NNLO calculations with MATRIX

Massimiliano Grazzini

University of Zurich

Universität Zürich[UZH]

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higgstools

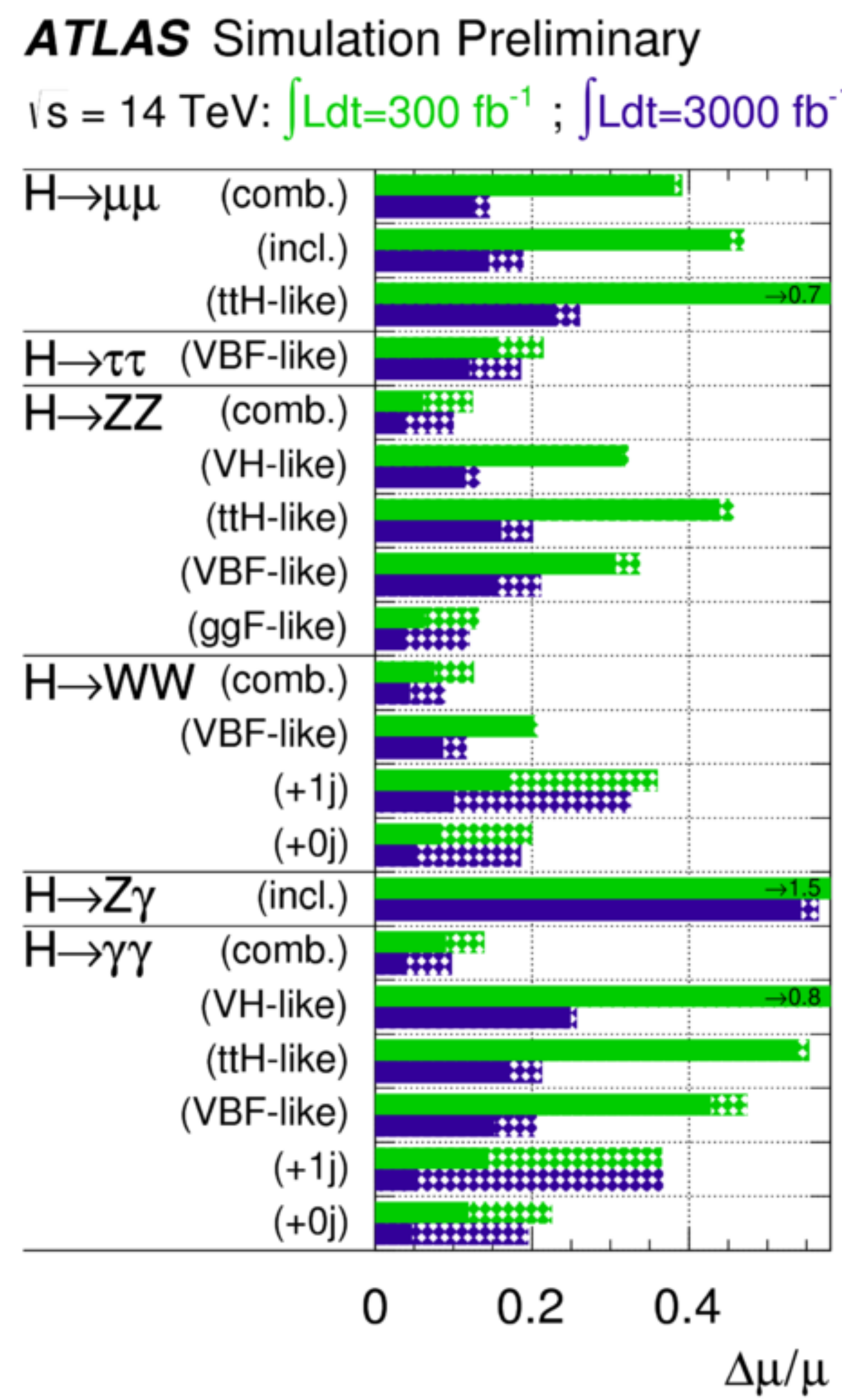
Outline

- Introduction
- q_T subtraction
- The MATRIX project
- Status of the code and usage
- Most recent results: $pp \to WZ + X$ at NNLO
- Beyond colour singlet: ttbar production
- Summary & Outlook

Introduction

The need for precise predictions to a variety of SM benchmark processes has been widely emphasised in the high-energy physics community.

Example: estimated uncertainty on the total signal strength μ for all Higgs final states in the different experimental categories used in the combination, assuming a SM Higgs boson with a mass of 125 GeV



Hashed areas show the impact of theory uncertainties

higher precision → NNLO

NNLO Les Houches 2013 wishlist includes processes with Higgs, vector bosons, heavy quarks and jets

NNLO methods

Broadly speaking there are two approaches that we can follow:

- Organise the calculation from scratch so as to cancel all the singularities
  - sector decomposition — T. Binoth, G.Heinrich (2000,2004); C.Anastasiou, K.Melnikov, F.Petriello (2004)
  - antenna subtraction — A. & T. Gehrmann, N. Glover (2005)
  - "colourful" subtraction — G, Somogyi, Z. Trocsanyi, V. Del Duca (2005, 2007)
  - join subtraction and sector decomposition — M.Czakon (2010,2011); R.Boughezal, K.Melnikov, F.Petriello (2011); F.Caola, K.Melnikov, R.Rontsch (2017)
- Start from an inclusive NNLO calculation (sometimes obtained through resummation) and combine it with an NLO calculation for n+1 parton process
  - q_T subtraction — S.Catani, MG (2007)
  - "N-jettiness" method — R.Boughezal, C.Focke,X.Liu, F.Petriello (2015); F.Tackmann et al. (2015)
  - recently introduced "Born projection" method for VBF — M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)

...and then we need the relevant two-loop amplitudes !

C.Anastasiou, F.Caola, M.Czakon, T.Gehrmann, N.Glover, M.Jaquier, A. Koukoutsakis
C.Oleari, K.Melnikov, L.Tancredi, M.E. Tejeda-Yeomans, A. von Manteuffel and many others

The q_T subtraction method

S. Catani, MG (2007)

The q_T subtraction method allows us to write the cross section to produce an arbitrary system F of non coloured particles in hadronic collisions as

$$d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\mathrm{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

process dependent hard-collinear function

NLO F+jets cross section computed with dipole subtraction

universal counterterm

The hard-collinear function $\mathcal{H}^F$ has been explicitly computed up to NNLO for vector and Higgs boson production

S. Catani, MG (2010)
S. Catani, L.Cieri, D. de Florian, G.Ferrera, MG (2013)

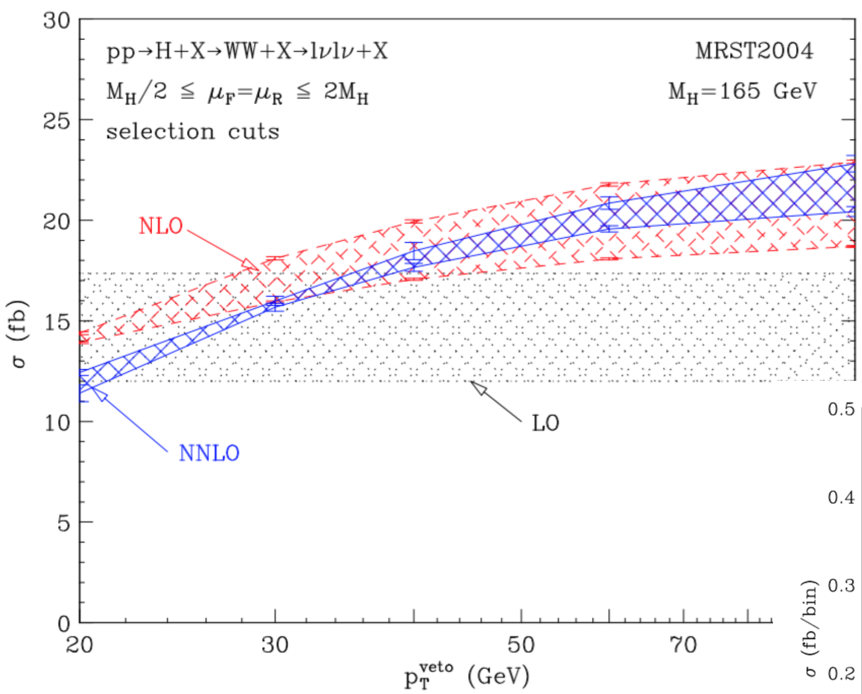
Its general form in terms of the relevant virtual amplitudes for an arbitrary colour singlet F has been provided up to NNLO

S. Catani, L.Cieri, D. de Florian, G.Ferrera, MG (2013)
T. Gehrmann, T.Lubbert,L.Yang (2014)

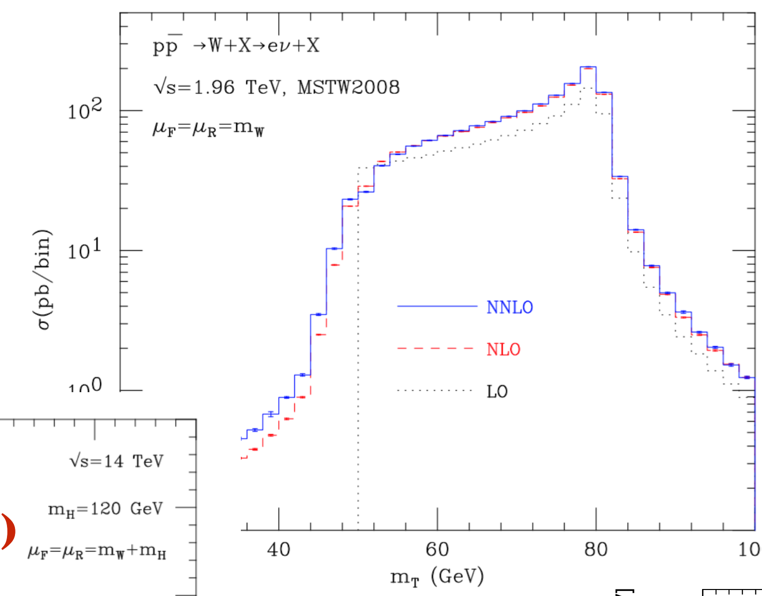
→ the method can be applied to the production of arbitrary colour singlets once the relevant amplitudes are available

