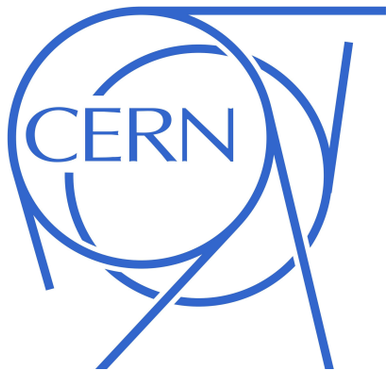
Vector-boson pair production at NNLO(+NNLL)

Marius Wiesemann



LHCTheory ERC meeting, Louvain-la-Neuve (Belgium)

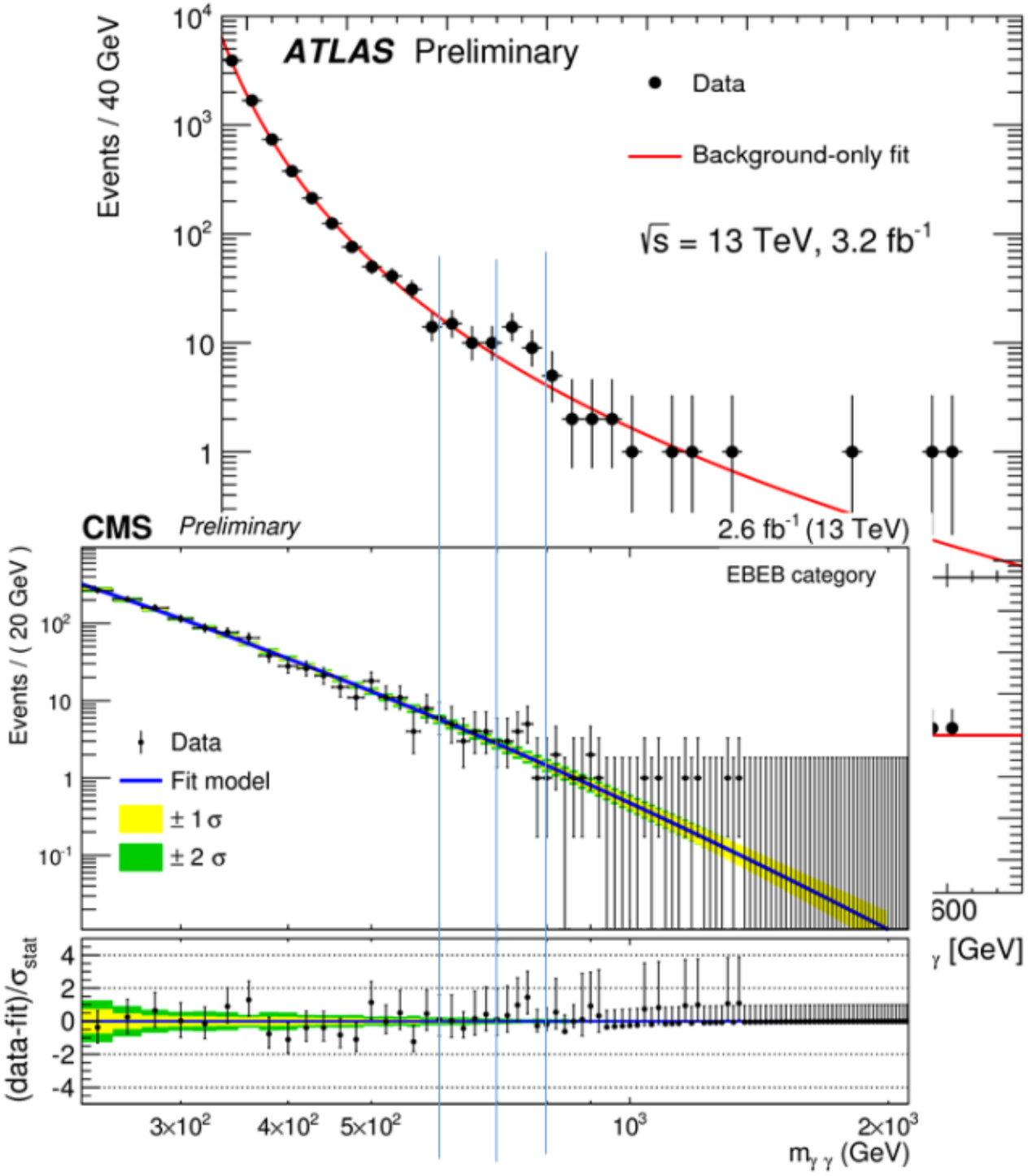
22-24 March, 2017

in collaboration with M. Grazzini, S. Kallweit, S. Pozzorini and D. Rathlev

Outline

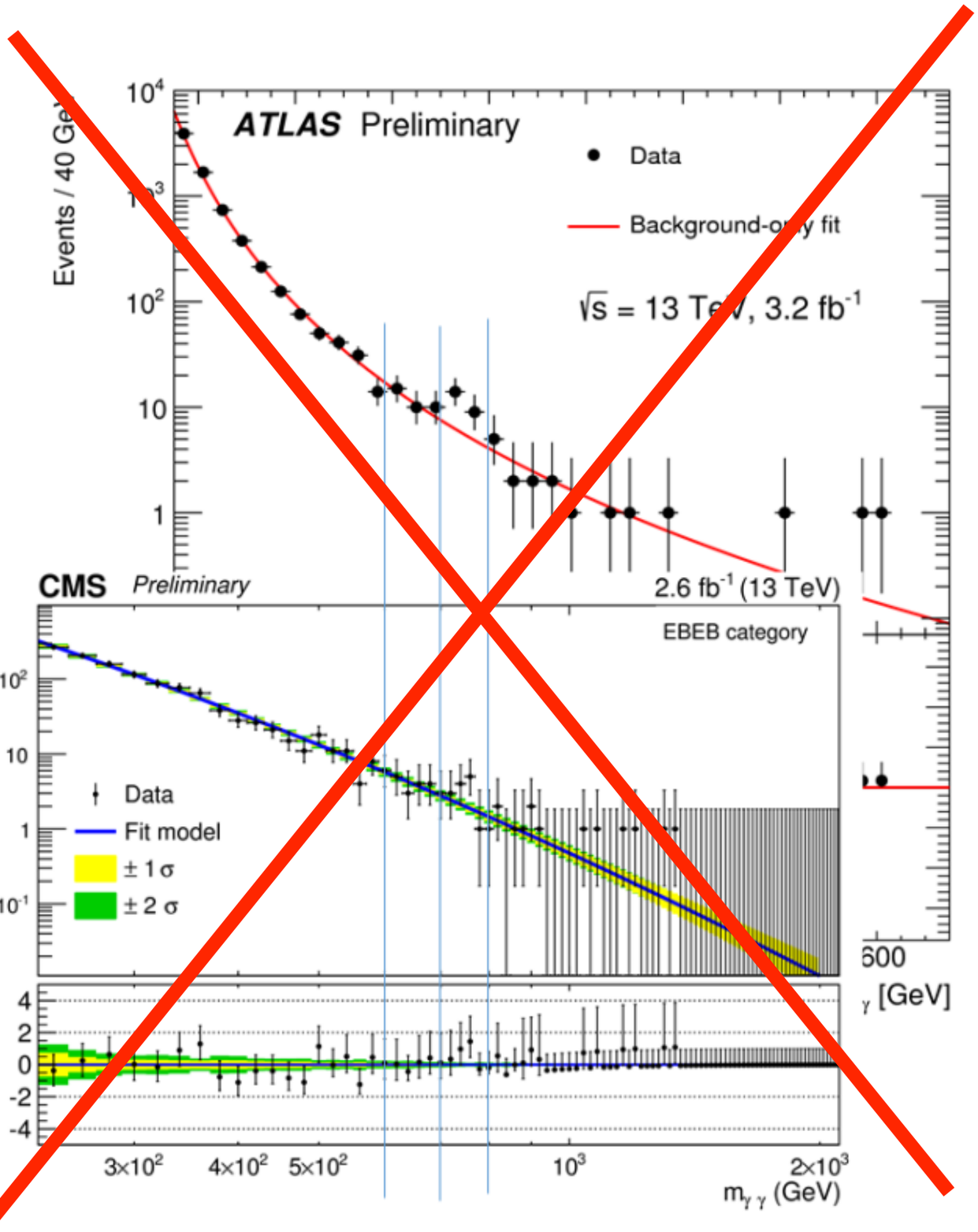
1. Motivation and introduction to precision computations
2. The MATRIX
   - Status of the code and NNLO
   - Status of p_T resummation at NNLL
3. Physics results
   - Inclusive diboson results produced with MATRIX
   - Differential diboson results produced with MATRIX
   - **very new:** pp→WZ→lllν at NNLO (fully differential)

2015 → 2016


ATLAS Preliminary
Data
Background-only fit
√s = 13 TeV, 3.2 fb-1
Events / 40 GeV
CMS Preliminary
2.6 fb-1 (13 TeV)
EBEB category
Events / (20 GeV)
Data
Fit model
± 1 σ
± 2 σ
(data-fit)/σstat
mγ γ (GeV)
γ [GeV]

2015

2016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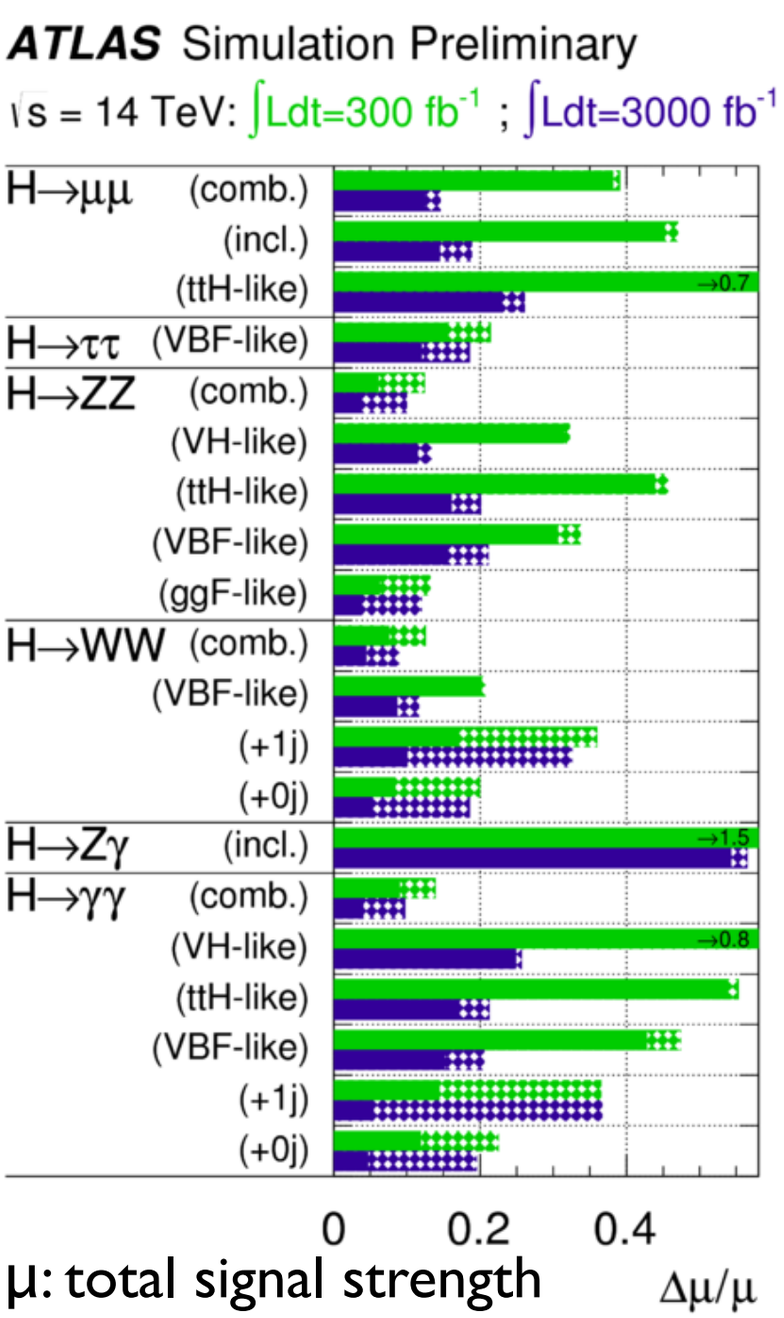
mγ γ (GeV)
γ [GeV]


