

NLO tutorial

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$t\bar{t}$ production at NLO

Part I: Fixed order

- 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? $p_T(t)$, $p_T(t\bar{t})$, $y(t)$ $M(t\bar{t})$, $\Delta\phi(t\bar{t})$



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`

Solution

Part I

- Learn the

- > `tuto`

- Generate

- > `gene`

The current model
MG5_aMC now loads
`import model loo`

INFO: Generating

- > `outp`

- Compute

- > `laun`

```
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@NL0 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=NL0
 - 2 Fixed order (no event generation and no MC@[N]L0 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=L0' at the prompt)
Type '0', 'auto', 'done' or just press enter when you are done.
[0, 1, 2, 3, 4, auto, done, order=L0, order=NL0, ...][60s to answer]

```
> fixed_order=ON
```

```
> order=L0 (for L0 run)
```

Solution

Part I

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MG5_aMC now l
import model

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*
*           W E L C O M E  t o  M A D G R A P H 5
*
```

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_L0

```
type '0', 'auto', 'done' or just press enter when you are done.
[0, 1, 2, 3, 4, auto, done, order=L0, order=NLO, ... ][60s to answer]
```

```
> fixed_order=ON
> order=L0 (for L0 run)
```

```
ted:
g):  order=NLO
      fixed_order=OFF
      shower=ON
      madspin=OFF
ult setting,
prompt)
```

Solution

Part I

- Select the analysis `analysis_HwU_pp_ttx` in the `F0_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=L0' at the prompt)
Type '0', 'auto', 'done' or just press enter when you are done.
[0, 1, 2, 3, 4, auto, done, order=L0, 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 / F0_analyse : F0_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.





Part I

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[0, 1, 2,

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INFO: will

Do you want

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you can al

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```
#####
#
# 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/R00T/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

FO_ar

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The followi

1 Perturba

2 Fixed or

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4 Decay pa

Either ty

or set an

Type '0',

[0, 1, 2,

>

INFO: will

Do you want

1 / param

2 / run

3 / FO_ar

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```
#####
#
# 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_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/R00T/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
```



Solution

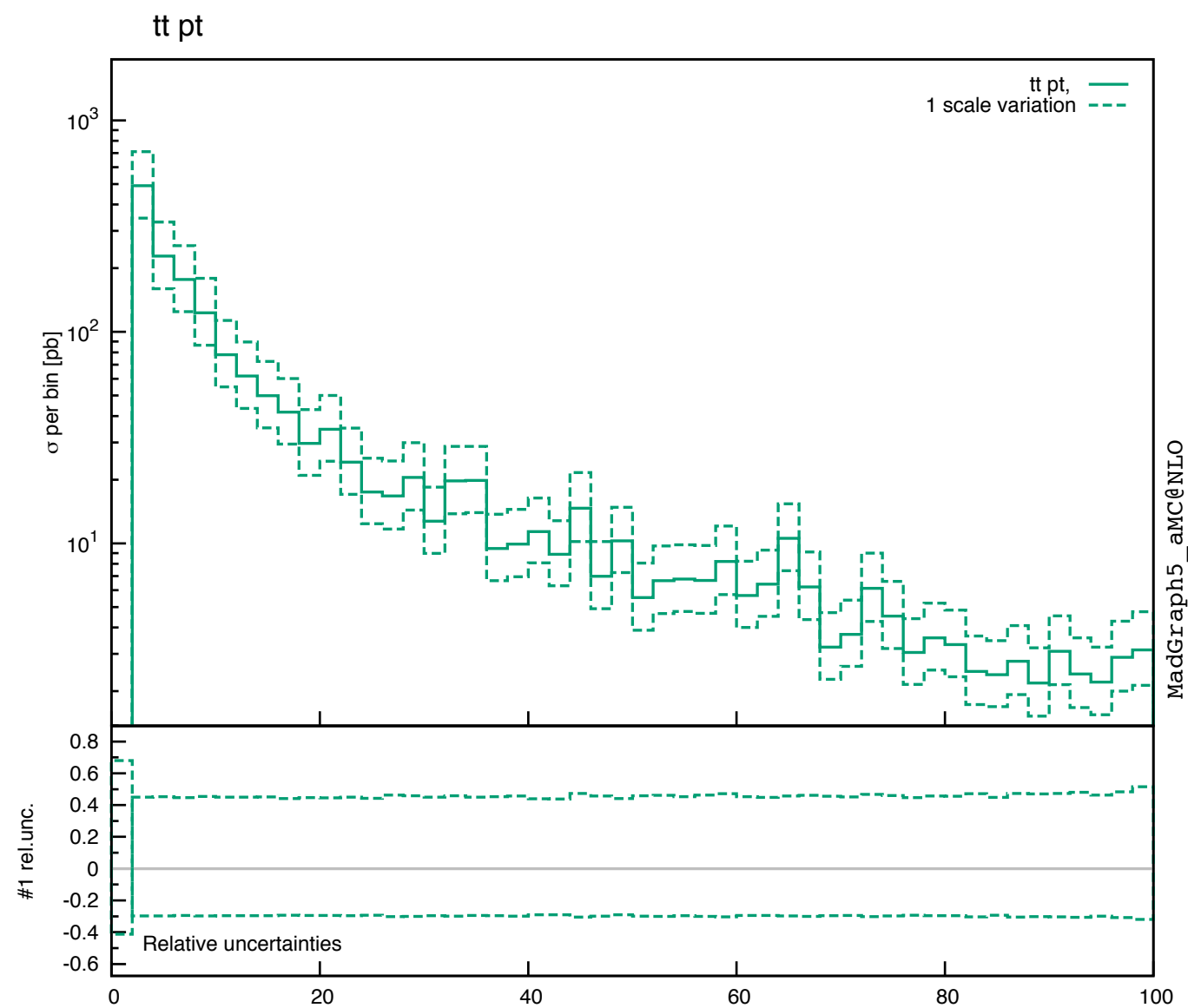
- The HwU (**H**istogram **w**ith **U**ncertainties) format

##& 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
```



Solution



Solution

Part I

- 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 $2 \rightarrow 2$ 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

Solution

Part I

- What are the histograms with $\mu_R = \dots$ $\mu_F = \dots$ for?