Available implementations

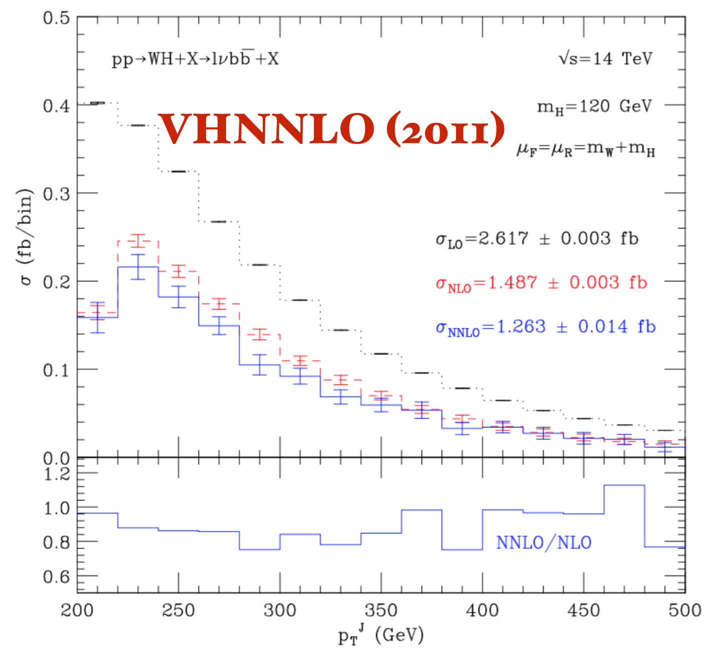
HNNLO (2008)



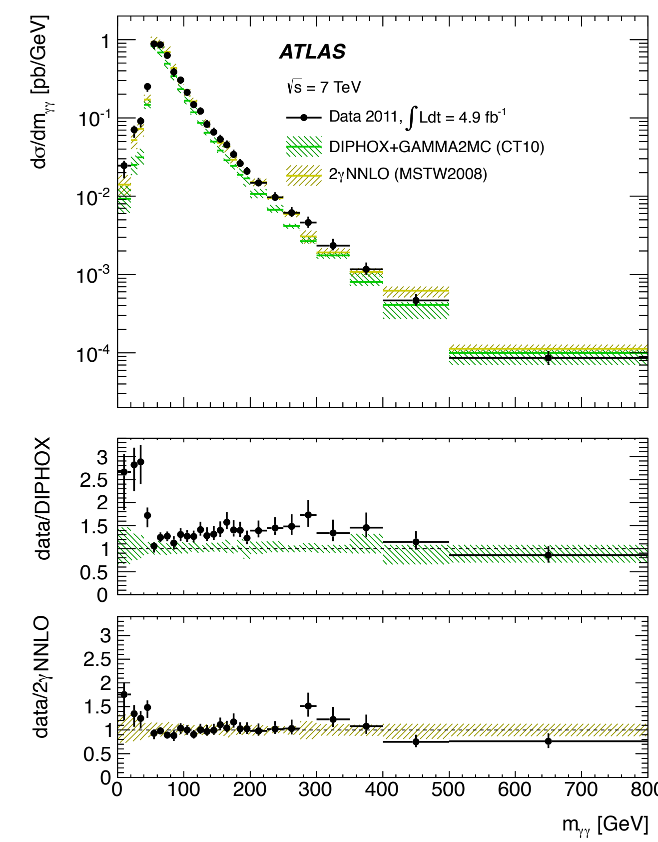
DYNNLO (2009)



VHNNLO (2011)



2γNNLO (2011)

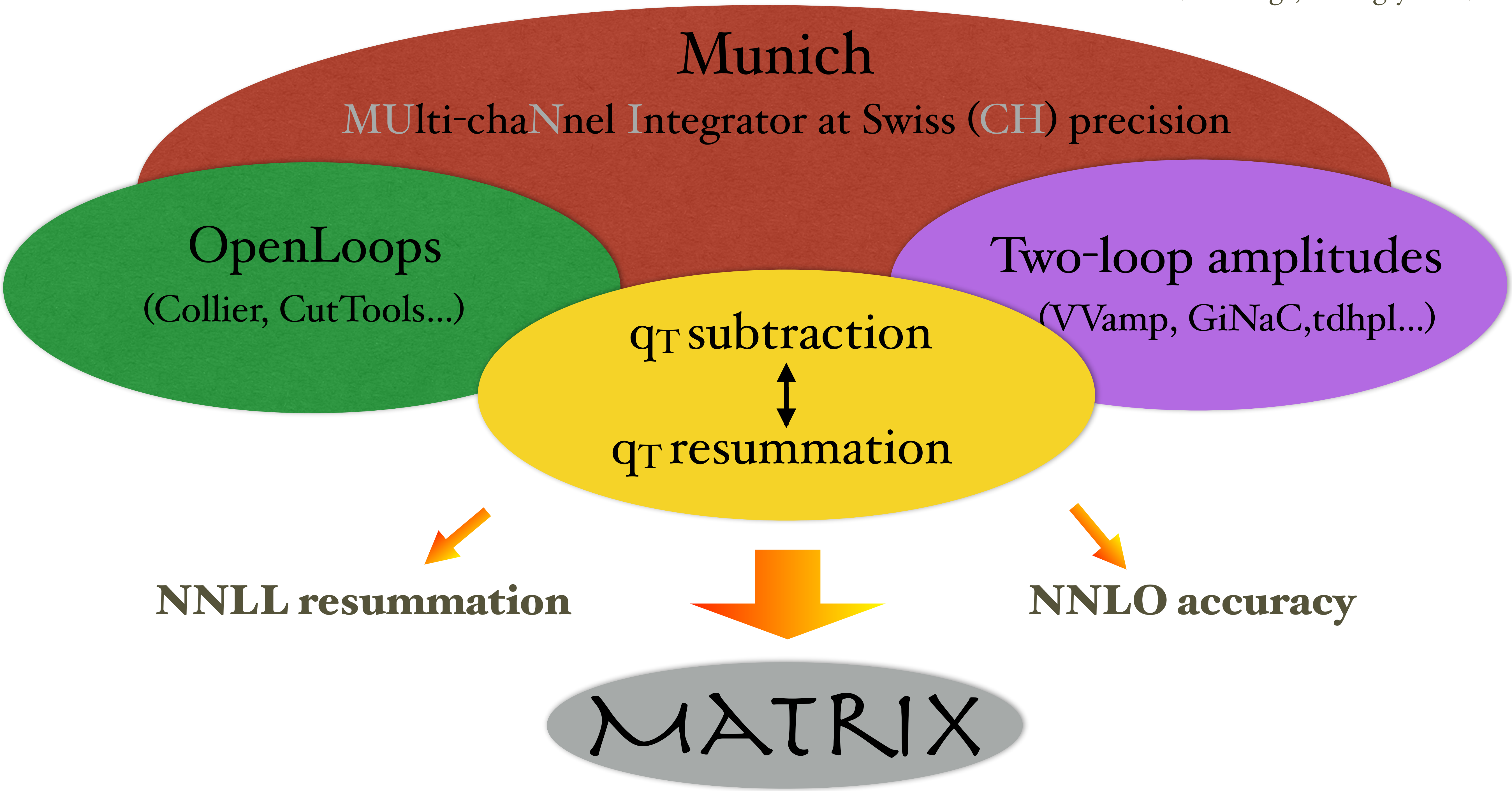


Up to now building up NNLO codes has been a craftsman work !

Generality of the method suggests that a single implementation in a general purpose program could be more efficient

