10^{-4}$	$^{+7.4\%}_{-6.0\%}$ $^{+1.7\%}_{-1.2\%}$
c.22*	$pp \to W^+W^-W^\pm Z$ (4f)	`p p > w+ w- wpm z`	$6.391 \pm 0.076 \cdot 10^{-4}$	$^{+4.4\%}_{-4.1\%}$ $^{+2.4\%}_{-1.8\%}$	$1.188 \pm 0.004 \cdot 10^{-3}$	$^{+8.4\%}_{-6.8\%}$ $^{+1.7\%}_{-1.2\%}$
c.23*	$pp \to W^+W^-W^\pm\gamma$ (4f)	`p p > w+ w- wpm a`	$8.115 \pm 0.064 \cdot 10^{-4}$	$^{+2.5\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.546 \pm 0.005 \cdot 10^{-3}$	$^{+7.9\%}_{-6.3\%}$ $^{+1.5\%}_{-1.1\%}$
c.24*	$pp \to W^+W^-ZZ$ (4f)	`p p > w+ w- z z`	$4.320 \pm 0.013 \cdot 10^{-4}$	$^{+4.4\%}_{-4.1\%}$ $^{+2.4\%}_{-1.7\%}$	$7.107 \pm 0.020 \cdot 10^{-4}$	$^{+7.0\%}_{-5.7\%}$ $^{+1.8\%}_{-1.3\%}$
c.25*	$pp \to W^+W^-Z\gamma$ (4f)	`p p > w+ w- z a`	$8.403 \pm 0.016 \cdot 10^{-4}$	$^{+3.0\%}_{-2.9\%}$ $^{+2.3\%}_{-1.7\%}$	$1.483 \pm 0.004 \cdot 10^{-3}$	$^{+7.2\%}_{-5.8\%}$ $^{+1.6\%}_{-1.2\%}$
c.26*	$pp \to W^+W^-\gamma\gamma$ (4f)	`p p > w+ w- a a`	$5.198 \pm 0.012 \cdot 10^{-4}$	$^{+0.6\%}_{-0.9\%}$ $^{+2.1\%}_{-1.6\%}$	$9.381 \pm 0.032 \cdot 10^{-4}$	$^{+6.7\%}_{-5.3\%}$ $^{+1.4\%}_{-1.1\%}$
c.27*	$pp \to W^\pm ZZZ$	`p p > wpm z z z`	$5.862 \pm 0.010 \cdot 10^{-5}$	$^{+5.1\%}_{-4.7\%}$ $^{+2.4\%}_{-1.8\%}$	$1.240 \pm 0.004 \cdot 10^{-4}$	$^{+9.9\%}_{-8.0\%}$ $^{+1.7\%}_{-1.2\%}$
c.28*	$pp \to W^\pm ZZ\gamma$	`p p > wpm z z a`	$1.148 \pm 0.003 \cdot 10^{-4}$	$^{+3.6\%}_{-3.5\%}$ $^{+2.2\%}_{-1.7\%}$	$2.945 \pm 0.008 \cdot 10^{-4}$	$^{+10.8\%}_{-8.7\%}$ $^{+1.3\%}_{-1.0\%}$
c.29*	$pp \to W^\pm Z\gamma\gamma$	`p p > wpm z a a`	$1.054 \pm 0.004 \cdot 10^{-4}$	$^{+1.7\%}_{-1.9\%}$ $^{+2.1\%}_{-1.7\%}$	$3.033 \pm 0.010 \cdot 10^{-4}$	$^{+10.6\%}_{-8.6\%}$ $^{+1.1\%}_{-0.8\%}$
c.30*	$pp \to W^\pm\gamma\gamma\gamma$	`p p > wpm a a a`	$3.600 \pm 0.013 \cdot 10^{-5}$	$^{+0.4\%}_{-1.0\%}$ $^{+2.0\%}_{-1.6\%}$	$1.246 \pm 0.005 \cdot 10^{-4}$	$^{+9.8\%}_{-8.1\%}$ $^{+0.9\%}_{-0.8\%}$
c.31*	$pp \to ZZZZ$	`p p > z z z z`	$1.989 \pm 0.002 \cdot 10^{-5}$	$^{+3.8\%}_{-3.6\%}$ $^{+2.2\%}_{-1.7\%}$	$2.629 \pm 0.008 \cdot 10^{-5}$	$^{+3.5\%}_{-3.0\%}$ $^{+2.2\%}_{-1.7\%}$
c.32*	$pp \to ZZZ\gamma$	`p p > z z z a`	$3.945 \pm 0.007 \cdot 10^{-5}$	$^{+1.9\%}_{-2.1\%}$ $^{+2.1\%}_{-1.6\%}$	$5.224 \pm 0.016 \cdot 10^{-5}$	$^{+3.3\%}_{-2.7\%}$ $^{+2.1\%}_{-1.6\%}$
c.33*	$pp \to ZZ\gamma\gamma$	`p p > z z a a`	$5.513 \pm 0.017 \cdot 10^{-5}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.1\%}_{-1.6\%}$	$7.518 \pm 0.032 \cdot 10^{-5}$	$^{+3.4\%}_{-2.6\%}$ $^{+2.0\%}_{-1.5\%}$
c.34*	$pp \to Z\gamma\gamma\gamma$	`p p > z a a a`	$4.790 \pm 0.012 \cdot 10^{-5}$	$^{+2.3\%}_{-3.1\%}$ $^{+2.0\%}_{-1.6\%}$	$7.103 \pm 0.026 \cdot 10^{-5}$	$^{+3.4\%}_{-3.2\%}$ $^{+1.6\%}_{-1.5\%}$
c.35*	$pp \to \gamma\gamma\gamma\gamma$	`p p > a a a a`	$1.594 \pm 0.004 \cdot 10^{-5}$	$^{+4.7\%}_{-5.7\%}$ $^{+1.9\%}_{-1.7\%}$	$3.389 \pm 0.012 \cdot 10^{-5}$	$^{+7.0\%}_{-6.7\%}$ $^{+1.3\%}_{-1.3\%}$

Process		Syntax	Cross section (pb)			
Heavy quarks and jets			LO 13 TeV		NLO 13 TeV	
d.1	$pp \to jj$	`p p > j j`	$1.162 \pm 0.001 \cdot 10^6$	$^{+24.9\%}_{-18.8\%}$ $^{+0.8\%}_{-0.9\%}$	$1.580 \pm 0.007 \cdot 10^6$	$^{+8.4\%}_{-9.0\%}$ $^{+0.7\%}_{-0.9\%}$
d.2	$pp \to jjj$	`p p > j j j`	$8.940 \pm 0.021 \cdot 10^4$	$^{+43.8\%}_{-28.4\%}$ $^{+1.2\%}_{-1.4\%}$	$7.791 \pm 0.037 \cdot 10^4$	$^{+2.1\%}_{-23.2\%}$ $^{+1.1\%}_{-1.3\%}$
d.3	$pp \to b\bar{b}$ (4f)	`p p > b b~`	$3.743 \pm 0.004 \cdot 10^3$	$^{+25.2\%}_{-18.9\%}$ $^{+1.5\%}_{-1.8\%}$	$6.438 \pm 0.028 \cdot 10^3$	$^{+15.9\%}_{-13.3\%}$ $^{+1.5\%}_{-1.7\%}$
d.4*	$pp \to b\bar{b}j$ (4f)	`p p > b b~ j`	$1.050 \pm 0.002 \cdot 10^3$	$^{+44.1\%}_{-28.5\%}$ $^{+1.6\%}_{-1.8\%}$	$1.327 \pm 0.007 \cdot 10^3$	$^{+6.8\%}_{-11.6\%}$ $^{+1.5\%}_{-1.8\%}$
d.5*	$pp \to b\bar{b}jj$ (4f)	`p p > b b~ j j`	$1.852 \pm 0.006 \cdot 10^2$	$^{+61.8\%}_{-35.6\%}$ $^{+2.1\%}_{-2.4\%}$	$2.471 \pm 0.012 \cdot 10^2$	$^{+8.2\%}_{-16.4\%}$ $^{+2.0\%}_{-2.3\%}$
d.6	$pp \to b\bar{b}b\bar{b}$ (4f)	`p p > b b~ b b~`	$5.050 \pm 0.007 \cdot 10^{-1}$	$^{+61.7\%}_{-35.6\%}$ $^{+2.9\%}_{-3.4\%}$	$8.736 \pm 0.034 \cdot 10^{-1}$	$^{+20.9\%}_{-22.0\%}$ $^{+2.9\%}_{-3.4\%}$
d.7	$pp \to t\bar{t}$	`p p > t t~`	$4.584 \pm 0.003 \cdot 10^2$	$^{+29.0\%}_{-21.1\%}$ $^{+1.8\%}_{-2.0\%}$	$6.741 \pm 0.023 \cdot 10^2$	$^{+9.8\%}_{-10.9\%}$ $^{+1.8\%}_{-2.1\%}$
d.8	$pp \to t\bar{t}j$	`p p > t t~ j`	$3.135 \pm 0.002 \cdot 10^2$	$^{+45.1\%}_{-29.0\%}$ $^{+2.2\%}_{-2.5\%}$	$4.106 \pm 0.015 \cdot 10^2$	$^{+8.1\%}_{-12.2\%}$ $^{+2.1\%}_{-2.5\%}$
d.9	$pp \to t\bar{t}jj$	`p p > t t~ j j`	$1.361 \pm 0.001 \cdot 10^2$	$^{+61.4\%}_{-35.6\%}$ $^{+2.6\%}_{-3.0\%}$	$1.795 \pm 0.006 \cdot 10^2$	$^{+9.3\%}_{-16.1\%}$ $^{+2.4\%}_{-2.9\%}$
d.10	$pp \to t\bar{t}t\bar{t}$	`p p > t t~ t t~`	$4.505 \pm 0.005 \cdot 10^{-3}$	$^{+63.8\%}_{-36.5\%}$ $^{+5.4\%}_{-5.7\%}$	$9.201 \pm 0.028 \cdot 10^{-3}$	$^{+30.8\%}_{-25.6\%}$ $^{+5.5\%}_{-5.9\%}$
d.11	$pp \to t\bar{t}b\bar{b}$ (4f)	`p p > t t~ b b~`	$6.119 \pm 0.004 \cdot 10^0$	$^{+62.1\%}_{-35.7\%}$ $^{+2.9\%}_{-3.5\%}$	$1.452 \pm 0.005 \cdot 10^1$	$^{+37.6\%}_{-27.5\%}$ $^{+2.9\%}_{-3.5\%}$