- QCD master formula

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

or better

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

- 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 $N^k\text{LO}$, the dependence is of $N^{k+1}\text{LO}$



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 $p p \rightarrow t \bar{t}$ [QCD]

Run at p-p collider (6500 + 6500 GeV)

Total cross-section: $6.871e+02 \pm 5.9e+00$ 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 $p p \rightarrow t \bar{t}$ [QCD]

Run at p-p collider (6500 + 6500 GeV)

Total cross-section: $4.622e+02 \pm 2.2e+00$ 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

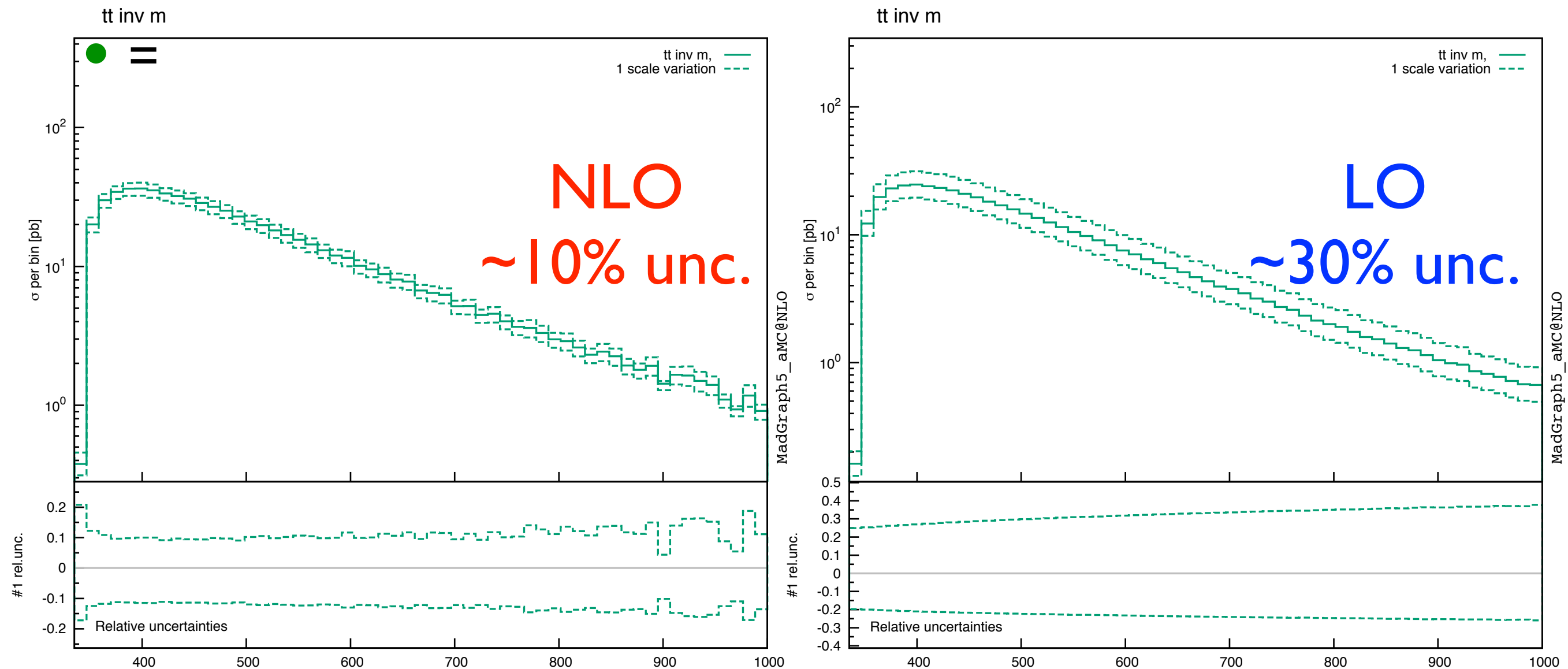
- Look at the LO and NLO cross-section we have just computed
 - Values with different scales are computed on the fly and the envelope is taken
- Typically LO has larger scale uncertainties
- To have scale uncertainties for distributions, one must fill one histogram per scale choice, and then take the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



