Tutorial On MadGraph5_aMC@NLO:

NLO Simulations

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NLO SIMULATIONS

- The NLO run mode is turned on with '[QCD]' in generation syntax.

```
> generate p p > e+ e- [QCD]
```

- While the LO mode will always compute the cross section and generate events, this is not always the case for NLO runs

- The NLO code can be run in two different ways:

  - Fixed-order (fNLO): no events will be generated. Compute cross sections (within cuts) and generate histograms on the fly.
  - NLO+PS: generate the unweighted event sample (up to a sign difference) and matched to parton shower via MC@NLO matching.

EXERCISES: TOP QUARK PAIR

- Learn the syntax by typing "tutorial aMCatNLO"
- Generate the top quark pair production at NLO.

```
./bin/mg5_aMC
> generate p p > t t~ [QCD]
> output MyNLOExample
> launch
```

- Check the run_card.dat. Note that it is different with that in LO mode.
- Compute both the LO and NLO cross sections at f(N)LO level.
- Choose the existing analysis file analysis_HwU_pp_ttx.o and specify it in FO_analyse_card.dat.
- Understand the histograms you get.

EXERCISES SOLUTION: FNLO

- Turn on f(N)LO (shower turned off automatically)

```
The following switches determine which programs are run:
/============== Description ==============|============== values ==============|========== other options ==========\
| 1. Type of perturbative computation      |          order = NLO                |    LO                              |
| 2. No MC@[N]LO matching / event generation |     fixed_order = ON               |    OFF                             |
| 3. Shower the generated events           |          shower = OFF  <= HERWIG6   |    OFF|PYTHIA6Q|PYTHIA6PT|PYTHIA8 |
| 4. Decay onshell particles               |         madspin = OFF              |    ON|onshell                      |
| 5. Add weights to events for new hypp.   |        reweight = OFF              |    ON|NLO|NLO_TREE|LO              |
| 6. Run MadAnalysis5 on the events generated |    madanalysis = OFF              |    ON                              |
\=========================================|====================================|====================================/
Either type the switch number (1 to 6) to change its setting,
Set any switch explicitly (e.g. type 'fixed_order=OFF' at the prompt)
Type 'help' for the list of all valid option
Type '0', 'auto', 'done' or just press enter when you are done.
```

Switch on fixed_order

- Edit run_card.dat

```
#*********************************************************************
# Number of points per itegration channel (ignored for aMC@NLO runs)  *
#*********************************************************************
 0.005   = req_acc_FO       ! Required accuracy (-1=ignored, and use the
                            ! number of points and iter. below)
# These numbers are ignored except if req_acc_FO is equal to -1
 5000    = npoints_FO_grid  ! number of points to setup grids
 4       = niters_FO_grid   ! number of iter. to setup grids
 10000   = npoints_FO       ! number of points to compute Xsec
 6       = niters_FO        ! number of iter. to compute Xsec
```

Decide the targeted accuracy for fixed-order calculations

EXERCISES SOLUTION: FNLO

- Edit FO_analyse_card.dat

```
#
# This file contains the settings for analyses to be linked to fixed
# order runs. Analysis 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', 'LHE' 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_HWU_pp_ttx.o
#
```