The MATRIX project

S. Kallweit, D. Rathlev, M.Wiesemann, MG
(+C.Hanga, H.Sargsyan…..)



Munich Automates qT subtraction and Resummation to Integrate X--sections

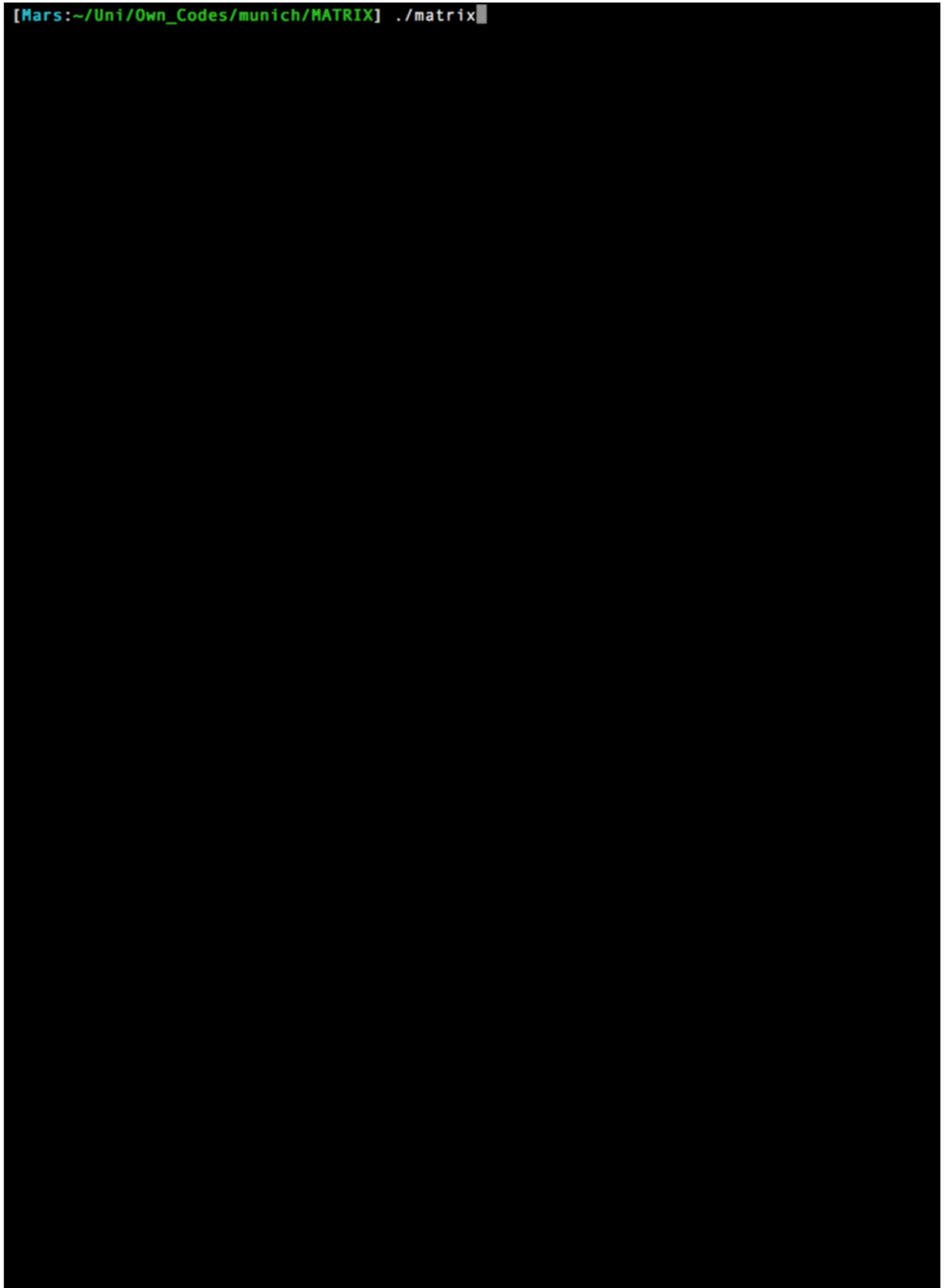
Status

- $pp \to Z/\gamma^* \ (\to l^+l^-)$ ✅ validated with DYNNLO 1.5 and analytically
- $pp \to W(\to l\nu)$ (✅) validation underway
- $pp \to H$ ✅ validated analytically
- $pp \to \gamma\gamma$ ✅ validated with 2γNNLO (version nov. 2015)
- $pp \to W\gamma \to l\nu\gamma$ ✅
- $pp \to Z\gamma \to l^+l^-\gamma$ ✅
- $pp \to ZZ(\to 4l)$ ✅
- $pp \to WW \to (l\nu l'\nu')$ ✅
- $pp \to ZZ/WW \to ll\nu\nu$ ✅ NEW
- $pp \to WZ \to l\nu ll$ ✅
- $pp \to HH$ (✅) not in first public release

MATRIX compilation

- After unpacking MATRIX start the code with

```
$$  ./matrix
```



MATRIX compilation

- After unpacking MATRIX start the code with

$$ ./matrix

- You are now to the MATRIX compilation shell. Type

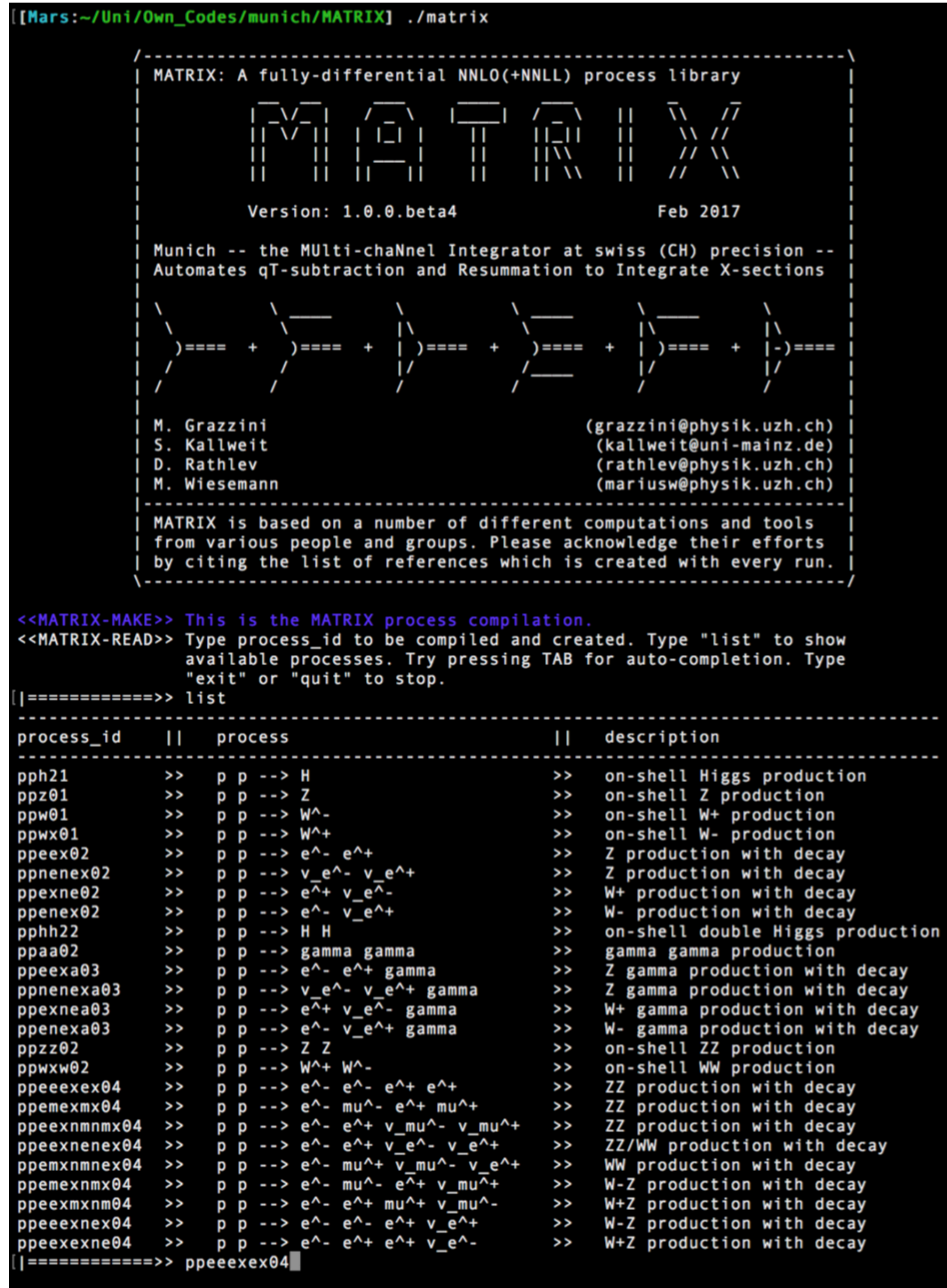
|===>> list

to list the available processes

- Select a process typing its ID, e.g.:

|===>> ppeeexex04

for pp→ZZ→4l



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for pp→ZZ→4l

- This will download Openloops, Cln, Ginac start the compilation process and finally create the MATRIX process folder

```
pph21          >>   p p --> H                      >>   on-shell Higgs production
ppz01          >>   p p --> Z                      >>   on-shell Z production
ppw01          >>   p p --> W^-                    >>   on-shell W+ production
ppwx01         >>   p p --> W^+                    >>   on-shell W- production
ppeex02        >>   p p --> e^- e^+                >>   Z production with decay
ppnenex02      >>   p p --> v_e^- v_e^+            >>   Z production with decay
ppexne02       >>   p p --> e^+ v_e^-              >>   W+ production with decay
ppenex02       >>   p p --> e^- v_e^+              >>   W- production with decay
pphh22         >>   p p --> H H                    >>   on-shell double Higgs production
ppaa02         >>   p p --> gamma gamma            >>   gamma gamma production
ppeexa03       >>   p p --> e^- e^+ gamma          >>   Z gamma production with decay
ppnenexa03     >>   p p --> v_e^- v_e^+ gamma      >>   Z gamma production with decay
ppexnea03      >>   p p --> e^+ v_e^- gamma        >>   W+ gamma production with decay
ppenexa03      >>   p p --> e^- v_e^+ gamma        >>   W- gamma production with decay
ppzz02         >>   p p --> Z Z                    >>   on-shell ZZ production
ppwxw02        >>   p p --> W^+ W^-                >>   on-shell WW production
ppeeexex04     >>   p p --> e^- e^- e^+ e^+        >>   ZZ production with decay
ppemexmx04     >>   p p --> e^- mu^- e^+ mu^+      >>   ZZ production with decay
ppeexnmnmx04   >>   p p --> e^- e^+ v_mu^- v_mu^+  >>   ZZ production with decay
ppeexnenex04   >>   p p --> e^- e^+ v_e^- v_e^+    >>   ZZ/WW production with decay
ppemxnmnex04   >>   p p --> e^- mu^+ v_mu^- v_e^+  >>   WW production with decay
ppemexnmx04    >>   p p --> e^- mu^- e^+ v_mu^+    >>   W-Z production with decay
ppeexmxnm04    >>   p p --> e^- e^+ mu^+ v_mu^-    >>   W+Z production with decay
ppeeexnex04    >>   p p --> e^- e^- e^+ v_e^+      >>   W-Z production with decay
ppeexexne04    >>   p p --> e^- e^+ e^+ v_e^-      >>   W+Z production with decay
|============>> ppeeexex04
<<MATRIX-MAKE>> Starting compilation...
<<MATRIX-MAKE>> Using compiled LHAPDF installation under
                (config/MATRIX_configuration) path_to_lhapdf=/usr/local/bin
                /lhapdf-config
<<MATRIX-MAKE>> Download and Compilation of OpenLoops via svn checkout from
                http://openloops.hepforge.org/svn/OpenLoops/branches/public into
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-external/OpenLoops-
                install...
<<MATRIX-MAKE>> Downloading OpenLoops...
<<MATRIX-MAKE>> Compiling OpenLoops...
<<MATRIX-MAKE>> MoRe already compiled. Remove folder
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-MoRe/MoRe-v1.0.0 if
                you want to re-compile...
<<MATRIX-MAKE>> Extracting and Compiling Cln from
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-
                external/cln-1.3.4.tar into
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-external/cln-
                install...
<<MATRIX-MAKE>> Extracting and Compiling Ginac from
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-
                external/ginac-1.6.2.tar into
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-external/ginac-
                install...
<<MATRIX-MAKE>> Compiling process <ppeeexex04>, this may take a while...
                (see make.log file to monitor the progress)
<<MATRIX-MAKE>> Downloading and compiling pplllll amplitude with OpenLoops...
<<MATRIX-MAKE>> Downloading and compiling pplllj amplitude with OpenLoops...
<<MATRIX-MAKE>> Downloading and compiling pplll2 amplitude with OpenLoops...
<<MATRIX-INFO>> Running on Mac. Trying to make relative paths of linked
                OpenLoops dylibs absolute. Please consider using
export DYLD_LIBRARY_PATH=DYLD_LIBRARY_PATH:/Users/Mars/Uni/Own_Codes/munich/MATRIX/src-ext
<<MATRIX-INFO>> in your terminal and possibly adding it to your
                .bashrc/.bash_profile, in case you still experience linking
                errors when running the code.
<<MATRIX-MAKE>> Creating process folder in "run"-directory: "/Users/Mars/Uni/Own
                _Codes/munich/MATRIX/run/ppeeexex04_MATRIX"...
<<MATRIX-INFO>> Process folder successfully created.
<<MATRIX-INFO>> Process generation finished, to go to the run directory type:
                cd /Users/Mars/Uni/Own_Codes/munich/MATRIX/run/ppeeexex04_MATRIX
<<MATRIX-INFO>> and start run by typing:
                ./bin/run_process
```

