MG5_aMC tutorial
Part 2: NLO

IWATE COLLIDER SCHOOL
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NLO Tutorials

- Part 1: fixed-order computations
- Part 2: event-generation and parton shower
- Part 3: Spin correlations at NLO

$t\bar{t}$ production at NLO

Part 1: 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? $p_T(t)$, $p_T(t\bar{t})$, $y(t)$ $M(t\bar{t})$, $\Delta\phi(t\bar{t})$
- What are the histograms with `muR=...` `muF=...` for?

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@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)
```

Solution

Part I

- Learn th
  - > tu
- Genera
  - > ge

```
The current m
MG5_aMC now l
 import model
. . .
INFO: Generat
. . .
```

  - > ou
- Compu
  - > la

```
INFO: ***********************************************************
*                                                         *
*          W E L C O M E  to  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_LO
```

```
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)
```

Solution

Part I

- 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.
```

Part I

- Select

FO_ar

- > l

```
The followi
 1 Perturba
 2 Fixed or
 3 Shower t
 4 Decay pa
  Either ty
  or set an
  Type '0',
 [0, 1, 2,
>
INFO: will
Do you want
  1 / param
  2 / run
  3 / FO_an
 you can al
   - enter
   - use th
     The se
```

```
##################################################################
#
# 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

FO_ar

- > l

```
The followi
 1 Perturba
 2 Fixed or
 3 Shower t
 4 Decay pa
  Either ty
  or set an
  Type '0',
 [0, 1, 2,
>
INFO: will
Do you want
  1 / param
  2 / run
  3 / FO_an
 you can al
   - enter
   - use th
     The se
```

```
#####################################################################
#
# 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/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
```

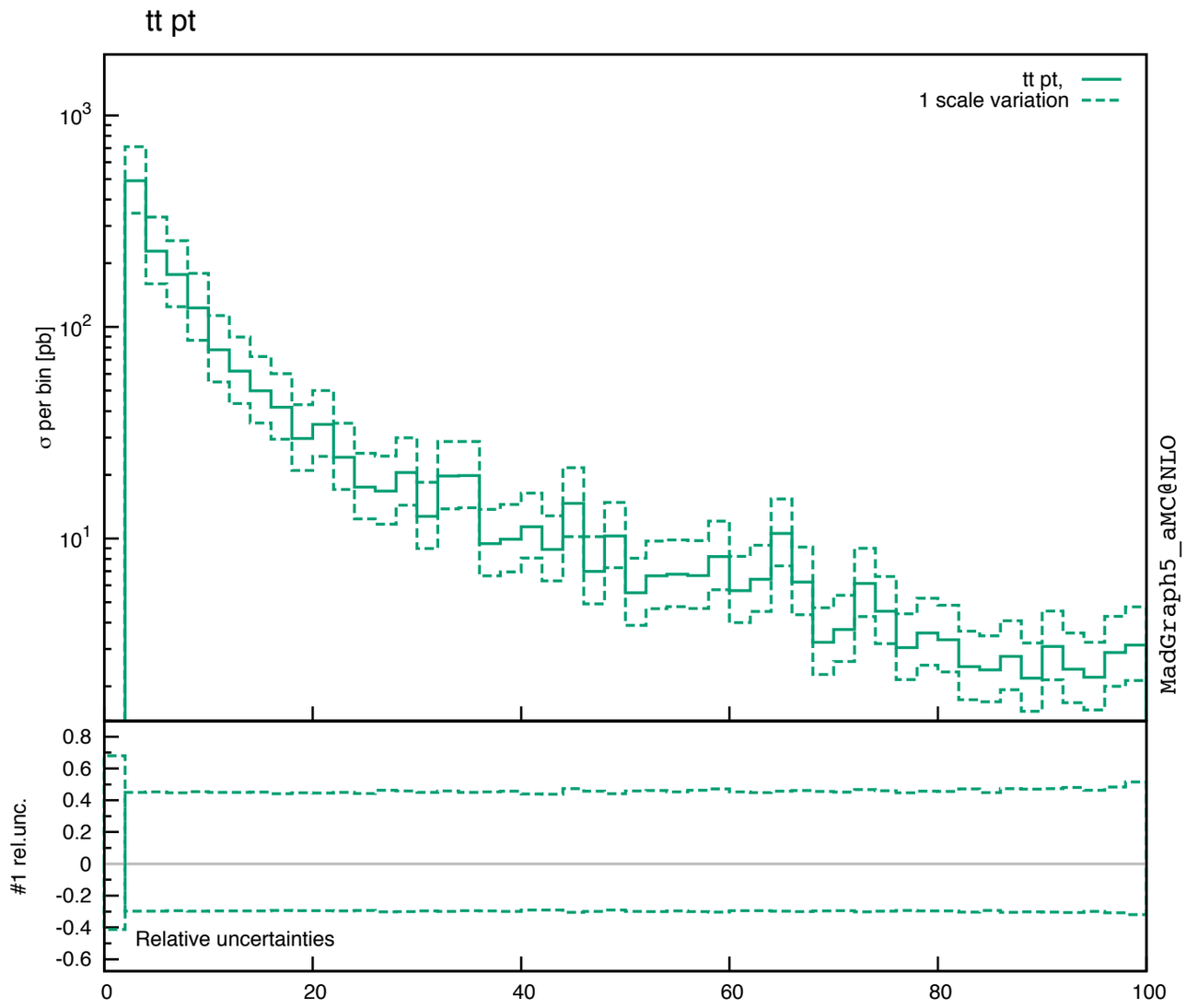
Solution

- 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
```