EXERCISES SOLUTION: FNLO

- Total cross section

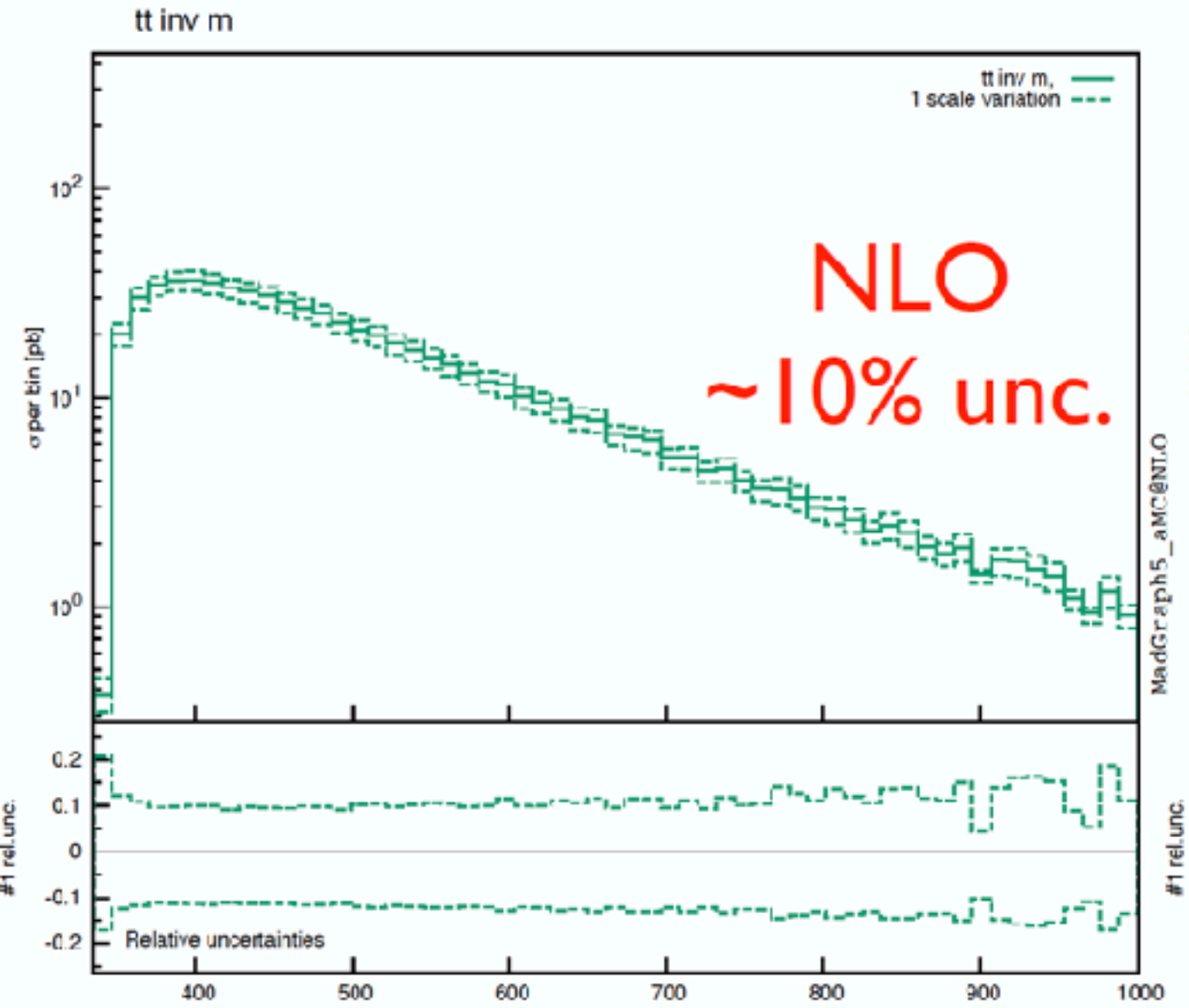
```
   Final results and run summary:
   Process p p > t t~ [QCD]
   Run at p-p collider (6500.0 + 6500.0 GeV)
   Total cross section: 6.301e+02 +- 2.4e+00 pb
   Scale variation (computed from histogram information):
      Dynamical_scale_choice 1 (envelope of 5 values):
         6.801e+02 pb  +10.4% -12.1%

INFO: The results of this run and the TkW and GnuPlot files with the plots have been saved in /Users/huasheng/Physics/MG5/MC5_aMC_v2_6_4/pp2ttxQCD/Events/run_01
INFO: Run complete
INFO:
quit
INFO:
```