MATRIX use

- We now move to the run directory and start the run script with

$$ ./bin/run_process

- First choose the name of the run

|===>> run_my_first_ZZ

- Adjust the input cards

|===>> parameter
|===>> model
|===>> distribution

- Then start the run

- With default input cards the code runs LO with 1% accuracy

```
[wiesemann:~/munich-http/MATRIX/run/ppeeexex04_MATRIX] ./bin/run_process

 MATRIX: A fully-differential NNLO(+NNLL) process library

 Version: 1.0.0.beta4                    Feb 2017

 Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
 Automates qT-subtraction and Resummation to Integrate X-sections

 M. Grazzini                          (grazzini@physik.uzh.ch)
 S. Kallweit                          (kallweit@uni-mainz.de)
 D. Rathlev                           (rathlev@physik.uzh.ch)
 M. Wiesemann                         (mariusw@physik.uzh.ch)

 MATRIX is based on a number of different computations and tools
 from various people and groups. Please acknowledge their efforts
 by citing the list of references which is created with every run.

<<MATRIX-READ>> Type name of folder for this run (has to start with "run_").
                "ENTER" to create and use "run_01". Press TAB or type "list" to
                show existing runs. Type "exit" or "quit" to stop. Any other
                folder will be created.
|============>> run_my_first_ZZ
<<MATRIX-READ>> Type one of the following commands: ("TAB" for auto-completion)
-----------------------------------------------------------------------------
General commands     ||  description
-----------------------------------------------------------------------------
help                 >>  Show help menu.
help <command>       >>  Show help message for specific <command>.
list                 >>  List available commands again.
exit                 >>  Stop the code.
quit                 >>  Stop the code.
-----------------------------------------------------------------------------
Input to modify      ||  description
-----------------------------------------------------------------------------
parameter            >>  Modify "parameter.dat" input file in editor.
model                >>  Modify "model.dat" input file in editor.
distribution         >>  Modify "distribution.dat" input file in editor.
-----------------------------------------------------------------------------
Run-mode to start    ||  description
-----------------------------------------------------------------------------
run                  >>  Start cross section computation in standard mode.
run_grid             >>  Start only grid setup phase.
run_pre              >>  Start only extrapolation (grid must be already done).
run_pre_and_main     >>  Start after grid setup (grid must be already done).
run_main             >>  Start only main run (other runs must be already done).
run_results          >>  Start only result combination.
run_gnuplot          >>  Start only gnuplotting the results.
setup_run            >>  Setup the run folder, but not start running.
delete_run           >>  Remove run folder (including input/log/result).
tar_run              >>  Create <run_folder>.tar (including input/log/result).
|============>> parameter
|============>> model
|============>> distribution
|============>> run
```

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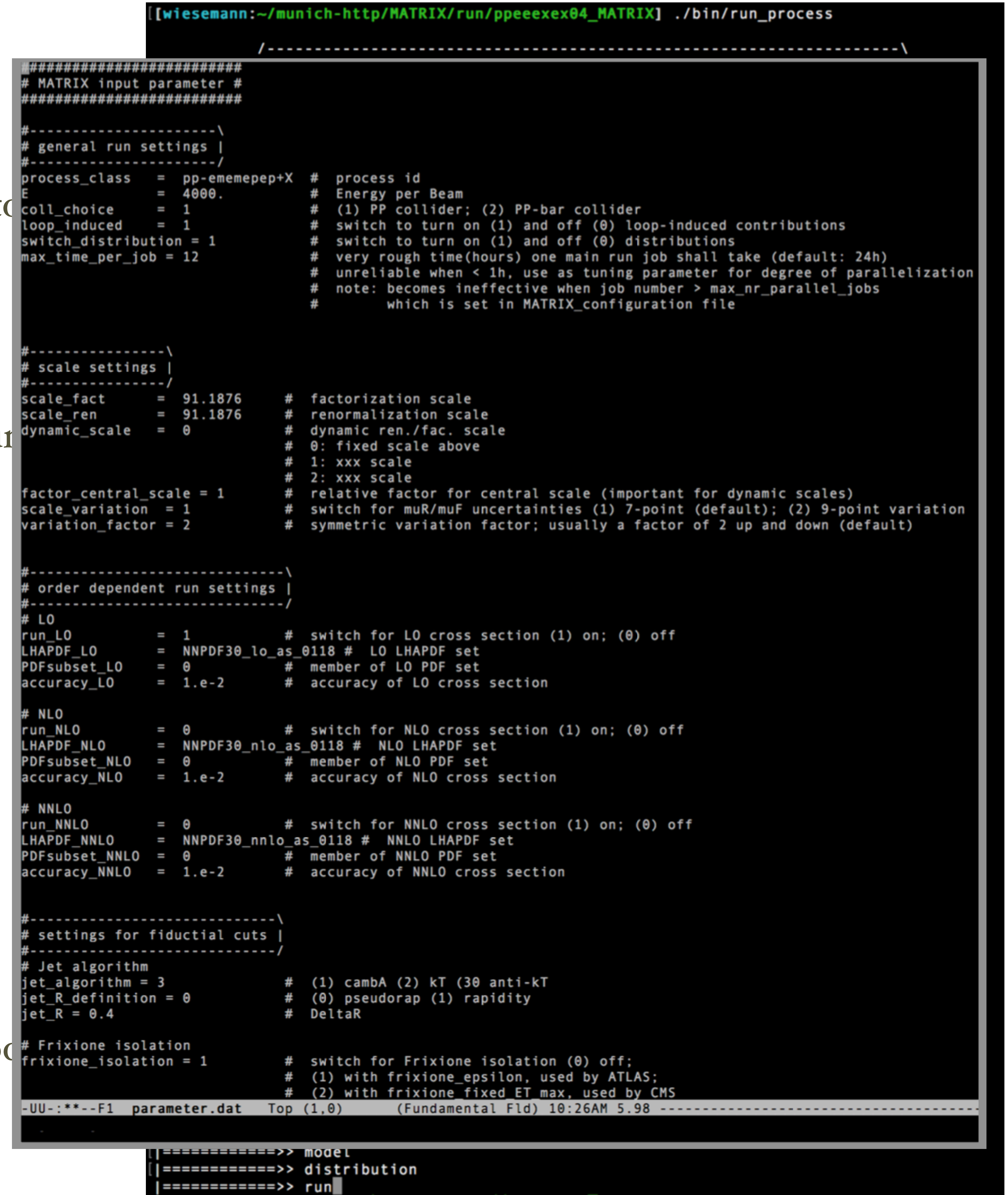

```
[wiesemann:~/munich-http/MATRIX/run/ppeeexex04_MATRIX] ./bin/run_process
/--------------------------------------------------------------------\
##########################
# MATRIX input parameter #
##########################

#----------------------\
# general run settings |
#----------------------/
process_class    =  pp-emmepep+X  #  process id
E                =  4000.         #  Energy per Beam
coll_choice      =  1             #  (1) PP collider; (2) PP-bar collider
loop_induced     =  1             #  switch to turn on (1) and off (0) loop-induced contributions
switch_distribution = 1           #  switch to turn on (1) and off (0) distributions
max_time_per_job = 12             #  very rough time(hours) one main run job shall take (default: 24h)
                                  #  unreliable when < 1h, use as tuning parameter for degree of parallelization
                                  #  note: becomes ineffective when job number > max_nr_parallel_jobs
                                  #        which is set in MATRIX_configuration file

#----------------\
# scale settings |
#----------------/
scale_fact       =  91.1876     #  factorization scale
scale_ren        =  91.1876     #  renormalization scale
dynamic_scale    =  0           #  dynamic ren./fac. scale
                                #  0: fixed scale above
                                #  1: xxx scale
                                #  2: xxx scale
factor_central_scale = 1        #  relative factor for central scale (important for dynamic scales)
scale_variation  = 1            #  switch for muR/muF uncertainties (1) 7-point (default); (2) 9-point variation
variation_factor = 2            #  symmetric variation factor; usually a factor of 2 up and down (default)

#-----------------------------\
# order dependent run settings |
#-----------------------------/
# LO
run_LO           =  1           #  switch for LO cross section (1) on; (0) off
LHAPDF_LO        =  NNPDF30_lo_as_0118 #  LO LHAPDF set
PDFsubset_LO     =  0           #  member of LO PDF set
accuracy_LO      =  1.e-2       #  accuracy of LO cross section

# NLO
run_NLO          =  0           #  switch for NLO cross section (1) on; (0) off
LHAPDF_NLO       =  NNPDF30_nlo_as_0118 #  NLO LHAPDF set
PDFsubset_NLO    =  0           #  member of NLO PDF set
accuracy_NLO     =  1.e-2       #  accuracy of NLO cross section

# NNLO
run_NNLO         =  0           #  switch for NNLO cross section (1) on; (0) off
LHAPDF_NNLO      =  NNPDF30_nnlo_as_0118 #  NNLO LHAPDF set
PDFsubset_NNLO   =  0           #  member of NNLO PDF set
accuracy_NNLO    =  1.e-2       #  accuracy of NNLO cross section

#----------------------------\
# settings for fiducial cuts |
#----------------------------/
# Jet algorithm
jet_algorithm = 3               #  (1) cambA (2) kT (30 anti-kT
jet_R_definition = 0            #  (0) pseudorap (1) rapidity
jet_R = 0.4                     #  DeltaR

# Frixione isolation
frixione_isolation = 1          #  switch for Frixione isolation (0) off;
                                #  (1) with frixione_epsilon, used by ATLAS;
                                #  (2) with frixione_fixed_ET_max, used by CMS
-UU-:**--F1  parameter.dat   Top (1,0)     (Fundamental Fld) 10:26AM 5.98 ------------------------
|============>> model
|============>> distribution
|============>> run
```