Scale uncertainties

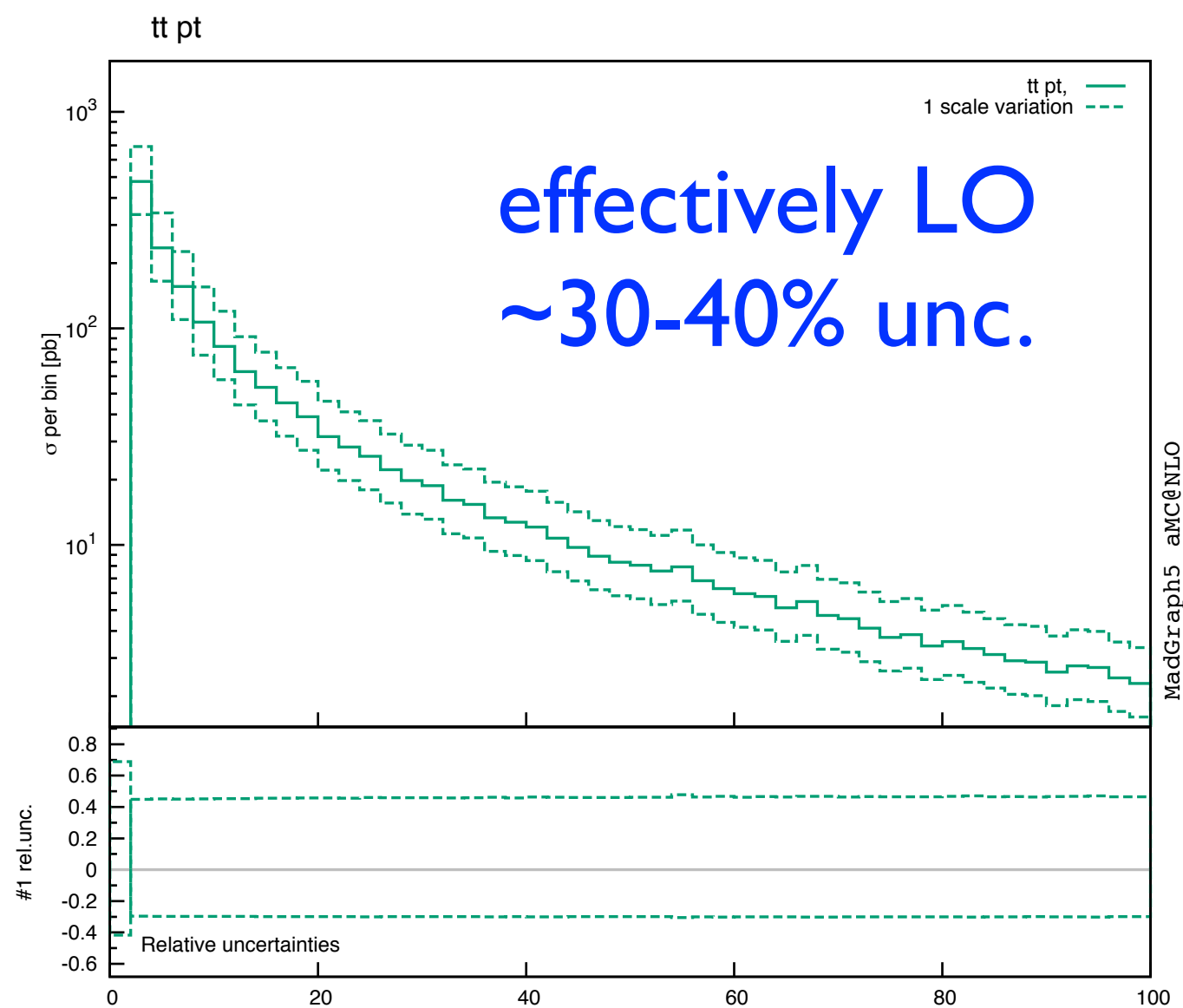
- Look at the LO and NLO cross-section we have just computed
 - Values with different scales are computed on the fly and the envelope is taken
- Typically LO has larger scale uncertainties
- To have scale uncertainties for distributions, one must fill one histogram per scale choice, and then take the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

Scale uncertainties



Scale uncertainties

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



$t\bar{t}$ production at NLO

Part 2: Event generation

- Generate an event sample at NLO and LO to be showered by Pythia8 (needs to be specified in the run_card) (> install pythia8 before generate/output)
- Shower and analyse it with the py8an_HwU_pp_ttx.o analysis (to be specified in the shower_card)
- False = reweight_scale in the run_card
- The histogramming routine (HwU.o) must also be added to the analysis files in the shower_card

```
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        = HwU.o py8an_HwU_pp_ttx.o # User's analysis and histogramming
                  # routines (please use .o as extension
                  # and use spaces to separate files).
                  # If the HwU.o files has to be linked,
                  # it should be put *first*.
```

- (Hint: you can shower an existing run with `./bin/shower run xx`)

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`

Solution

Part 2

- Generate a NLO event
- Shower it with the r (the shower_card)
 - `cd my_ttbar_n`
 - `./bin/aMCatNL`
 - `> launch`
 - `> fixed_order`
 - `> shower=ON`
- Edit `run_card`
- Edit `shower_card`

specified in

```
# 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!!!!
*
*****
*
PYTHIA8   = 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)
*
*****
*
```

Solution

Part 2

- Generate a NLO event
- Shower it with the r (the shower_card)
 - `cd my_ttbar_n`
 - `./bin/aMCatNL`
 - `> launch`
 - `> fixed_order`
 - `> shower=ON`
- Edit `run_card`
- Edit `shower_card`

specified in

```
# 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!!!!
*
*****
*
PYTHIA8  = parton_shower
*****
# Renormalization and factorization scales
*
# ( *****
# 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)
F             # Default: "stdhep Fmcfio"
F             # PYTHIA > 8.200 may require library dl
91 EXTRAPATHS  = ../lib   # Path to the extra-libraries
91             # Default: "../lib"
91 INCLUDEPATHS =         # Path to header files needed by c++
***          # Dir names separated by white spaces
ANALYSE      = py8an_HwU_pp_ttx.o HwU.o
# R          # routines (please use .o as extension
#           # and use spaces to separate files)
*****
*
```

Solution

Part 2

- Generate a NLO event
- Shower it with the `shower_card`
- `cd my_ttbar_`
- `./bin/aMCatNLO`
- `> launch`
- `> fixed_order`
- `> 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: $6.772e+02 \pm 2.1e+00$ 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