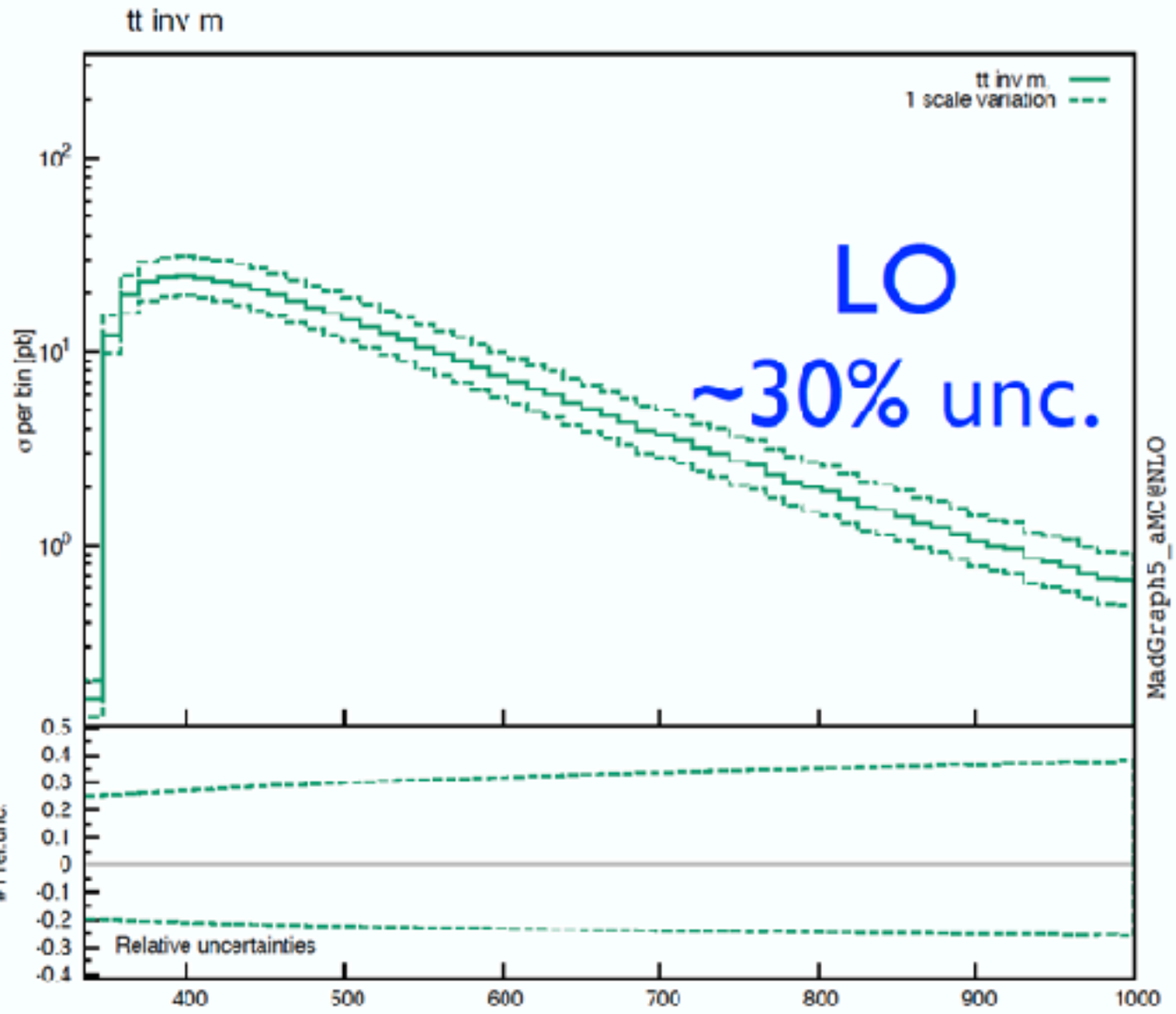
Central value Numerical integration error