MATRIX use

- We now move to the run directory and start the run script with

$$ ./bin/run_process

- First choose the name of the run

|===>> run_my_first_ZZ

- Adjust the input cards

|===>> parameter
|===>> model
|===>> distribution

- Then start the run

- With default input cards the code runs LO with 1% accuracy

- Automatic evaluation of 7-point or 9-point scale variations

```
|============>> run
<<MATRIX-INFO>> New Run folder created: /home/wiesemann/munich-
                http/MATRIX/run/ppeeexex04_MATRIX/run_my_first_ZZ.
<<MATRIX-INFO>> Using LHAPDF version 5.9.1...
<<MATRIX-INFO>> Now it's time for running...
<<MATRIX-INFO>> Running in multicore mode...
<<MATRIX-INFO>> Starting grid setup (warmup)...
<<MATRIX-JOBS>> | 2017-03-04 09:52:10 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:52:15 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:54:50 | Queued: 0 | Running: 1 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-03-04 09:54:55 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-03-04 09:54:55 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> Starting runs to extrapolate runtimes from accuracy (pre run)...
<<MATRIX-JOBS>> | 2017-03-04 09:54:55 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:00 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:15 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:15 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Extrapolating runtimes...
<<MATRIX-JOBS>> | 2017-03-04 09:55:15 | Queued: 1 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:20 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:20 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:20 | Queued: 0 | Running: 0 | Finished: 1 |

          /---------------------------------------------------\
          |       Preliminary (inaccurate) result for:         |
          |      p p --> e^- e^- e^+ e^+    @ 8 TeV LHC        |
          \---------------------------------------------------/
                #--------\
                # LO-run |
                #--------/
<MATRIX-RESULT> PDF: NNPDF30_lo_as_0118
<MATRIX-RESULT> Total rate (possibly within cuts):
<MATRIX-RESULT> LO:      3.558 fb +/- 0.018 fb    (muR, muF unc.:  +2.9%  -3.9%)
<MATRIX-RESULT> This result is very inaccurate and only a rough estimate!
<MATRIX-RESULT> Wait until the main run finishes to get the final result!

<<MATRIX-INFO>> Starting cross section computation (main run)...
<<MATRIX-JOBS>> | 2017-03-04 09:55:20 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:25 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:40 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:40 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Collecting and combining results...
<<MATRIX-JOBS>> | 2017-03-04 09:55:40 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> Plotting results with gnuplot...
<<MATRIX-INFO>> Trying to plot: pT_lep1_lep2__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_ep1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_lep1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: m_lep1_lep2__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: dR_em1_ep1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_lep2__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_em1__LO
```

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<<MATRIX-INFO>> Collecting and combining results...
<<MATRIX-JOBS>> | 2017-03-04 09:55:40 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-03-04 09:55:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> Plotting results with gnuplot...
<<MATRIX-INFO>> Trying to plot: pT_lep1_lep2__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_ep1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_lep1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: m_lep1_lep2__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: dR_em1_ep1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_lep2__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_em1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: n_jets__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.


                 /----------------------------------------------------\
                 |                  Final result for:                  |
                 |         p p --> e^- e^- e^+ e^+    @ 8 TeV LHC      |
                 \----------------------------------------------------/

<MATRIX-RESULT> 1 separate run was made

               #--------\
               # LO-run |
               #--------/
<MATRIX-RESULT> PDF: NNPDF30_lo_as_0118
<MATRIX-RESULT> Total rate (possibly within cuts):
<MATRIX-RESULT> LO:      3.554 fb +/- 0.013 fb   (muR, muF unc.:  +2.9%  -3.9%)