Process		Syntax	Cross section (pb)			
Heavy quarks+vector bosons			LO 13 TeV		NLO 13 TeV	
e.1	$pp \to W^\pm b\bar{b}$ (4f)	`p p > wpm b b~`	$3.074 \pm 0.002 \cdot 10^2$	$^{+42.3\%}_{-29.2\%}$ $^{+2.0\%}_{-1.6\%}$	$8.162 \pm 0.034 \cdot 10^2$	$^{+29.8\%}_{-23.6\%}$ $^{+1.5\%}_{-1.2\%}$
e.2	$pp \to Z b\bar{b}$ (4f)	`p p > z b b~`	$6.993 \pm 0.003 \cdot 10^2$	$^{+33.5\%}_{-24.4\%}$ $^{+1.0\%}_{-1.4\%}$	$1.235 \pm 0.004 \cdot 10^3$	$^{+19.9\%}_{-17.4\%}$ $^{+1.0\%}_{-1.4\%}$
e.3	$pp \to \gamma b\bar{b}$ (4f)	`p p > a b b~`	$1.731 \pm 0.001 \cdot 10^3$	$^{+51.9\%}_{-34.8\%}$ $^{+1.6\%}_{-2.1\%}$	$4.171 \pm 0.015 \cdot 10^3$	$^{+33.7\%}_{-27.1\%}$ $^{+1.4\%}_{-1.9\%}$
e.4*	$pp \to W^\pm b\bar{b}j$ (4f)	`p p > wpm b b~ j`	$1.861 \pm 0.003 \cdot 10^2$	$^{+42.5\%}_{-27.7\%}$ $^{+0.7\%}_{-0.7\%}$	$3.957 \pm 0.013 \cdot 10^2$	$^{+27.0\%}_{-21.0\%}$ $^{+0.7\%}_{-0.6\%}$
e.5*	$pp \to Z b\bar{b}j$ (4f)	`p p > z b b~ j`	$1.604 \pm 0.001 \cdot 10^2$	$^{+42.4\%}_{-27.6\%}$ $^{+0.9\%}_{-1.1\%}$	$2.805 \pm 0.009 \cdot 10^2$	$^{+21.0\%}_{-17.6\%}$ $^{+0.8\%}_{-1.0\%}$
e.6*	$pp \to \gamma b\bar{b}j$ (4f)	`p p > a b b~ j`	$7.812 \pm 0.017 \cdot 10^2$	$^{+51.2\%}_{-32.0\%}$ $^{+1.0\%}_{-1.5\%}$	$1.233 \pm 0.004 \cdot 10^3$	$^{+18.9\%}_{-19.9\%}$ $^{+1.0\%}_{-1.5\%}$
e.7	$pp \to t\bar{t}W^\pm$	`p p > t t~ wpm`	$3.777 \pm 0.003 \cdot 10^{-1}$	$^{+23.9\%}_{-18.0\%}$ $^{+2.1\%}_{-1.6\%}$	$5.662 \pm 0.021 \cdot 10^{-1}$	$^{+11.2\%}_{-10.6\%}$ $^{+1.7\%}_{-1.3\%}$
e.8	$pp \to t\bar{t}Z$	`p p > t t~ z`	$5.273 \pm 0.004 \cdot 10^{-1}$	$^{+30.5\%}_{-21.8\%}$ $^{+1.8\%}_{-2.1\%}$	$7.598 \pm 0.026 \cdot 10^{-1}$	$^{+9.7\%}_{-11.1\%}$ $^{+1.9\%}_{-2.2\%}$
e.9	$pp \to t\bar{t}\gamma$	`p p > t t~ a`	$1.204 \pm 0.001 \cdot 10^0$	$^{+29.6\%}_{-21.3\%}$ $^{+1.6\%}_{-1.8\%}$	$1.744 \pm 0.005 \cdot 10^0$	$^{+9.8\%}_{-11.0\%}$ $^{+1.7\%}_{-2.0\%}$
e.10*	$pp \to t\bar{t}W^\pm j$	`p p > t t~ wpm j`	$2.352 \pm 0.002 \cdot 10^{-1}$	$^{+40.9\%}_{-27.1\%}$ $^{+1.3\%}_{-1.0\%}$	$3.404 \pm 0.011 \cdot 10^{-1}$	$^{+11.2\%}_{-14.0\%}$ $^{+1.2\%}_{-0.9\%}$
e.11*	$pp \to t\bar{t}Zj$	`p p > t t~ z j`	$3.953 \pm 0.004 \cdot 10^{-1}$	$^{+46.2\%}_{-29.5\%}$ $^{+2.7\%}_{-3.0\%}$	$5.074 \pm 0.016 \cdot 10^{-1}$	$^{+7.0\%}_{-12.3\%}$ $^{+2.5\%}_{-2.9\%}$
e.12*	$pp \to t\bar{t}\gamma j$	`p p > t t~ a j`	$8.726 \pm 0.010 \cdot 10^{-1}$	$^{+45.4\%}_{-29.1\%}$ $^{+2.3\%}_{-2.6\%}$	$1.135 \pm 0.004 \cdot 10^0$	$^{+7.5\%}_{-12.2\%}$ $^{+2.2\%}_{-2.5\%}$
e.13*	$pp \to t\bar{t}W^-W^+$ (4f)	`p p > t t~ w+ w-`	$6.675 \pm 0.006 \cdot 10^{-3}$	$^{+30.9\%}_{-21.9\%}$ $^{+2.1\%}_{-2.0\%}$	$9.904 \pm 0.026 \cdot 10^{-3}$	$^{+10.9\%}_{-11.8\%}$ $^{+2.1\%}_{-2.1\%}$
e.14*	$pp \to t\bar{t}W^\pm Z$	`p p > t t~ wpm z`	$2.404 \pm 0.002 \cdot 10^{-3}$	$^{+26.6\%}_{-19.6\%}$ $^{+2.5\%}_{-1.8\%}$	$3.525 \pm 0.010 \cdot 10^{-3}$	$^{+10.6\%}_{-10.8\%}$ $^{+2.3\%}_{-1.6\%}$
e.15*	$pp \to t\bar{t}W^\pm\gamma$	`p p > t t~ wpm a`	$2.718 \pm 0.003 \cdot 10^{-3}$	$^{+25.4\%}_{-18.9\%}$ $^{+2.3\%}_{-1.8\%}$	$3.927 \pm 0.013 \cdot 10^{-3}$	$^{+10.3\%}_{-10.4\%}$ $^{+2.0\%}_{-1.5\%}$
e.16*	$pp \to t\bar{t}ZZ$	`p p > t t~ z z`	$1.349 \pm 0.014 \cdot 10^{-3}$	$^{+29.3\%}_{-21.1\%}$ $^{+1.7\%}_{-1.5\%}$	$1.840 \pm 0.007 \cdot 10^{-3}$	$^{+7.9\%}_{-9.9\%}$ $^{+1.7\%}_{-1.5\%}$
e.17*	$pp \to t\bar{t}Z\gamma$	`p p > t t~ z a`	$2.548 \pm 0.003 \cdot 10^{-3}$	$^{+30.1\%}_{-21.5\%}$ $^{+1.7\%}_{-1.6\%}$	$3.656 \pm 0.012 \cdot 10^{-3}$	$^{+9.7\%}_{-11.0\%}$ $^{+1.8\%}_{-1.9\%}$
e.18*	$pp \to t\bar{t}\gamma\gamma$	`p p > t t~ a a`	$3.272 \pm 0.006 \cdot 10^{-3}$	$^{+28.4\%}_{-20.6\%}$ $^{+1.3\%}_{-1.1\%}$	$4.402 \pm 0.015 \cdot 10^{-3}$	$^{+7.8\%}_{-9.7\%}$ $^{+1.4\%}_{-1.4\%}$

Process		Syntax	Cross section (pb)			
Single-top			LO 13 TeV		NLO 13 TeV	
f.1	$pp \to tj$ (t-channel)	`p p > tt j $$ w+ w-`	$1.520 \pm 0.001 \cdot 10^2$	$^{+9.4\%}_{-11.9\%}$ $^{+0.4\%}_{-0.6\%}$	$1.563 \pm 0.005 \cdot 10^2$	$^{+1.4\%}_{-1.8\%}$ $^{+0.4\%}_{-0.6\%}$

Loop proliferation

- in the last 10 years, many different techniques have been developed in order to compute any one-loop process.
- They (roughly) fall into 3 classes
  - Tensor reduction
  - Generalized unitarity
  - Integrand reduction

Passarino, Veltman, 1979
Denner, Dittmaier, hep-ph/509141
Binoth, Guillet, Heinrich, Pilon, Reiter, arXiv:0810.0992

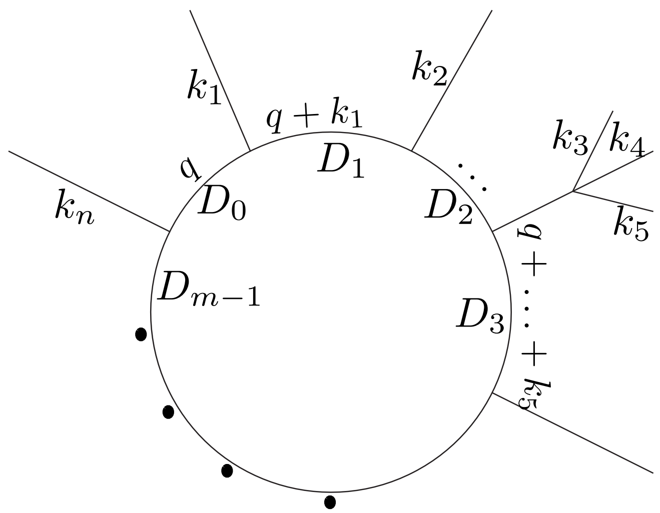
Bern, Dixon, Dunbar, Kosower, hep-ph/9403226 + …
Ellis, Giele, Kunszt, arXiv:0708.2398
+ Melnikov, arXiv:0806.3467

Ossola, Papadopoulos, Pittau, hep-ph/0609007
Del Aguila, Pittau, hep-ph/0404120
Mastrolia, Ossola, Reiter, Tramontano, arXiv:1006.0710

Basics of loops: Passarino-Veltman reduction

- Any one-loop amplitude can be written as a linear combination of a basis of integrals

$$\begin{aligned} A(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\ &+ \sum_{i_0<i_1<i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\ &+ \sum_{i_0<i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\ &+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\ &+ R \end{aligned}$$



$$D(i_1,i_2,i_3,i_4) = \int \frac{d^D q}{N} \frac{1}{D_{i_1} D_{i_2} D_{i_3} D_{i_4}}$$

$$C(i_1,i_2,i_3) = \int \frac{d^D q}{N} \frac{1}{D_{i_1} D_{i_2} D_{i_3}}$$

$$B(i_1,i_2) = \int \frac{d^D q}{N} \frac{1}{D_{i_1} D_{i_2}}$$

$$A(i_1) = \int \frac{d^D q}{N} \frac{1}{D_{i_1}}$$

- Integrals can be computed once for all and coded into libraries

QCDLoops, Ellis, Zanderighi
OneLoop, Van Hameren
...

- Coefficients can be found by computing analytically the amplitude and solving (algebraically) a system of equations
  - In practice feasible only for low multiplicities

Passarino-Veltman reduction at the integrand level

Ossola, Papadopoulos, Pittau, hep-ph/0609007
CutTools: Ossola, Papadopoulos, Pittau, arXiv:0711.3596

- The integrand of the loop amplitude can be written as

$$A(\bar{q}) = \frac{N(q)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

$$\begin{aligned} N(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0,i_1,i_2,i_3}^{m-1} D_i \\ &+ \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0,i_1,i_2}^{m-1} D_i \\ &+ \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0,i_1}^{m-1} D_i \\ &+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{m-1} D_i \\ &+ \tilde{P}(q) \prod_{i}^{m-1} D_i \,. \end{aligned}$$

a,b,c,d are the same as in the previous slide;
ã,b̃,c̃,d̃ gives 0 after integration (spurious terms)

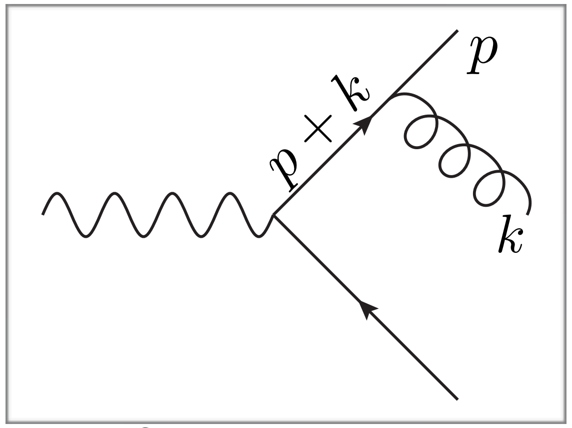
- The system of equation can be cast in a triangolar form and solved numerically at each point in the phase-space:
  - Fix external momenta
  - Choose *q* such that all *D*'s vanish but D_1,D_2,D_3,D_4 → get the coefficient *d(1234)*
  - Do that for all 4-point integrals, then for 3-point ones, until all coefficients are known

The evil is in the details

- Numerical approach: must work in *D=4*
  - But scalar integrals are computed in *D=D*
  - Mismatch gives origin to the rational terms (*R*) which need to be added in order to get the correct result
  - Two kind of rational terms exist:
    - Rational terms that originates from the denominators (R_1): can be obtained from the amplitude without extra infos
    - Rational terms that originates from the numerator (R_2): need to be added to the amplitude, can be provided as extra Feynman rules
      - Are in a finite number
      - Can be computed once for all from the model
    - UV renormalisation done via extra Feynman rules as well

Subtraction of Infra-Red divergences: Problem #1

- Real and virtual contributions are not separately finite
- Numerical integration (in D=4): can integrate only finite quantities
- QCD helps: divergences have an universal structure:



$(p+k)^2 = 2E_pE_k(1-\cos\theta_{pk})$

- Soft:

$$\lim_{k\to 0} |M_{n+1}|^2 \simeq \sum_{ij} |M_n^{ij}|^2 \frac{p_i p_j}{p_i k \; p_j k}$$

- Collinear:

$$\lim_{p//k} |M_{n+1}|^2 \simeq |M_n|^2 \; P^{AP}(z)$$

- Use universality of limits to build local counterterms to render *n* and *n+1* body contributions finite

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V - \int d\Phi_1 \; C + \int d\Phi_1 \; \left(C + d\sigma^{n+1}_R\right)$$

Integrating C is much simpler than than R
Can be done in D=D dimension (once and for all)

Subtraction of Infra-Red divergences: Problem #2

- Real emissions can have singularities in different regions of the phase-space:
- E.g. $gg \to t\bar{t}g$:
  - g collinear to g or g
  - g soft
- Numeric integrators (VEGAS) are quite dumb (still, that is the best one can do): peaks need to be well aligned with the integration variables
- *"Divide et impera"* solution: integrate one singularity at the time, with the most suitable phase-space parameterisation:

$$|M|^2 = \sum_{ij} S_{ij} \, |M|^2 = \sum_{ij} |M|^2_{ij} \qquad \sum S_{ij} = 1$$

$$S_{ij} \to 1 \text{ if } k_i \cdot k_j \to 0 \qquad S_{ij} \to 0 \text{ if } k_{m\neq i} \cdot k_{n\neq j} \to 0$$

Advantages:

- Parallelization: Each contribution can be integrated independently, with a suitable PS parameterization
- The number of contribution grows at most as n^2
- Symmetries can be used to reduce the numbers of contributions
  - E.g: only 3 contributions for $gg \to g \ldots g$