Solution


tt pt
tt pt,
1 scale variation
σ per bin [pb]
10^3
10^2
10^1
MadGraph5_aMC@NLO
#1 rel.unc.
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Relative uncertainties
0
20
40
60
80
100

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 $2\to2$ 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 `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^{k}LO, the dependence is of N^{k+1}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 > 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

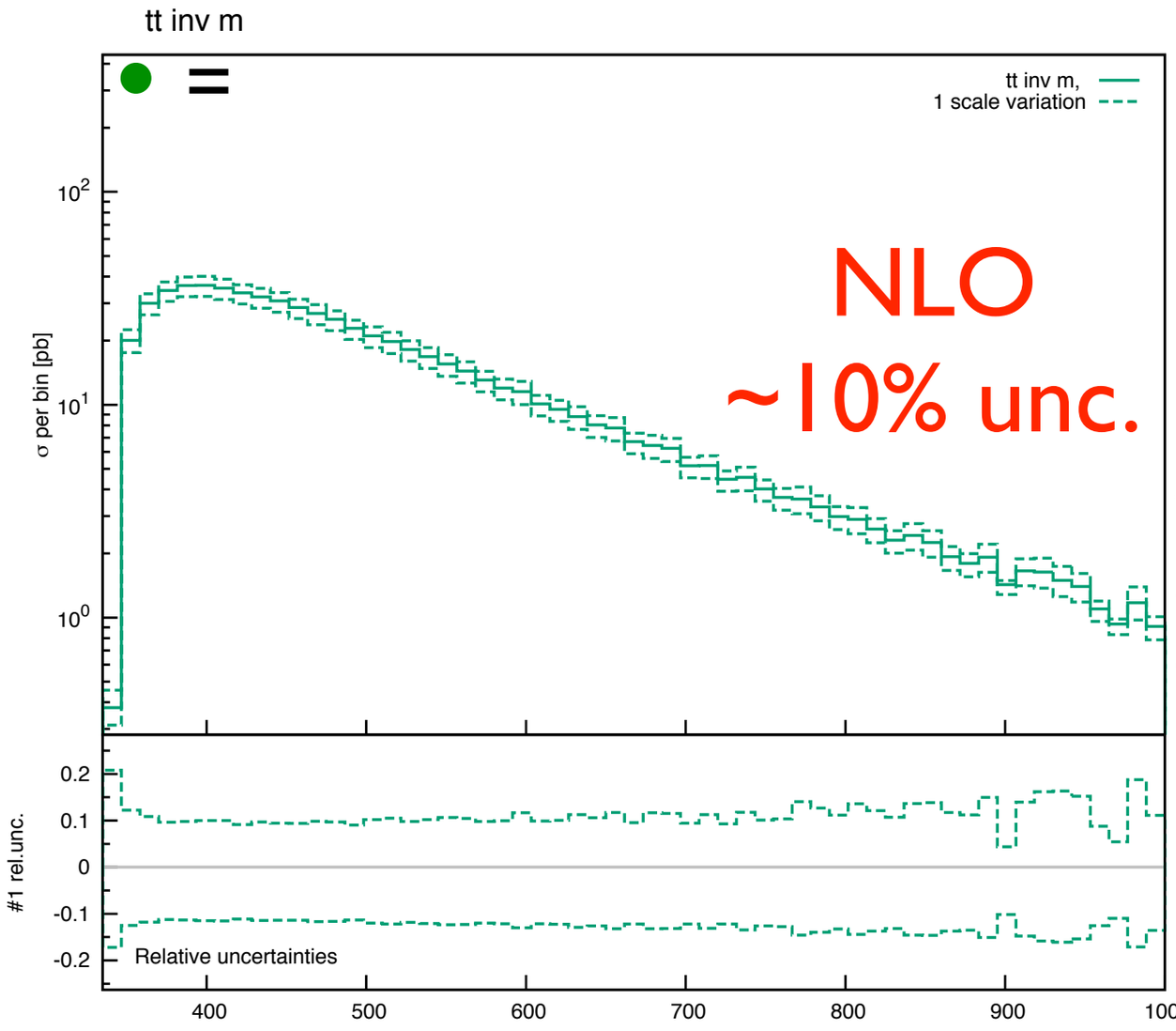
Scale uncertainties

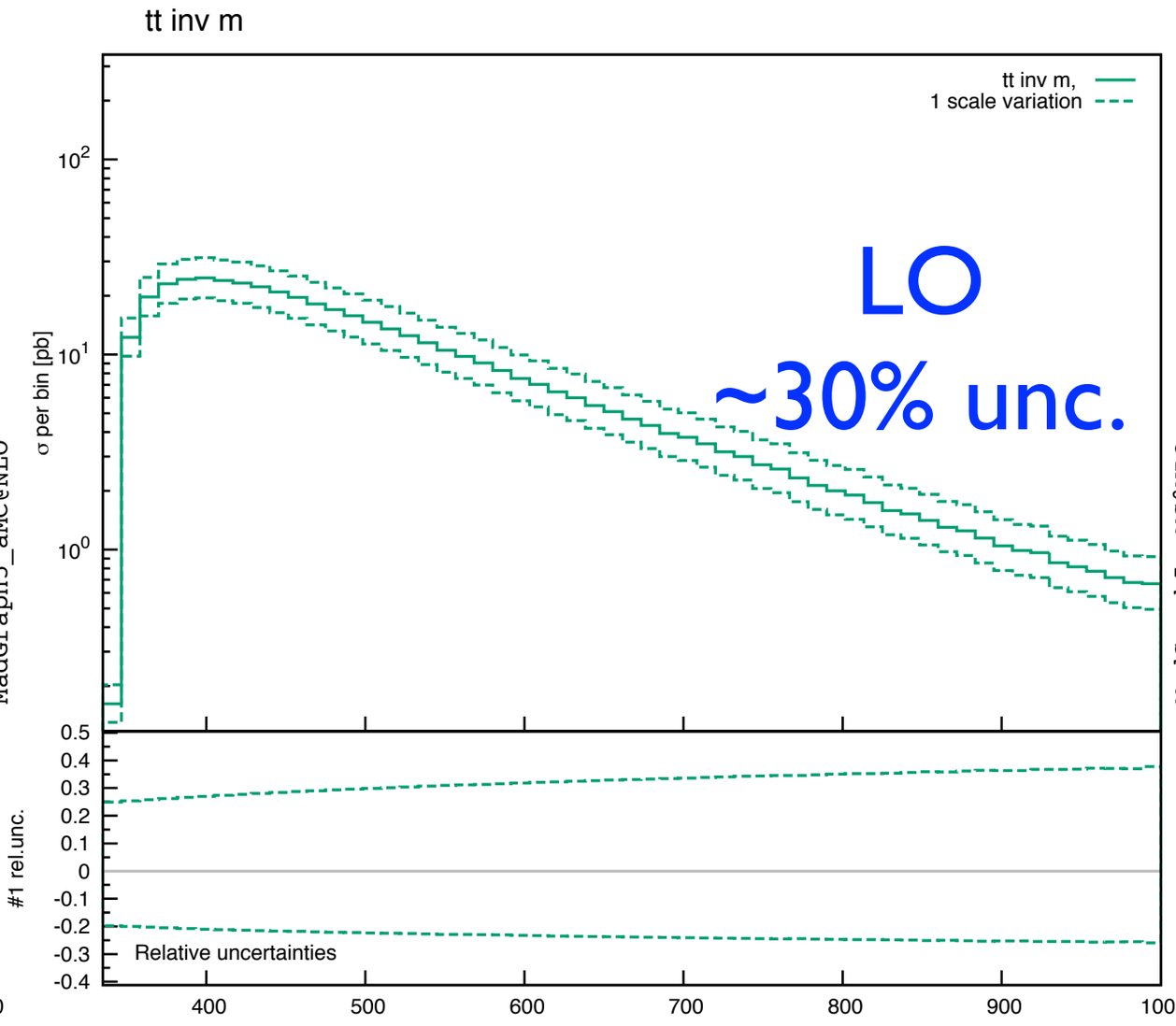
- Look at the LO and NLO cross-section we have just computed
  - Values with different scales are computed on the fly and the envelope is taken
- Typically LO has larger scale uncertainties
- To have scale uncertainties for distributions, one must fill one histogram per scale choice, and then take the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