<MATRIX-RESULT> All results (including the distributions) can be found in:
<MATRIX-RESULT> /home/wiesemann/munich-http/MATRIX/run/ppeeexex04_MATRIX/result/run_my_fi
[wiesemann:~/munich-http/MATRIX/run/ppeeexex04_MATRIX]
```

Stability of the subtraction procedure

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\rm{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

The q_T subtraction counterterm is non-local → the difference in the square bracket is evaluated with a cut-off r_{cut} on the ratio $r = q_T/Q$

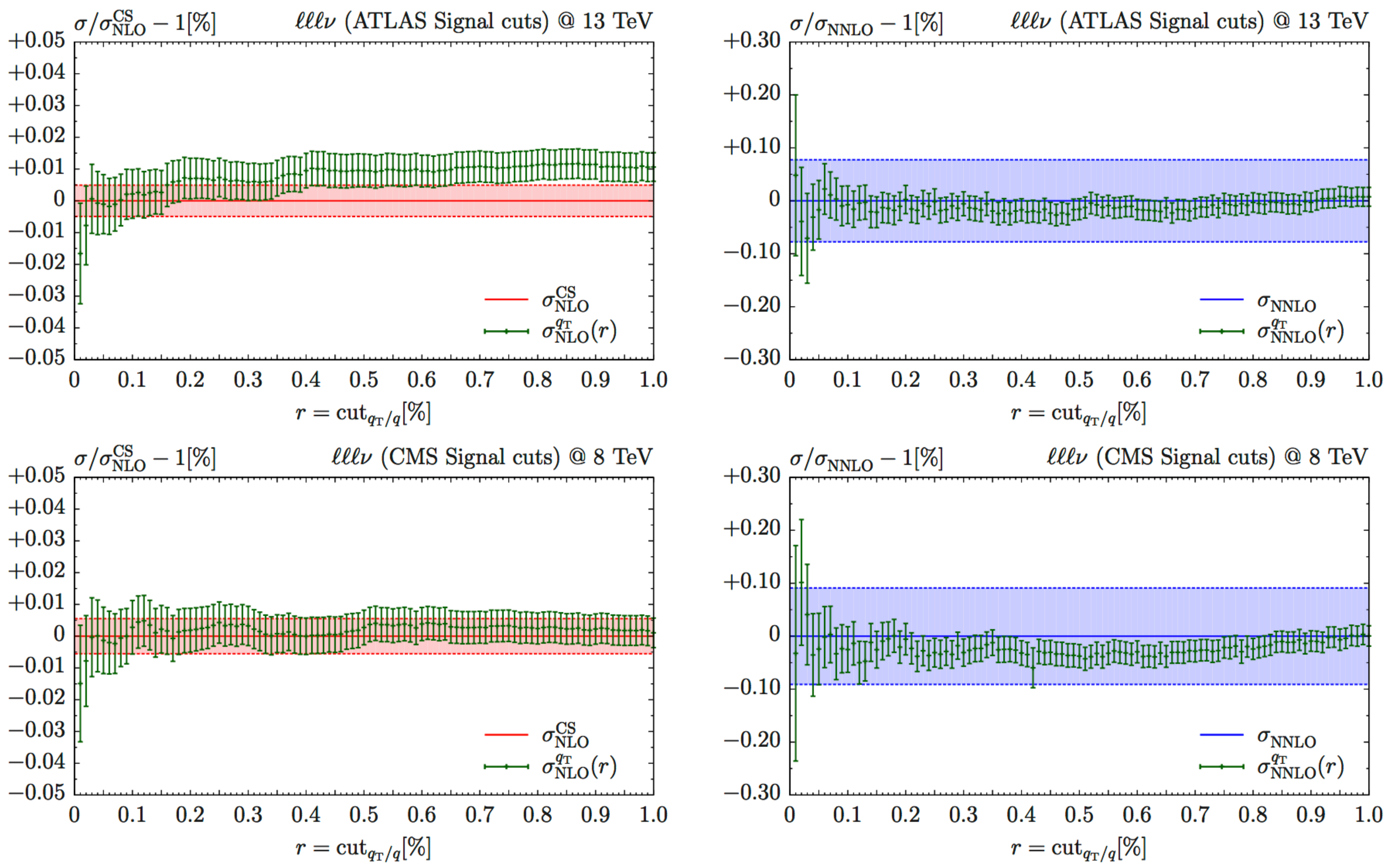
In our implementation q_T subtraction indeed works as a slicing method

It is important to monitor the dependence of our results on r_{cut}

MATRIX allows for a simultaneous evaluation of the NNLO cross section for different values of r_{cut}

The dependence on r_{cut} is used by the code to provide an estimate of the systematic uncertainty in any NNLO run

Stability of the subtraction procedure

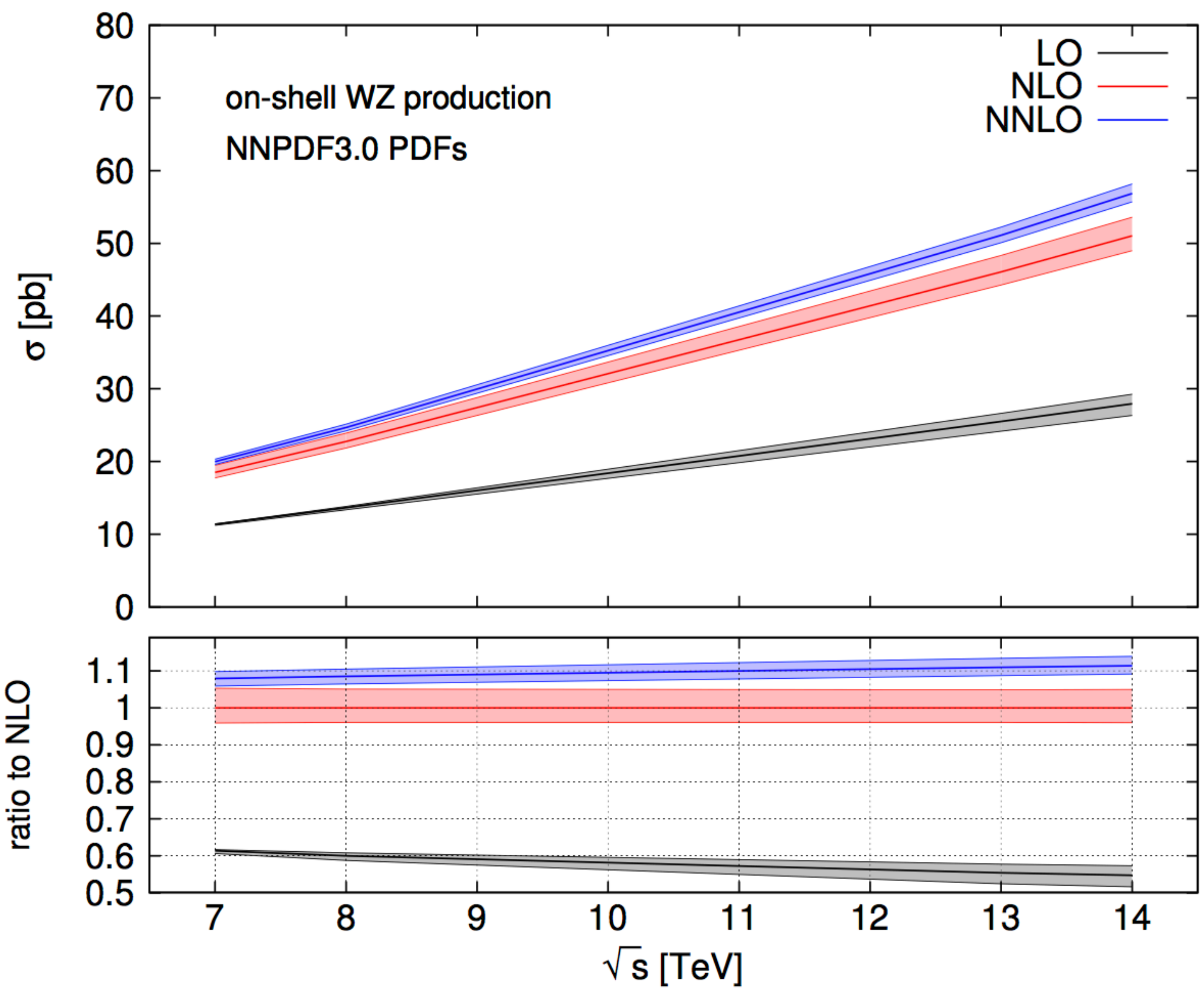


For all processes we consider (except those involving photons) the NNLO uncertainties are at the 0.1% level or smaller

Most recent results: WZ

WZ: inclusive cross section

S. Kallweit, D. Rathlev, M.Wiesemann, MG (2016)



Use NNPDF3.0 with $\mu_F = \mu_R = (m_W + m_Z)/2$ as central scale

On shell cross section: relative large QCD effects due to an approximate radiation zero at LO

. U. Baur, T. Han and J. Ohnemus (1994)

From 7 to 14 TeV:

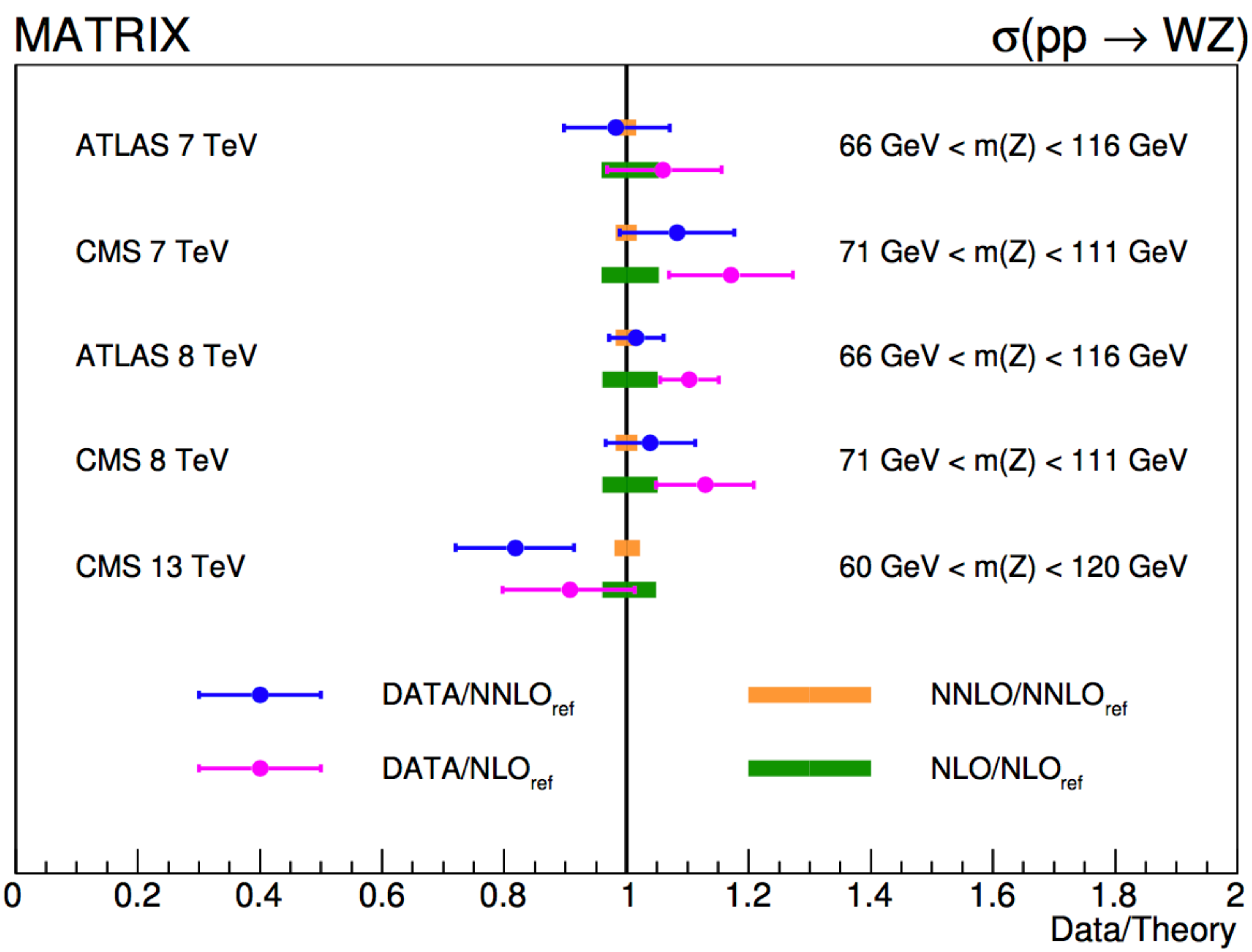
NLO effects range from 62 to 82%

NNLO effects range from 8 to 11%

Scale uncertainties reduced down to the 2% level

WZ: inclusive cross section

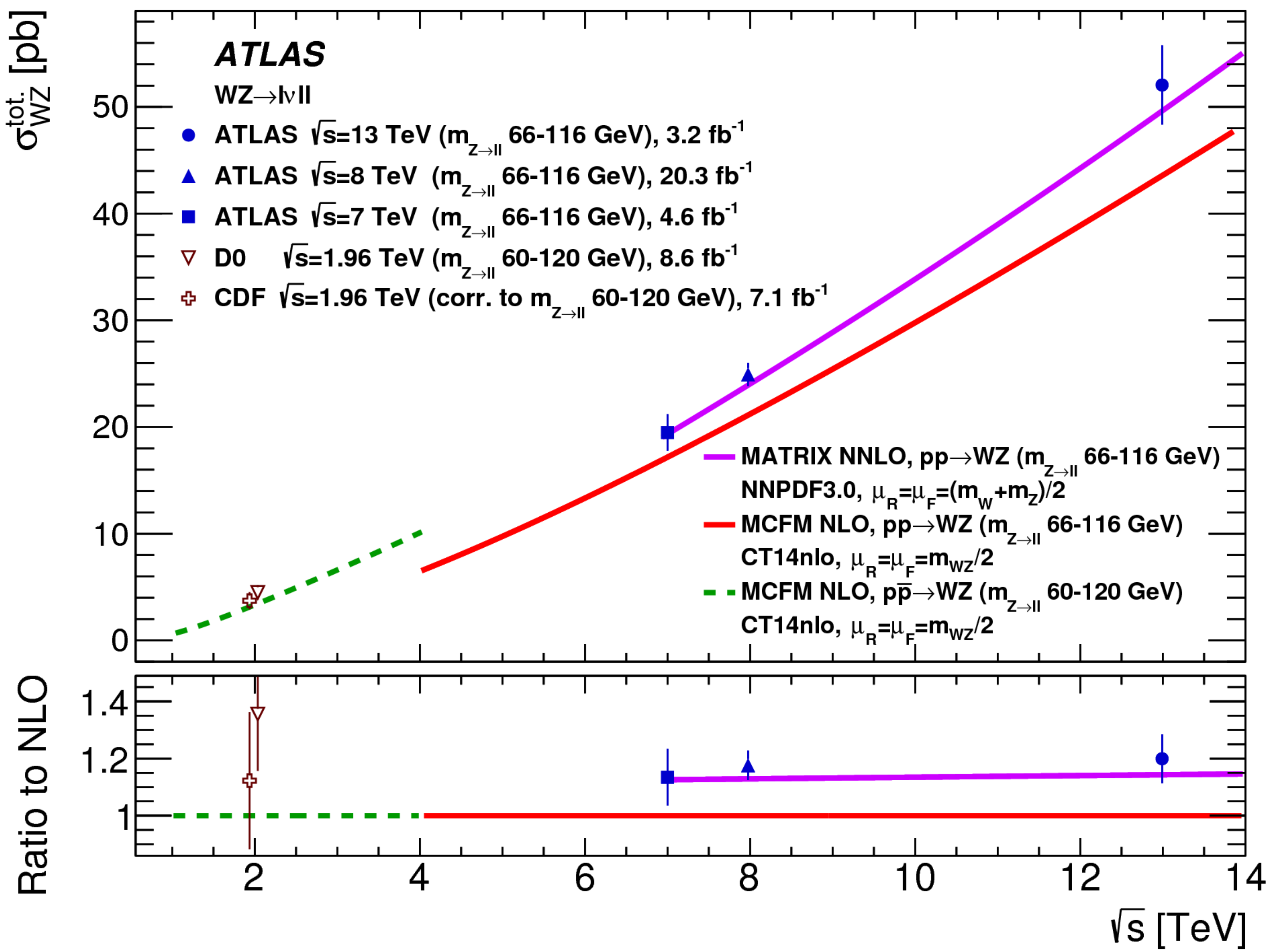
S. Kallweit, D. Rathlev, M.Wiesemann, MG (2016)



NNLO corrections nicely improve the agreement with the data (with the exception of CMS at 13 TeV where, however, the uncertainties are still large)

WZ: inclusive cross section

S. Kallweit, D. Rathlev, M.Wiesemann, MG (2016)



NNLO corrections nicely improve the agreement with the data (with the exception of CMS at 13 TeV where, however, the uncertainties are still large)

WZ: fully differential

S. Kallweit, D. Rathlev, M.Wiesemann, MG (2017)

Setup: NNPDF3.0

central scale choice: $\mu_F=\mu_R=1/2\,(m_Z+m_W)$

$pp \to l' \nu_{l'}\, l^+ l^-$

ATLAS fiducial region: requires identification of the leptons coming from the W and the Z boson (non trivial in the case of identical flavours)

Pair with highest P is assigned to the Z boson

$$P = \left| \frac{1}{m_{\ell\ell}^2 - m_Z^2 + i\,\Gamma_Z\, m_Z} \right|^2 \cdot \left| \frac{1}{m_{\ell'\nu_{\ell'}}^2 - m_W^2 + i\,\Gamma_W\, m_W} \right|^2$$

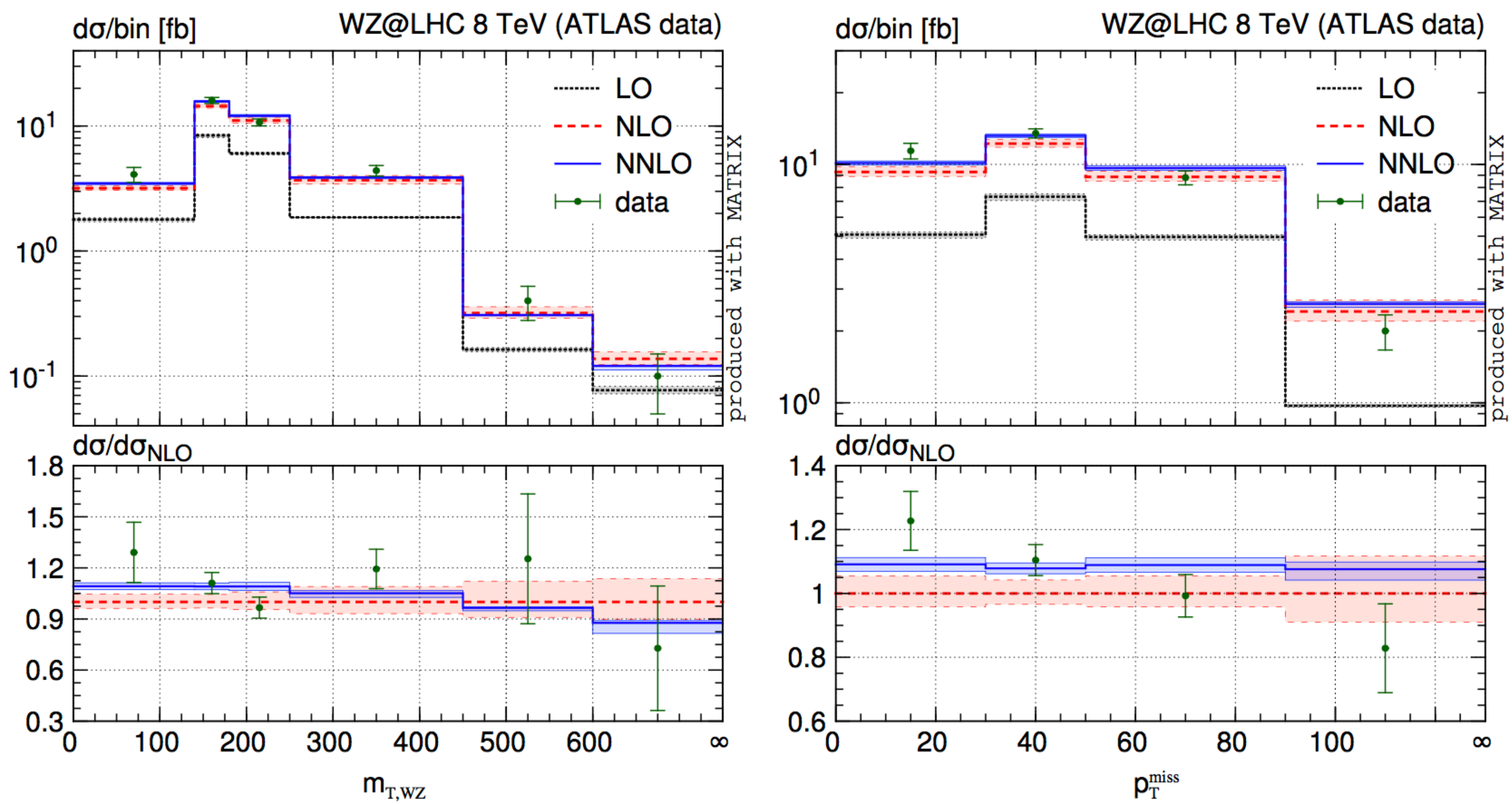
Fiducial cuts:

$p_{Tl} > 15$ GeV $\quad |\eta_l| < 2.5 \quad p_{Tl'} > 20$ GeV $\quad |\eta_{l'}| < 2.5$

$|m_{ll} - m_Z| < 10$ GeV $\quad m_{TW} > 30$ GeV $\quad \Delta R_{ll} > 0.2 \quad \Delta R_{ll'} > 0.3$

WZ: fully differential

S. Kallweit, D. Rathlev, M. Wiesemann, MG (2017)



- NNLO effects on the relevant distributions improve the agreement with ATLAS data mostly due to the improved normalisation
- Slightly different shape for $p_{T\mathrm{miss}}$ distribution which is driven by W^-Z