750-GEV DIPHOTON EXCESS...
AAAND IT'S GONE!
imgflip.com

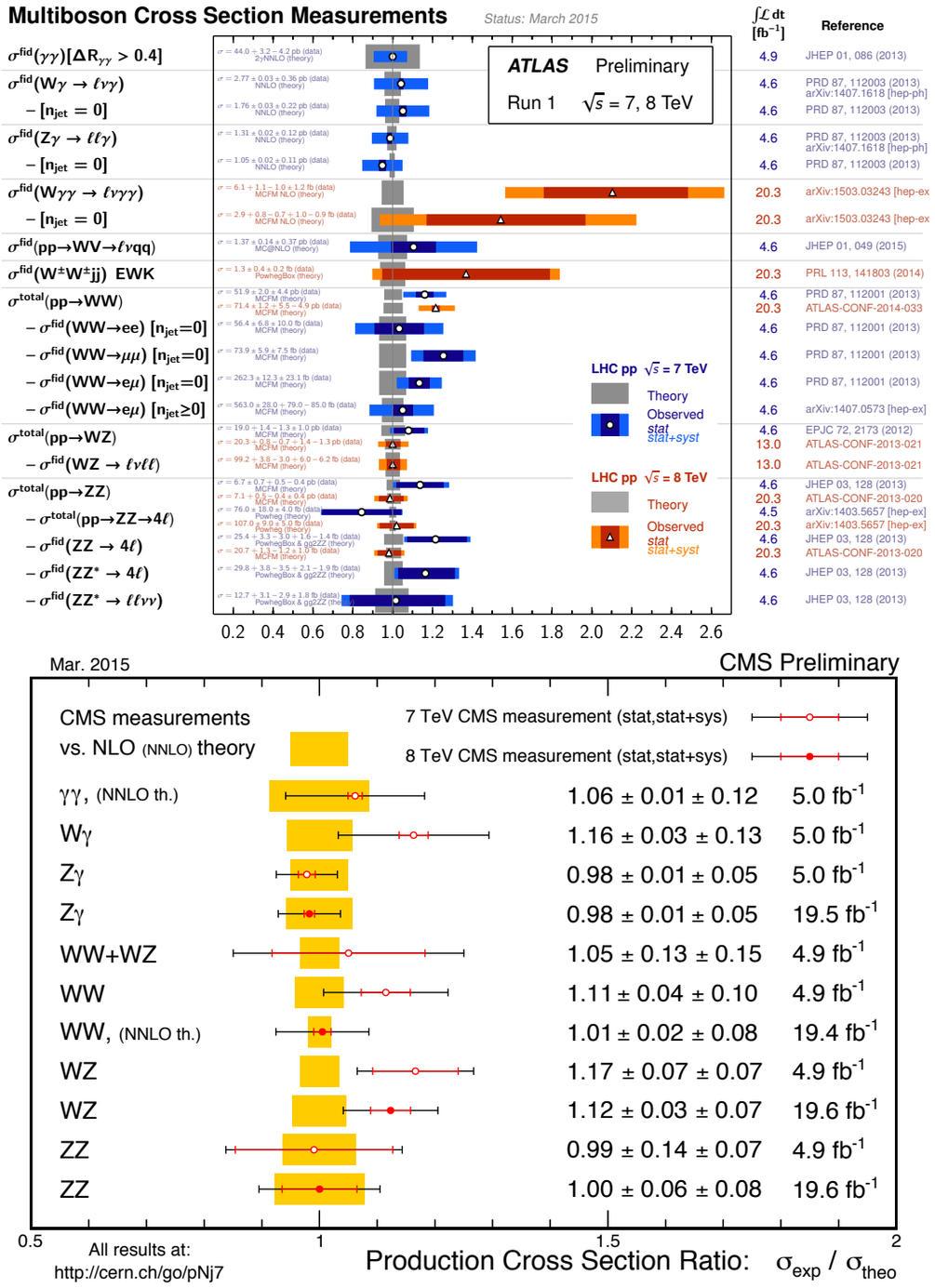

Diphoton Excess
2015 - 2016
R.I.P.
FutureGravestone.com

Introduction

Higgs

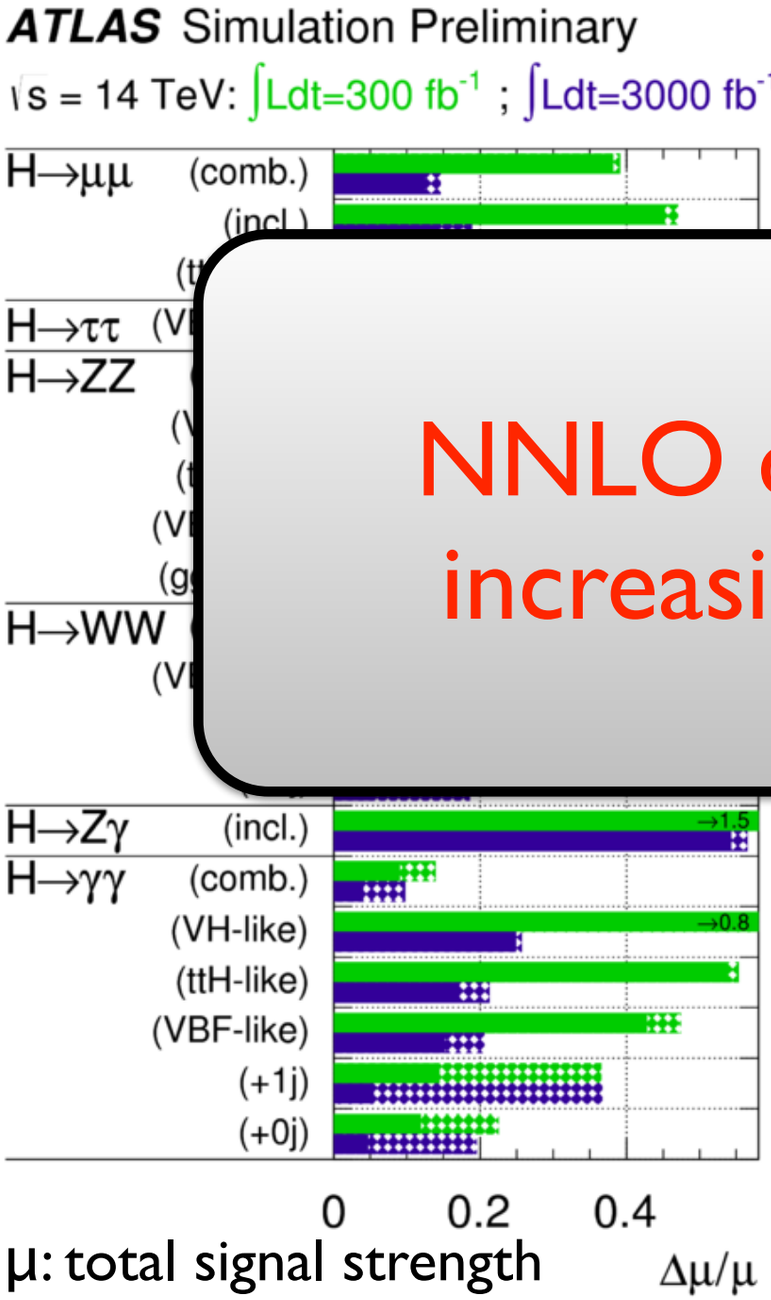


vector-boson pairs

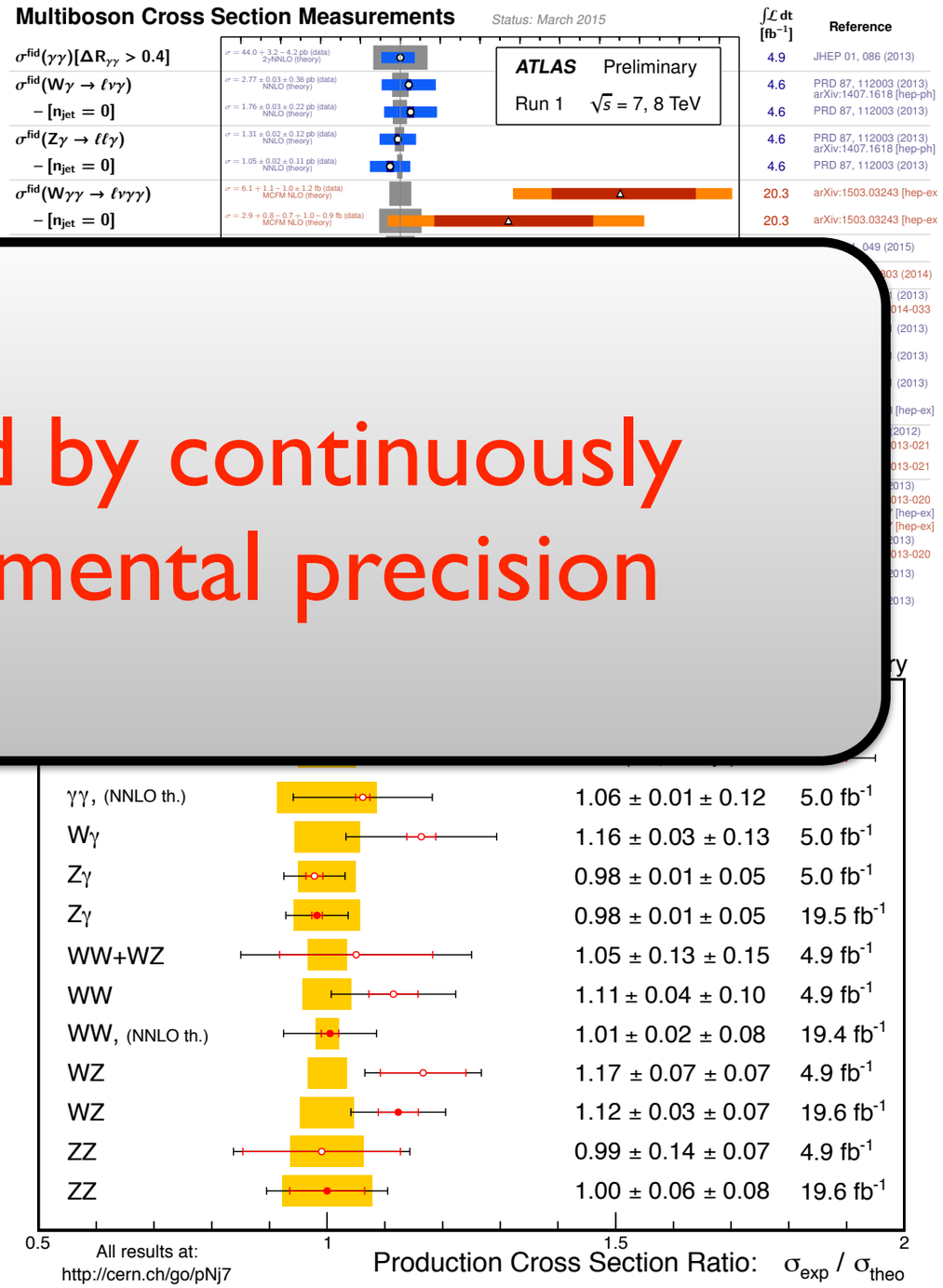


Introduction

Higgs



vector-boson pairs



NNLO demanded by continuously increasing experimental precision

NNLO methods

Schemes with local cancellation of singularities

- Sector decomposition [Binoth, Heinrich '00 '04] [Anastasio, Melnikov, Petriello '04]
- Antenna subtraction [Gehrmann-de Ridder, Gehrmann, Glover '05]
- STRIPPER (FKS+sec.dec.) [Czakon '10, '11]
- Colourful subtraction [Somogyi, Trocsanyi, Del Duca '05, '07]

Schemes that start from F+1jet process at NLO

- p_T subtraction [Catani, Grazzini '07]
- N-jettiness subtraction [Tackmann et al. '15], [Boughezal, Liu, Petriello '15]
- (Born projection method) [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

NNLO methods

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Two-loop amplitudes required for each process!

p_T subtraction master formula:

$$d\sigma_{\mathrm{NNLO}} = \left[d\sigma_{\mathrm{NLO}}^{F+1\mathrm{jet}} - \Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}} \right] + \mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}$$

[Catani, Grazzini '07]

p_T subtraction master formula:

$$d\sigma_{\rm NNLO} = \left[d\sigma^{F+1{\rm jet}}_{\rm NLO} - \Sigma_{\rm NNLO} \otimes d\sigma_{\rm LO}\right] + \mathcal{H}_{\rm NNLO} \otimes d\sigma_{\rm LO}$$

[Catani, Grazzini '07]

subtraction terms known from resummation:

$$d\sigma^{F+1{\rm jet}} \xrightarrow{p_T \ll Q} \left[d\sigma^{(\rm res)}\right]_{\rm f.o.} \equiv \Sigma(p_T/Q) \otimes d\sigma_{\rm LO}$$

Resummation formula:

$$\frac{d\sigma^{(\rm res)}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$

[Collins, Soper, Sterman '85], [Bozzi, Catani, de Florian, Grazzini '06]

p_T subtraction master formula:

$$d\sigma_{\rm NNLO} = \left[d\sigma_{\rm NLO}^{F+1\rm jet} - \Sigma_{\rm NNLO} \otimes d\sigma_{\rm LO}\right] + \mathcal{H}_{\rm NNLO} \otimes d\sigma_{\rm LO}$$

[Catani, Grazzini '07]

subtraction terms known from resummation:

$$d\sigma^{F+1\rm jet} \xrightarrow{p_T \ll Q} \left[d\sigma^{(\rm res)}\right]_{\rm f.o.} \equiv \Sigma(p_T/Q) \otimes d\sigma_{\rm LO}$$

NNLO accuracy consequence of unitarity:

$$\int dp_T^2 \, \frac{d\sigma^{(\rm res)}}{dp_T^2\, dy\, dM\, d\Omega} = \mathcal{H} \otimes d\sigma_{\rm LO} \qquad \left(\ln(Q^2 b^2/b_0^2) \to \ln(Q^2 b^2/b_0^2 + 1)\right)$$

Resummation formula:

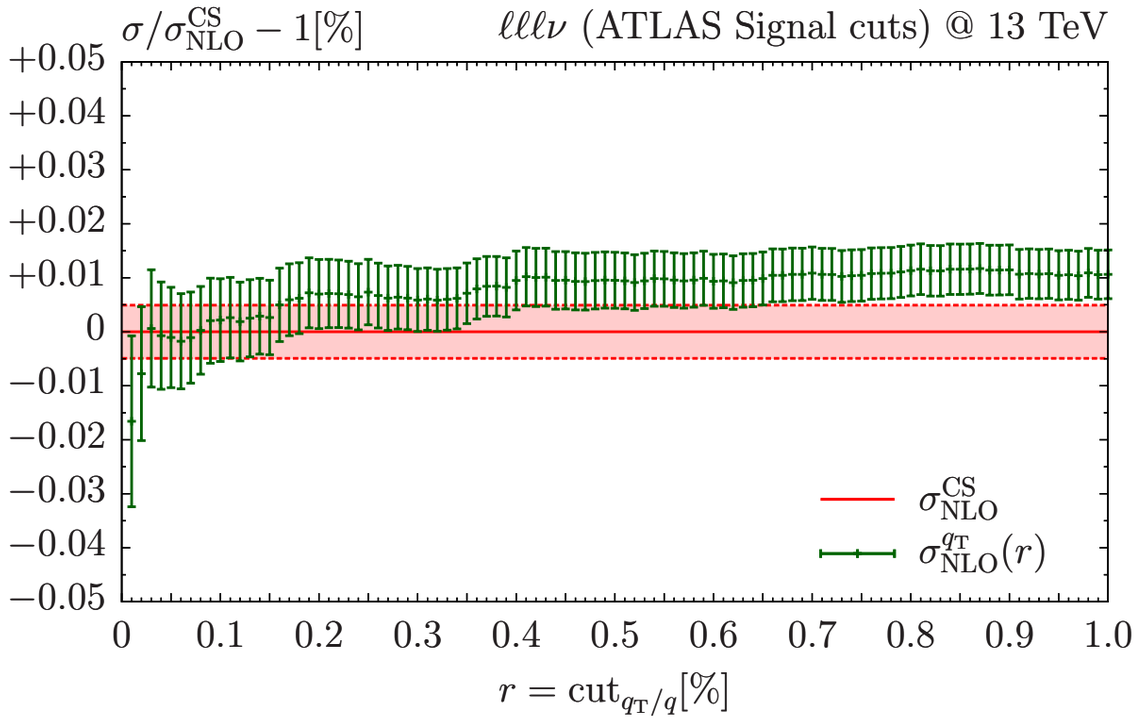
$$\frac{d\sigma^{(\rm res)}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$

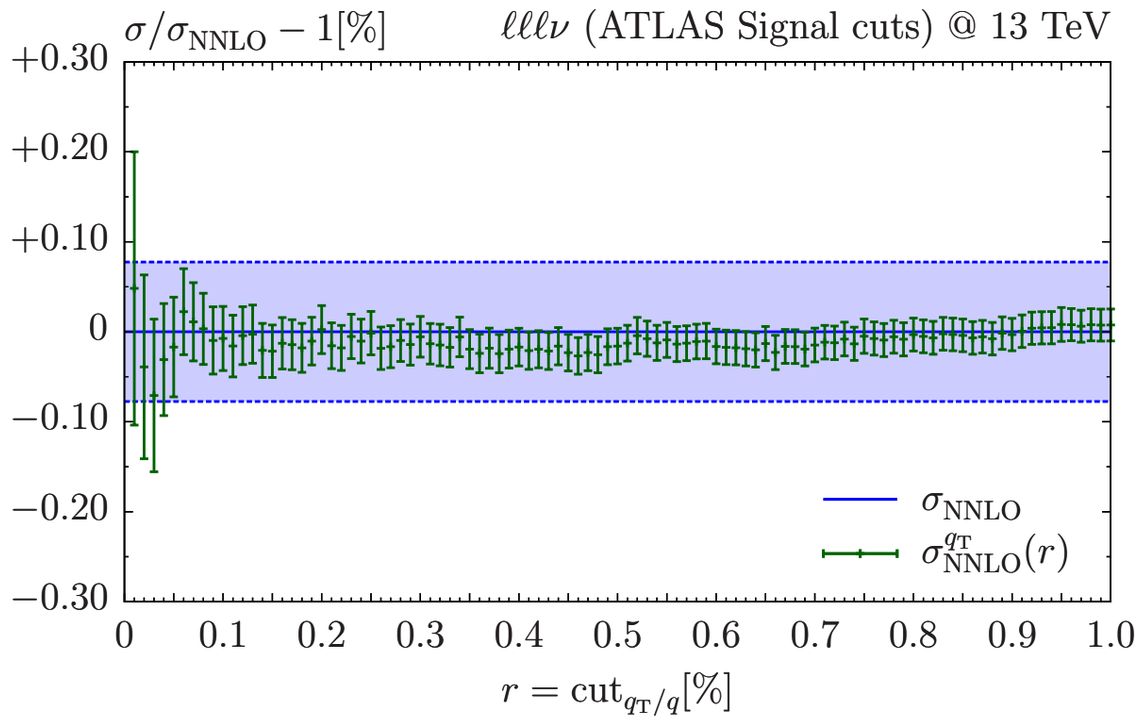
[Collins, Soper, Sterman '85], [Bozzi, Catani, de Florian, Grazzini '06]

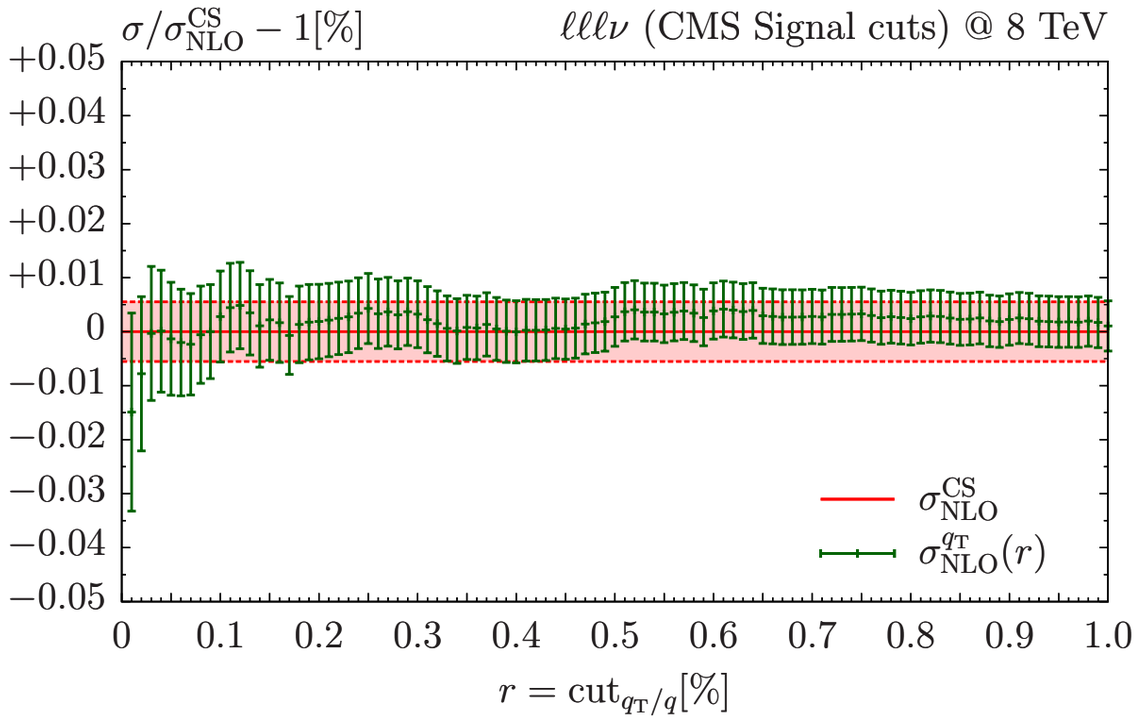
WZ fully differential at NNLO

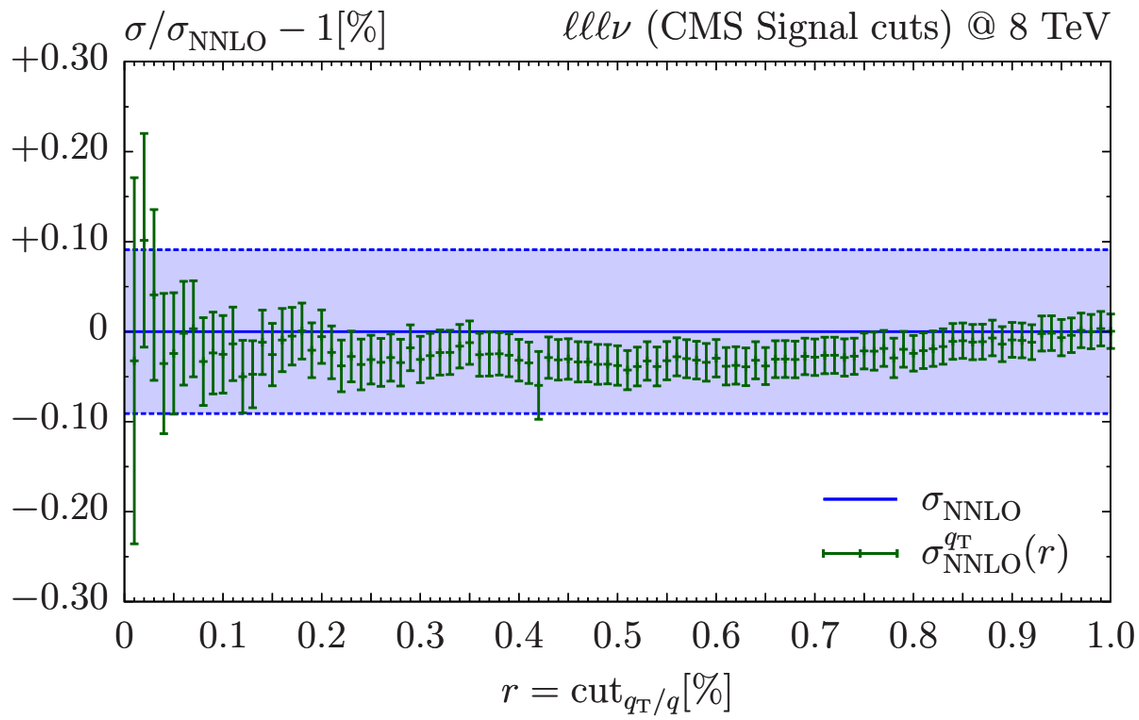
[Grazzini, Kallweit, MW '17]

stability of r_{cut} dependence









We implemented...

The MATRIX team

Dirk "Cypher" Rathlev

Massimiliano "Morpheus" Grazzini

Stefan "Neo" Kallweit

Marius "Trinity" Wiesemann

The MATRIX team

Dirk "Cypher" Rathlev

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Marius "Trinity" Wiesemann

The MATRIX framework

[Grazzini, Kallweit, Rathlev, MW] (+Sargsyan)

Amplitudes	
OpenLoops (Collier, CutTOols, ...)	Dedicated 2-loop codes (VVamp, GiNaC, tdhpl, ...)

Munich

MUlti-chaNnel Integrator at Swiss (CH) precision

q_T subtraction $\Leftrightarrow$ q_T resummation

NNLO

NNLL

Matrix

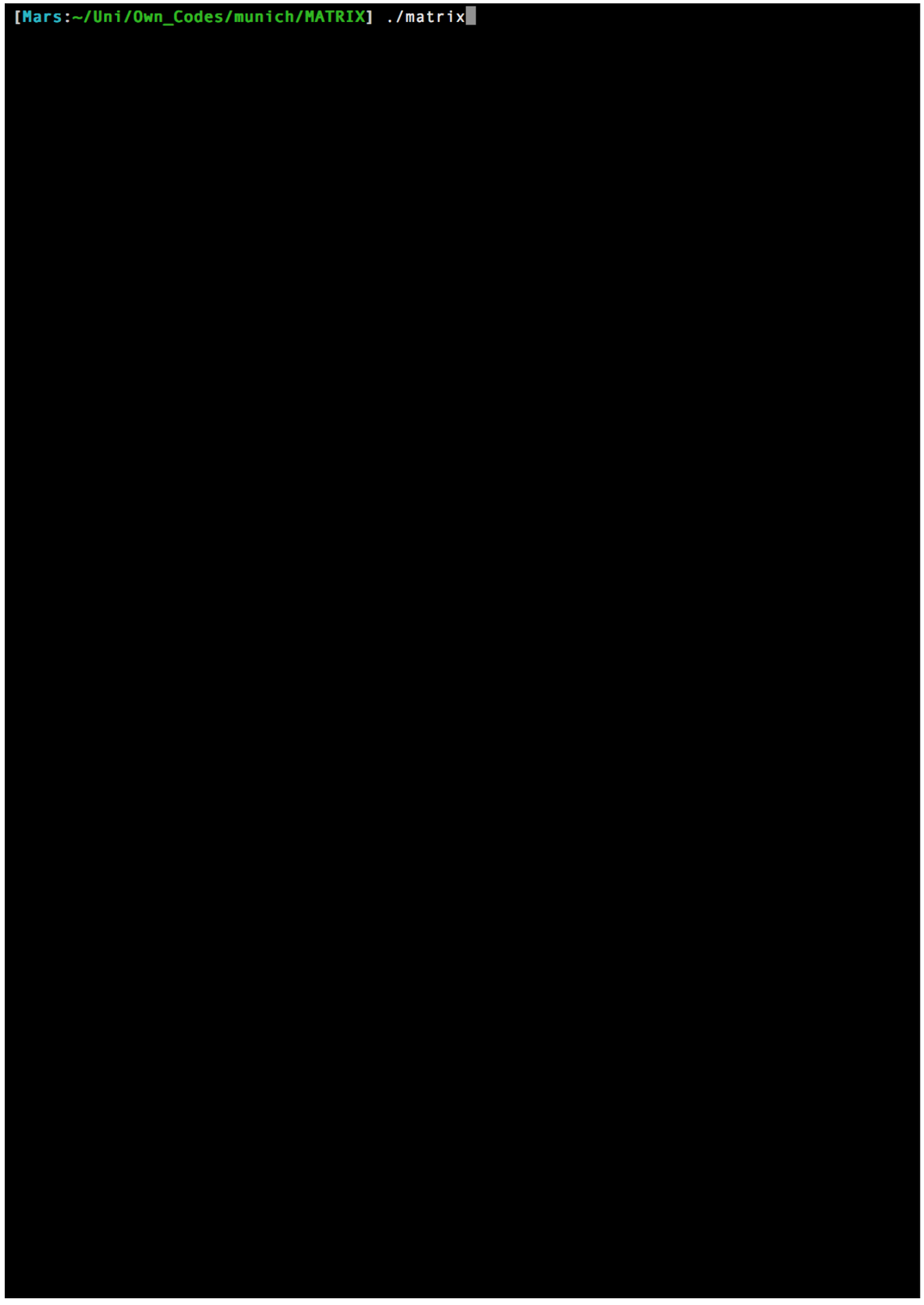
Munich Automates qT Subtraction and Resummation to Integrate X-sections.