P
*
routines (please use .o as extension
and use spaces to separate files)

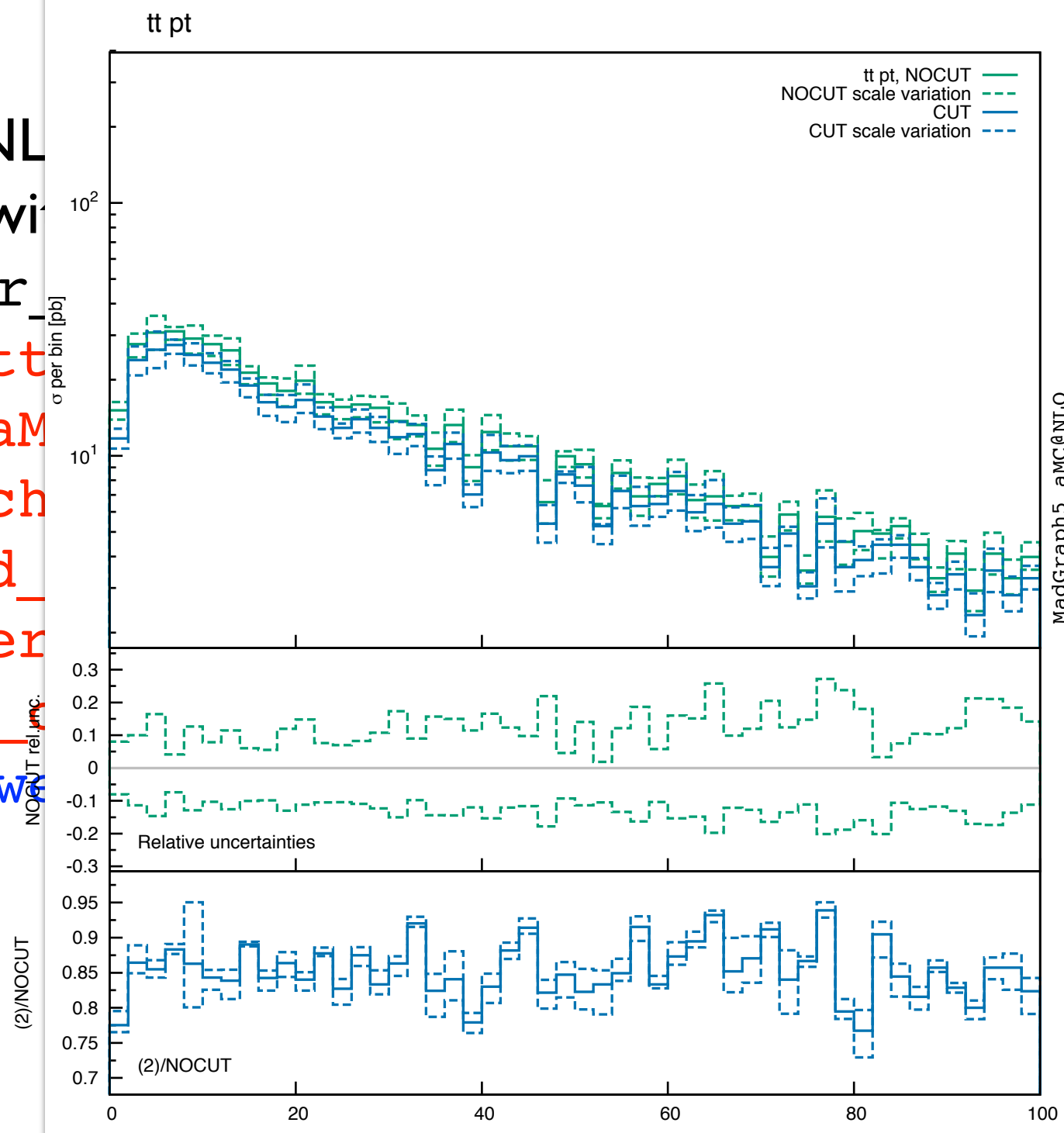
*

in

Solution

Part 2

- Generate a NLO calculation
- Shower it with a parton shower
- `cd my_tt`
- `./bin/amc@NLO`
- `> launch`
- `> fixed_order`
- `> shower`
- Edit `run_01`
- Edit `show`



ts evol.

in

my_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

as extension
rate files)

The events

```
<initrwt>
  <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>
</initrwt>
</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
  <rwt>
    <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>
    . . .
```

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



NLO exercise

$t\bar{t}$ production at NLO

Part 3: Decay and spin correlations

- Generate a NLO event sample to be showered by Pythia8
- Shower and analyse it with the `py8an_HwU_pp_tttx.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 undecayed 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` $\rightarrow$ `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 3

- 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 3

- Generate a NLO event
- Shower it with the r (the shower_card)
 - `cd my_ttbar_n`
 - `./bin/aMCatNLO`
 - `> launch`
 - `> fixed_order`
 - `> shower=ON`
- Edit `run_card`
- Edit `shower_card`

specified in

```
# 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!!!!
*
*****
*
PYTHIA8    = 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 3

- Generate a NLO event
- Shower it with the r (the shower_card)
 - `cd my_ttbar_n`
 - `./bin/aMCatNL`
 - `> launch`
 - `> fixed_order`
 - `> shower=ON`
- Edit `run_card`
- Edit `shower_card`

specified in