More details…

- Local subtraction is done as a modified '+' prescription
  - Subtract only close enough to the singularity

$$d\sigma_{ij}^{(n+1)}(r) = \left(\frac{1}{\xi_i}\right)_c \left(\frac{1}{1-y_{ij}}\right)_\delta \left((1-y_{ij})\xi_i^2 \mathcal{M}^{(n+1,0)}(r)\right) \mathcal{S}_{ij}(r) \frac{J^{n_L^{(B)}}}{\mathcal{N}(r)} d\xi_i dy_{ij} d\varphi_i d\widetilde{\phi}_n^{ij}$$

$$\int_0^{\xi_{\max}} d\xi_i f(\xi_i) \left(\frac{1}{\xi_i}\right)_c = \int_0^{\xi_{\max}} d\xi_i \frac{f(\xi_i) - f(0)\Theta(\xi_{cut} - \xi_i)}{\xi_i},$$

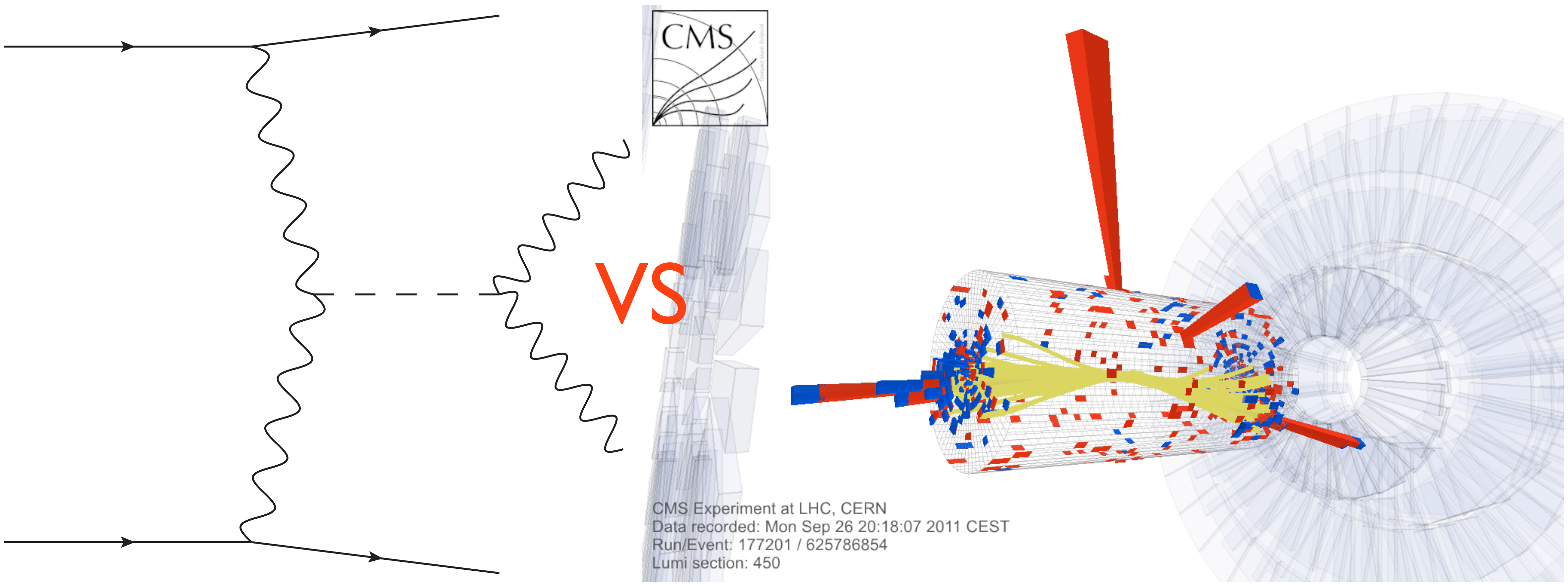
$$\int_{-1}^{1} dy_{ij} g(y_{ij}) \left(\frac{1}{1-y_{ij}}\right)_\delta = \int_{-1}^{1} dy_{ij} \frac{g(y_{ij}) - g(1)\Theta(y_{ij} - 1 + \delta)}{1 - y_{ij}}$$

  - This is (a summary of) the so-called FKS-subtraction
    (Frixione, Kunszt, Signer, hep-ph/9512328)

Why to care about showering?

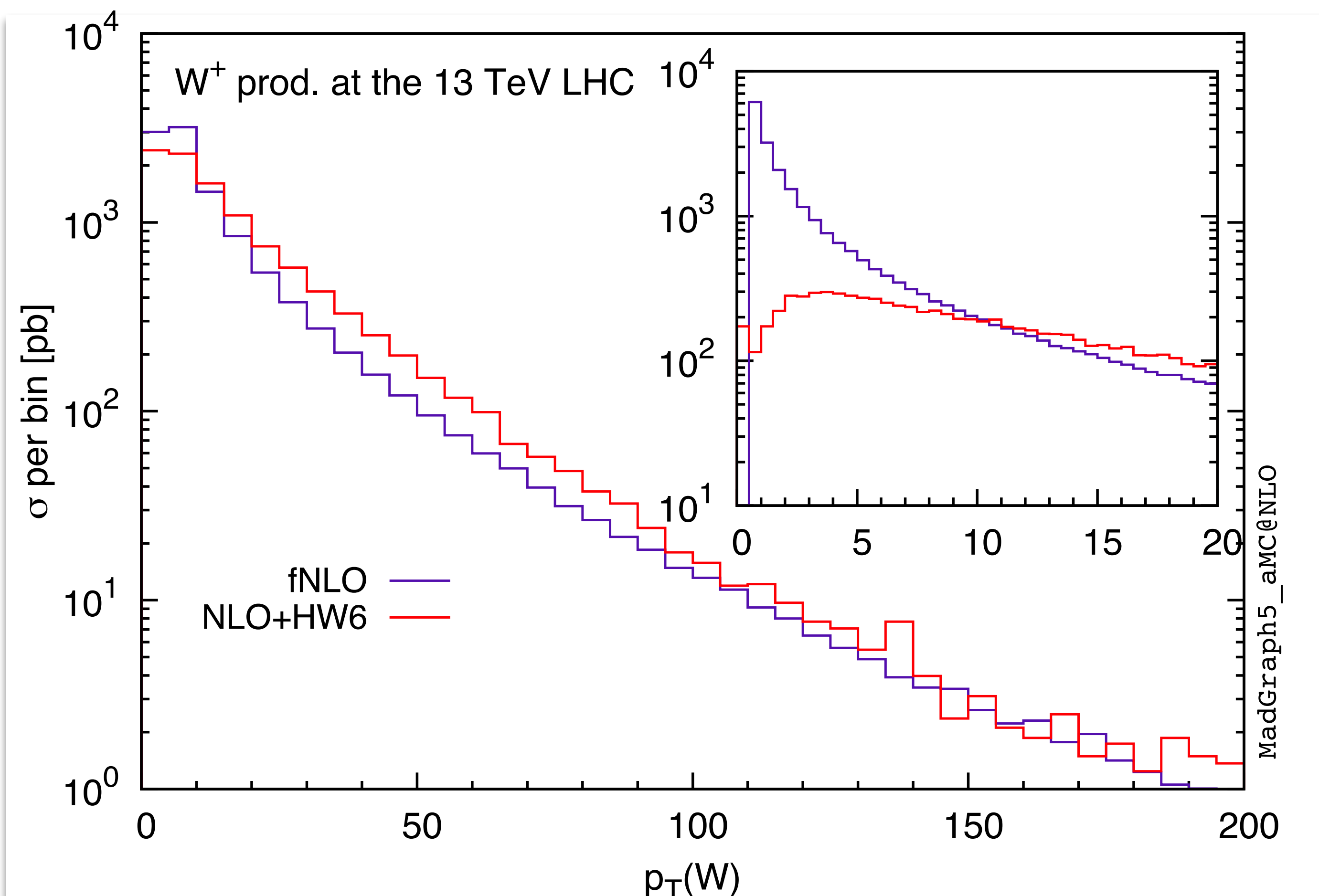
Why to care about showering?

- Quarks and gluons undergo confinement: need to a description of final states in terms of hadrons

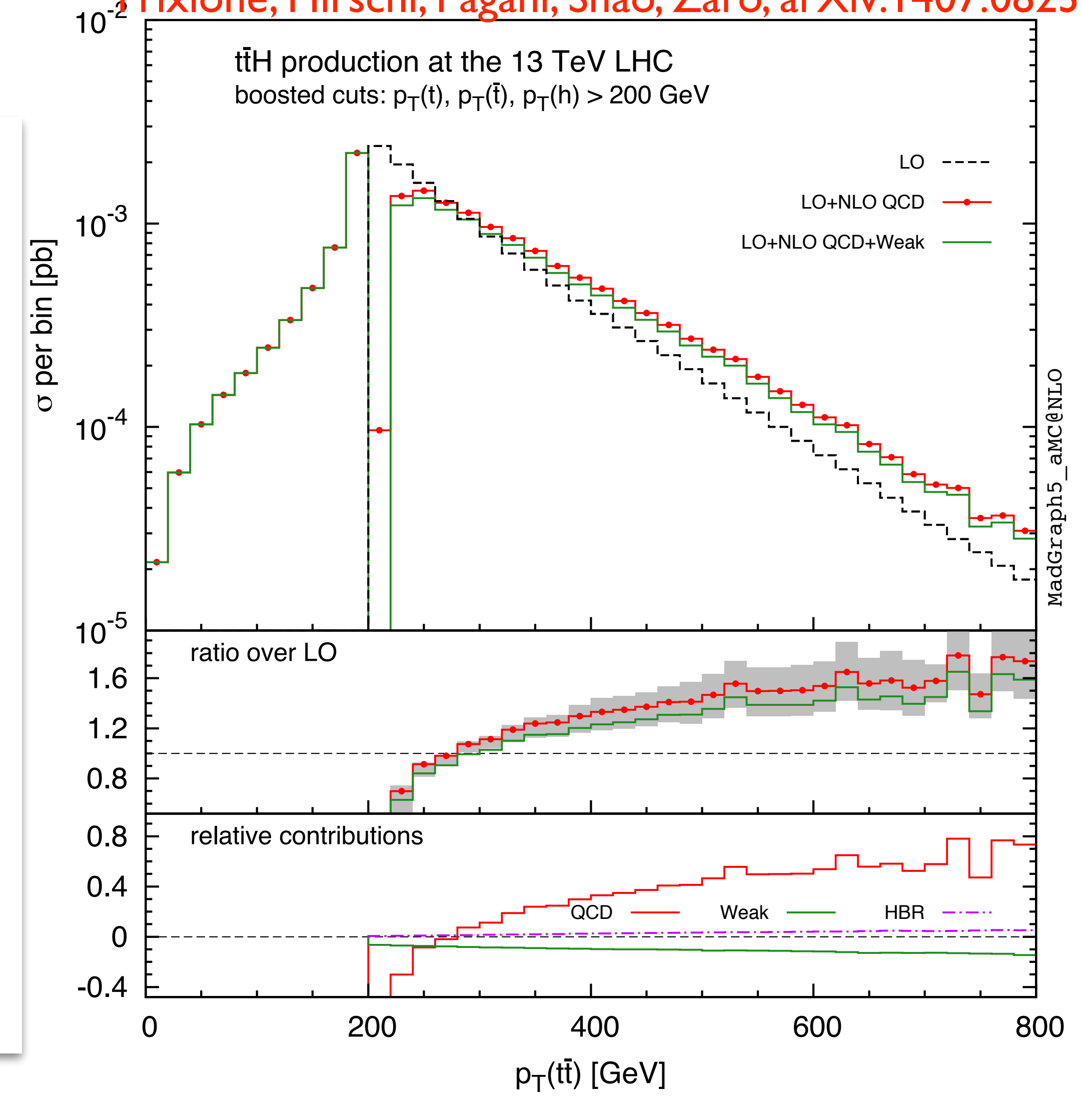


Why to care about showering?

- Quarks and gluons undergo confinement: need to a description of final states in terms of hadrons
- Parton shower cures bad behaviours of fixed-order computations and resums soft logarithms



Frixione, Hirschi, Pagani, Shao, Zaro, arXiv:1407.0823



(Unweighted) event generation and matching to parton-showers

MC@NLO: Frixione, Webber hep-ph/0204244

- Problem #1: the *n* and *n+1* body cross-sections are not separately finite at NLO
  - Cannot unweight an infinite cross-section
- Problem #2: when showering events, one must not double count radiation from the shower and the real-emission matrix-element
- Solution: introduce the so-called Monte-Carlo counterterms

$$\frac{d\sigma_{\text{“}MC@NLO\text{”}}}{dO} = \left[\int d\Phi_n (B + V + \int d\Phi_1 MC)\right] I^n_{MC}(O) + \left[\int d\Phi_{n+1}(R - MC)\right] I^{n+1}_{MC}(O)$$

S-events H-events

  - They are related to the shower Sudakov

$$I^k_{MC} = \Delta + \Delta d\Phi_1 \frac{MC}{B} + \dots \qquad \Delta = \exp\left[-\int d\Phi_1 \frac{MC}{B}\right]$$

$$MC = J \frac{1}{t_{MC}} \frac{\alpha_s}{2\pi} P(z^{MC}) B$$

  - MC is shower-dependent (i.e. the same sample of event has to be showered with a specific parton shower)

aMC@NLO

- Can write the code for computing cross-section at NLO for any process (limited only by CPU time)
- 2 main run modes (at LO and NLO):
  - fixed-order
    - do not generate events. Just compute the cross-section and optionally fill histograms on the fly
  - PS matching
    - generate events *à la* MC@NLO. Distributions obtained from NLO events are unphysical unless events are showered
- In either case, the cross-section has to be the same within statistical uncertainties

Including the decay in NLO samples

- How to deal with unstable particles (e.g. top) at the NLO?
  - Cannot use decay-chain syntax: gauge invariance violated at NLO
- Very rough solution:
  - Let the shower decay the particles: spin correlations are lost
- Very refined solution:
  - Generate process with only stable particles (`pp>l+l-vv~bb~`): includes spin correlations, off-shell effects, non resonant contributions, ...
    - Needs special treatment of intermediate resonances (e.g. complex-mass scheme)
    - Computationally very expensive
    - Only needed when background is enhanced or when aiming at very high precision

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Anything in between?