process	status	comment
pp→Z/γ*(→ℓℓ/νν)	✓	validated analytically + DYNNLO
pp→W(→ℓν)	(✓)	to be validated (with CKM)
pp→H	✓	validated analytically
pp→γγ	✓	validated with 2γNNLO
pp→Zγ→ℓℓγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→Zγ→νγγ	✓	**NEW**
pp→Wγ→ℓνγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ	✓	[Cascioli et al. '14]
pp→ZZ→ℓℓℓℓ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ→ℓℓℓ'ℓ'	✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ→ℓℓν'ν'	✓	**NEW**
pp→ZZ/WW→ℓℓνν	✓	**NEW**
pp→WW	✓	[Gehrmann et al. '14]
pp→WW→ℓν ℓ'ν'	✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
pp→WZ	✓	[Grazzini, Kallweit, Rathlev, MW '16]
pp→WZ→ℓνℓℓ	✓	**NEW HERE:** fully differential
pp→WZ→ℓ'ν'ℓℓ	✓	**NEW HERE:** fully differential
pp→HH	(✓)	not in first public release

enter the MATRIX

- After unpacking the MATRIX package start the code with:

```
$$ ./matrix
```



enter the MATRIX

- After unpacking the MATRIX package start the code with:

```
$$ ./matrix
```

- which brings you to MATRIX compilation shell, type

```
|===>> list
```

- to list all available process IDs. Select a process typing its ID, eg:

```
|===>> ppeeexex04
```

```
[[Mars:~/Uni/Own_Codes/munich/MATRIX] ./matrix

          /-------------------------------------------------------------------\
          | 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-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
[|============>> list
-------------------------------------------------------------------------------------
process_id    ||   process                          ||   description
-------------------------------------------------------------------------------------
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
```

enter the MATRIX

- After unpacking the MATRIX package start the code with:

```
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```

- which brings you to MATRIX compilation shell, type

```
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```

- to list all available process IDs. Select a process typing its ID, eg:

```
|===>> ppeeexex04
```

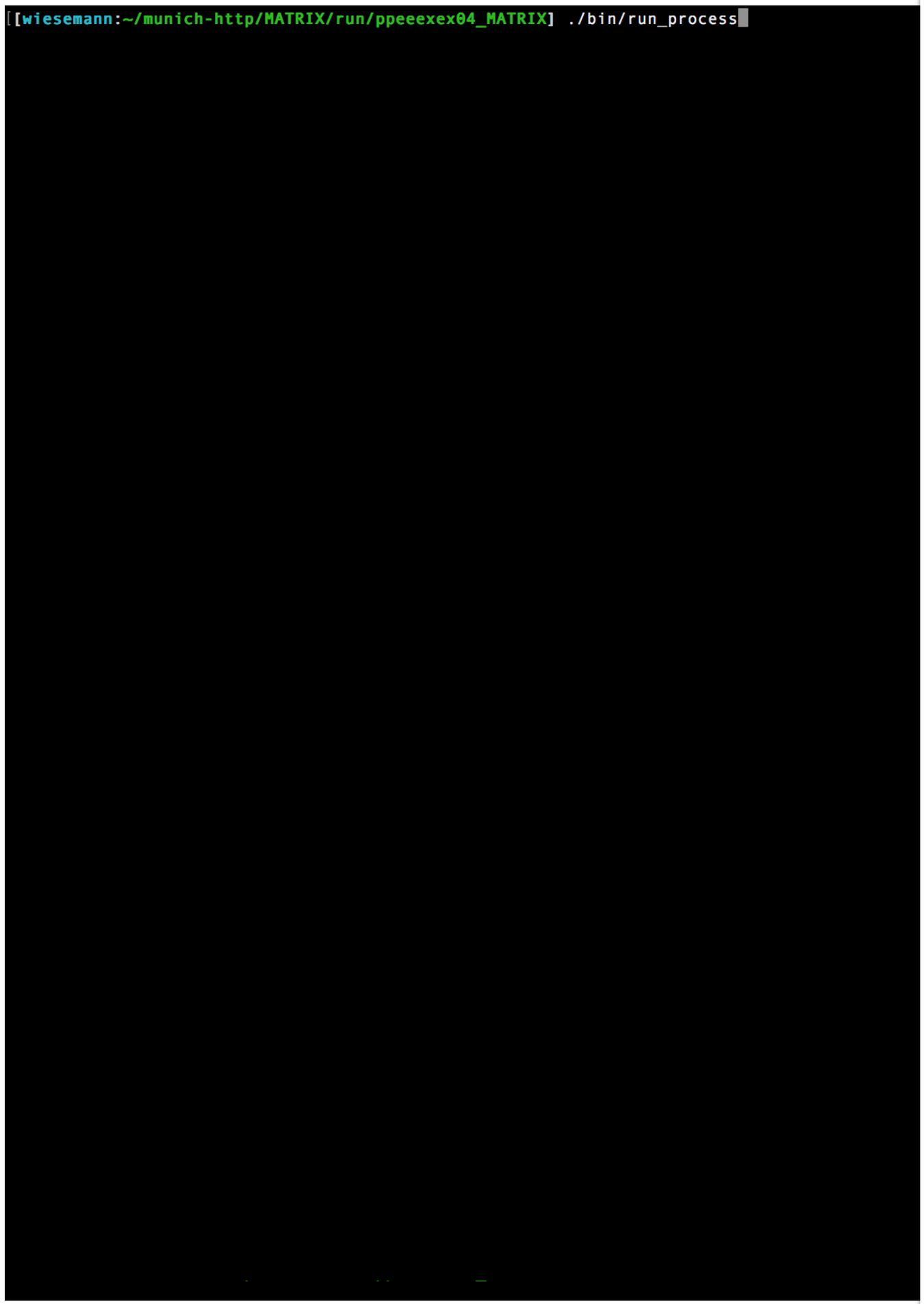
- for pp→ZZ→4ℓ, this will start the automatic compilation including:
  - dowload/compilation of OpenLoops
  - compilation of Cln and Ginac
  - MATRIX compilation
  - download OpenLoops amplitudes
  - creation of MATRIX process run folder

```
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 pllll amplitude with OpenLoops...
<<MATRIX-MAKE>> Downloading and compiling pllllj amplitude with OpenLoops...
<<MATRIX-MAKE>> Downloading and compiling pllll2 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
[Mars:~/Uni/Own_Codes/munich/MATRIX]
```

enter the MATRIX

- After changing into the run directory we start the run script

```
$ ./bin/run_process
```



enter the MATRIX

- After changing into the run directory we start the run script

```
$ ./bin/run_process
```

- First, choose a name for the run:

```
|===>> run_my_first_ZZ
```

```
[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
```

enter the MATRIX

- After changing into the run directory we start the run script

```
$ ./bin/run_process
```

- First, choose a name for the run:

```
|===>> run_my_first_ZZ
```

- The MATRIX run shell has many options, eg, modify input files typing:

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

```
[[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
```

enter the MATRIX

- After changing into the directory we start the r

```
$ ./bin/run_proces
```

- First, choose a name for

```
|===>> run_my_firs
```

- The MATRIX run shell options, eg, modify input

```
|===>> parameter
```

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

          /-------------------------------------------------------------------\
          | MATRIX: A fully-differential NNLO(+NNLL) process library          |
```

```
##########################
# MATRIX input parameter #
##########################

#---------------------\
# general run settings |
#---------------------/
process_class    =  pp-ememepep+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 fiductial 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 ----------
```

enter the MATRIX

- After changing into the run directory we start the run script

```
$ ./bin/run_process
```

- First, choose a name for the run:

```
|===>> run_my_first_ZZ
```

- The MATRIX run shell has many options, eg, modify input files typing:

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```

- Now we can start the run, type

```
|===>> run
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```
[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                |
 |                                                                         |
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 |                                                                         |
 | \         \ ____      \         \ ____      \ ____      \             |
 |  \         \          |\         \          |\          |\            |
 |   )====  +  )====  +  | )====  +  )====  +  | )====  +  |-)====       |
 |  /         /          |/         /____      |/          |/            |
 | /         /           /         /           /           /             |
 |                                                                         |
 | M. Grazzini                                (grazzini@physik.uzh.ch)     |
 | S. Kallweit                                 (kallweit@uni-mainz.de)     |
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<<MATRIX-READ>> Type name of folder for this run (has to start with "run_").
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setup_run           >>   Setup the run folder, but not start running.
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tar_run             >>   Create <run_folder>.tar (including input/log/result).
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[|============>> model
[|============>> distribution
 |============>> run
```

enter the MATRIX

- After changing into the run directory we start the run script

```
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```
|===>> parameter
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```

- Now we can start the run, type

```
|===>> run
```

- The code goes through all run phases and collects the results at the very end. With default inputs it runs LO with 1% accuracy.

```
[|============>> 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
```

enter the MATRIX

- After changing into the run directory we start the run script

```
$ ./bin/run_process
```

- First, choose a name for the run:

```
|===>> run_my_first_ZZ
```

- The MATRIX run shell has many options, eg, modify input files typing:

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

- Now we can start the run, type

```
|===>> run
```

- The code goes through all run phases and collects the results at the very end. With default inputs it runs LO with 1% accuracy.

```
                  /-------------------------------------------------\
                  |       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 |
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<<MATRIX-INFO>> All runs successfully finished.
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<<MATRIX-INFO>> Plotting results with gnuplot...
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<<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_fir
[wiesemann:~/munich-http/MATRIX/run/ppeeexex04_MATRIX]
```

Status of the code

- **Closed beta started almost one year ago!**
  - PROCESSES: (slightly) restricted number of processes from previous slide
  - ACCURACY: NNLO QCD
  - WHO: provided to experimentalists from ATLAS and CMS
- CURRENTLY SUPPORTED:
  - local and cluster running: LSF (lxplus), SLURM, condor; Torque/PBS, SGE
  - easy to add new schedulers

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- **Public release in preparation!**
  - Full list of processes
  - TIME FRAME: within next couple of months

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- **Public release in preparation!**
  - Full list of processes
  - TIME FRAME: within next couple of months
- Plans beyond first release:
  - enable NNLO+NNLL p_T resummation
  - NLO QCD corrections for loop-induced gg contributions
  - add NLO EW effects to certain processes
  - add resummation for further observables

Status of p_T resummation

- p_T = transverse momentum of Born-level system, eg: $p_{T,4\ell}$ in $pp \to ZZ \to 4\ell$
- Why resummation? Observable divergent for $p_T \to 0$ at fixed order!
- p_T subtraction $\leftrightarrow$ p_T resummation: all NNLO directly also at NNLL

$$d\sigma_{\rm NNLO} = \left[d\sigma_{\rm NLO}^{F+1\rm jet} - \Sigma_{\rm NNLO} \otimes d\sigma_{\rm LO} \right] + \mathcal{H}_{\rm NNLO} \otimes d\sigma_{\rm LO}$$

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$$d\sigma_{\underset{+\mathrm{NNLL}}{\mathrm{NNLO}}} = \left[d\sigma_{\mathrm{NLO}}^{F+1\mathrm{jet}} - \Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}} \right] + \cancel{\mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}}$$

$$\frac{d\sigma^{(\mathrm{res})}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$

$$\int dp_T^2\, \frac{d\sigma^{(\mathrm{res})}}{dp_T^2\, dy\, dM\, d\Omega} = \mathcal{H} \otimes d\sigma_{\mathrm{LO}}$$