WZ: fully differential: NP searches

S. Kallweit, D. Rathlev, M.Wiesemann, MG (2017)

Three lepton+MET signature relevant for many NP searches

We follow the CMS analysis of CMS-PAS-SUS-16 024

Selection cuts:

definition of the selection cuts for $pp \to \ell'^{\pm}\nu_{\ell'}\ell^+\ell^- + X, \quad \ell,\ell' \in \{e,\mu\}$
$p_{T,\ell_1} > 25(20)\,\text{GeV if } \ell_1 = e(\mu), \quad p_{T,\ell_1} > 25\,\text{GeV if } \ell_1 = \mu \text{ and } \ell_{\geq 2} \neq \mu$
$p_{T,\ell_{\geq 2}} > 15(10)\,\text{GeV if } \ell_{\geq 2} = e(\mu), \quad \lvert\eta_e\rvert < 2.5, \quad \lvert\eta_\mu\rvert < 2.4,$
$\lvert m_{3\ell} - m_Z\rvert > 15\,\text{GeV}, \quad m_{\ell^+\ell^-} > 12\,\text{GeV}$

Four categories are considered:

Category I:	no additional cut
Category II:	$p_T^{\text{miss}} > 200\,\text{GeV}$
Category III:	$m_{T,W} > 120\,\text{GeV}$
Category IV:	$m_{ll} > 105\,\text{GeV}$

Dynamic scale more appropriate here

$$\mu_R = \mu_F = \mu_0 \equiv \frac{1}{2}\left(\sqrt{m_Z^2 + p_{T,\ell_z\ell_z}^2} + \sqrt{m_W^2 + p_{T,\ell_w\nu_{\ell_w}}^2}\right)$$

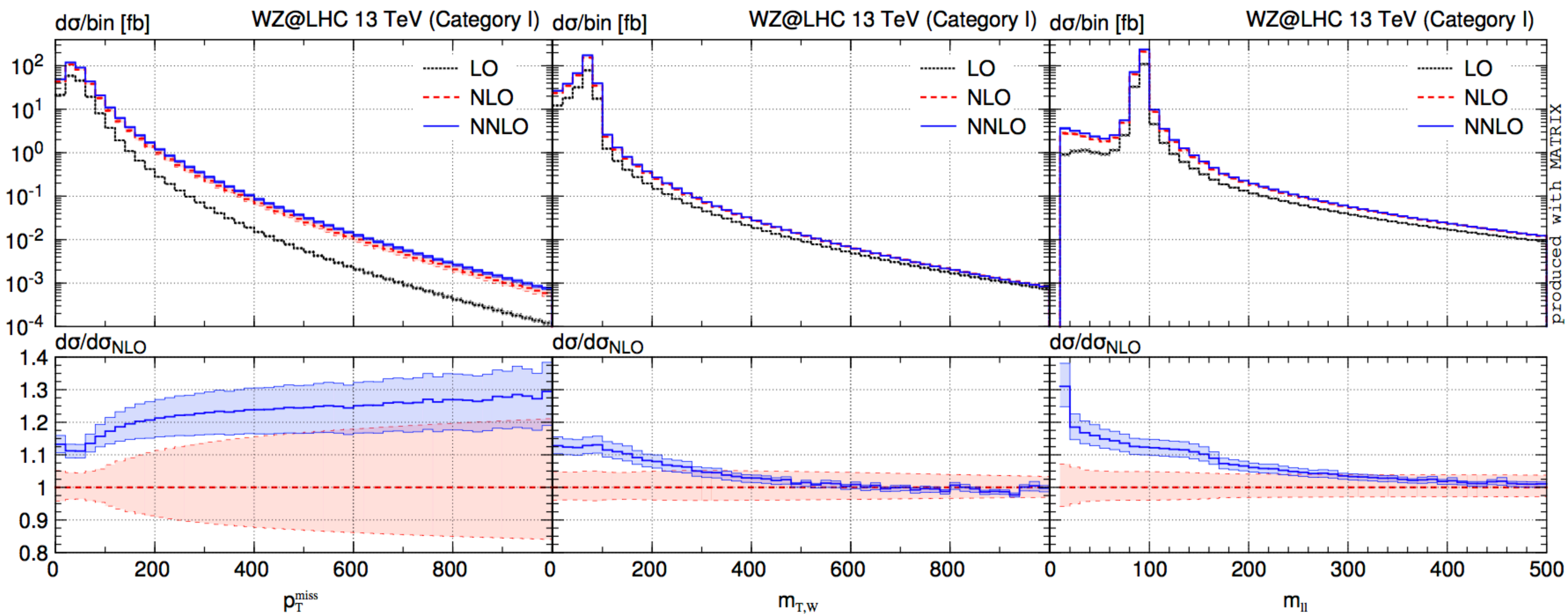
WZ: fully differential: NP searches

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm NLO}/\sigma_{\rm LO}-1$	$\sigma_{\rm NNLO}/\sigma_{\rm NLO}-1$
Category I					
$\ell'^+\ell^+\ell^-$	$49.45(0)^{+4.9\%}_{-5.8\%}$	$94.12(2)^{+4.8\%}_{-3.9\%}$	$105.9(1)^{+2.3\%}_{-2.2\%}$	90.3%	12.6%
$\ell^+\ell^+\ell^-$	$48.97(0)^{+4.8\%}_{-5.8\%}$	$93.13(2)^{+4.8\%}_{-3.9\%}$	$104.7(1)^{+2.2\%}_{-2.1\%}$	90.2%	12.4%
$\ell'^-\ell^+\ell^-$	$32.04(0)^{+5.3\%}_{-6.3\%}$	$63.68(3)^{+5.0\%}_{-4.1\%}$	$71.89(4)^{+2.3\%}_{-2.2\%}$	98.7%	12.9%
$\ell^-\ell^+\ell^-$	$31.74(0)^{+5.3\%}_{-6.3\%}$	$63.00(2)^{+5.0\%}_{-4.1\%}$	$71.13(4)^{+2.2\%}_{-2.2\%}$	98.5%	12.9%
combined	$162.2(0)^{+5.0\%}_{-6.0\%}$	$313.9(1)^{+4.9\%}_{-4.0\%}$	$353.7(3)^{+2.2\%}_{-2.2\%}$	93.5%	12.7%
Category II					
$\ell'^+\ell^+\ell^-$	$0.3482(0)^{+2.8\%}_{-2.8\%}$	$1.456(0)^{+13\%}_{-11\%}$	$1.799(1)^{+5.2\%}_{-5.4\%}$	318%	23.6%
$\ell^+\ell^+\ell^-$	$0.3486(0)^{+2.8\%}_{-2.8\%}$	$1.452(0)^{+13\%}_{-11\%}$	$1.789(1)^{+5.1\%}_{-5.4\%}$	316%	23.2%
$\ell'^-\ell^+\ell^-$	$0.1644(0)^{+2.6\%}_{-2.7\%}$	$0.5546(1)^{+12\%}_{-9.9\%}$	$0.6631(4)^{+4.3\%}_{-4.8\%}$	237%	19.6%
$\ell^-\ell^+\ell^-$	$0.1645(0)^{+2.6\%}_{-2.7\%}$	$0.5535(1)^{+12\%}_{-9.9\%}$	$0.6600(3)^{+4.2\%}_{-4.7\%}$	237%	19.2%
combined	$1.026(0)^{+2.7\%}_{-2.8\%}$	$4.015(1)^{+13\%}_{-10\%}$	$4.911(3)^{+4.9\%}_{-5.2\%}$	292%	22.3%
Category III					
$\ell'^+\ell^+\ell^-$	$0.3642(0)^{+1.5\%}_{-2.2\%}$	$0.5909(1)^{+4.3\%}_{-3.3\%}$	$0.6373(16)^{+1.6\%}_{-1.6\%}$	62.3%	7.86%
$\ell^+\ell^+\ell^-$	$1.090(0)^{+1.7\%}_{-2.4\%}$	$1.904(0)^{+4.8\%}_{-3.8\%}$	$2.071(2)^{+1.9\%}_{-1.9\%}$	74.7%	8.79%
$\ell'^-\ell^+\ell^-$	$0.2055(0)^{+2.0\%}_{-2.8\%}$	$0.3447(1)^{+4.5\%}_{-3.4\%}$	$0.3731(9)^{+1.6\%}_{-1.7\%}$	67.8%	8.22%
$\ell^-\ell^+\ell^-$	$0.6463(1)^{+2.1\%}_{-2.9\%}$	$1.136(0)^{+4.8\%}_{-3.7\%}$	$1.232(1)^{+1.7\%}_{-1.7\%}$	75.8%	8.42%
combined	$2.306(0)^{+1.8\%}_{-2.5\%}$	$3.976(1)^{+4.7\%}_{-3.7\%}$	$4.313(6)^{+1.8\%}_{-1.8\%}$	72.4%	8.50%
Category IV					