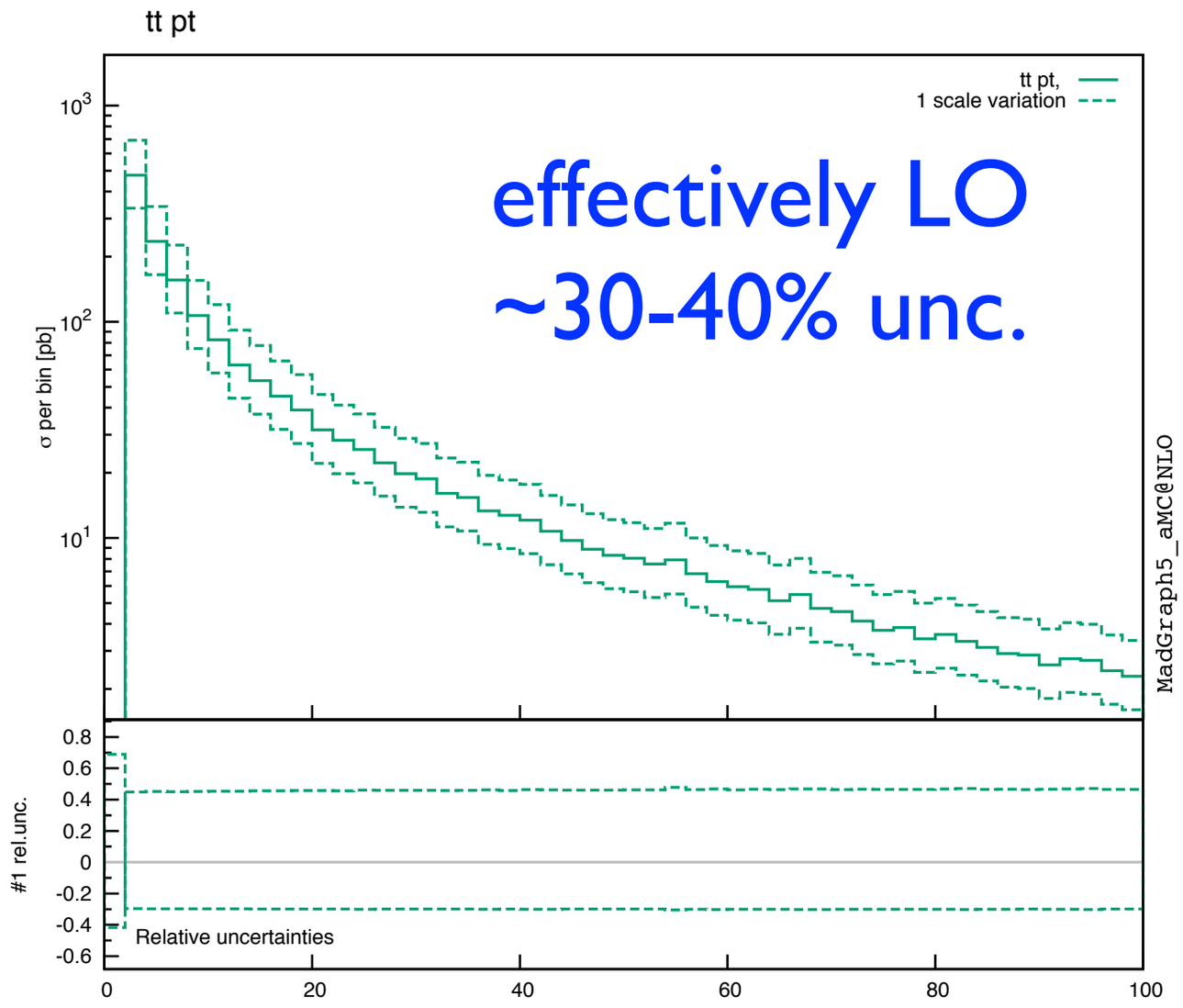
Scale uncertainties





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`)
- Shower and analyse it with the `py8an_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`

```
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 ever
  - Shower it with the r specified in the `shower_card`)
    - `cd my_ttbar_n`
    - `./bin/aMCatNL`
    - `> launch`
    - `> fixed_order`
    - `> shower=ON`
  - Edit `run_card`
  - Edit `shower_car`

```
# 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 ever
  - Shower it with the r
    specified in the `shower_card`)
    - `cd my_ttbar_n`
    - `./bin/aMCatNL`
    - `> launch`
    - `> fixed_order`
    - `> shower=ON`
  - Edit `run_card`
  - Edit `shower_car`

```
# 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
*
# (
*