Renormalisation/factorisation scale uncertainty

EXERCISES SOLUTION: FNLO

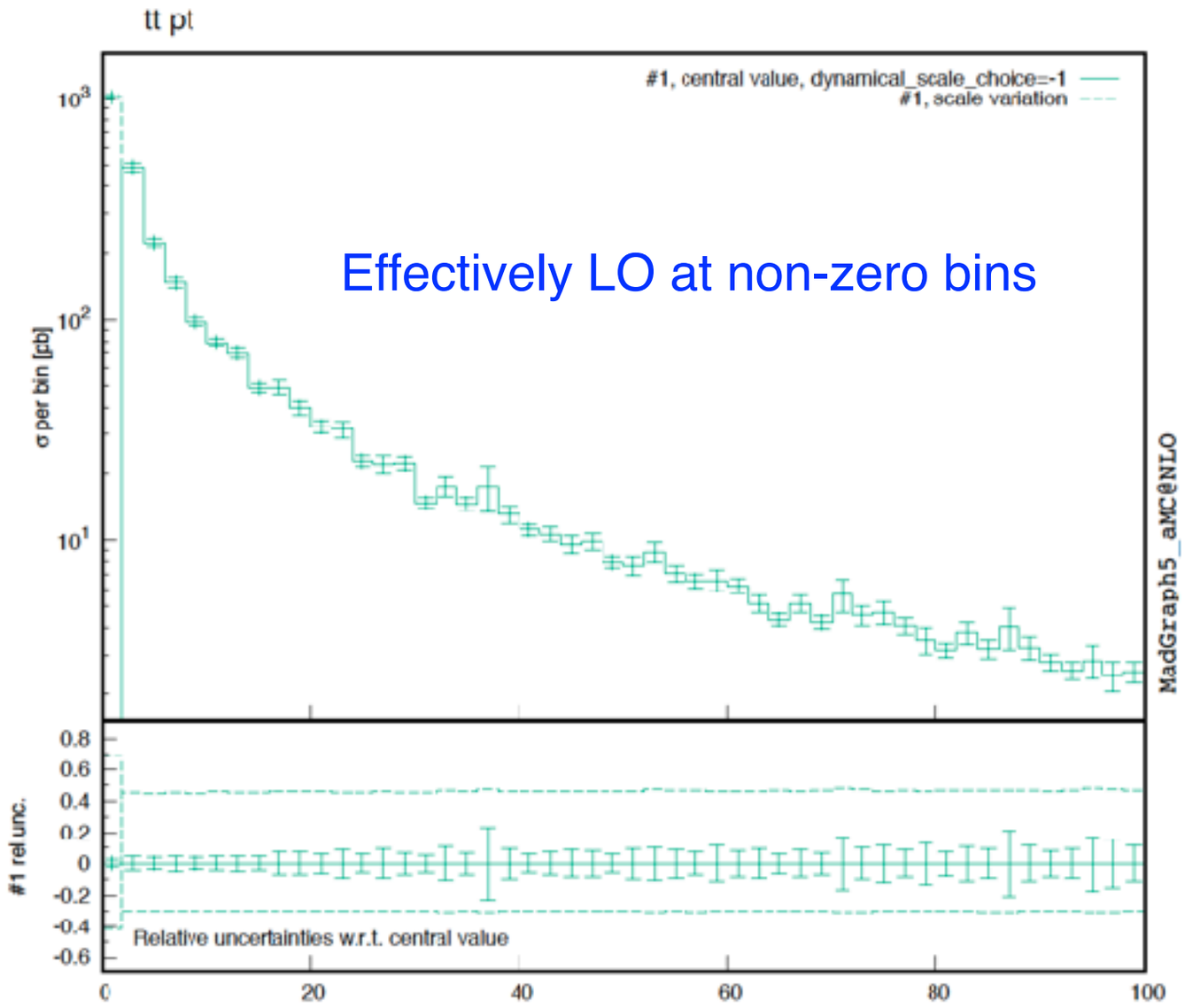
- Differential distributions
  - Check the MyNLOExample/FixedOrderAnalysis/analysis_HwU_pp_ttx.f





EXERCISES SOLUTION: FNLO

- Differential distributions
  - Check the MyNLOExample/FixedOrderAnalysis/analysis_HwU_pp_ttx.f