Spin correlations made easy: MadSpin

Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

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- Wish-list:
  - For a given event sample (LO or MC@NLO), include the decay of any final state particle
  - Keep spin correlations
  - Generate decayed unweighted events

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  - For a given event sample (LO or MC@NLO), include the decay of any final state particle
  - Keep spin correlations
  - Generate decayed unweighted events
- Solution:
  - Read event
  - Generate decay kinematics
  - Reweight the event with ratio $|M_{P+D}|^2 / |M_P|^2$
  - Or do secondary unweighting
    - Generate many decay configurations until $|M_{P+D}|^2 / |M_P|^2 > \text{Rand}()\ \max\left(|\mathrm{M_{P+D}}|^2 / |\mathrm{M_P}|^2\right)$

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- This was been done for the first time for $t\bar{t}$ and singletop

Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198

Spin correlations made easy: MadSpin

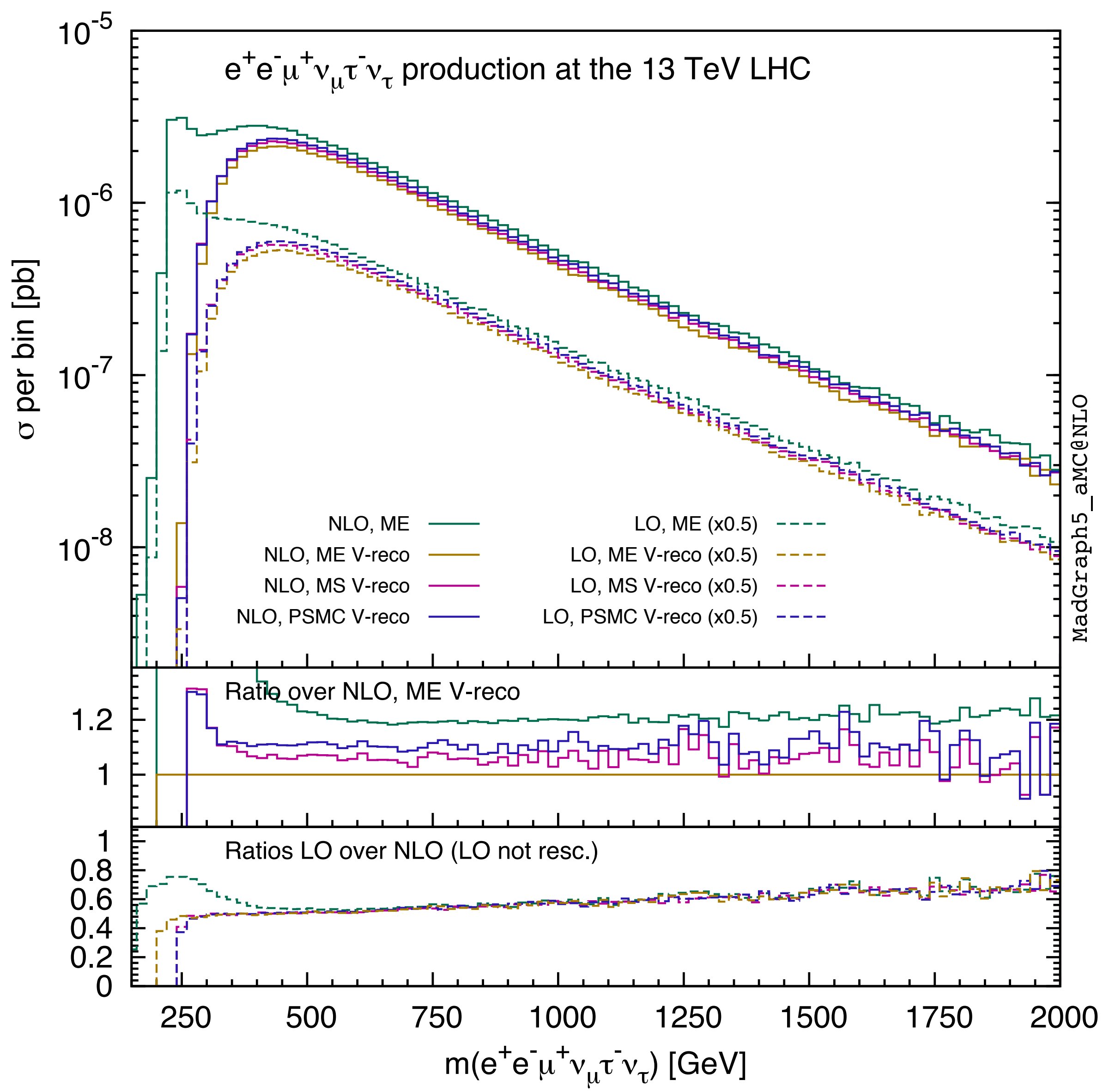
Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

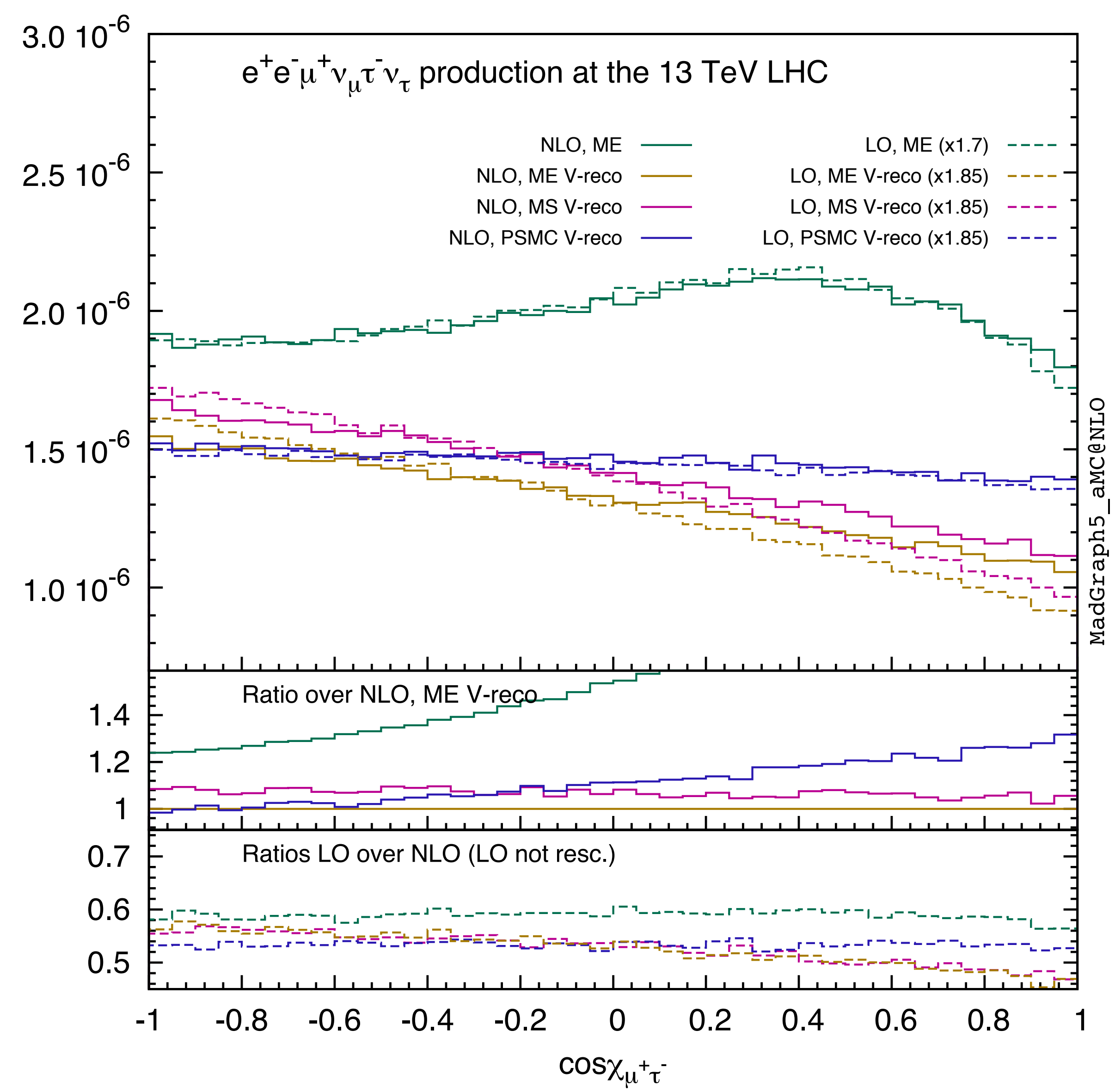
- How to deal with MC@NLO events?
- Spin correlations usually have tiny effects on observables
  - Include them at tree level
- For H (*n*+*1* body) events, use decayed real-emission matrix-element
- For S (*n* body) events, use decaysed born matrix-element
- This guarantees NLO accuracy for observables related to production (e.g. top pt)
- This includes all spin correlation for observables related to production + decay (apart non-factorizable ones)

Spin correlations made easy: MadSpin

Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

- Example: 6 lepton production at NLO (arXiv:1405.0301)





Time for

NLO exercise
$t\bar{t}$ production at NLO

Part 1

- Learn the syntax:
  - `> tutorial aMCatNLO`
- Generate the code for $t\bar{t}$ production at NLO
- Compute the LO and NLO cross-section (run at fixed order)
- Select the analysis `analysis_HwU_pp_ttx.o` in the `FO_analyse_card` to generate histograms (need `GnuPlot` installed)
- In the NLO histograms, which of these variables are described at the NLO? $p_T(t)$, $p_T(t\bar{t})$, $y(t)$ $M(t\bar{t})$, $\Delta\phi(t\bar{t})$
- What are the histograms with `muR=...` `muF=...` for?

NLO exercise
Solution

Part I

- Learn the syntax:
  - `> tutorial NLO`
- Generate the code for $t\bar{t}$ production at NLO
  - `> generate p p > t t~ [QCD]`

```
The current model sm does not allow to generate loop corrections of type QCD.
MG5_aMC now loads 'loop_sm'.
 import model loop_sm
. . .
INFO: Generating FKS-subtracted matrix elements for born process: g g > t t~  [ QCD ] (1 / 9)
. . .
```

  - `> output my_ttbar_nlo`
- Compute the LO and NLO cross-section
  - `> launch`

NLO exercise Solution

Part I

- Learn the synt
  - > tutorial
- Generate the
  - > generate

```
The current model sm does n
MG5_aMC now loads 'loop_sm'
 import model loop_sm
. . .
INFO: Generating FKS-subtra
. . .
```

  - > output m
- Compute the
  - > launch

```
INFO: ************************************************************
*                                                          *
*           W E L C O M E  to  M A D G R A P H 5           *
*                      a M C @ N L O                       *
*                                                          *
*                 *                       *                *
*                   *        * *        *                  *
*                     * * * * 5 * * * *                    *
*                   *        * *        *                  *
*                 *                       *                *
*                                                          *
*         VERSION 2.2.1                 2014-09-25         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*                 http://amcatnlo.cern.ch                  *
*                                                          *
*               Type 'help' for in-line help.              *
*                                                          *
************************************************************
launch auto
The following switches determine which operations are executed:
 1 Perturbative order of the calculation:                              order=NLO
 2 Fixed order (no event generation and no MC@[N]LO matching):   fixed_order=OFF
 3 Shower the generated events:                                       shower=ON
 4 Decay particles with the MadSpin module:                         madspin=OFF
  Either type the switch number (1 to 4) to change its default setting,
  or set any switch explicitly (e.g. type 'order=LO' at the prompt)
  Type '0', 'auto', 'done' or just press enter when you are done.
 [0, 1, 2, 3, 4, auto, done, order=LO, order=NLO, ... ][60s to answer]
> fixed_order=ON
> order=LO (for LO run)
```

NLO exercise
Solution

Part I

- Learn the sy
  - > tutori
- Generate th
  - > genera

The current model sm do
MG5_aMC now loads 'loop
 import model loop_sm
. . .
INFO: Generating FKS-su
. . .