```
# 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!!!!
*
*****
*
PYTHIA8    = parton_shower ←
*****
# Renormalization and factorization scales
*
# ( *****
# 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)
F           # Default: "stdhep Fmcfio"
F           # PYTHIA > 8.200 may require library dl
91 EXTRAPATHS = ../lib   # Path to the extra-libraries
91           # Default: "../lib"
91 INCLUDEPATHS =        # Path to header files needed by c++
***          # Dir names separated by white spaces
ANALYSE     = py8an_HwU_pp_ttx.o HwU.o ←
# R          # routines (please use .o as extension
#           # and use spaces to separate files)
*****
*
```

NLO exercise Solution

Part 3

- Generate a NLO event
- Shower it with the
the shower_card
 - `cd my_ttbar_`
 - `./bin/aMCatN`
 - `> launch`
 - `> fixed_order`
 - `> shower=ON`
- Edit `run_card`
- Edit `shower_ca`

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: $6.772e+02 \pm 2.1e+00$ 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

P
*
routines (please use .o as extension
and use spaces to separate files)

*

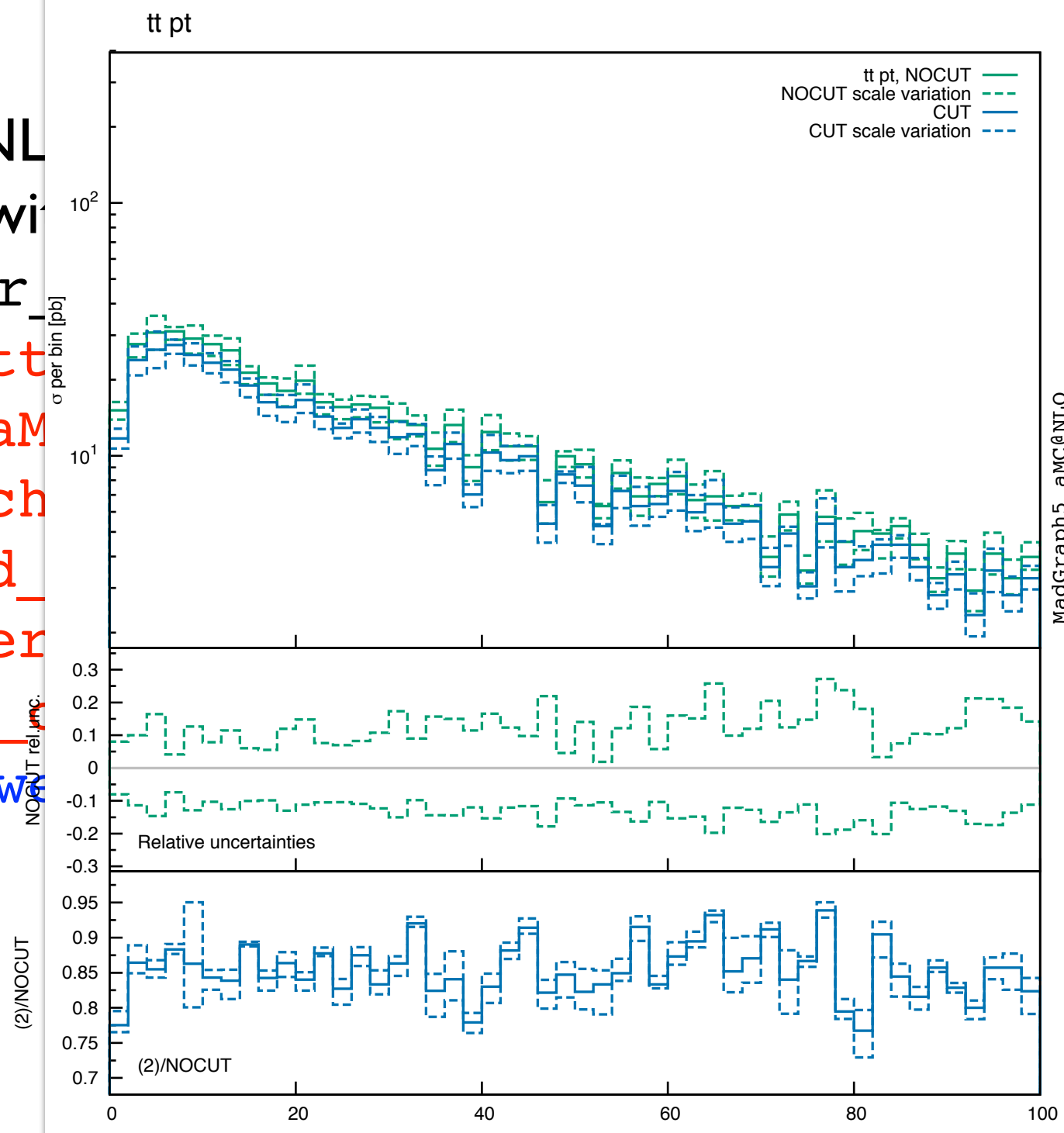
in



NLO exercise Solution

Part 3

- Generate a NLO calculation
- Shower it with Pythia 8
- `cd my_tt`
- `./bin/amc@NLO`
- `> launch`
- `> fixed_order`
- `> shower`
- Edit `run_01.py`
- Edit `show_results.py`



ts evol.

my_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

as extension
rate files)

in

The events

```
<initrwt>
  <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>
</initrwt>
</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
  <rwt>
    <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>
    . . .
```

- 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 3

- 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 3

- 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_weight 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 3

- Use MadSpin to generate a dilepton (interference) decayed sample

- `./bin/aMCatNL`
- `> decay_event`
- edit the `madspin`

```
#####
##                               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_weight 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 3

- Re-analyse the decayed and undecayed sample with the `py6an_HwU_pp_lplm` analysis and check 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 3