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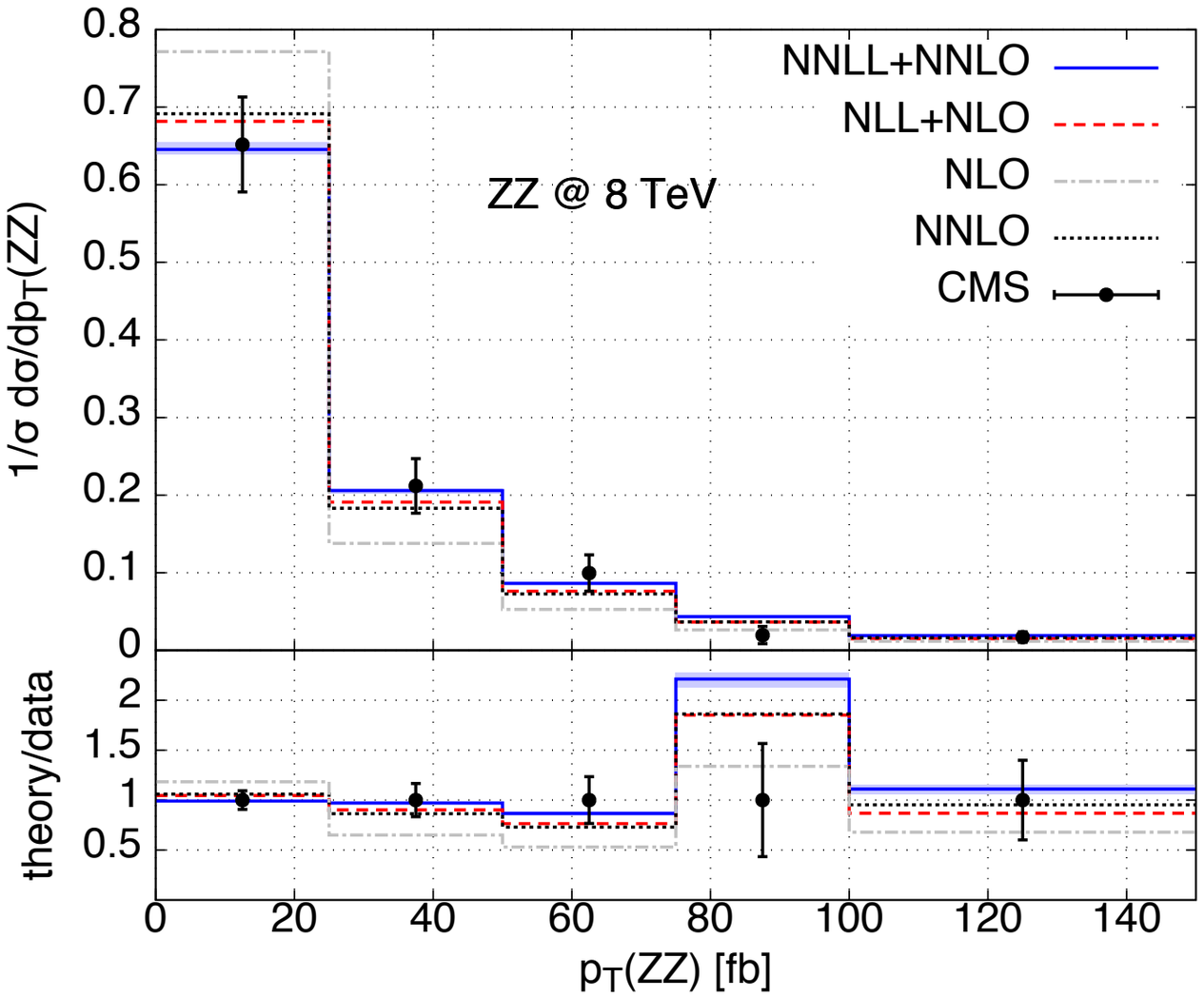
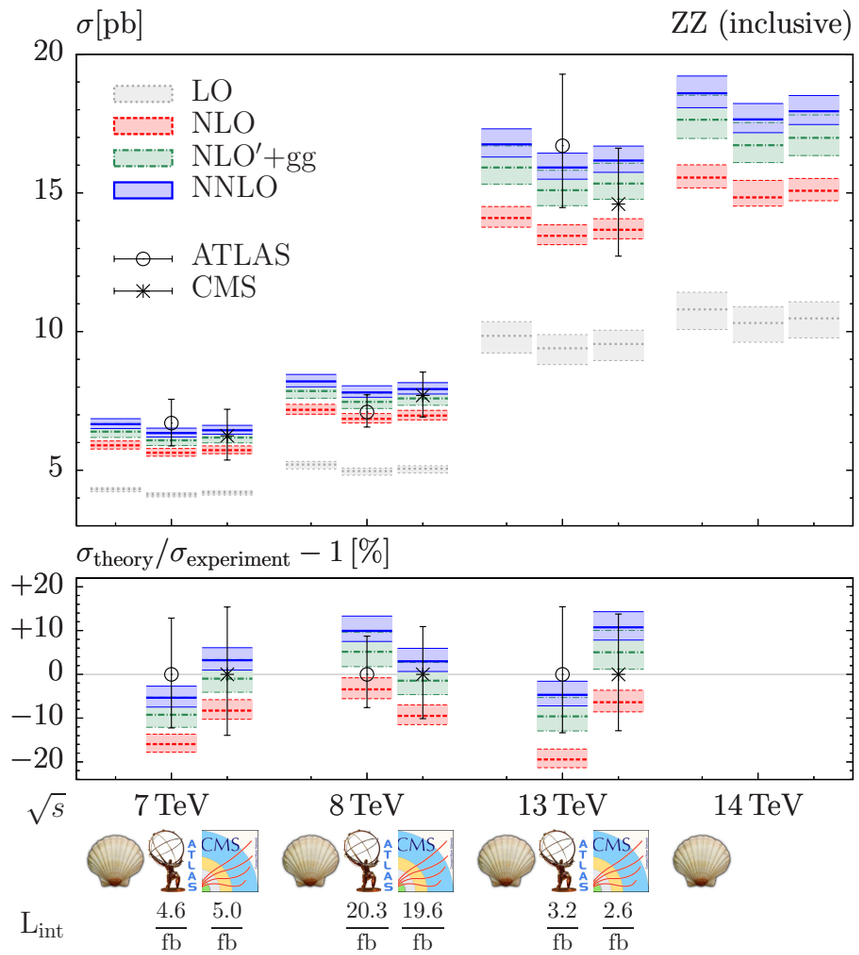
- Why resummation? Observable divergent for $p_T \to 0$ at fixed order!
- p_T subtraction $\leftrightarrow$ p_T resummation: all NNLO directly also at NNLL
- currently restricted to a charge-neutral final-state system (ie, no W and WZ)
- will **not** be included in first public version (due to lack of testing time)
- first application to on-shell WW/ZZ

[Grazzini, Kallweit, Rathlev, MW '15]



Physics results

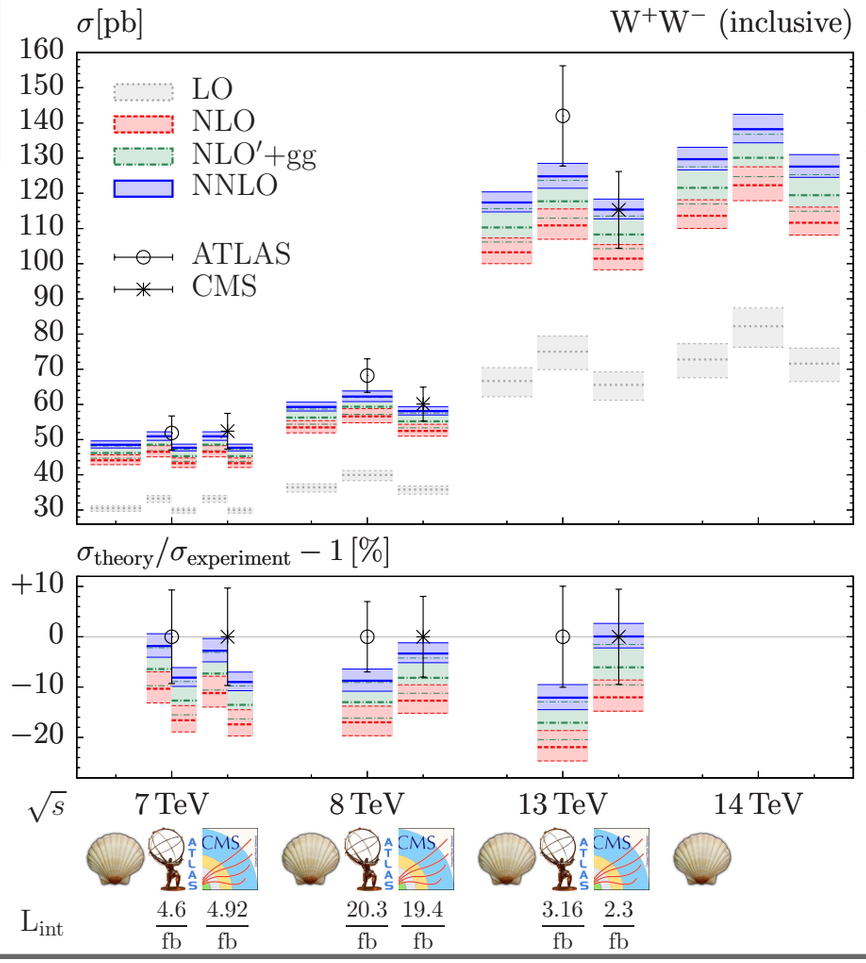
Inclusive diboson results: NNLO vs data

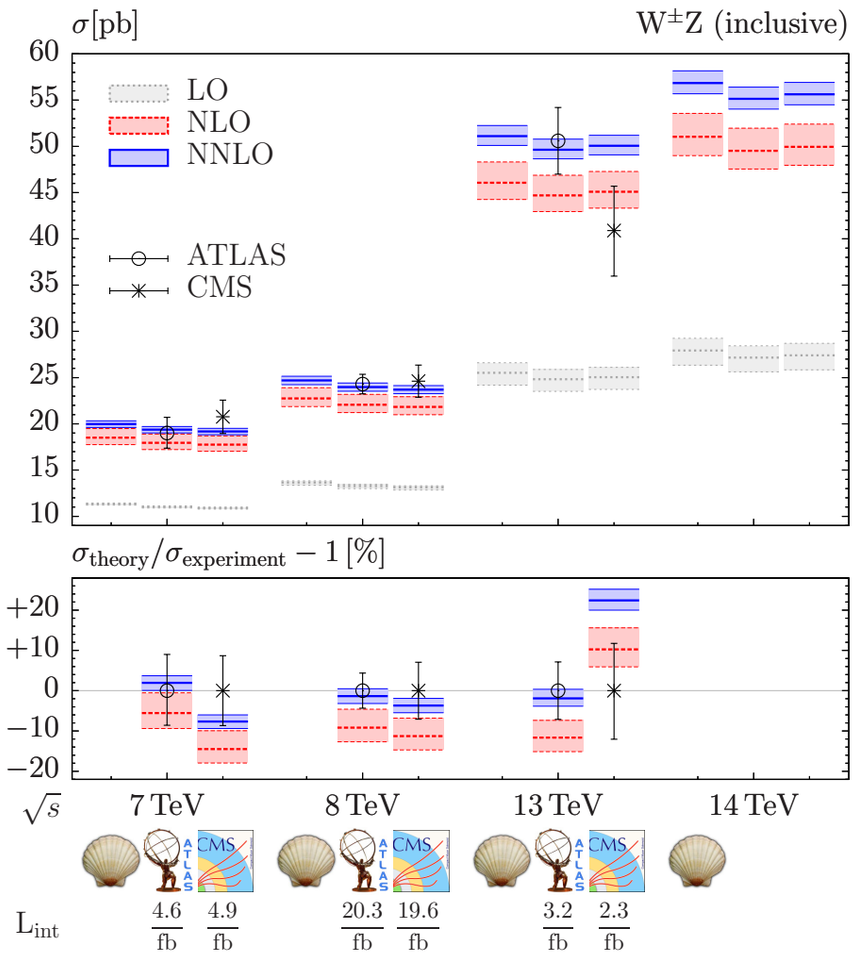


[Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]

[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi '14]