  - > output
- Compute th
  - > launch

```
INFO: ************************************************************
*                                                          *
*          W E L C O M E  to  M A D G R A P H 5            *
*
...
ted:
                                            order=NLO
g):                                   fixed_order=OFF
                                           shower=ON
                                          madspin=OFF
ult setting,
 prompt)
 Type '0', 'auto', 'done' or just press enter when you are done.
 [0, 1, 2, 3, 4, auto, done, order=LO, order=NLO, ... ][60s to answer]
> fixed_order=ON
> order=LO (for LO run)
```

```
INFO:
      Final results and run summary:
      Process p p > t t~ [QCD]
      Run at p-p collider (6500 + 6500 GeV)
      Total cross-section:      6.871e+02 +- 5.9e+00 pb
      Ren. and fac. scale uncertainty: +9.7% -11.7%

INFO: The results of this run and the HwU and GnuPlot
files with the plots have been saved in /Users/marcozaro/
Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/Events/run_01

INFO:
      Final results and run summary:
      Process p p > t t~ [QCD]
      Run at p-p collider (6500 + 6500 GeV)
      Total cross-section:      4.622e+02 +- 2.2e+00 pb
      Ren. and fac. scale uncertainty: +29.8% -22.3%

INFO: The results of this run and the HwU and GnuPlot
files with the plots have been saved in /Users/marcozaro/
Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/Events/run_02_LO
```

NLO exercise Solution

Part 1

- Select the analysis `analysis_HwU_pp_ttx` in the `FO_analyse_card` to generate histograms
  - `> launch my_ttbar_nlo`

```
The following switches determine which operations are executed:
 1 Perturbative order of the calculation:                              order=NLO
 2 Fixed order (no event generation and no MC@[N]LO matching):   fixed_order=ON
 3 Shower the generated events:                                       shower=OFF
 4 Decay particles with the MadSpin module:                          madspin=OFF
  Either type the switch number (1 to 4) to change its default setting,
  or set any switch explicitly (e.g. type 'order=LO' at the prompt)
  Type '0', 'auto', 'done' or just press enter when you are done.
 [0, 1, 2, 3, 4, auto, done, order=LO, order=NLO, ... ][60s to answer]
>
INFO: will run in mode: NLO
Do you want to edit a card (press enter to bypass editing)?
  1 / param      : param_card.dat
  2 / run        : run_card.dat
  3 / FO_analyse : FO_analyse_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.
   - call an external program (ASperGE/MadWidth/...).
     Type 'help' for the list of available command
 [0, done, 1, param, 2, run, 3, FO_analyse, enter path][60s to answer]
```

Part I

- Select t

FO_ana

- > la

```
The following
 1 Perturbati
 2 Fixed orde
 3 Shower the
 4 Decay part
  Either type
  or set any
  Type '0', '
 [0, 1, 2, 3,
>
INFO: will ru
Do you want t
  1 / param
  2 / run
  3 / FO_analy
 you can also
   - enter the
   - use the
     The set
     Type 'he
   - call an
     Type 'he
 [0, done, 1,
```

```
################################################################################
#
# This file contains the settings for analyses to be linked to aMC@NLO
# fixed order runs. Analyse files are meant to be put (or linked)
# inside <PROCDIR>/FixedOrderAnalysis/ (<PROCDIR> is the name of the
# exported process directory). See the
# <PROCDIR>/FixedOrderAnalysis/analysis_template.f file for details on
# how to write your own analysis.
#
################################################################################
#
# Analysis format. Can either be 'topdrawer', 'root', 'HwU' or 'none'.
# When choosing HwU, it comes with a GnuPlot wrapper. When choosing
# topdrawer, the histogramming package 'dbook.f' is included in the
# code, while when choosing root the 'rbook_fe8.f' and 'rbook_be8.cc'
# are included. If 'none' is chosen, all the other entries below have
# to be set empty.
FO_ANALYSIS_FORMAT = HwU
#
# Needed extra-libraries (FastJet is already linked):
FO_EXTRALIBS =
#
# (Absolute) path to the extra libraries. Directory names should be
# separated by white spaces.
FO_EXTRAPATHS =
#
# (Absolute) path to the dirs containing header files needed by the
# libraries (e.g. C++ header files):
FO_INCLUDEPATHS =
#
# User's analysis (to be put in the <PROCDIR>/FixedOrderAnalysis/
# directory). Please use .o as extension and white spaces to separate
# files.
FO_ANALYSE = analysis_td_template.o
#
#
## When linking with root, the following settings are a working
## example on lxplus (CERN). When using this, comment out the lines
## above and replace <PATH_TO_ROOT> with the physical path to root,
## e.g. /afs/cern.ch/sw/lcg/app/releases/ROOT/5.34.11/x86_64-slc6-gcc46-dbg/root/
#FO_ANALYSIS_FORMAT = root
#FO_EXTRALIBS = Core Cint Hist Matrix MathCore RIO dl Thread
#FO_EXTRAPATHS = <PATH_TO_ROOT>/lib
#FO_INCLUDEPATHS = <PATH_TO_ROOT>/include
#FO_ANALYSE = analysis_root_template.o
```

Part I

- Select t

FO_ana

- > la

The following
 1 Perturbati
 2 Fixed orde
 3 Shower the
 4 Decay part
  Either type
  or set any
  Type '0', '
 [0, 1, 2, 3,
>
INFO: will ru
Do you want t
  1 / param
  2 / run
  3 / FO_analy
 you can also
   - enter the
   - use the
     The set
     Type 'he
   - call an
     Type 'he
 [0, done, 1,

```
########################################################################
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#
# (Absolute) path to the dirs containing header files needed by the
# libraries (e.g. C++ header files):
FO_INCLUDEPATHS =
#
# User's analysis (to be put in the <PROCDIR>/FixedOrderAnalysis/
# directory). Please use .o as extension and white spaces to separate
# files.
FO_ANALYSE = analysis_HwU_pp_ttx.o
#
#
## When linking with root, the following settings are a working
## example on lxplus (CERN). When using this, comment out the lines
## above and replace <PATH_TO_ROOT> with the physical path to root,
## e.g. /afs/cern.ch/sw/lcg/app/releases/ROOT/5.34.11/x86_64-slc6-gcc46-dbg/root/
#FO_ANALYSIS_FORMAT = root
#FO_EXTRALIBS = Core Cint Hist Matrix MathCore RIO dl Thread
#FO_EXTRAPATHS = <PATH_TO_ROOT>/lib
#FO_INCLUDEPATHS = <PATH_TO_ROOT>/include
#FO_ANALYSE = analysis_root_template.o
```

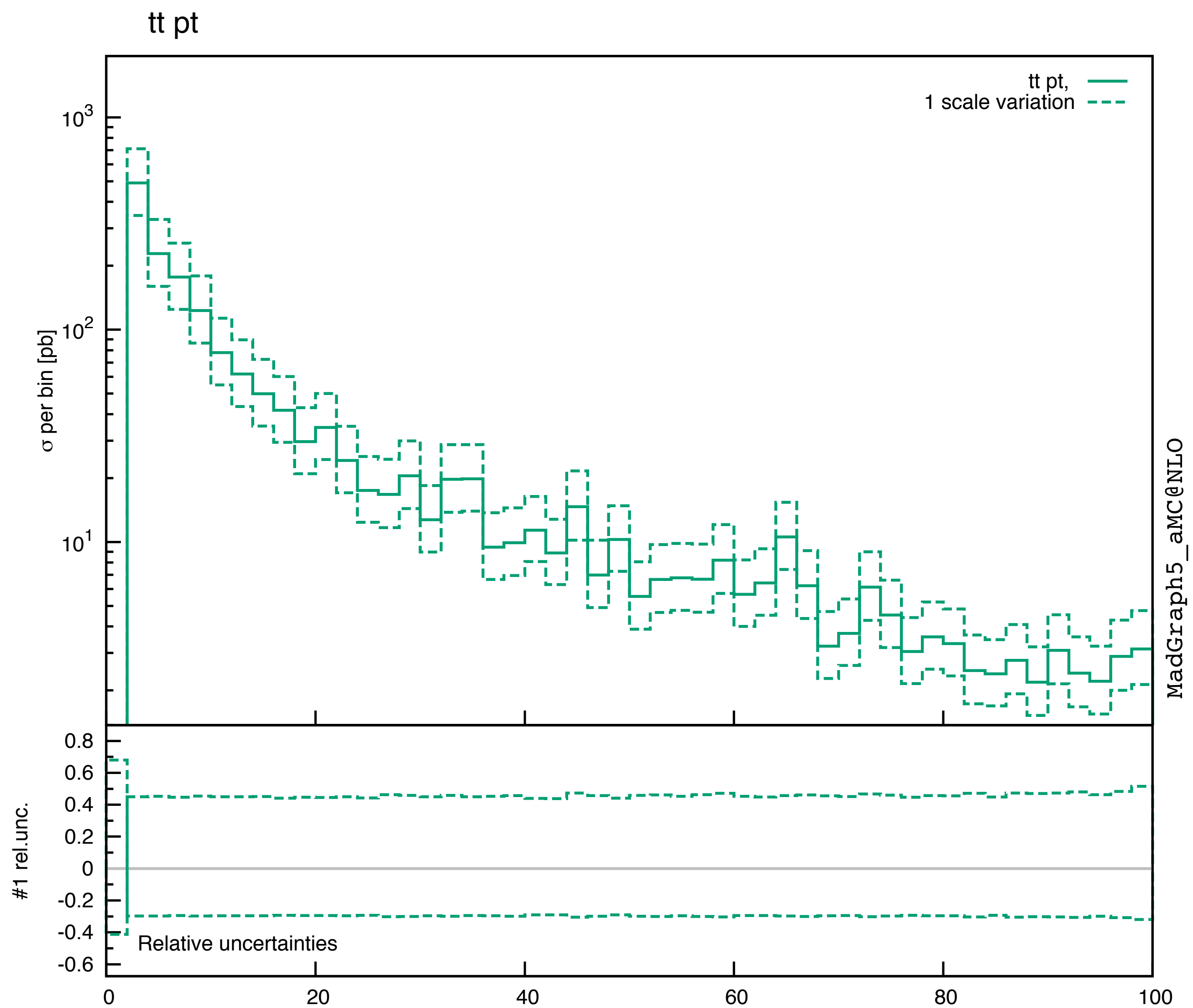
NLO exercise: solution

- The HwU (Histogram with Uncertainties) format

```
 ##& xmin & xmax & central value & dy & delta_mu_min @aux & delta_mu_max @aux & muR=1.00 muF=1.00 & muR=1.00 muF=2.00 &
muR=1.00 muF=0.50 & muR=2.00 muF=1.00 & muR=2.00 muF=2.00 & muR=2.00 muF=0.50 & muR=0.50 muF=1.00 & muR=0.50 muF=2.00 &
muR=0.50 muF=0.50

<histogram> 50 "tt pt |X_AXIS@LIN |Y_AXIS@LOG"
  +0.0000000e+00   +2.0000000e+00   -1.0242367e+03   +2.5047252e+01  -1.7206530e+03   -6.0160203e+02   -1.0242367e+03
-9.0715087e+02   -1.1432407e+03   -6.8421704e+02   -6.0160203e+02   -7.6882229e+02   -1.5496422e+03   -1.3802509e+03
-1.7206530e+03
  +2.0000000e+00   +4.0000000e+00   +4.9088904e+02   +2.0297264e+01  +3.4493531e+02   +7.1188196e+02   +4.9088904e+02
+4.5019210e+02   +5.3086979e+02   +3.7613186e+02   +3.4493531e+02   +4.0679297e+02   +6.5832080e+02   +6.0377117e+02
+7.1188196e+02
  +4.0000000e+00   +6.0000000e+00   +2.2787754e+02   +2.3122314e+01  +1.5999659e+02   +3.3086836e+02   +2.2787754e+02
+2.0857157e+02   +2.4714205e+02   +1.7482611e+02   +1.5999659e+02   +1.8963760e+02   +3.0513912e+02   +2.7932554e+02
+3.3086836e+02
  +6.0000000e+00   +8.0000000e+00   +1.7671803e+02   +9.5392210e+00  +1.2453269e+02   +2.5575724e+02   +1.7671803e+02
+1.6227348e+02   +1.9111959e+02   +1.3562893e+02   +1.2453269e+02   +1.4669918e+02   +2.3651862e+02   +2.1720764e+02
+2.5575724e+02
  +8.0000000e+00   +1.0000000e+01   +1.2311654e+02   +7.1903869e+00  +8.6399100e+01   +1.7898773e+02   +1.2311654e+02
+1.1261446e+02   +1.3369767e+02   +9.4461506e+01   +8.6399100e+01   +1.0258866e+02   +1.6483914e+02   +1.5078780e+02
+1.7898773e+02
  +1.0000000e+01   +1.2000000e+01   +7.8022445e+01   +1.0748137e+01  +5.4873577e+01   +1.1315020e+02   +7.8022445e+01
+7.1570742e+01   +8.4452355e+01   +5.9823787e+01   +5.4873577e+01   +6.4760050e+01   +1.0454718e+02   +9.5909144e+01
+1.1315020e+02
  +1.2000000e+01   +1.4000000e+01   +6.1770611e+01   +3.2903213e+00  +4.3437593e+01   +8.9537046e+01   +6.1770611e+01
```