- 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`

```
# 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)
```



Part 3

- `./bin/`

- edit the

- Shower

- `./bin/`

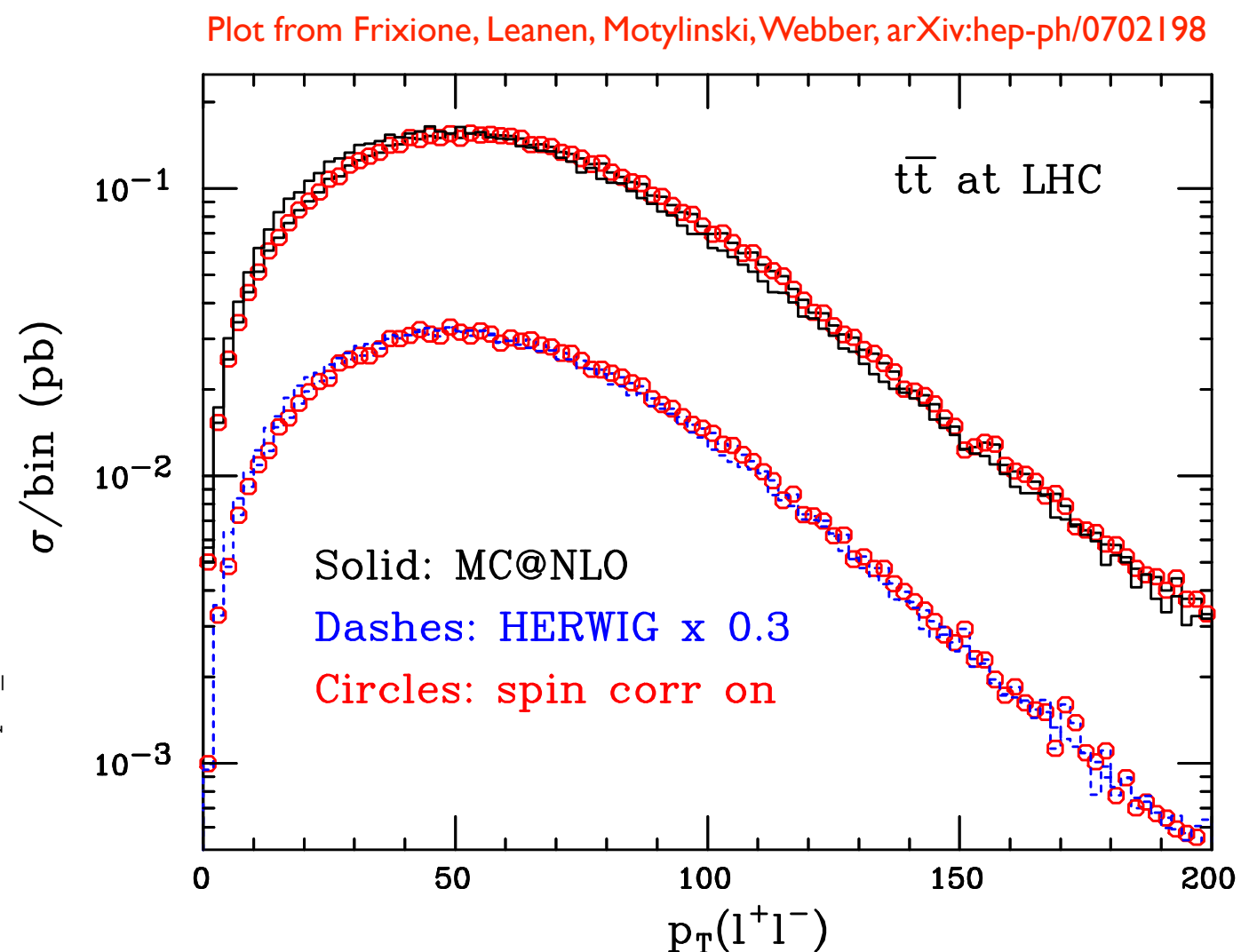
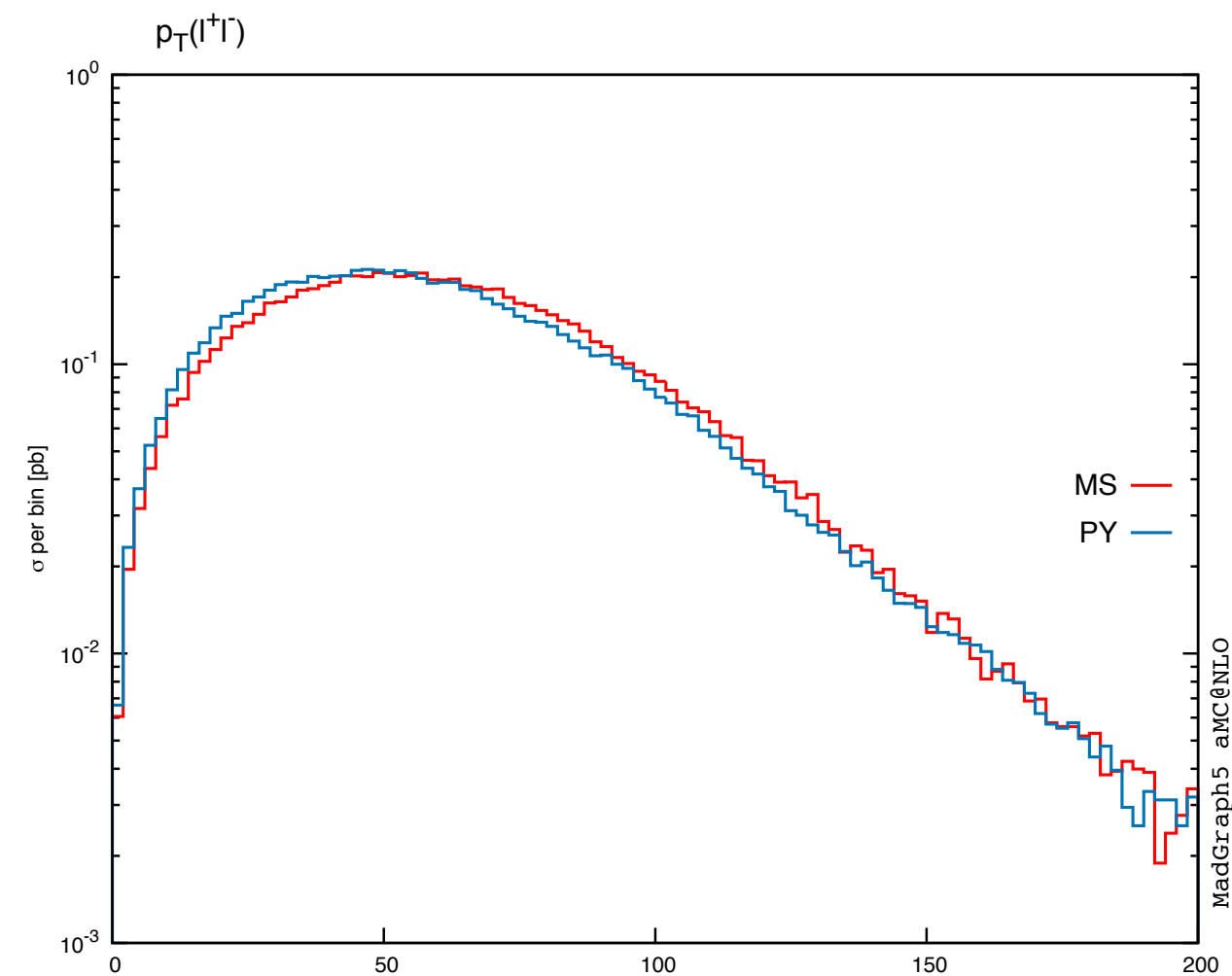
```
*  
performed by *  
*  
  
*****  
*****  
*  
not want to *  
analysis (to *  
*  
*  
*****  
  
are library dl  
ties  
  
ded by c++  
white spaces  
n8.o ←  
(as extension  
te files)
```