# 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      = py8an_HwU_pp_ttx.o HwU.o
                                  # routines (please use .o as extension
                                  # and use spaces to separate files)
```

Solution

Part 2

- Generate a NLO eve
  - Shower it with the in the shower_card
    - `cd my_ttbar_`
    - `./bin/aMCatN`
    - `> launch`
    - `> fixed_orde`
    - `> 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 +- 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

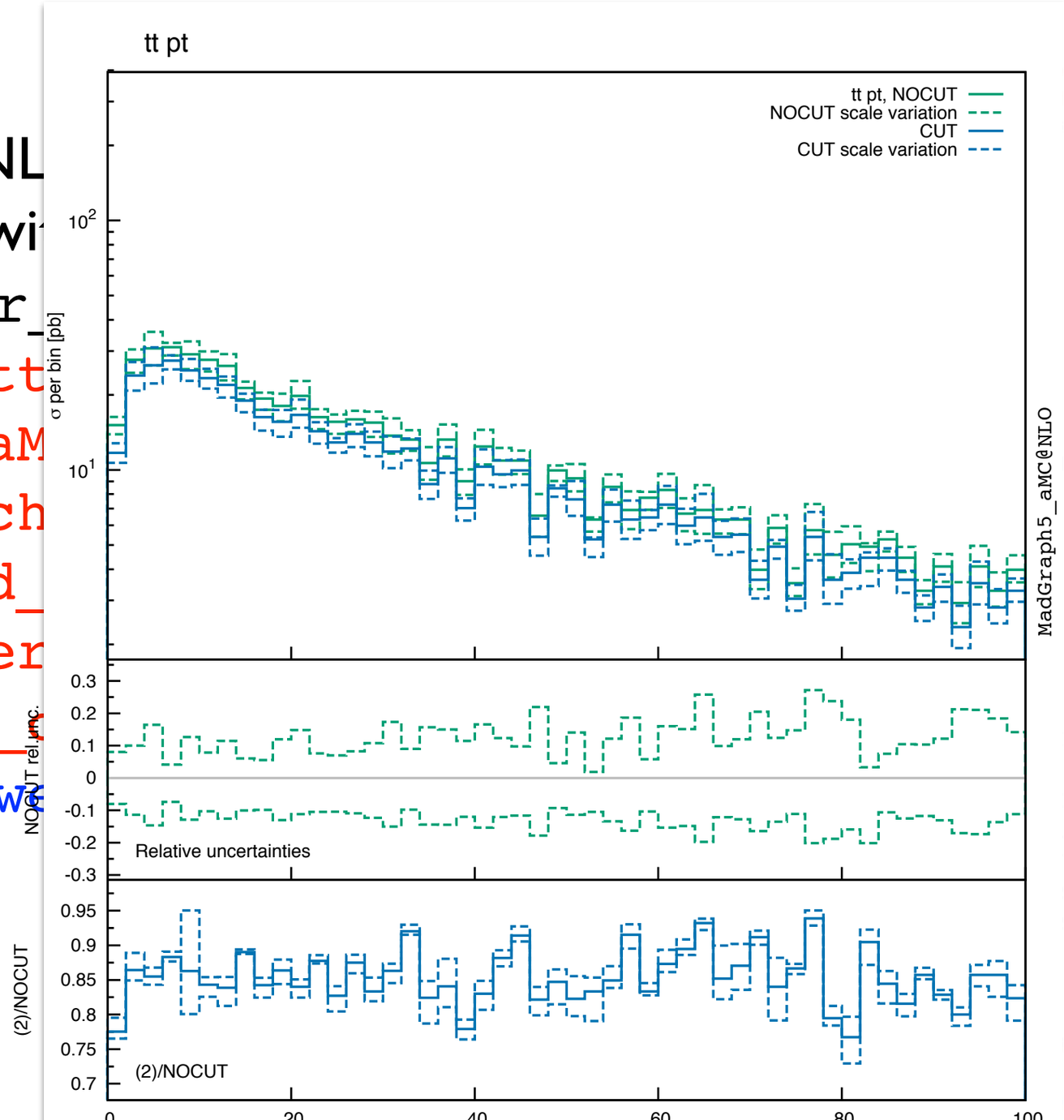
INFO: The /Users/marcozaro/Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/Events/
run_12/events.lhe.gz file has been generated.
. . .
INFO: Preparing MCatNLO run
INFO: Compiling MCatNLO for PYTHIA6Q...
INFO:                          ... done
INFO: Showering events...
INFO: (Running in /Users/marcozaro/Physics/MadGraph/2.2.3new/my_tt_nlo_qcd/
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
```