NLO exercise
Solution



NLO exercise Solution

Part 1

- In the NLO histograms, which of these variables are described at the NLO? $p_T(t)$, $p_T(t\bar{t})$, $y(t)$ $M(t\bar{t})$, $\Delta\phi(t\bar{t})$
  - Some of these variables are trivial at LO, because of 2→2 kinematics
    - t and $\bar{t}$ are always back to back:
      $d\sigma/d\Delta\Phi(t\bar{t}) = \delta(\Delta\Phi - \pi)$
      $d\sigma/dp_T(t\bar{t}) = \delta(p_T - 0)$
  - $p_T(t\bar{t})$ and $\Delta\phi(t\bar{t})$ are non-trivial if the cross-section is at least at NLO: they are effectively described with LO accuracy
  - The other variables are described at NLO

NLO exercise
Solution

Part I

- What are the histograms with `muR=...` `muF=...` for?
  - QCD master formula

$$\sigma(pp \to t\bar{t}) = \sum_{ab} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \times \hat{\sigma}(ab \to t\bar{t})$$

    or better

$$\sigma(pp \to t\bar{t}) = \sum_{ab} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \times \hat{\sigma}(ab \to t\bar{t}; \mu_F, \mu_R, \alpha_S(\mu_R))$$

  - What are $\mu_{F/R}$?
    - They are arbitrary scales needed to renormalise the strong coupling and to reabsorb initial state IR-divergences in PDFs, chosen to be of the order of the hard scattering scales (sum of masses, p_T, ...)
    - The all-order cross-section is independent of the choice of $\mu_{F/R}$
    - At N^kLO, the dependence is of $N^{k+1}LO$
    - Computing the cross-section with different scales can be a way to estimate uncertainties due to missing higher orders
    - How much scales are varied is arbitrary, usually in the range [0.5, 2]

Scale uncertainties

Scale uncertainties

- Look at the LO and NLO cross-section we have just computed
  - Values with different scales are computed on the fly and the envelope is taken

```
INFO:
       Final results and run summary:
       Process p p > t t~ [QCD]
       Run at p-p collider (6500 + 6500 GeV)
       Total cross-section:      6.871e+02 +- 5.9e+00 pb
       Ren. and fac. scale uncertainty: +9.7% -11.7%

INFO: The results of this run and the TopDrawer file with
the plots have been saved in /Users/marcozaro/Physics/
MadGraph/2.2.3new/my_tt_nlo_qcd/Events/run_01

INFO:
       Final results and run summary:
       Process p p > t t~ [QCD]
       Run at p-p collider (6500 + 6500 GeV)
       Total cross-section:      4.622e+02 +- 2.2e+00 pb
       Ren. and fac. scale uncertainty: +29.8% -22.3%

INFO: The results of this run and the TopDrawer file with
the plots have been saved in /Users/marcozaro/Physics/
MadGraph/2.2.3new/my_tt_nlo_qcd/Events/run_02_LO
```

Scale uncertainties

- Look at the LO and NLO cross-section we have just computed
  - Values with different scales are computed on the fly and the envelope is taken
- Typically LO has larger scale uncertainties

Scale uncertainties

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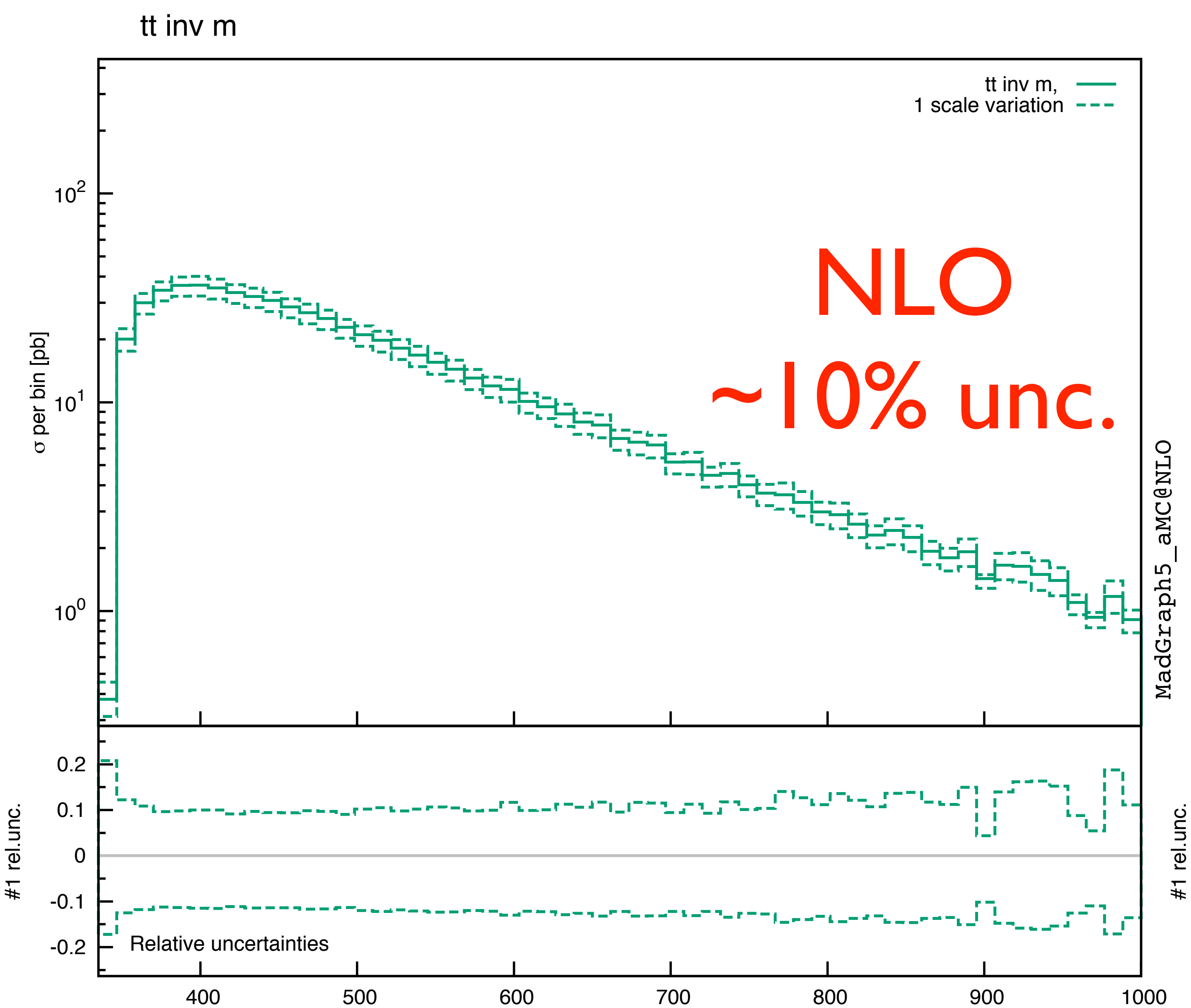
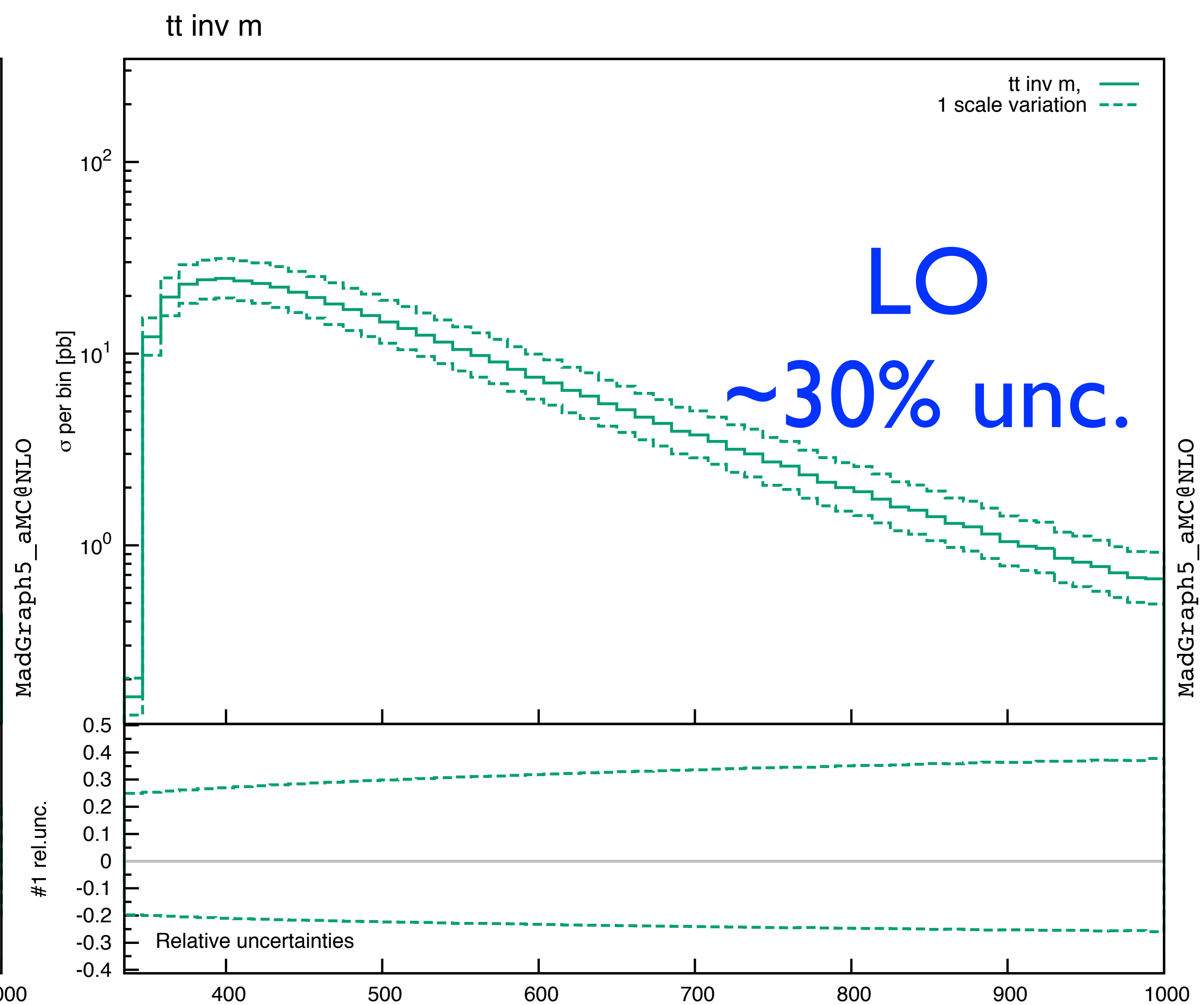
- To have scale uncertainties for distributions, one must fill one histogram per scale choice, and then take the envelope

Scale uncertainties

- Look at the LO and NLO cross-section we have just computed
  - Values with different scales are computed on the fly and the envelope is taken
- Typically LO has larger scale uncertainties
- To have scale uncertainties for distributions, one must fill one histogram per scale choice, and then take the envelope
- The same is possible for PDF uncertainties