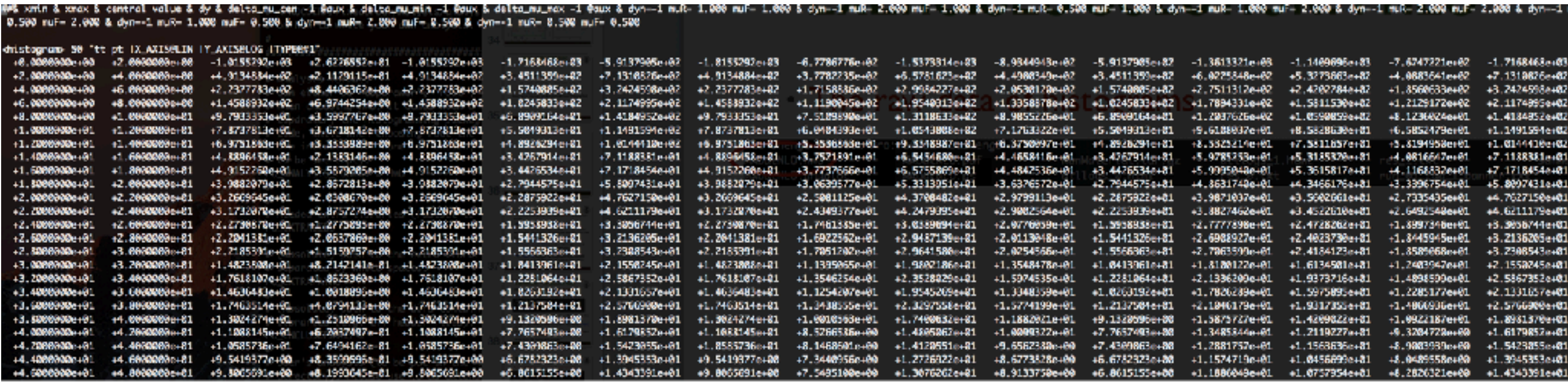


EXERCISES SOLUTION: FNLO

- The raw data of histograms

```
Hua-Sheng's MacBook-Pro:run_01 huasheng$ ls
MADatNLO.HwU            MADatNLO.pdf            RunMaterial.tar.gz      alllogs_1.html          res_1.txt               summary.txt
MADatNLO.gnuplot        MADatNLO.ps             alllogs_0.html          res_0.txt               run_01_tag_1_banner.txt
```

- Histogram With Uncertainty (HwU)



TAKE HOME EXERCISES: FNLO

- 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

EXERCISES: NLO+PS

- Generate NLO event sample showered by Pythia8
  - Warning: the NLO LHE sample should be regenerated if one changes the shower program
  - Remember to install boost via 'install boost'
- In default, HepMC file will be generated.
- Use MadAnalysis5 to read them and to make plots
  - Next tutorial !
- Instead of generating HepMC files, try to generate histograms directory.
  - Use the existing analysis file py8an_HwU_pp_ttx.o and put it in shower_card.dat
  - Hint: you can shower an existing run with ./bin/shower run_XX

EXERCISES SOLUTION: NLO+PS

- Turn on NLO+PS with PS=Pythia8

```
| 1. Type of perturbative computation              order = NLO
| 2. No MC@[N]LO matching / event generation  fixed_order = OFF
| 3. Shower the generated events                   shower = PYTHIA8
| 4. Decay onshell particles                      madspin = OFF
| 5. Add weights to events for new hypp.          reweight = OFF
| 6. Run MadAnalysis5 on the events generated  madanalysis = OFF
Either type the switch number (1 to 6) to change its setting,
Set any switch explicitly (e.g. type 'fixed_order=ON' at the prompt)
Type 'help' for the list of all valid option
Type '0', 'auto', 'done' or just press enter when you are done.
```

Specify shower = Pythia8

- Edit run_card.dat

Change the number of events

```
  tag_1 = run_tag ! name of the run
#*********************************************************************
# Number of LHE events (and their normalization) and the required    *
# (relative) accuracy on the Xsec.                                   *
# These values are ignored for fixed order runs                      *
#*********************************************************************
  100000        = nevents ! Number of unweighted events requested
  -1.0  = req_acc ! Required accuracy (-1=auto determined from nevents)
  -1    = nevt_job ! Max number of events per job in event generation.
                   !  (-1= no split).
#*********************************************************************
```

EXERCISES SOLUTION: NLO+PS

- Edit shower_card.dat

```
# DM_3 = 24:0:Neg:1:Any = 13 14
#*********************************************************************
# 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.                      *
# Remember that if your analysis uses hbook or is in the HwU format,  *
# you must also add to hbook.o or HwU.o to the ANALYSE list as well.  *
#*********************************************************************
extralibs = pythia8 boost_iostreams z dl stdc++ # Extra-libraries (not LHAPDF)
                                # Default: "stdhep Fmcfio"
                                # PYTHIA > 8.200 may require library dl
extrapaths = ../lib /Users/huasheng/Physics/MG5/MG5_aMC_v2_6_4/HEPTools/pythia8//lib /opt/local/lib /Users/huasheng/Physics/MG5/MG5_aMC\
_v2_6_4/HEPTools/zlib/lib /Users/huasheng/Physics/MG5/MG5_aMC_v2_6_4/HEPTools/boost/lib # Path to the extra-libraries
                                # Default: "../lib"
INCLUDEPATHS =                  # Path to header files needed by c++
                                # Dir names separated by white spaces
ANALYSE      =                  # User's analysis and histogramming
                                # routines (please use .o as extension
                                # and use spaces to separate files)
```

```
libboost_filesystem.dylib
libboost_graph.a
libboost_graph.dylib
libboost_iostreams.a
libboost_iostreams.dylib
libboost_log.a
libboost_log.dylib
libboost_log_setup.a
libboost_log_setup.dylib
libboost_math_c99.a
libboost_math_c99.dylib
libboost_math_c99f.a
libboost_math_c99f.dylib
libboost_math_tr1.a
libboost_math_tr1.dylib
Hua-Shengs-MacBook-Pro:lib huasheng$ pwd
/Users/huasheng/Physics/MG5/MG5_aMC_v2_6_4/HEPTools/b
Hua-Shengs-MacBook-Pro:lib huasheng$
```

Libraries required !