NLO exercise

Solution

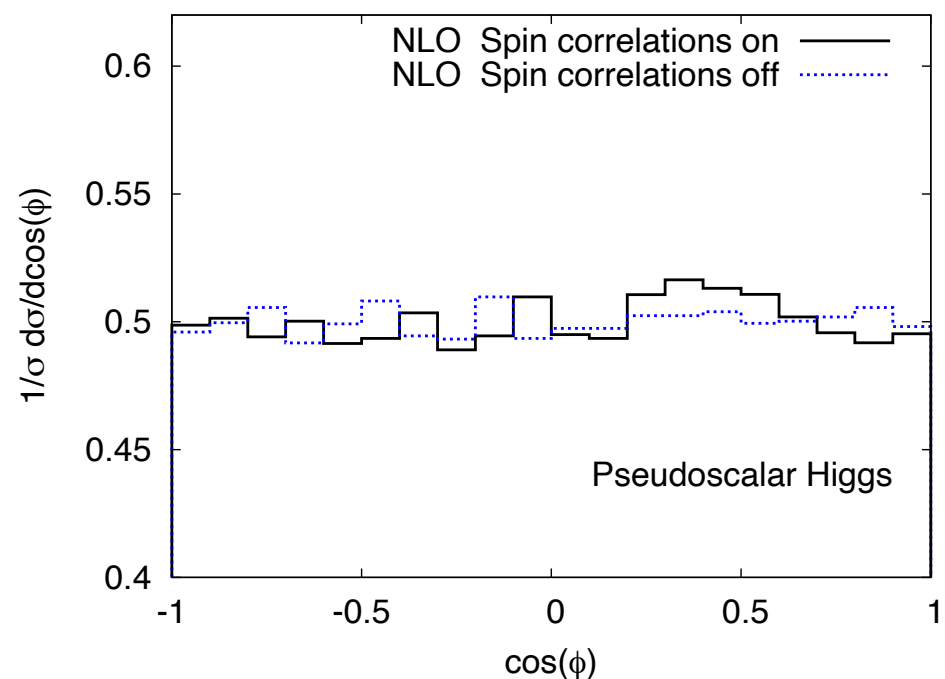
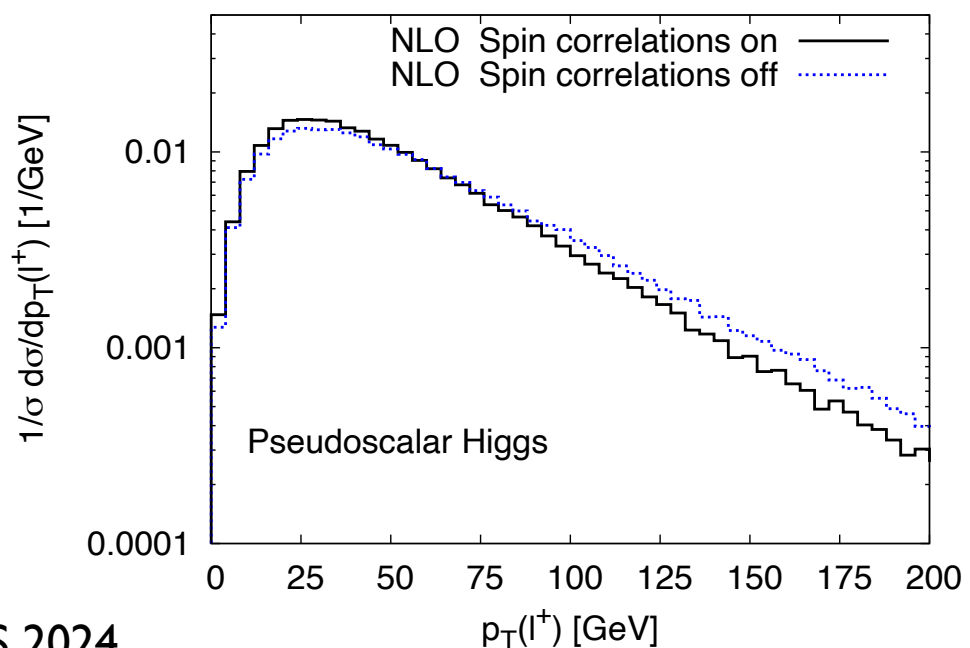
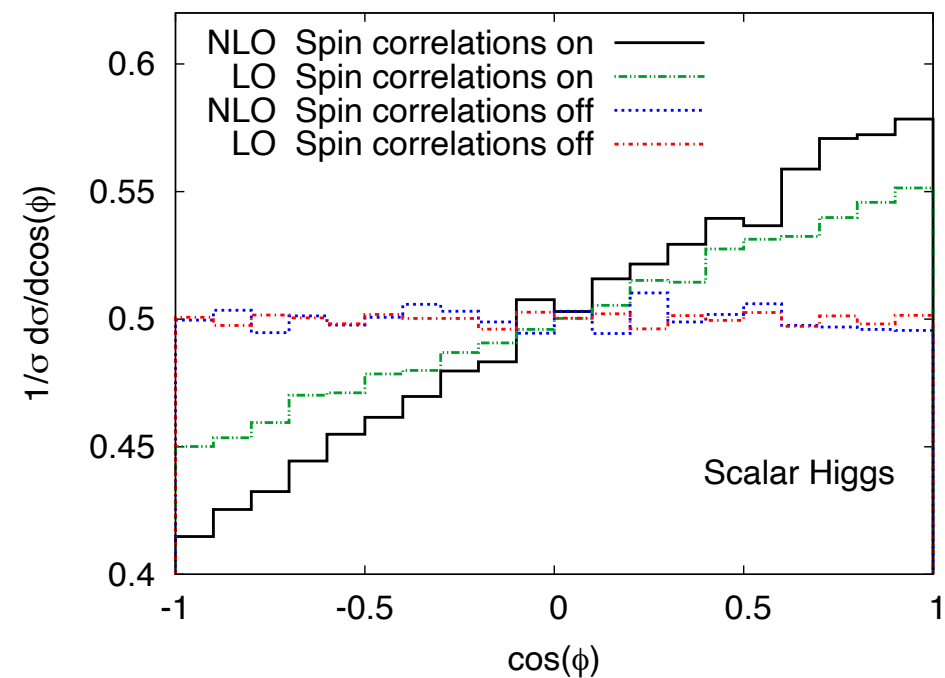
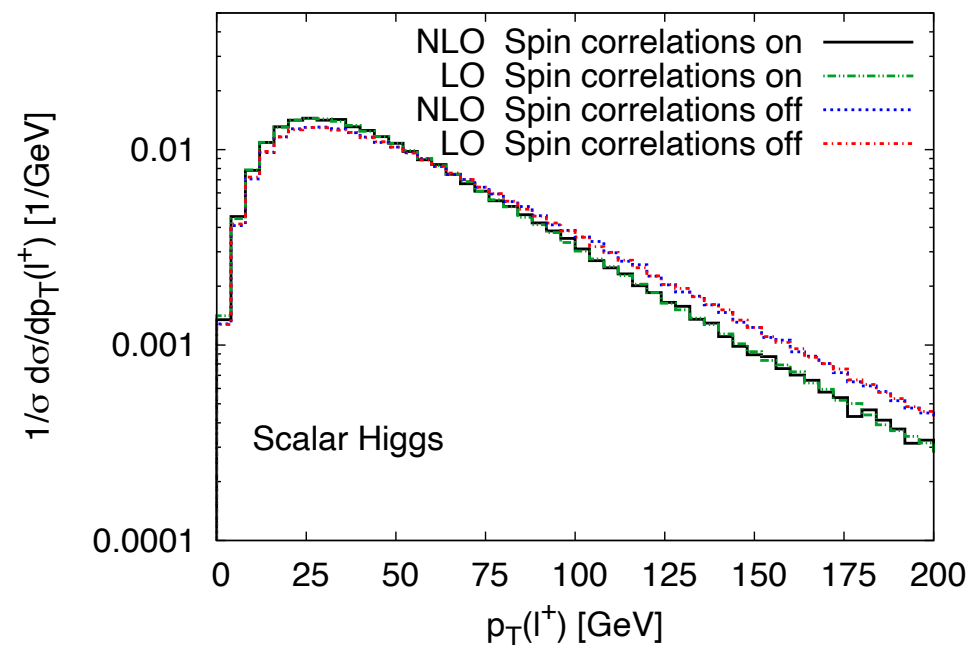
Part 3

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



Spin correlations in $t\bar{t}H$

- In $t\bar{t}H$, spin correlations are crucial to distinguish a scalar vs pseudo scalar Higgs boson!



Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460