```
# R                                  # routines (please use .o as extension
*                                    # and use spaces to separate files)
#*********************************************************************
*
```

Solution

Part 2

- Generate a NL
  - Shower it wi
    the `shower_`
    - `cd my_tt`
    - `./bin/aM`
    - `> launch`
    - `> fixed_`
    - `> shower`
- Edit `run_`
- Edit `show`




```
ts evol.
                                                                    in
                                                                    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
MadGraph5_aMC@NLO
                                                                    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>
```

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

```
  <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>
   . . .
```

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_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 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 ever
  - Shower it with the r specified in the `shower_card`)
    - `cd my_ttbar_n`
    - `./bin/aMCatNL`
    - `> launch`
    - `> fixed_order`
    - `> shower=ON`
  - Edit `run_card`
  - Edit `shower_car`

```
# 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 ever
  - Shower it with the r
    specified in the `shower_card`)
    - `cd my_ttbar_n`
    - `./bin/aMCatNL`
    - `> launch`
    - `> fixed_order`
    - `> shower=ON`
  - Edit `run_card`
  - Edit `shower_car`

```
# 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
*
# (
*
# 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      = py8an_HwU_pp_ttx.o HwU.o
                                  # routines (please use .o as extension
                                  # and use spaces to separate files)
```

NLO exercise
Solution

Part 3

- Generate a NLO eve
  - Shower it with the in the shower_card
    - `cd my_ttbar_`
    - `./bin/aMCatN`
    - `> launch`
    - `> fixed_orde`
    - `> 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 +- 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
```

```
# R                                    # routines (please use .o as extension
*                                      # and use spaces to separate files)
#*********************************************************************
*
```

NLO exercise
Solution

Part 3

- Generate a NL
  - Shower it wi
    the shower_
    - cd my_tt
    - ./bin/aM
    - > launch
    - > fixed_
    - > shower
  - Edit run_
  - Edit show

in

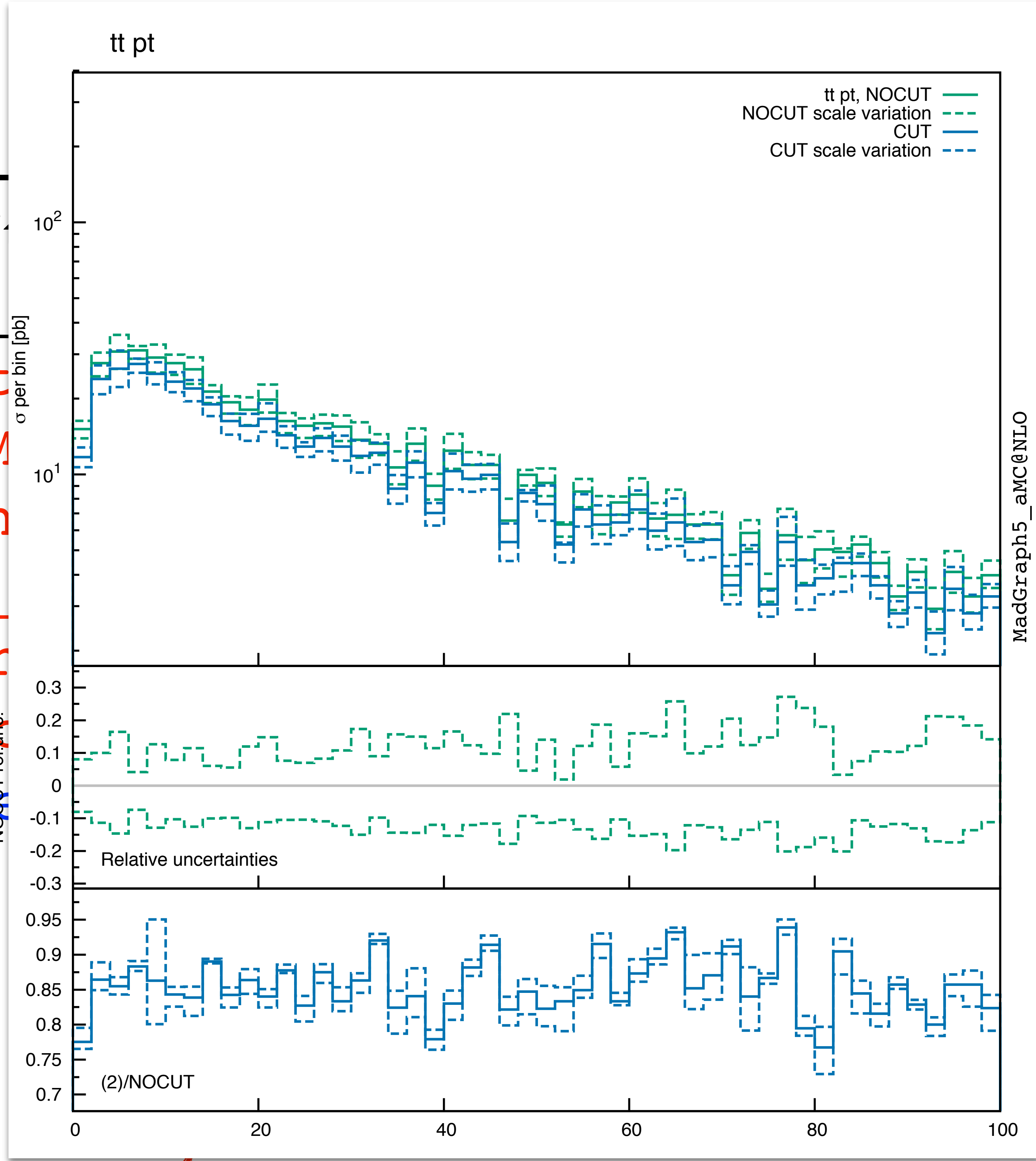
ts evol.

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>
    . . .
```