Make sure all library paths there !

EXERCISES SOLUTION: NLO+PS

- Result: HepMC file

```
Hua-Shengs-MacBook-Pro:run_02 huasheng$ ls
RunMaterial.tar.gz              events.lhe.gz                   res_2.txt
alllogs_0.html                  events_PYTHIA8_0.hepmc.gz       run_02_tag_1_banner.txt
alllogs_1.html                  res_0.txt                       summary.txt
alllogs_2.html                  res_1.txt
```

- In order to generate the histograms instead of HepMC files

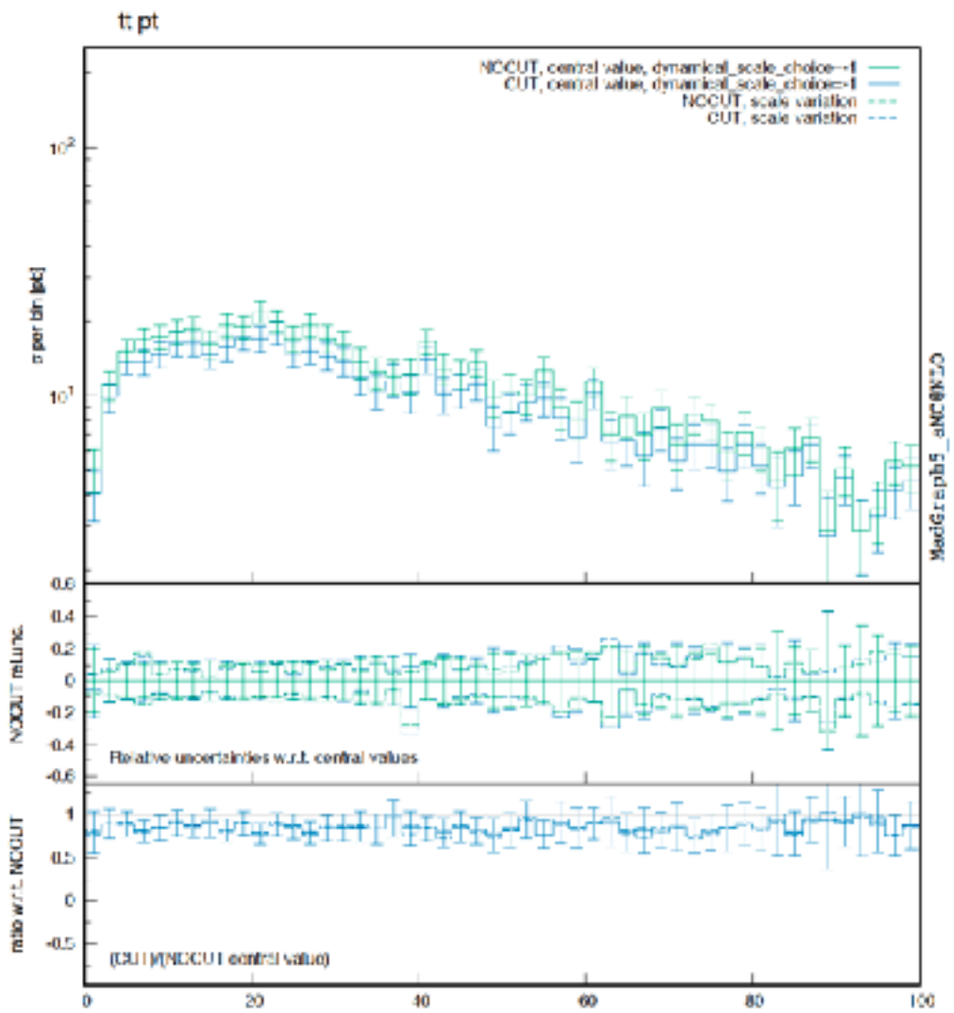
- Edit shower_card.dat

```
# 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.                       *
# Remember that if your analysis uses hbook or is in the HwU format,   *
# you must also add to hbook.o or HwU.o to the ANALYSE list as well.   *
#**********************************************************************
extralibs = pythia8 boost_iostreams z dl stdc++ # Extra-libraries (not LHAPDF)
                                # Default: "stdhep Fmcfio"
                                # PYTHIA > 8.200 may require library dl
extrapaths = ../lib /Users/huasheng/Physics/MG5/MG5_aMC_v2_6_4/HEPTools/pythia8//lib /opt/local/lib /Users/huasheng/Physics/MG5/MG5_aMC\
_v2_6_4/HEPTools/zlib/lib /Users/huasheng/Physics/MG5/MG5_aMC_v2_6_4/HEPTools/boost/lib # Path to the extra-libraries
                                # Default: "../lib"
INCLUDEPATHS =                  # Path to header files needed by c++
                                # dir names separated by white spaces
ANALYSE     = HwU.o   py8an_HwU_pp_ttx.o   # User's analysis and histogramming
                                # routines (please use .o as extension
                                # and use spaces to separate files)
```