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

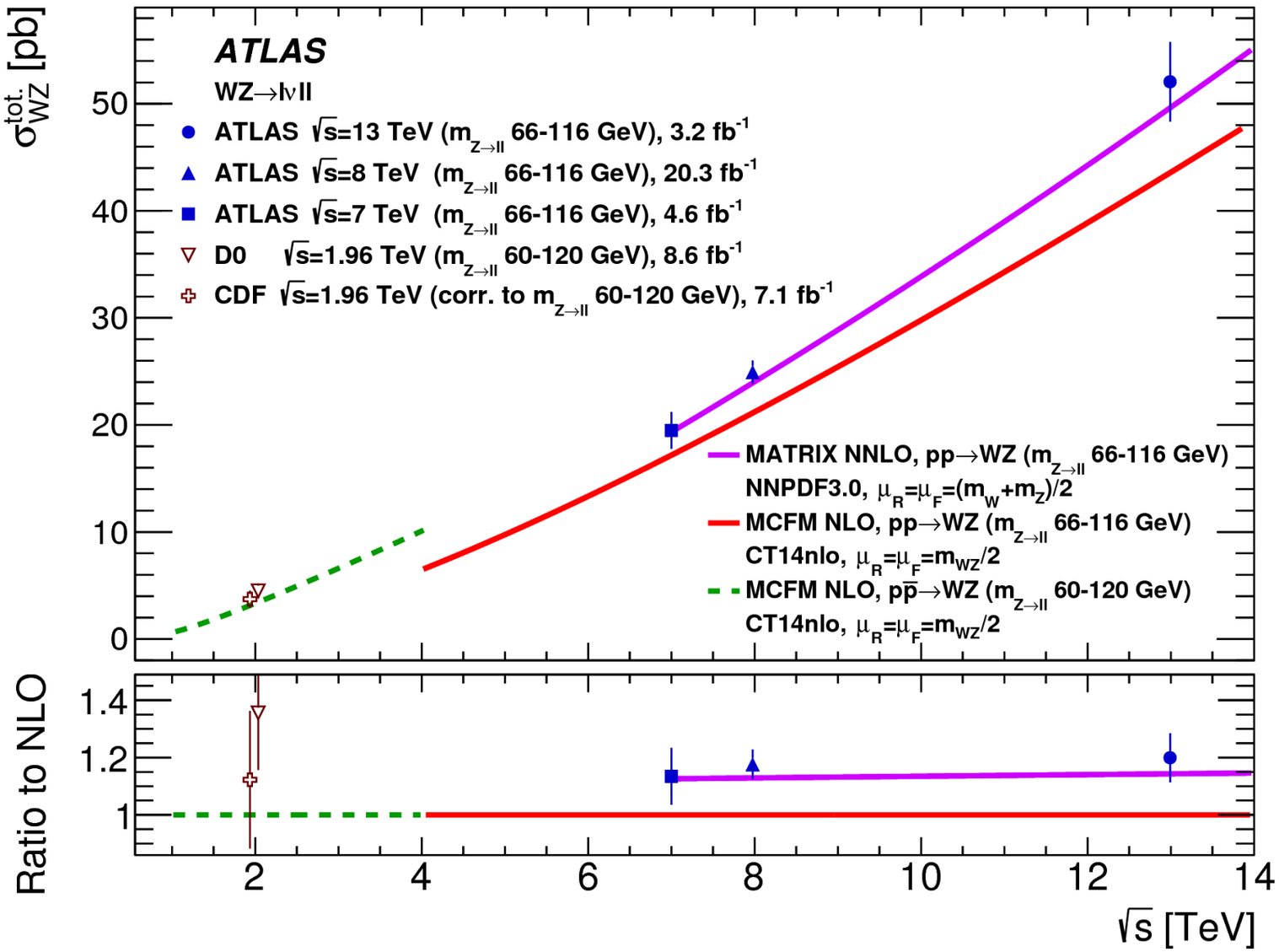




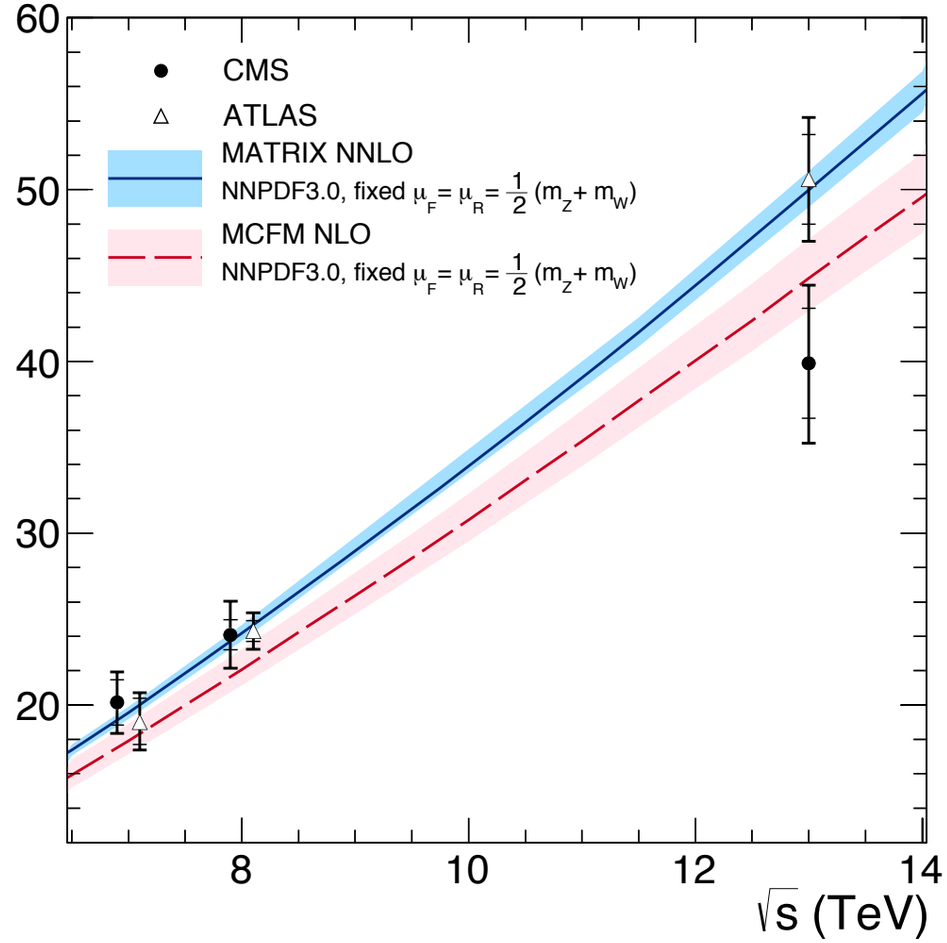
[Grazzini, Kallweit, Rathlev, MW '16]

Inclusive diboson results: NNLO vs data

[ATLAS '16]



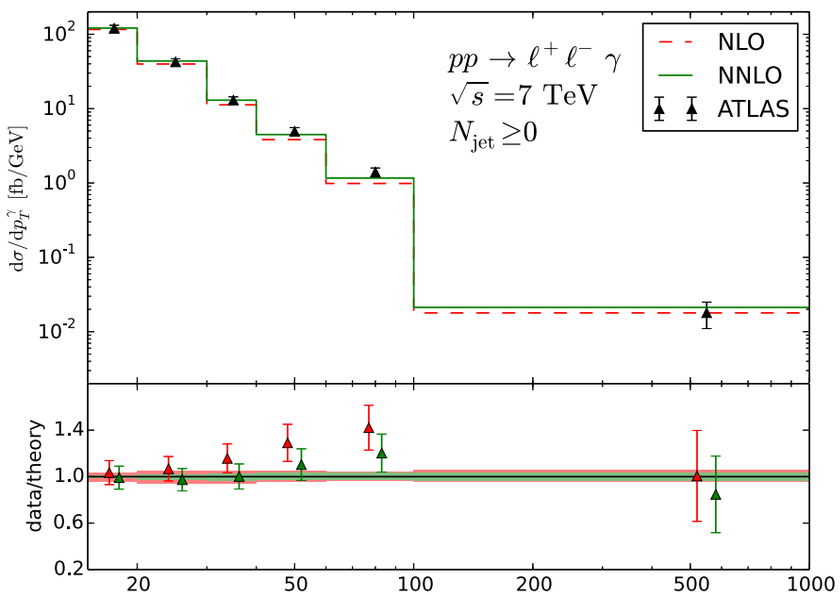
[CMS '16]



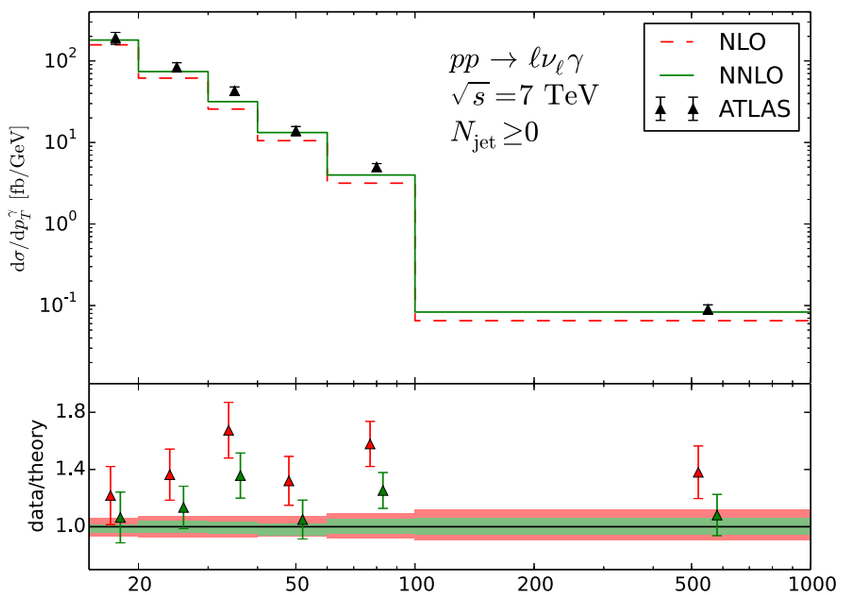
Differential diboson results: NNLO vs data

[Grazzini, Kallweit, Rathlev '15]

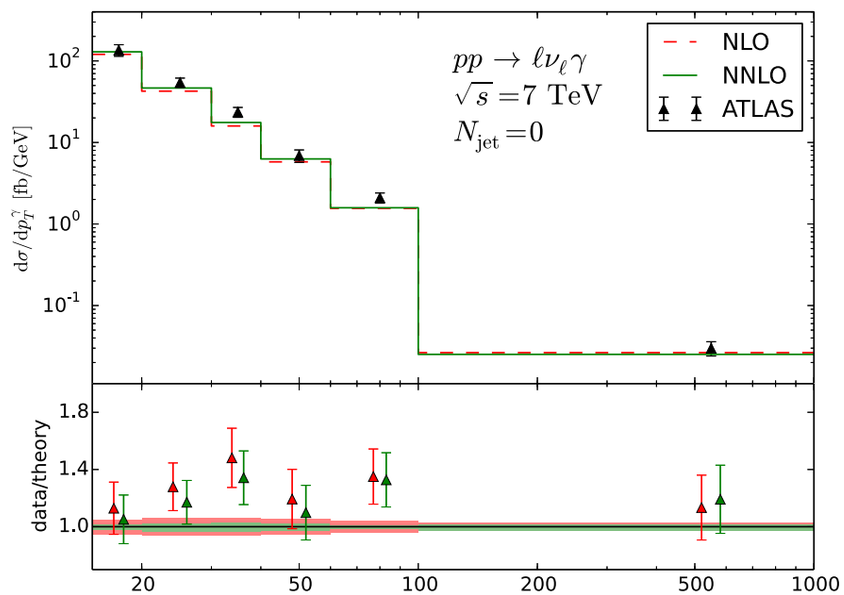
Zγ:



Wγ:

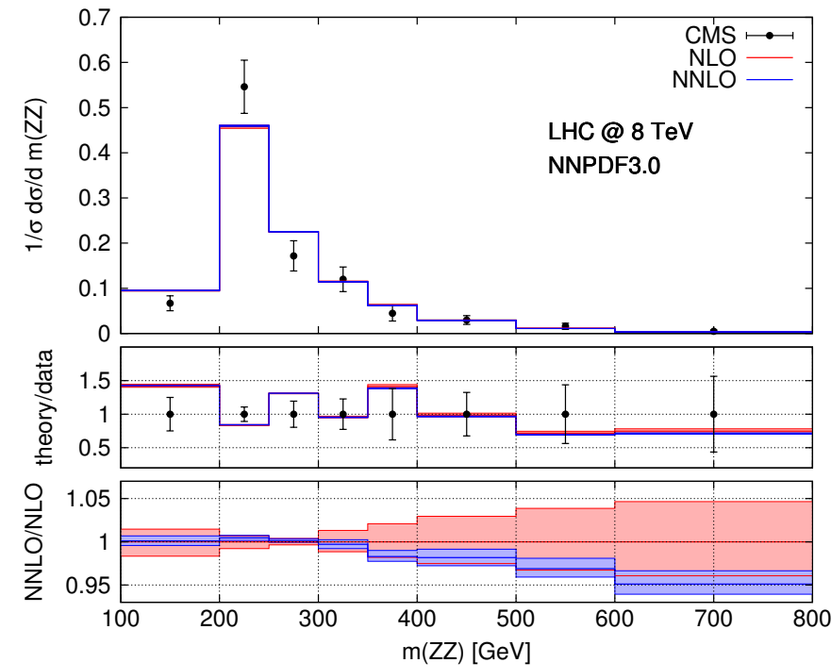


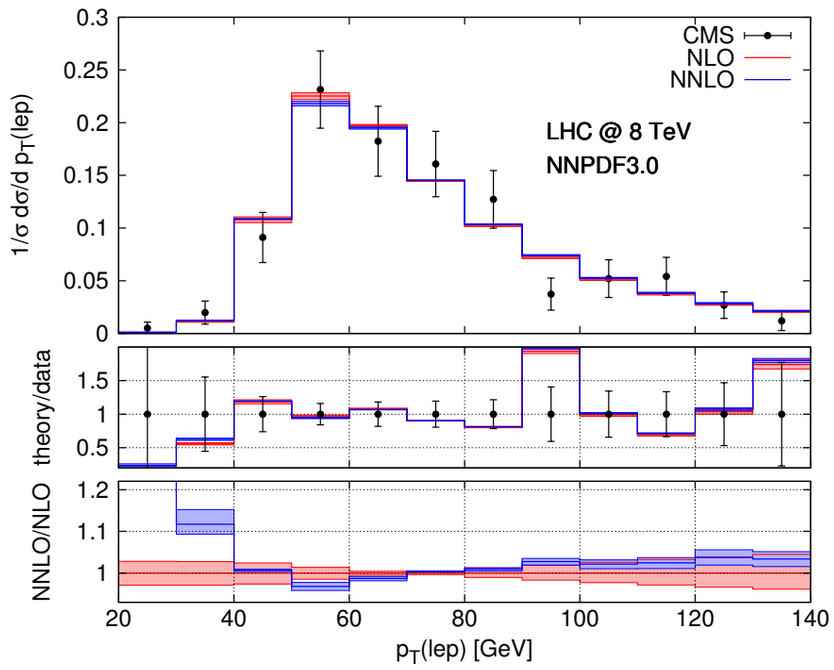
Wγ:

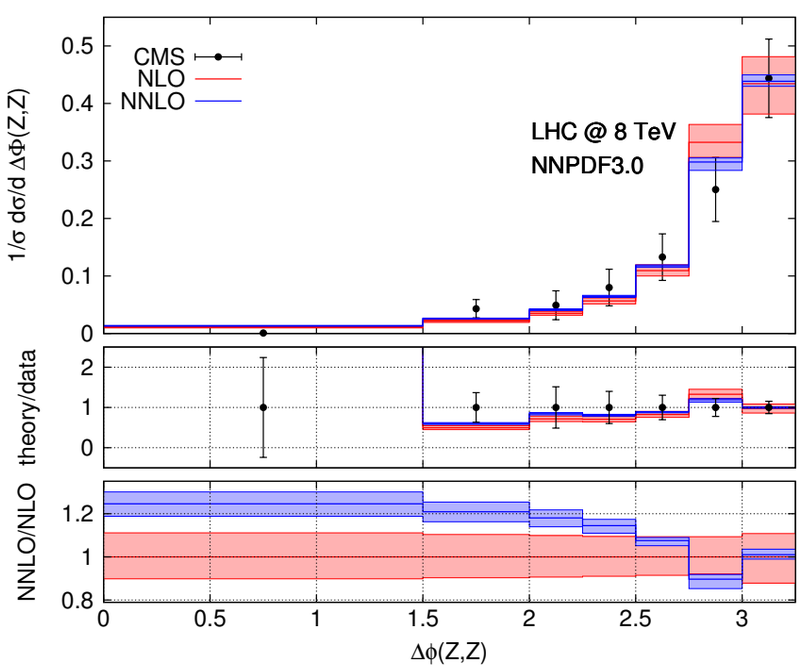


ZZ:

[Grazzini, Kallweit, Rathlev '15]







Differential diboson results: WW at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

σ [fb]	8 TeV	13 TeV
LO	$425.41(4)\,^{+2.8\%}_{-3.6\%}$	$778.99\ (8)\,^{+5.7\%}_{-6.7\%}$
NLO	$623.47(6)\,^{+3.6\%}_{-2.9\%}$	$1205.11(12)\,^{+3.9\%}_{-3.1\%}$
NLO′+gg	$655.83(8)\,^{+4.3\%}_{-3.3\%}$	$1286.81(13)\,^{+4.8\%}_{-3.7\%}$
NNLO	$690.4(5)\,^{+2.2\%}_{-1.9\%}$	$1370.9(11)\,^{+2.6\%}_{-2.3\%}$

fiducial rates (WW cuts)