- 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_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 3

- Use MadSpin to gen[illegible] e
  - `./bin/aMCatNL[illegible]`
  - `> decay_event[illegible]`
  - edit the `madspin[illegible]`

```
#************************************
#*                        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

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

with the first events

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_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 sampl
  - `./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)
```

NLO exercise
Solution

Part 3

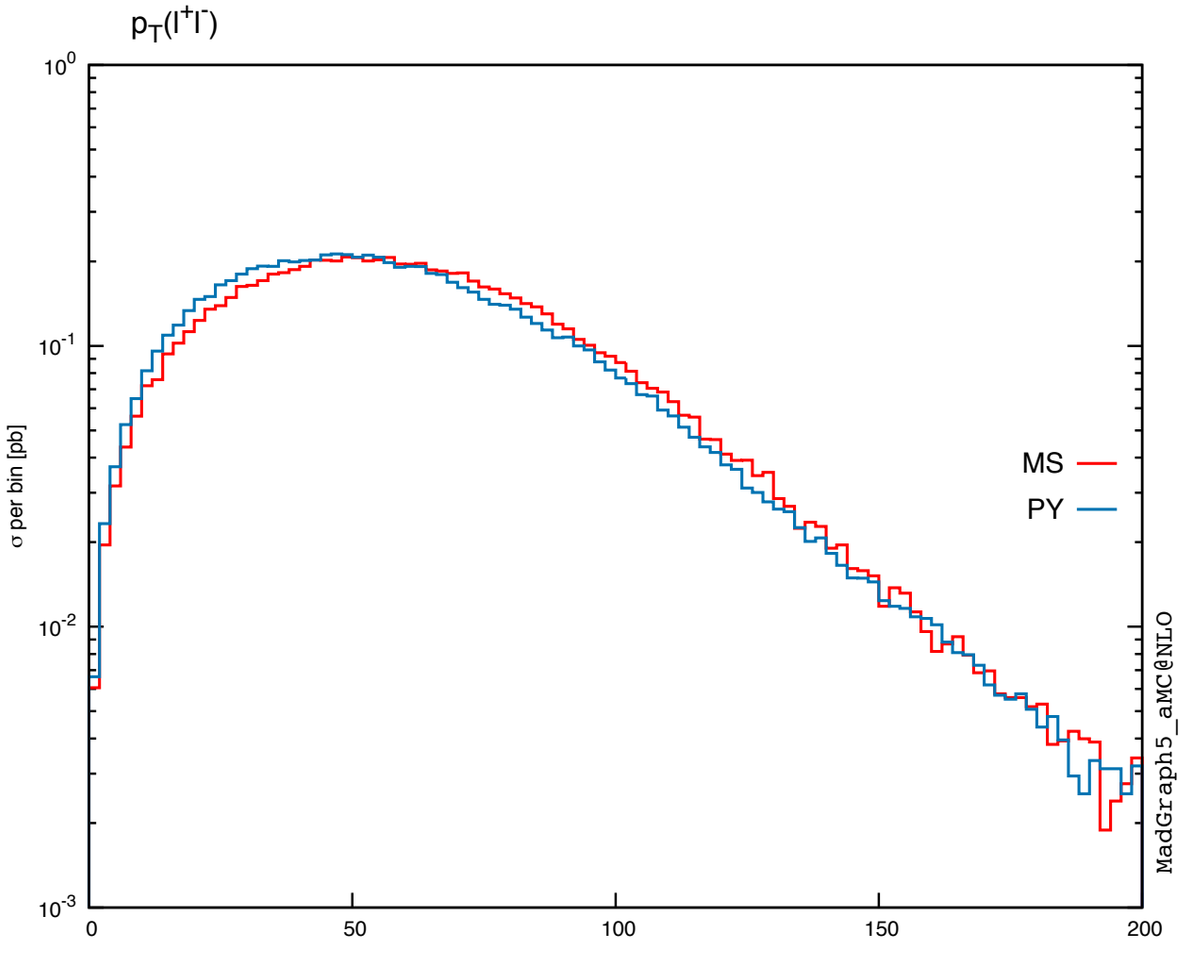
- Re-analyse the decayed and undecided sample with the `py6an_HwU_pp_lplm` analysis and check the the lepton pair p_T
  - Re-shower the un-decayed sample
  - `./bin/`
  - edit the
  - Shower
  - `./bin/`

```
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
```