EXERCISES SOLUTION: NLO+PS

- Result: histograms
  - Check the MyNLOExample/MCatNLO/PY8Analyzer/py8an_HwU_pp_ttx.f

```
Hua-Sheng-MacBook-Pro:run_03 huasheng$ ls
RunMaterial.tar.gz              events.lhe.gz                   res_1.txt
alllogs_0.html                  plot_PYTHIA8_1_0.HwU            res_2.txt
alllogs_1.html                  plot_PYTHIA8_1_0.gnuplot        run_03_tag_1_banner.txt
alllogs_2.html                  res_0.txt                       summary.txt
```



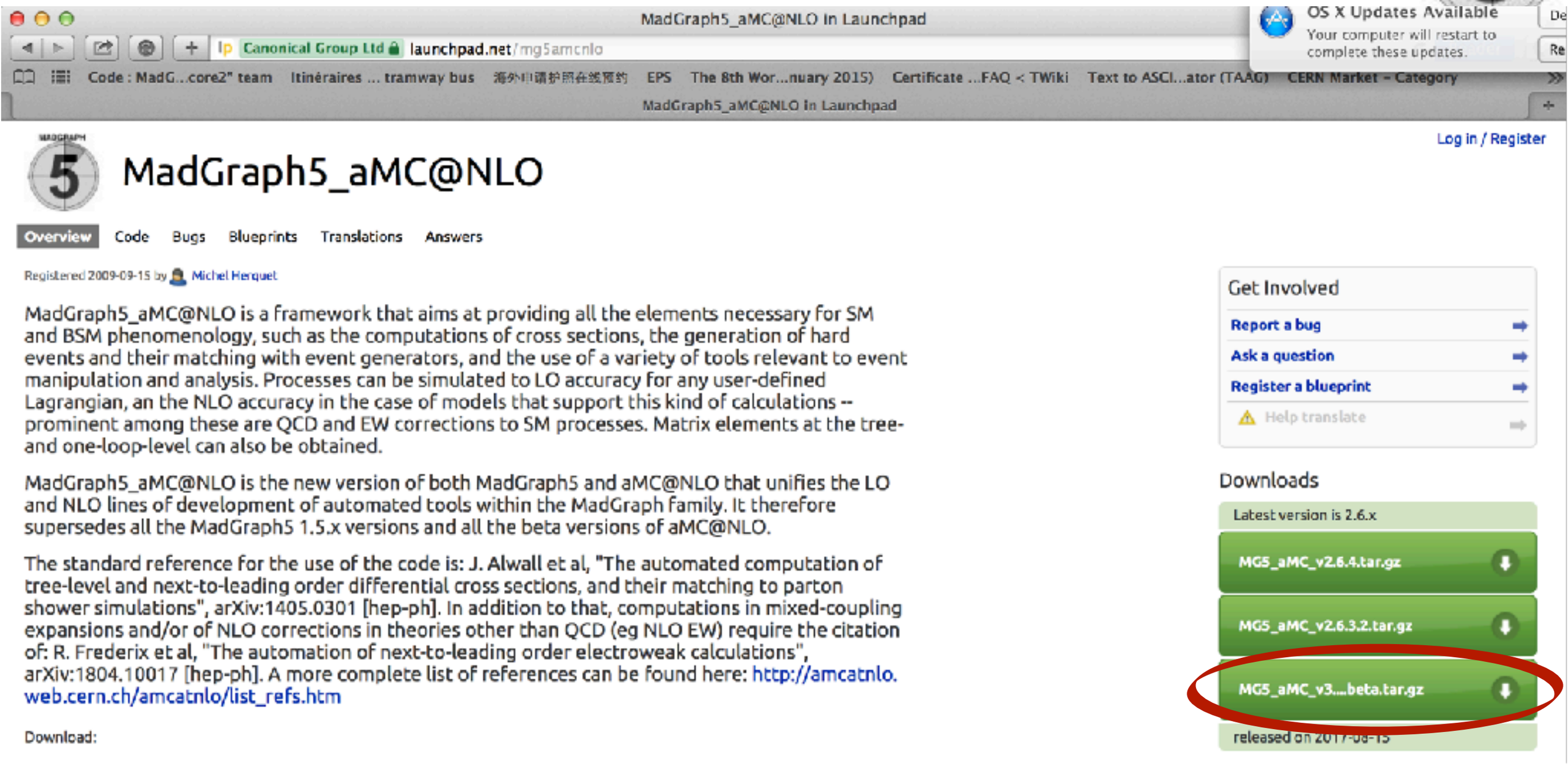
EXERCISES SOLUTION: NLO+PS

- Result: LHE file (need correct shower to be physical)

```
<initrwgt>
  <weightgroup name='scale_variation   -1' combine='envelope'>
    <weight id='1001'> dyn=  -1 muR=0.10000E+01 muF=0.10000E+01 </weight>
    <weight id='1002'> dyn=  -1 muR=0.20000E+01 muF=0.10000E+01 </weight>
    <weight id='1003'> dyn=  -1 muR=0.50000E+00 muF=0.10000E+01 </weight>
    <weight id='1004'> dyn=  -1 muR=0.10000E+01 muF=0.20000E+01 </weight>
    <weight id='1005'> dyn=  -1 muR=0.20000E+01 muF=0.20000E+01 </weight>
    <weight id='1006'> dyn=  -1 muR=0.50000E+00 muF=0.20000E+01 </weight>
    <weight id='1007'> dyn=  -1 muR=0.10000E+01 muF=0.50000E+00 </weight>
    <weight id='1008'> dyn=  -1 muR=0.20000E+01 muF=0.50000E+00 </weight>
    <weight id='1009'> dyn=  -1 muR=0.50000E+00 muF=0.50000E+00 </weight>
  </weightgroup>
</initrwgt>