$\ell'^+\ell^+\ell^-$	$2.500(0)^{+3.1\%}_{-3.9\%}$	$4.299(1)^{+4.1\%}_{-3.4\%}$	$4.682(2)^{+1.7\%}_{-1.6\%}$	72.0%	8.92%
$\ell^+\ell^+\ell^-$	$2.063(0)^{+3.4\%}_{-4.2\%}$	$3.740(1)^{+4.5\%}_{-3.6\%}$	$4.160(2)^{+2.2\%}_{-2.0\%}$	81.3%	11.2%
$\ell'^-\ell^+\ell^-$	$1.603(0)^{+3.4\%}_{-4.4\%}$	$2.805(1)^{+4.2\%}_{-3.5\%}$	$3.058(1)^{+1.7\%}_{-1.6\%}$	75.0%	9.01%
$\ell^-\ell^+\ell^-$	$1.373(0)^{+3.8\%}_{-4.7\%}$	$2.591(1)^{+4.7\%}_{-3.9\%}$	$2.904(1)^{+2.2\%}_{-2.1\%}$	88.7%	12.1%
combined	$7.540(1)^{+3.4\%}_{-4.2\%}$	$13.44(0)^{+4.4\%}_{-3.6\%}$	$14.80(1)^{+1.9\%}_{-1.8\%}$	78.2%	10.2%

Very large corrections especially in Category II where NNLO effects can reach O(20%)

Different impact of radiative corrections on W^+Z and W^-Z due to the different partonic channels that contribute at LO

WZ: fully differential: NP searches



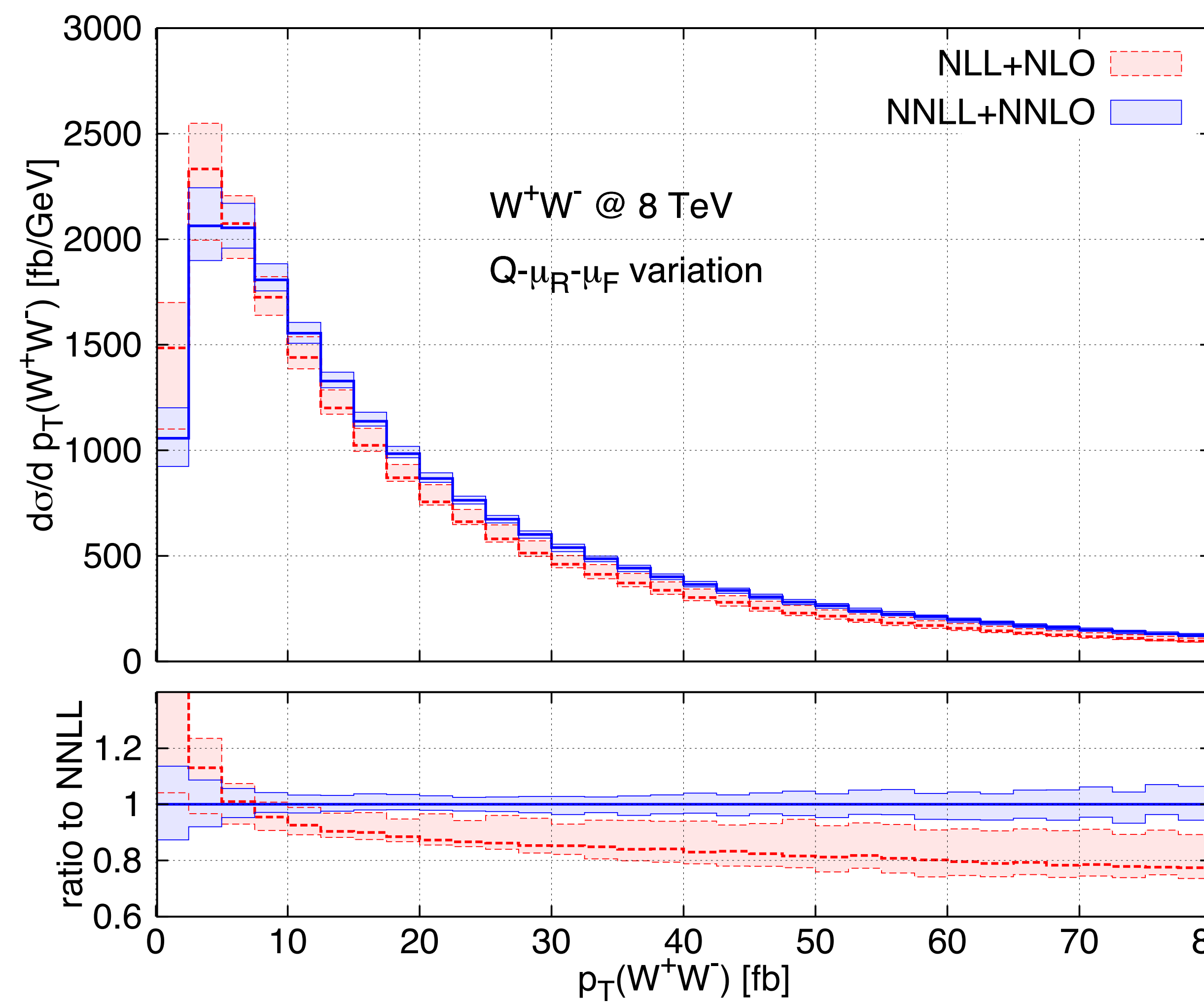
The use of a dynamical scale is essential to obtain perturbative stable distributions

Inclusion of NNLL+NNLO resummation

S. Kallweit, D. Rathlev, M.Wiesemann,MG (2015)

The subtraction counterterm used in our NNLO calculations is obtained from transverse-momentum resummation

➡ Our calculational framework can be extended to include the resummation of the logarithmically enhanced terms at small p_T



First application: NNLL+NNLO spectrum for WW and ZZ production

Beyond colour singlets: top-quark production

R.Bonciani, S.Catani, H.Sargsyan and A.Torre , MG (2015)

The q_T subtraction method can be extended to heavy-quark production

We have used this method to compute ttbar production at NLO and to include all the off-diagonal partonic channels at NNLO

σ(pb)	NLO	$O(\alpha_S^4)_{qg}$	$O(\alpha_S^4)_{qq+qq'}$
q_T subtraction	226.2(1)	-2.25(5)	1.51(3)
Top++	226.3	-2.253	1.48

pp, 8 TeV

σ(fb)	NLO	$O(\alpha_S^4)_{qg}$	$O(\alpha_S^4)_{qq+qq'}$
q_T subtraction	7083(3)	-61.5(5)	1.33(1)
Top++	7086	-61.53	1.33

ppbar, 2 TeV

Summary & Outlook

- The q_T subtraction method has been used to perform a number of important NNLO calculations where a coloured singlet final state is produced in hadron collisions

- The calculations were implemented in numerical codes which are to a large extent independent from each other

- We provide a new NNLO parton level generator which implements all these calculations in a unique framework and includes all the vector-boson pair production processes

→ MATRIX

- The program combines the MUNICH Monte Carlo framework with amplitudes from Openloops and q_T subtraction and will eventually include transverse-momentum resummation at NNLL

Summary & Outlook

- The computation of two-loop helicity amplitudes for vector boson pair production allows realistic NNLO predictions for all these processes, including the leptonic decays and off-shell effects

- Closed beta version released about one year ago

- First public version including single vector and Higgs boson production and all the diboson processes ready to be released

- Some items on our to do list:

  - NLO gg in WW and ZZ
  - Include EW corrections
  - Include anomalous couplings/BSM effects
  - inclusion of processes with a heavy-quark pair

Thank you !