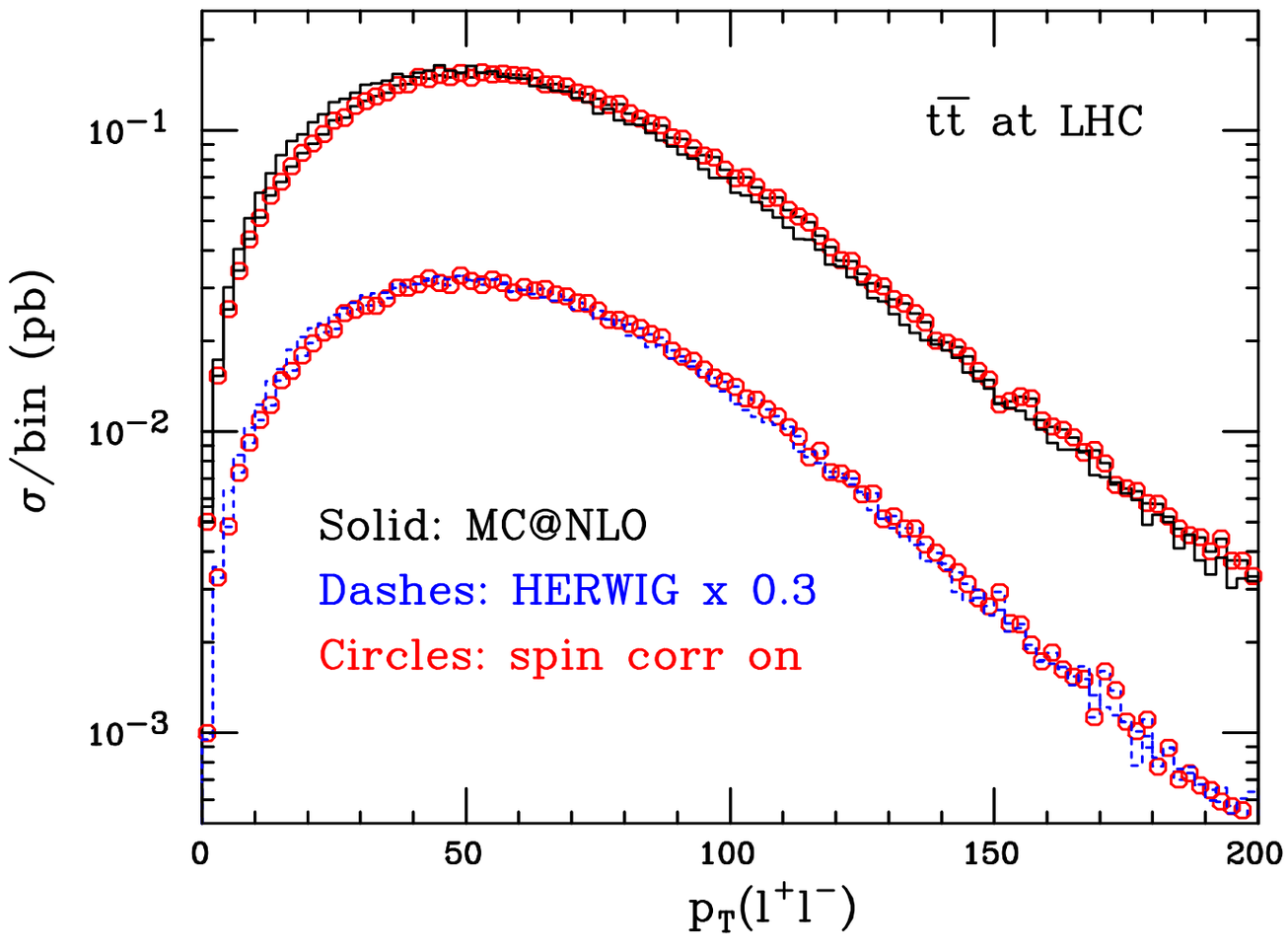
NLO exercise
Solution

Part 3

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

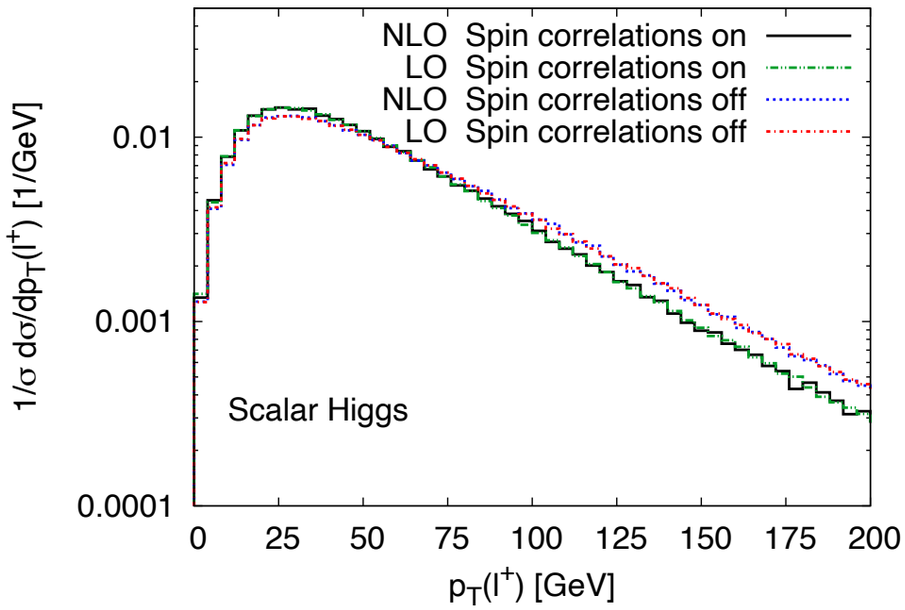


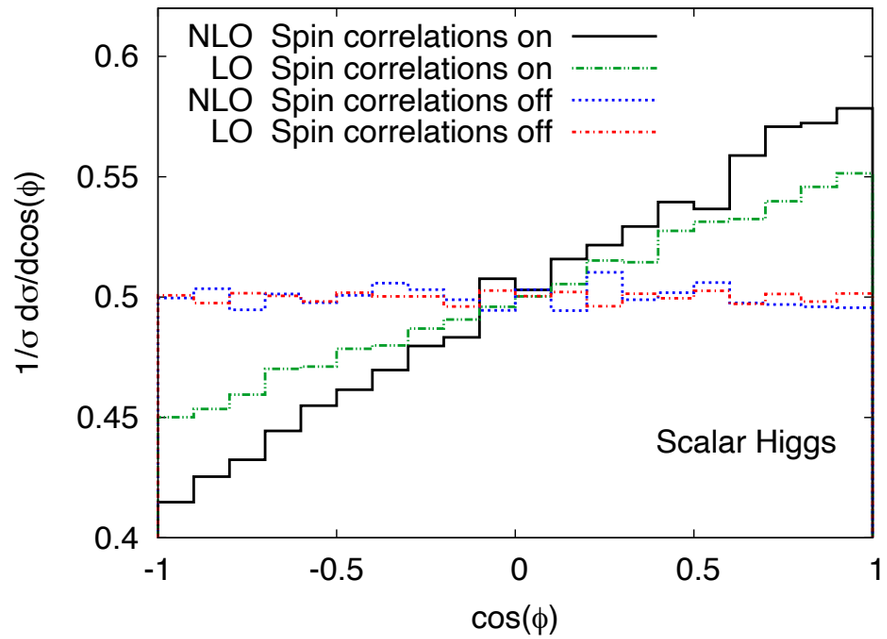
Plot from Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198