</header>
<init>
  2212   2212 0.65000000E+04 0.65000000E+04 -1 -1 244800 244800 -4   1
0.67732468E+03 0.38432666E+01 0.13001881E+04      0
</init>
<event>
4      0 0.13001881E+04 0.11780576E+03 0.75467711E-02 0.10610484E+00
      21 -1    0    0  501  502 0.00000000E+00 0.00000000E+00 0.59797002E+03 0.59797002E+03 0.00000000E+00 0.0000E+00 0.9000E+01
      21 -1    0    0  502  503 0.00000000E+00 0.00000000E+00 -.60283167E+02 0.60283167E+02 0.00000000E+00 0.0000E+00 0.9000E+01
       6  1    1    2  501    0 0.61030847E+01 0.74739250E+02 0.23026277E+03 0.29761241E+03 0.17300000E+03 0.0000E+00 0.9000E+01
      -6  1    1    2    0  503 -.61030847E+01 -.74739250E+02 0.30742408E+03 0.36064078E+03 0.17300000E+03 0.0000E+00 0.9000E+01
#aMCatNLO 1  0  0  2  3 0.33272654E+02 0.00000000E+00  9  5  0 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
<rwgt>
 <wgt id='1001'> 0.13002E+04 </wgt>
 <wgt id='1002'> 0.10415E+04 </wgt>
 <wgt id='1003'> 0.16642E+04 </wgt>
 <wgt id='1004'> 0.14027E+04 </wgt>
 <wgt id='1005'> 0.11166E+04 </wgt>
 <wgt id='1006'> 0.18080E+04 </wgt>
 <wgt id='1007'> 0.11653E+04 </wgt>
 <wgt id='1008'> 0.94099E+03 </wgt>
 <wgt id='1009'> 0.14783E+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

TAKE HOME EXERCISES: NLO EW



- NLO EW can be generated with fNLO only at the moment.
- Add '[QCD QED]' or '[QED]' in the generation syntax.