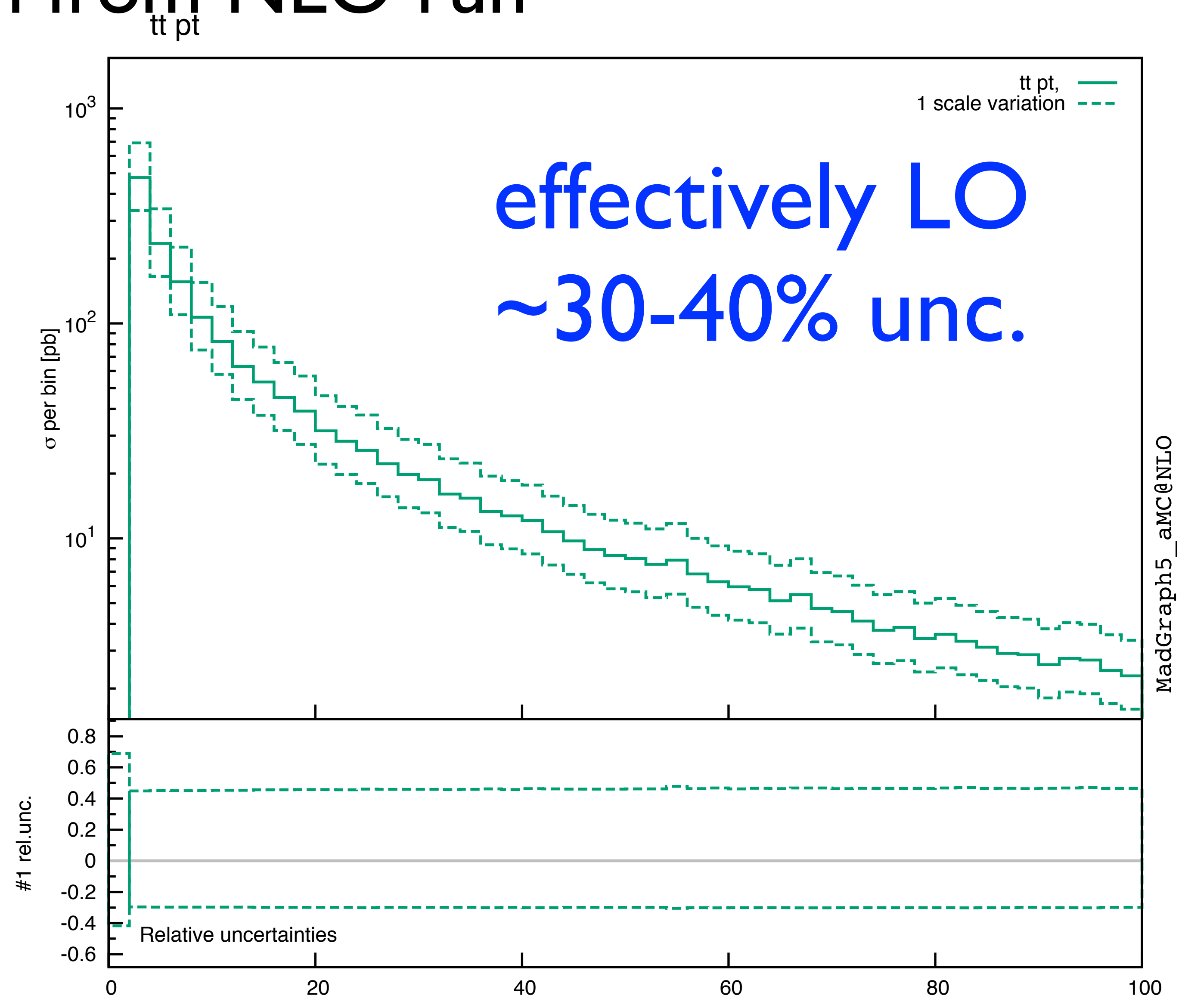
Scale uncertainties





Scale uncertainties

$p_T(t\bar{t})$ histogram from NLO run



NLO exercise
$t\bar{t}$ production at NLO

Part 2

- Generate a NLO event sample to be showered by Pythia6Q
- Shower and analyse it with the `py6an_HwU_pp_ttx.o` analysis (to be specified in the `shower_card`)
- The histogramming routine (`HwU.o`) must also be added to the analysis files in the `shower_card` (Hint: you can shower an existing run with `./bin/shower run_xx`)
- Use MadSpin to generate a di-leptonic (into muons) decayed sample
- Re-analyse the decayed and undecided sample with the `py6an_HwU_pp_lplm.o` analysis and check the lepton pair p_T
  - The analysis (in `MCatNLO/PYAnalyzer/py6an_HwU_pp_lplm.f`) has to be slightly modified:
    - `IORI.LE.10` → `IORI.LE.20` at lines 186, 190
  - To tell Pythia to perform di-leptonic decays, add these lines in the `shower_card` ('Decay channels' block; antiparticles are decayed as particles)
    - ```
      DM_1 = 6 > 24 5 @1d0 @100
      DM_2 = 24 > 14 -13 @1d0 @100
      ```
      ```

NLO exercise
Solution

Part 2

- Generate a NLO event sample to be showered by Pythia6Q
  - Shower it with the `mcatnlo_pyan_pp_ttx` analysis (to be specified in the `shower_card`)
    - `cd my_ttbar_nlo`
    - `./bin/aMCatNLO`
    - `> launch`
    - `> fixed_order=OFF`
    - `> shower=ON`
    - Edit `run_card`
    - Edit `shower_card`

NLO exercise Solution

Part 2

- Generate a NLO event sa
  - Shower it with the mca ... cified in the shower_card)
    - cd my_ttbar_nlo
    - ./bin/aMCatNLO
    - > launch
    - > fixed_order=OF
    - > shower=ON
  - Edit run_card
  - Edit shower_card

```
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.
*
#***********************************************************************
*
 nn23nlo    = pdlabel    ! PDF set
 244600     = lhaid      ! if pdlabel=lhapdf, this is the lhapdf number
#***********************************************************************
*
# Include the NLO Monte Carlo subtr. terms for the following parton
*
# shower (HERWIG6 | HERWIGPP | PYTHIA6Q | PYTHIA6PT | PYTHIA8)
*
# WARNING: PYTHIA6PT works only for processes without FSR!!!!
*
#***********************************************************************
*
  PYTHIA6Q   = parton_shower
#***********************************************************************
*
# Renormalization and factorization scales
*
# (Default functional form for the non-fixed scales is the sum of
*
# the transverse masses of all final state particles and partons. This
*
# can be changed in SubProcesses/set_scales.f)
*
#***********************************************************************
*
 F         = fixed_ren_scale  ! if .true. use fixed ren scale
 F         = fixed_fac_scale  ! if .true. use fixed fac scale
 91.188    = muR_ref_fixed    ! fixed ren reference scale
 91.188    = muF1_ref_fixed   ! fixed fact reference scale for pdf1
 91.188    = muF2_ref_fixed   ! fixed fact reference scale for pdf2
#***********************************************************************
*
# Renormalization and factorization scales (advanced and NLO options)
*
#***********************************************************************
*
```

NLO exercise Solution

Part 2

- Generate a NLO event sa
  - Shower it with the mca cified in the shower_card)
    - cd my_ttbar_nlo
    - ./bin/aMCatNLO
    - > launch
    - > fixed_order=OF
    - > shower=ON
  - Edit run_card
  - Edit shower_card

```
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.
*
#***********************************************************************
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# WARNING: PYTHIA6PT works only for processes without FSR!!!!
*
#***********************************************************************
*
  PYTHIA6Q    = parton_shower
#***********************************************************************
*
# Renormalization and factorization scales
*
# (
*
# t
*
# c
*
#**
*
 F
 F
 91
 91
 91
#**
*
# R
*
#***********************************************************************
*
```

```
#***********************************************************************
# Extra Libraries/analyses                                             *
# The following lines need to be changed if the user does not want to  *
# create a StdHEP/HepMC file, but to directly run an own analysis (to  *
# be placed in HWAnalyzer or analogous MCatNLO subfolders).            *
# Please use files in those folders as examples.                       *
#***********************************************************************
EXTRALIBS    =      # Extra-libraries (not LHAPDF)
                          # Default: "stdhep Fmcfio"
                          # PYTHIA > 8.200 may require library dl
EXTRAPATHS   = ../lib     # Path to the extra-libraries
                          # Default: "../lib"
INCLUDEPATHS =            # Path to header files needed by c++
                          # Dir names separated by white spaces
ANALYSE      = mcatnlo_pyan_pp_ttx.o mcatnlo_hbook_gfortran8.o
                          # routines (please use .o as extension
                          # and use spaces to separate files)
```

NLO exercise Solution

Part 2

- Generate a NLO event s
  - Shower it with the mca ne shower_card)
    - cd my_ttbar_nlo
    - ./bin/aMCatNLO
    - > launch
    - > fixed_order=O
    - > shower=ON
  - Edit run_card
  - Edit shower_card

```
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.
```

```
      Summary:
      Process p p > t t~ [QCD]
      Run at p-p collider (6500 + 6500 GeV)
      Total cross-section: 6.772e+02 +- 2.1e+00 pb
      Ren. and fac. scale uncertainty: +11.5% -13.0%
      Number of events generated: 100000
      Parton shower to be used: PYTHIA6Q
      Fraction of negative weights: 0.20
      Total running time :  6m 58s

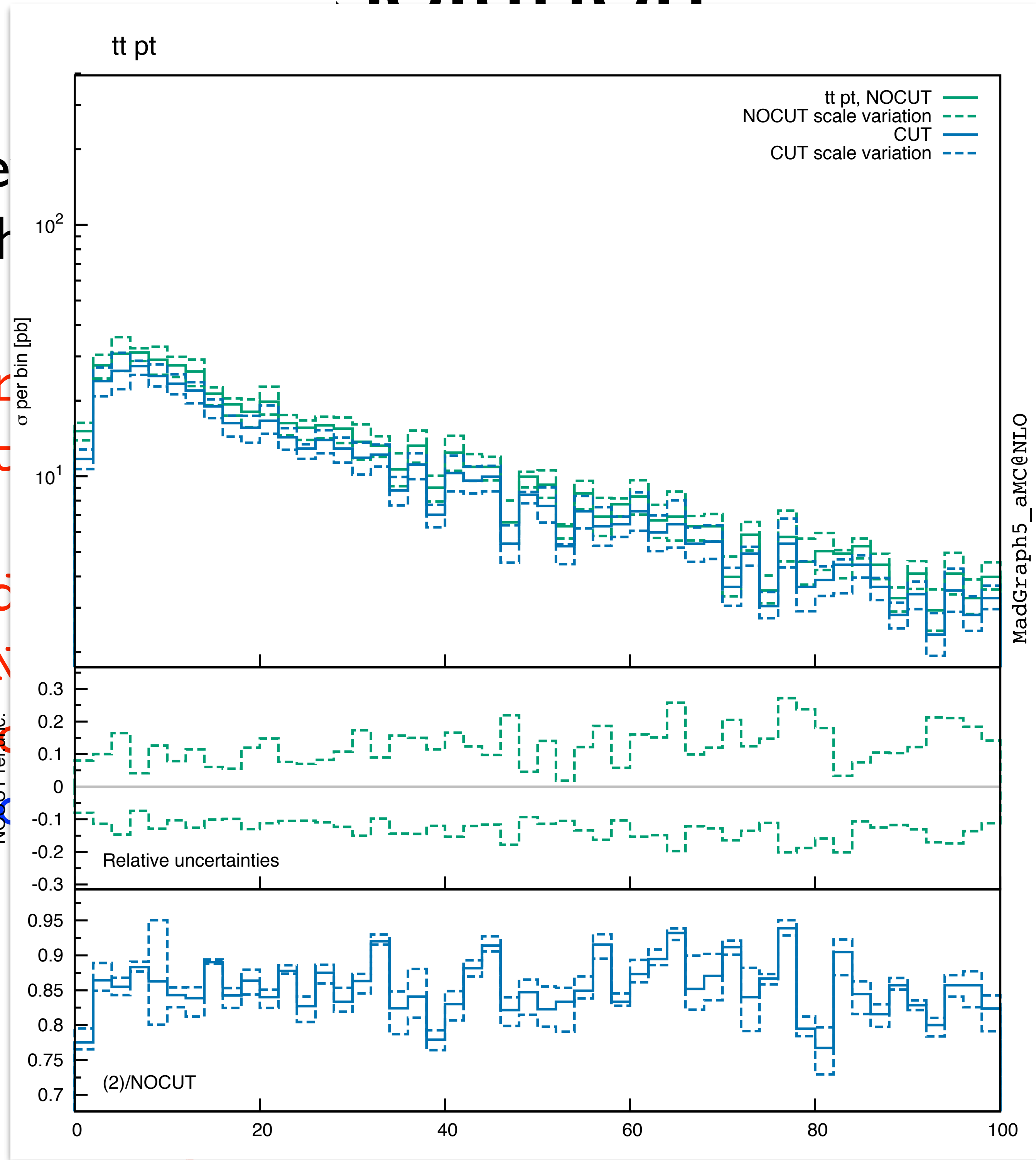
INFO: The /Users/marcozaro/Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/Events/
run_12/events.lhe.gz file has been generated.
. . .
INFO: Preparing MCatNLO run
INFO: Compiling MCatNLO for PYTHIA6Q...
INFO:                      ... done
INFO: Showering events...
INFO: (Running in /Users/marcozaro/Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/
MCatNLO/RUN_PYTHIA6Q_3)
INFO:  Idle: 0,  Running: 1,  Completed: 0 [ current time: 12h32 ]
INFO:  Idle: 0,  Running: 0,  Completed: 1 [  2m 35s  ]
INFO:  Idle: 0,  Running: 0,  Completed: 0 [ current time: 12h34 ]
INFO: The file /Users/marcozaro/Physics/MadGraph/2.3.1/ttbar/Events/run_01/
plot_PYTHIA6Q_1_0.HwU has been generated, with histograms in the HwU and
GnuPlot formats, obtained by showering the parton-level file /Users/
marcozaro/Physics/MadGraph/2.3.1/ttbar/Events/run_01/events.lhe.gz with
PYTHIA6Q.
INFO: Run complete
```

```
# and use spaces to separate files)
#****************************************************************************
*
```

NLO exercise
Solution

Part 2

- Generate a NLO e
  - Shower it with th ... he shower_card)
    - cd my_ttbar
    - ./bin/aMCat
    - > launch
    - > fixed_ord
    - > shower=ON
  - Edit run_car
  - Edit shower_c



ts evol.