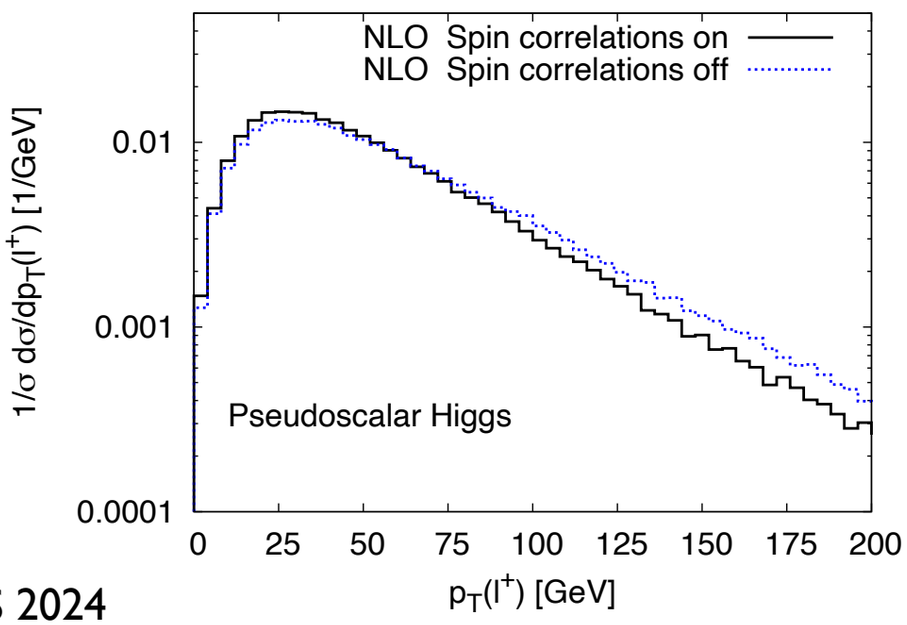


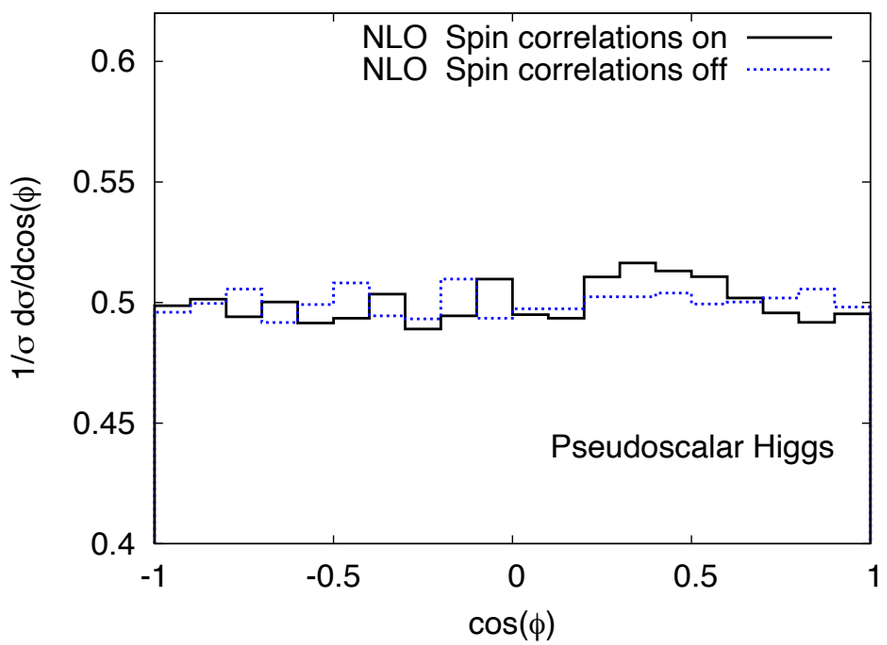
Spin correlations in ttH

- In ttH, spin correlations are crucial to distinguish a scalar vs pseudo scalar Higgs boson!









Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460