y_tt_nlo_qcd/Events/

2.3new/my_tt_nlo_qcd/

ime: 12h32]
]
ime: 12h34]
/ttbar/Events/run_01/
ams in the HwU and
l file /Users/
vents.lhe.gz with

o as extension
rate files)
****

The events

```
<initrwgt>
  <weightgroup type='scale_variation' combine='envelope'>
    <weight id='1001'> muR=0.10000E+01 muF=0.10000E+01 </weight>
    <weight id='1002'> muR=0.10000E+01 muF=0.20000E+01 </weight>
    <weight id='1003'> muR=0.10000E+01 muF=0.50000E+00 </weight>
    <weight id='1004'> muR=0.20000E+01 muF=0.10000E+01 </weight>
    <weight id='1005'> muR=0.20000E+01 muF=0.20000E+01 </weight>
    <weight id='1006'> muR=0.20000E+01 muF=0.50000E+00 </weight>
    <weight id='1007'> muR=0.50000E+00 muF=0.10000E+01 </weight>
    <weight id='1008'> muR=0.50000E+00 muF=0.20000E+01 </weight>
    <weight id='1009'> muR=0.50000E+00 muF=0.50000E+00 </weight>
  </weightgroup>
</initrwgt>
</header>
<init>
 2212   2212 0.65000000E+04 0.65000000E+04 -1 -1 244600 244600 -4   1
0.68147533E+03 0.22760274E+01 0.11811897E+04      0
</init>
<event>
4      0 -.11811897E+04 0.68991465E+03 0.75467716E-02 0.11800000E+00
      21 -1    0    0  501  502 0.00000000E+00 0.00000000E+00 0.16695776E+03 0.16695776E+03 0.00000000E+00 0.0000E+00 0.9000E+01
      21 -1    0    0  502  503 -.00000000E+00 -.00000000E+00 -.83539498E+03 0.83539498E+03 0.00000000E+00 0.0000E+00 0.9000E+01
       6  1    1    2  501    0 -.87405313E+02 -.30435858E+03 -.46344397E+03 0.58735266E+03 0.17300000E+03 0.0000E+00 0.9000E+01
      -6  1    1    2    0  503 0.87405313E+02 0.30435858E+03 -.20499324E+03 0.41500008E+03 0.17300000E+03 0.0000E+00 0.9000E+01
#aMCatNLO 1  5  3  3  2 0.21343976E+03 0.35860250E+02 9  0  0 0.10000001E+01 0.15353083E+01 0.66887201E+00 0.00E+00 0.0E+00
<rwgt>
 <wgt id='1001'> -.11812E+04 </wgt>
 <wgt id='1002'> -.10571E+04 </wgt>
 <wgt id='1003'> -.13263E+04 </wgt>
 <wgt id='1004'> -.88285E+03 </wgt>
 <wgt id='1005'> -.79006E+03 </wgt>
 <wgt id='1006'> -.99128E+03 </wgt>
 <wgt id='1007'> -.16151E+04 </wgt>
 <wgt id='1008'> -.14453E+04 </wgt>
 <wgt id='1009'> -.18135E+04 </wgt>
</rwgt>
</event>
```

- Each event keeps information about scale variations
- To obtain scale uncertainties use the extra weights to fill histograms and take the envelope

NLO exercise
Solution

Part 2

- Use MadSpin to generate a di-leptonic (into muons) decayed sample
  - `./bin/aMCatNLO`
  - `> decay_events run_xx`
  - edit the `madspin_card`

NLO exercise
Solution

Part 2

- Use MadSpin to generate a di-leptonic (into muons) decayed sample
  - `./bin/aMCatNLO`
  - `> decay_events run_xx`
  - edit the `madspin_card`

```
#************************************************************
#*                        MadSpin                           *
#*                                                          *
#*    P. Artoisenet, R. Frederix, R. Rietkerk, O. Mattelaer *
#*                                                          *
#*    Part of the MadGraph5_aMC@NLO Framework:              *
#*    The MadGraph5_aMC@NLO Development Team - Find us at   *
#*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
#*                                                          *
#************************************************************
#Some options (uncomment to apply)
#
# set seed 1
# set Nevents_for_max_weigth 75 # number of events for the estimate of the max. weight
# set BW_cut 15                # cut on how far the particle can be off-shell
 set max_weight_ps_point 400  # number of PS to estimate the maximum for each event
#
# specify the decay for the final state particles
decay t > w+ b, w+ > mu+ vm
decay t~ > w- b~, w- > mu- vm~
# running the actual code
launch
~
```

NLO exercise
Solution

Part 2

- Use MadSpin to generat[...]
  - ./bin/aMCatNLO
  - > decay_events r[...]
  - edit the madspin_ca[...]

```
#*********************************
#*                    MadSpin
#*
#*    P. Artoisenet, R. Frederix,
#*
#*    Part of the MadGraph5_aMC@N
#*    The MadGraph5_aMC@NLO Devel
#*    https://server06.fynu.ucl.a
#*
#*********************************
#Some options (uncomment to apply
#
# set seed 1
# set Nevents_for_max_weigth 75 #
# set BW_cut 15                 #
 set max_weight_ps_point 400  # number of PS to estimate the maximum for each event
#
# specify the decay for the final state particles
decay t > w+ b, w+ > mu+ vm
decay t~ > w- b~, w- > mu- vm~
# running the actual code
launch
~
```

```
 . . .
INFO: MadSpin: Estimate the maximum weight
INFO:
INFO:    Estimating the maximum weight
INFO:    *****************************
INFO:      Probing the first 139 events
INFO:      with 400 phase space points
INFO:
INFO: Event 1/139 :  0.059s
INFO: Event 6/139 :  0.99s
INFO: Event 11/139 :  1.3s
 . . .
INFO: Decaying the events...
INFO: Event nb 1000  2.6s
INFO: Event nb 2000  4.9s
INFO: Event nb 3000  7s
 . . .
INFO: Decayed events have been written in /Users/marcozaro/Physics/
MadGraph/2.2.3new/my_tt_nlo_qcd/Events/run_01/events_decayed.lhe.gz
INFO: The decayed event file has been moved to the following location:
INFO: /Users/marcozaro/Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/Events/
run_01_decayed_1/events.lhe.gz
INFO: MadSpin Done
```

MS estimates

$$\max\left(|M_{P+D}|^2 / |M_P|^2\right)$$

with the first events

NLO exercise
Solution

Part 2

- Re-analyse the decayed and undecided sample with the `py6an_HwU_pp_lplm` analysis and check the the lepton pair p_T
  - Re-shower the un-decayed sample
  - `./bin/shower run_xx`
  - edit the `shower_card`
  - Shower the decayed sample
  - `./bin/shower run_xx_decayed_1`

NLO exercise
Solution

Part 2

- Re-analyse the decayed and undecided sample with the `py6an_HwU_pp_lplm` analysis and check the the lepton pair p_T
  - Re-shower the un-decayed sample
  - `./bin/shower run_xx`
  - edit the `shower_card`
  - Shower the decayed sample
  - `./bin/shower run_xx_de`

```
# Decay channels                                                        *
# Write down the decay channels for the resonances, to be performed by *
# the shower.                                                           *
...
DM_1 = 6 > 24 5 @1d0 @100
DM_2 = -6 > -24 -5 @1d0 @100
DM_3 = 24 > 14 -13 @1d0 @100
DM_4 = -24 > -14 13 @1d0 @100
#***********************************************************************
#***********************************************************************
# Extra Libraries/analyses                                              *
# The following lines need to be changed if the user does not want to  *
# create a StdHEP/HepMC file, but to directly run an own analysis (to   *
# be placed in HWAnalyzer or analogous MCatNLO subfolders).             *
# Please use files in those folders as examples.                        *
#***********************************************************************
EXTRALIBS    =       # Extra-libraries (not LHAPDF)
                                # Default: "stdhep Fmcfio"
                                # PYTHIA > 8.200 may require library dl
EXTRAPATHS   = ../lib           # Path to the extra-libraries
                                # Default: "../lib"
INCLUDEPATHS =                  # Path to header files needed by c++
                                # Dir names separated by white spaces
ANALYSE      = mcatnlo_pyan_pp_lplm.o mcatnlo_hbook_gfortran8.o
                                # routines (please use .o as extension
                                # and use spaces to separate files)
```

NLO exercise
Solution

Part 2

- Re-analyse the decayed and undecided sample with the `py6an_HwU_pp_lplm` analysis and check the the lepton pair p_T
  - Re-shower the un-decayed sample
  - `./bin/sh`
  - edit the `sh`
  - Shower the
  - `./bin/sh`

```
INFO: Preparing MCatNLO run
INFO: Compiling MCatNLO for PYTHIA6Q...
INFO:                           ... done
INFO: Showering events...
INFO: (Running in /Users/marcozaro/Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/
MCatNLO/RUN_PYTHIA6Q_3)
INFO:  Idle: 0,  Running: 1,  Completed: 0 [ current time: 12h32 ]
INFO:  Idle: 0,  Running: 0,  Completed: 1 [  2m 35s  ]
INFO:  Idle: 0,  Running: 0,  Completed: 0 [ current time: 12h34 ]
INFO: The file /Users/marcozaro/Physics/MadGraph/2.3.1/ttbar/Events/run_01/
plot_PYTHIA6Q_2_0.HwU has been generated, with histograms in the HwU and
GnuPlot formats, obtained by showering the parton-level file /Users/
marcozaro/Physics/MadGraph/2.3.1/ttbar/Events/run_01/events.lhe.gz with
PYTHIA6Q.
INFO: Run complete
. . .
INFO:  Idle: 0,  Running: 1,  Completed: 0 [ current time: 12h32 ]
INFO:  Idle: 0,  Running: 0,  Completed: 1 [  2m 35s  ]
INFO:  Idle: 0,  Running: 0,  Completed: 0 [ current time: 12h34 ]
INFO: INFO: The file /Users/marcozaro/Physics/MadGraph/2.3.1/ttbar/Events/
run_01_decayed_1/plot_PYTHIA6Q_1_0.HwU has been generated, with histograms in
the HwU and GnuPlot formats, obtained by showering the parton-level file /
Users/marcozaro/Physics/MadGraph/2.3.1/ttbar/Events/run_01_decayed_1/
events.lhe.gz with PYTHIA6Q.
INFO: Run complete
```

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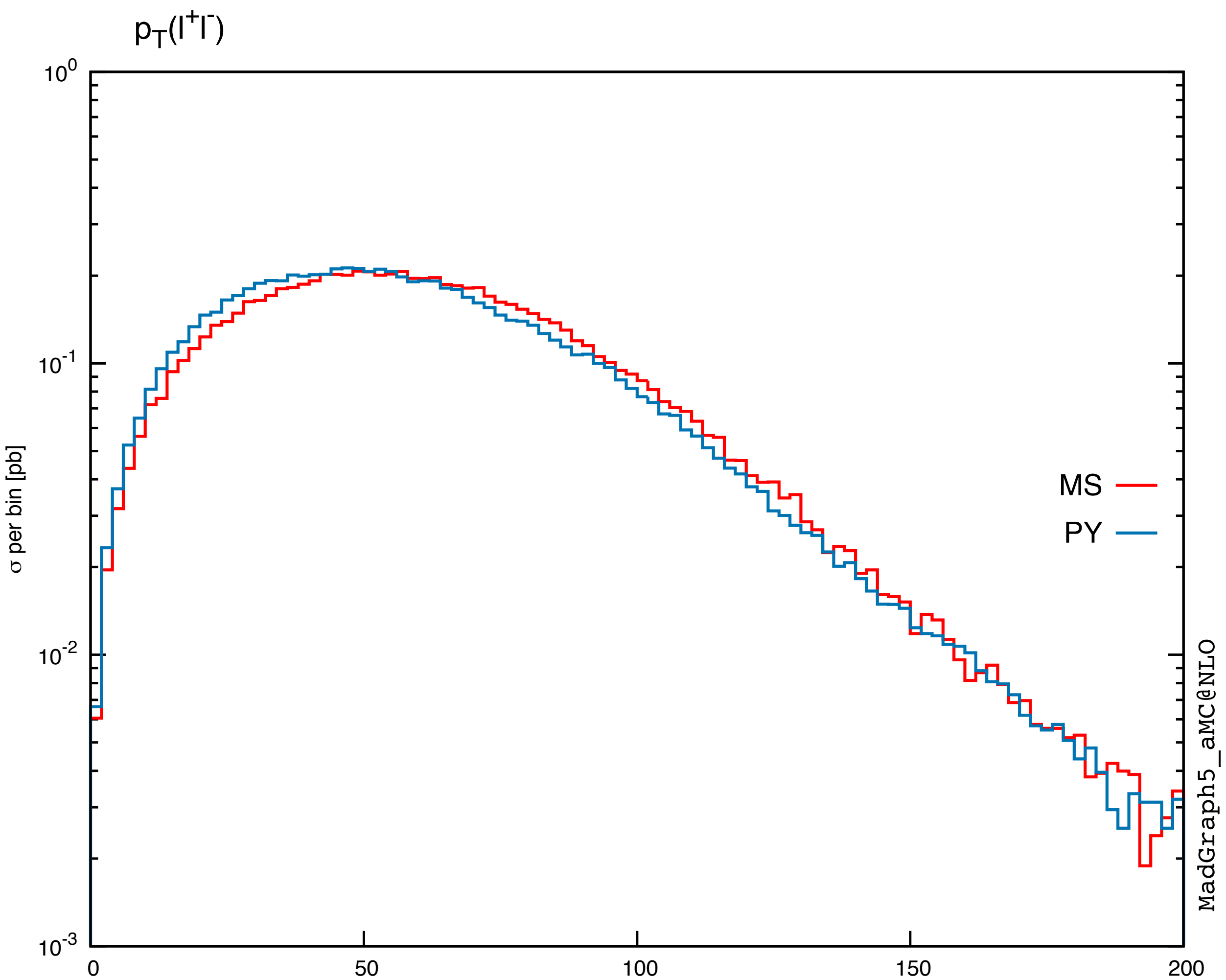
```

NLO exercise Solution

Part 2

- Re-analyse the decayed and undecided sample with the `mcatnlo_pyan_pp_lplm` analysis and check the the lepton pair p_T



Plot from Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198