8 TeV	13 TeV
$147.23(2)\,^{+3.4\%}_{-4.4\%}$	$233.04(2)\,^{+6.6\%}_{-7.6\%}$
$153.07(2)\,^{+1.9\%}_{-1.6\%}$	$236.19(2)\,^{+2.8\%}_{-2.4\%}$
$166.41(3)\,^{+1.3\%}_{-1.3\%}$	$267.31(4)\,^{+1.5\%}_{-2.1\%}$
$164.1\ (1)\,^{+1.3\%}_{-0.8\%}$	$261.5(2)\,^{+1.9\%}_{-1.2\%}$

NLO'+gg = NLO+gg BOTH with NNLO PDFs

→ acceptances (WW cuts)

$A = \sigma^{\text{cuts}}/\sigma^{\text{inclusive}}$	8 TeV	13 TeV
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	$0.29915(6)^{+0.8\%}_{-1.0\%}$
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	$0.19599(4)^{+4.4\%}_{-4.7\%}$
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	$0.20773(5)^{+3.2\%}_{-3.1\%}$
NNLO	$0.2378(4)\,^{+1.3\%}_{-0.9\%}$	$0.1907(3)\,^{+1.2\%}_{-0.9\%}$

Differential diboson results: WW at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

fiducial rates (WW cuts)

σ [fb]	8 TeV		13 TeV	
LO	$425.41(4)\,^{+2.8\%}_{-3.6\%}$	+47%	$778.99\ (8)\,^{+5.7\%}_{-6.7\%}$	+55%
NLO	$623.47(6)\,^{+3.6\%}_{-2.9\%}$	+5.2%	$1205.11(12)\,^{+3.9\%}_{-3.1\%}$	+6.8%
NLO′+gg	$655.83(8)\,^{+4.3\%}_{-3.3\%}$	+5.3%	$1286.81(13)\,^{+4.8\%}_{-3.7\%}$	+6.5%
NNLO	$690.4(5)\,^{+2.2\%}_{-1.9\%}$		$1370.9(11)\,^{+2.6\%}_{-2.3\%}$	

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Differential diboson results: WW at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

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NNLO	$690.4(5)\ ^{+2.2\%}_{-1.9\%}$		$1370.9(11)\ ^{+2.6\%}_{-2.3\%}$	

	8 TeV		13 TeV	
	$147.23(2)^{+3.4\%}_{-4.4\%}$	+4%	$233.04(2)^{+6.6\%}_{-7.6\%}$	+1.3%
	$153.07(2)^{+1.9\%}_{-1.6\%}$	+8.7%	$236.19(2)^{+2.8\%}_{-2.4\%}$	+13%
	$166.41(3)^{+1.3\%}_{-1.3\%}$	-1.4%	$267.31(4)^{+1.5\%}_{-2.1\%}$	-2.2%
	$164.1\ (1)^{+1.3\%}_{-0.8\%}$		$261.5(2)\ ^{+1.9\%}_{-1.2\%}$	

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NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	$0.19599(4)^{+4.4\%}_{-4.7\%}$
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	$0.20773(5)^{+3.2\%}_{-3.1\%}$
NNLO	$0.2378(4)\ ^{+1.3\%}_{-0.9\%}$	$0.1907(3)\ ^{+1.2\%}_{-0.9\%}$

Differential diboson results: WW at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

fiducial rates (WW cuts)

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$166.41(3)^{+1.3\%}_{-1.3\%}$	-1.4%	$267.31(4)^{+1.5\%}_{-2.1\%}$	-2.2%
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NLO'+gg = NLO+gg BOTH with NNLO PDFs

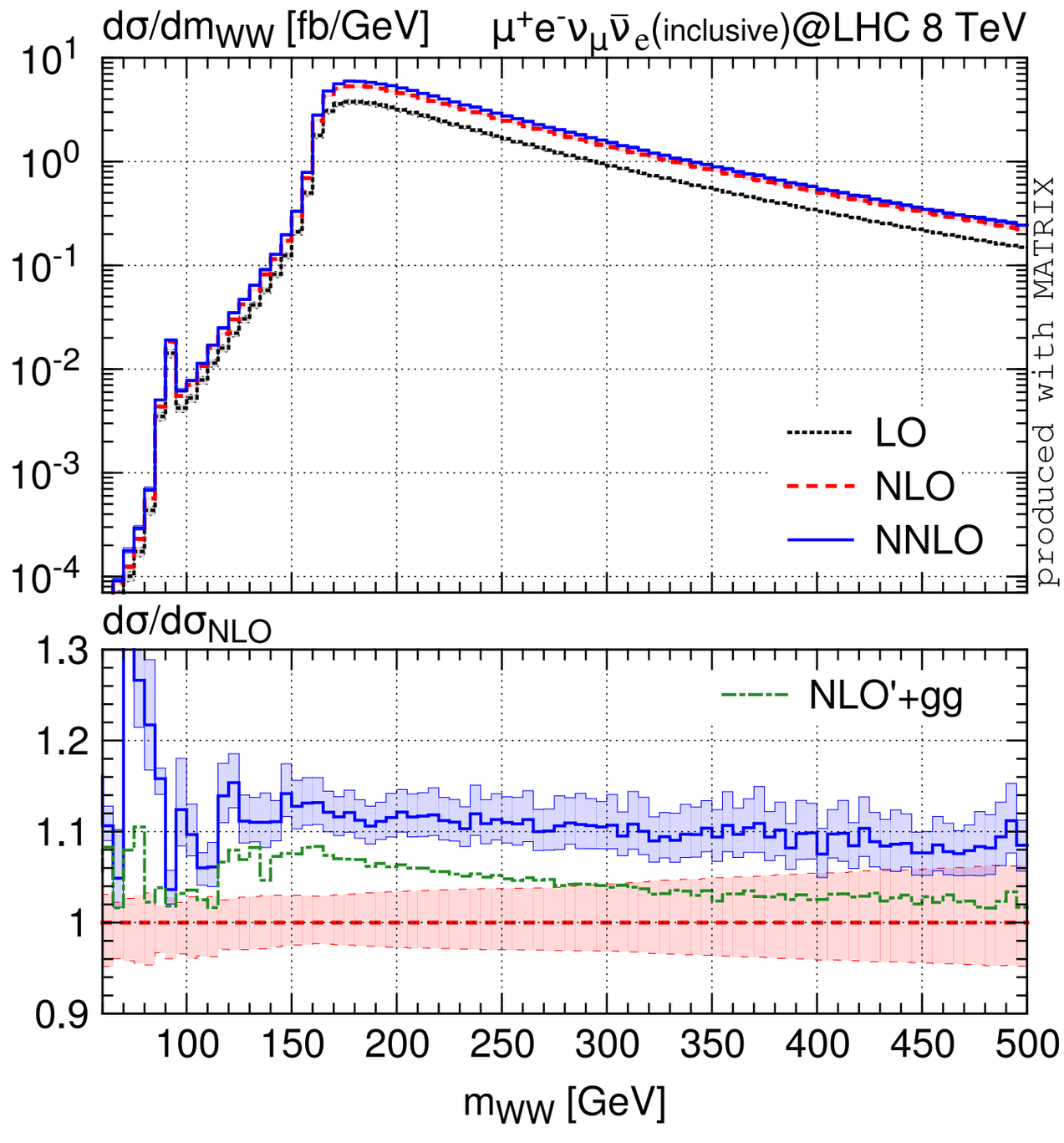
→ acceptances (WW cuts)

$A = \sigma^{\text{cuts}}/\sigma^{\text{inclusive}}$	8 TeV		13 TeV	
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	+29%	$0.29915(6)^{+0.8\%}_{-1.0\%}$	+34%
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	+3.3%	$0.19599(4)^{+4.4\%}_{-4.7\%}$	+6%
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	-6.3%	$0.20773(5)^{+3.2\%}_{-3.1\%}$	-8.2%
NNLO	$0.2378(4)\ ^{+1.3\%}_{-0.9\%}$		$0.1907(3)\ ^{+1.2\%}_{-0.9\%}$	

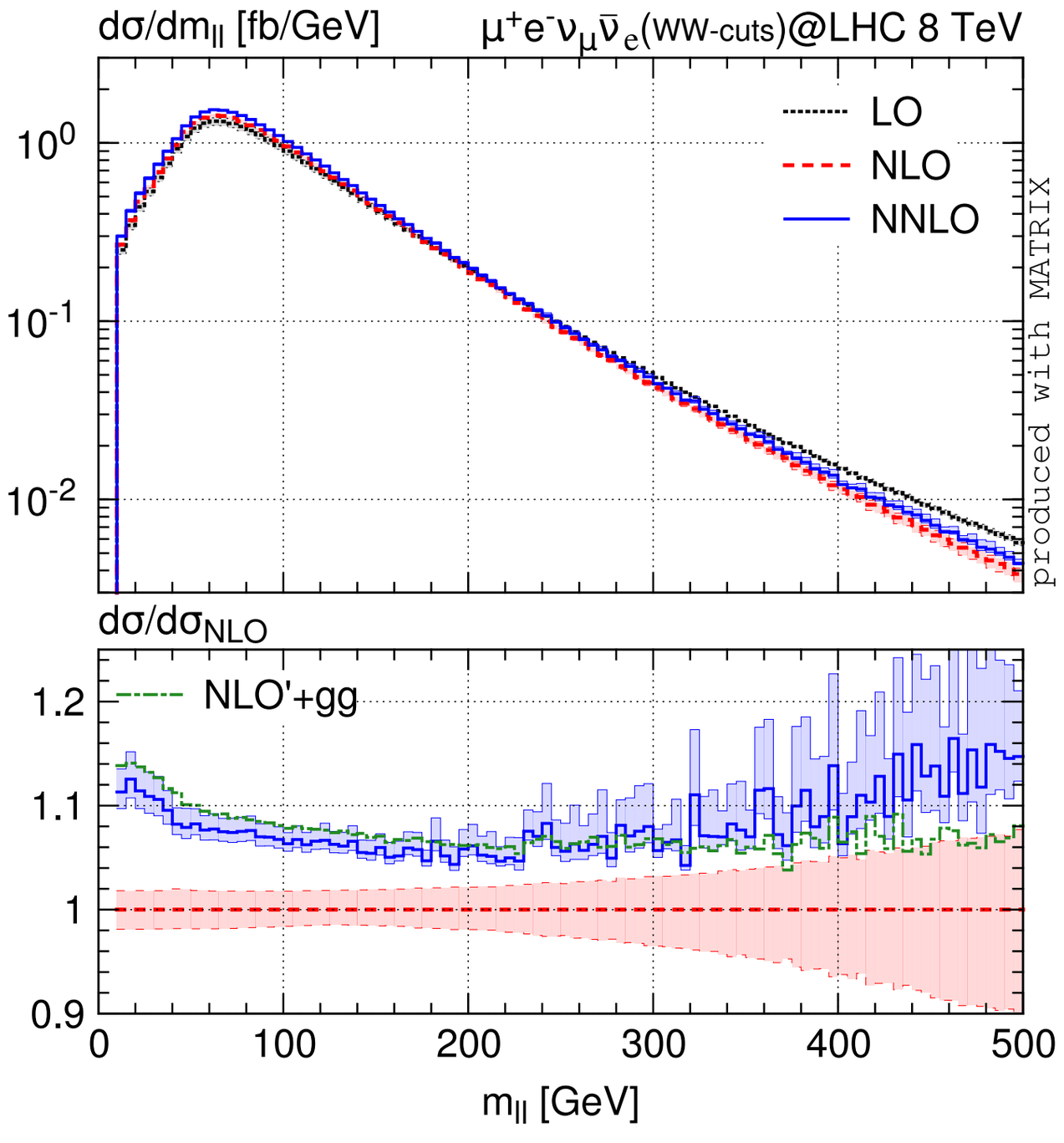
Differential diboson results: WW at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive

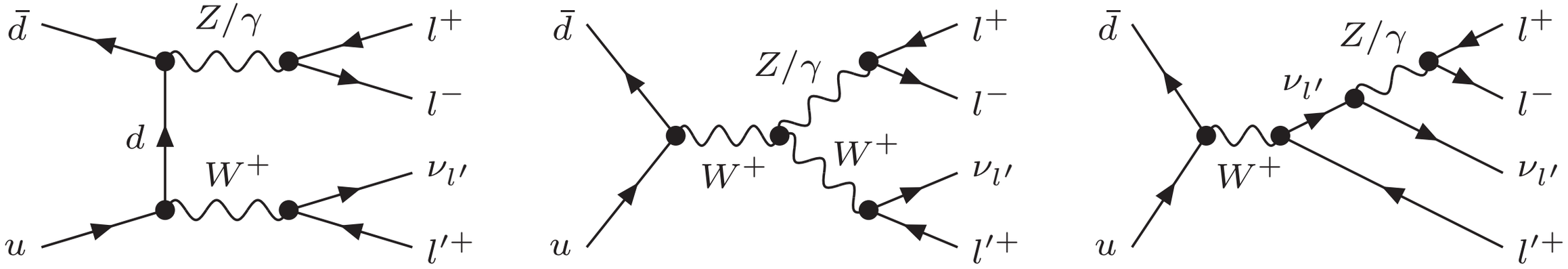


WW cuts



WZ fully differential at NNLO

[Grazzini, Kallweit, MW]



- no loop-induced gg component at NNLO
- Large QCD corrections due to radiation zero [Baur, Han, Ohnemus '94]

  → Large (~10%) NNLO corrections found for inclusive cross section [Grazzini, Kallweit Rathlev, MW '16]
- access to trilinear gauge coupling → relevance for BSM physics
- Diboson processes at NNLO completed!

WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

SM measurements

- various channels:
  - different-flavor (DF) channels

    $pp \to \mu^+\nu_\mu\, e^+e^-$, $pp \to e^+\nu_e\, \mu^+\mu^-$ (identical for massless fermions)

    $pp \to \mu^-\nu_\mu\, e^+e^-$, $pp \to e^-\nu_e\, \mu^+\mu^-$ (identical for massless fermions)
  - same-flavor (SF) channels

    $pp \to e^+\nu_e\, e^+e^-$, $pp \to \mu^+\nu_\mu\, \mu^+\mu^-$ (identical for massless fermions)

    $pp \to e^-\nu_e\, e^+e^-$, $pp \to \mu^-\nu_\mu\, \mu^+\mu^-$ (identical for massless fermions)
- fiducial phase space (ATLAS/CMS) for $pp \to l'\nu_{l'}ll$ $(l,l' \in \{e,\mu\})$
  - Z/W reconstruction: trivial for DF; CMS: Z=lepton pair closest to m_Z, ATLAS: "resonant shape" for SF [arXiv:1603.02151]

for all possible combinations of pairs $W=(l',\nu_{l'})$ and $Z=(l^+,l^-)$ compute

$$P = \left| \frac{1}{m^2_{(\ell^+,\ell^-)} - \left(m_Z^{\rm PDG}\right)^2 + i\,\Gamma_Z^{\rm PDG}\, m_Z^{\rm PDG}} \right|^2 \times \left| \frac{1}{m^2_{(\ell',\nu_{\ell'})} - \left(m_W^{\rm PDG}\right)^2 + i\,\Gamma_W^{\rm PDG}\, m_W^{\rm PDG}} \right|^2$$

and identify W and Z bosons by combination with highest estimator value P

WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

SM measurements

- various channels:
  - different-flavor (DF) channels

    $pp \to \mu^+\nu_\mu\, e^+e^-$, $pp \to e^+\nu_e\, \mu^+\mu^-$ (identical for massless fermions)

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  - Z/W reconstruction: trivial for DF; CMS: Z=lepton pair closest to m_Z, ATLAS: "resonant shape" for SF

	definition of the fiducial volume for $pp \to \ell^\pm_{\rm w}\nu_{\ell_{\rm w}}\ell^+_{\rm z}\ell^-_{\rm z}$, $\quad \ell,\ell_{\rm w},\ell_{\rm z} \in \{e,\mu\}$
ATLAS 8/13 TeV (cf. Ref. [5, 6])	$p_{T,\ell_{\rm z}} > 15\,\text{GeV}$, $\quad p_{T,\ell_{\rm w}} > 20\,\text{GeV}$, $\quad \eta_\ell < 2.5$, $\quad \lvert m_{\ell_{\rm z}\ell_{\rm z}} - m_Z\rvert < 10\,\text{GeV}$, $\quad m_{T,W} > 30\,\text{GeV}$, $\quad \Delta R_{\ell_{\rm z}\ell_{\rm z}} > 0.2$, $\quad \Delta R_{\ell_{\rm z}\ell_{\rm w}} > 0.3$
CMS 13 TeV (cf. Ref. [7])	$p_{T,\ell_{\rm z},1} > 20\,\text{GeV}$, $\quad p_{T,\ell_{\rm z},2} > 10\,\text{GeV}$, $\quad p_{T,\ell_{\rm w}} > 20\,\text{GeV}$, $\quad \eta_\ell < 2.5$, $\quad 60\,\text{GeV} < m_{\ell_{\rm z}\ell_{\rm z}} < 120\,\text{GeV}$, $\quad m_{\ell^+\ell^-} > 4\,\text{GeV}$

WZ fully differential at NNLO [Grazzini, Kallweit, MW]

SM measurements

ATLAS (8 TeV):

$\mu^\pm e^+ e^-$	$18.32(0)^{+2.3\%}_{-3.2\%}$	$32.76(1)^{+5.4\%}_{-4.1\%}$	$35.53(2)^{+1.8\%}_{-1.9\%}$	$36.3 \pm 5.4\%(\text{stat}) \pm 2.6\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm \mu^+ \mu^-$				$35.7 \pm 5.3\%(\text{stat}) \pm 3.7\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm e^+ e^-$	$18.37(0)^{+2.3\%}_{-3.2\%}$	$32.85(1)^{+5.4\%}_{-4.1\%}$	$35.64(2)^{+1.8\%}_{-1.9\%}$	$38.1 \pm 6.2\%(\text{stat}) \pm 4.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^\pm \mu^+ \mu^-$				$33.3 \pm 4.7\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
combined	$18.35(0)^{+2.3\%}_{-3.2\%}$	$32.81(1)^{+5.4\%}_{-4.1\%}$	$35.59(2)^{+1.8\%}_{-1.9\%}$	$35.1 \pm 2.7\%(\text{stat}) \pm 2.4\%(\text{syst}) \pm 2.2\%(\text{lumi})$

ATLAS (13 TeV):

$\mu^\pm e^+ e^-$	$28.83(0)^{+5.4\%}_{-6.5\%}$	$57.69(1)^{+5.4\%}_{-4.3\%}$	$63.93(3)^{+2.3\%}_{-2.1\%}$	$55.1 \pm 11.1\%(\text{stat}) \pm 5.1\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$e^\pm \mu^+ \mu^-$				$75.2 \pm 9.5\%(\text{stat}) \pm 5.3\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^\pm e^+ e^-$	$28.90(0)^{+5.4\%}_{-6.5\%}$	$57.84(1)^{+5.4\%}_{-4.3\%}$	$64.09(3)^{+2.2\%}_{-2.1\%}$	$50.5 \pm 14.2\%(\text{stat}) \pm 10.6\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$\mu^\pm \mu^+ \mu^-$				$63.6 \pm 8.9\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.3\%(\text{lumi})$
combined	$28.86(0)^{+5.4\%}_{-6.5\%}$	$57.76(1)^{+5.4\%}_{-4.3\%}$	$64.01(3)^{+2.3\%}_{-2.1\%}$	$63.2 \pm 5.2\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.4\%(\text{lumi})$

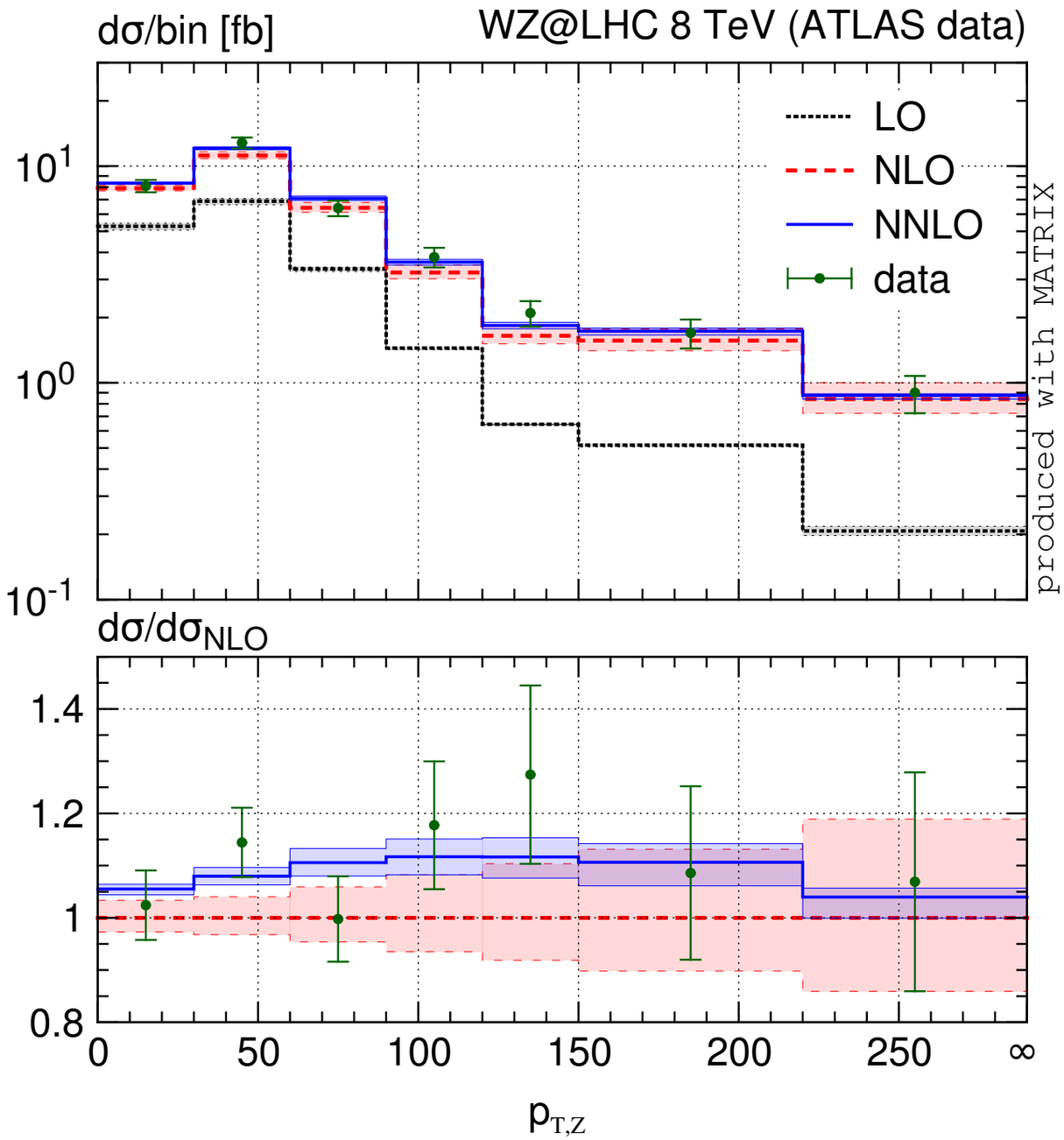
CMS (13 TeV):

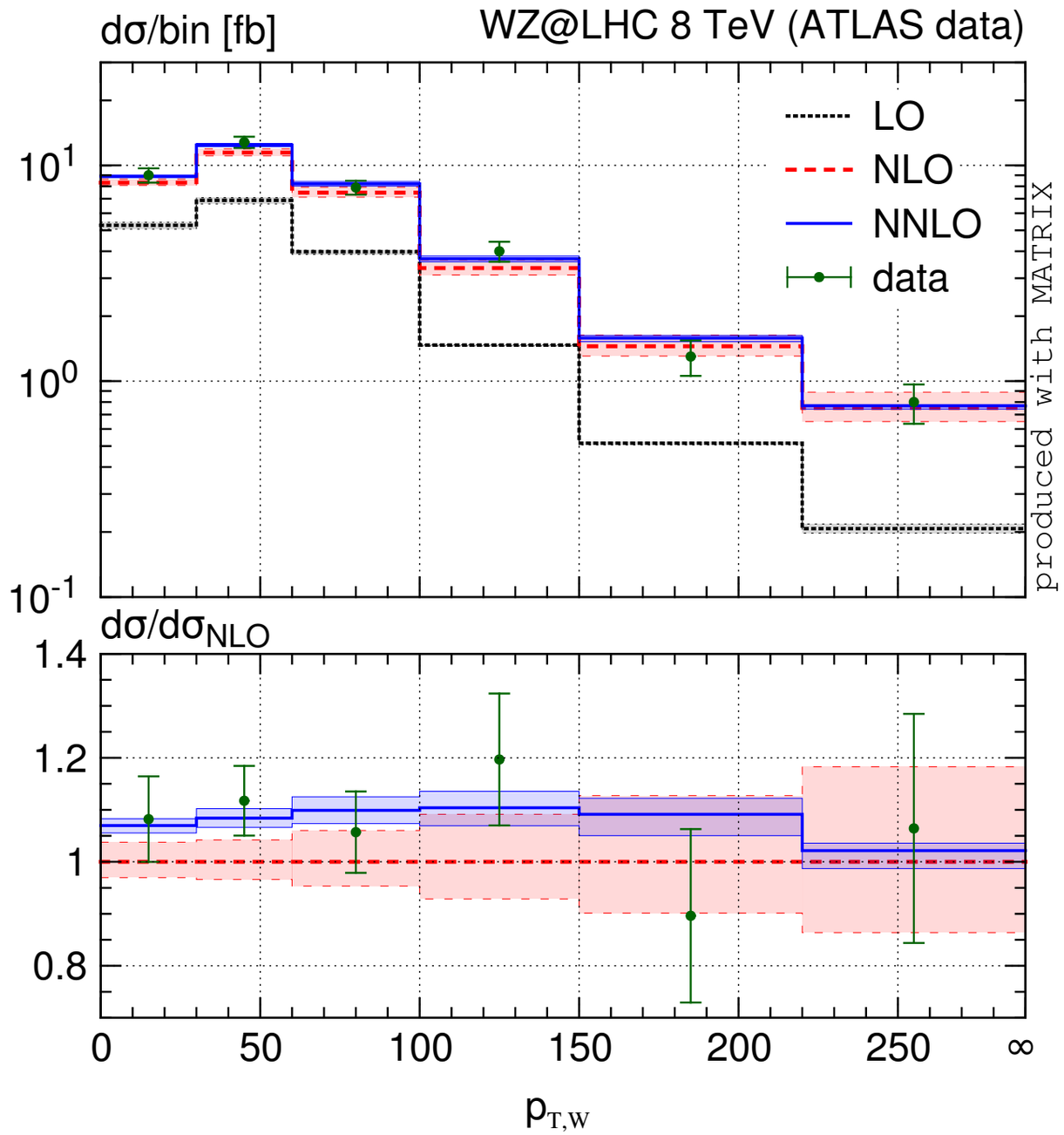
channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{CMS} [fb]
combined	$148.4(0)^{+5.4\%}_{-6.4\%}$	$301.4(1)^{+5.5\%}_{-4.5\%}$	$334.3(2)^{+2.3\%}_{-2.1\%}$	$258 \pm 8.1\%(\text{stat})^{+7.4\%}_{-7.7\%}(\text{syst}) \pm 3.1(\text{lumi})$

WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

SM measurements

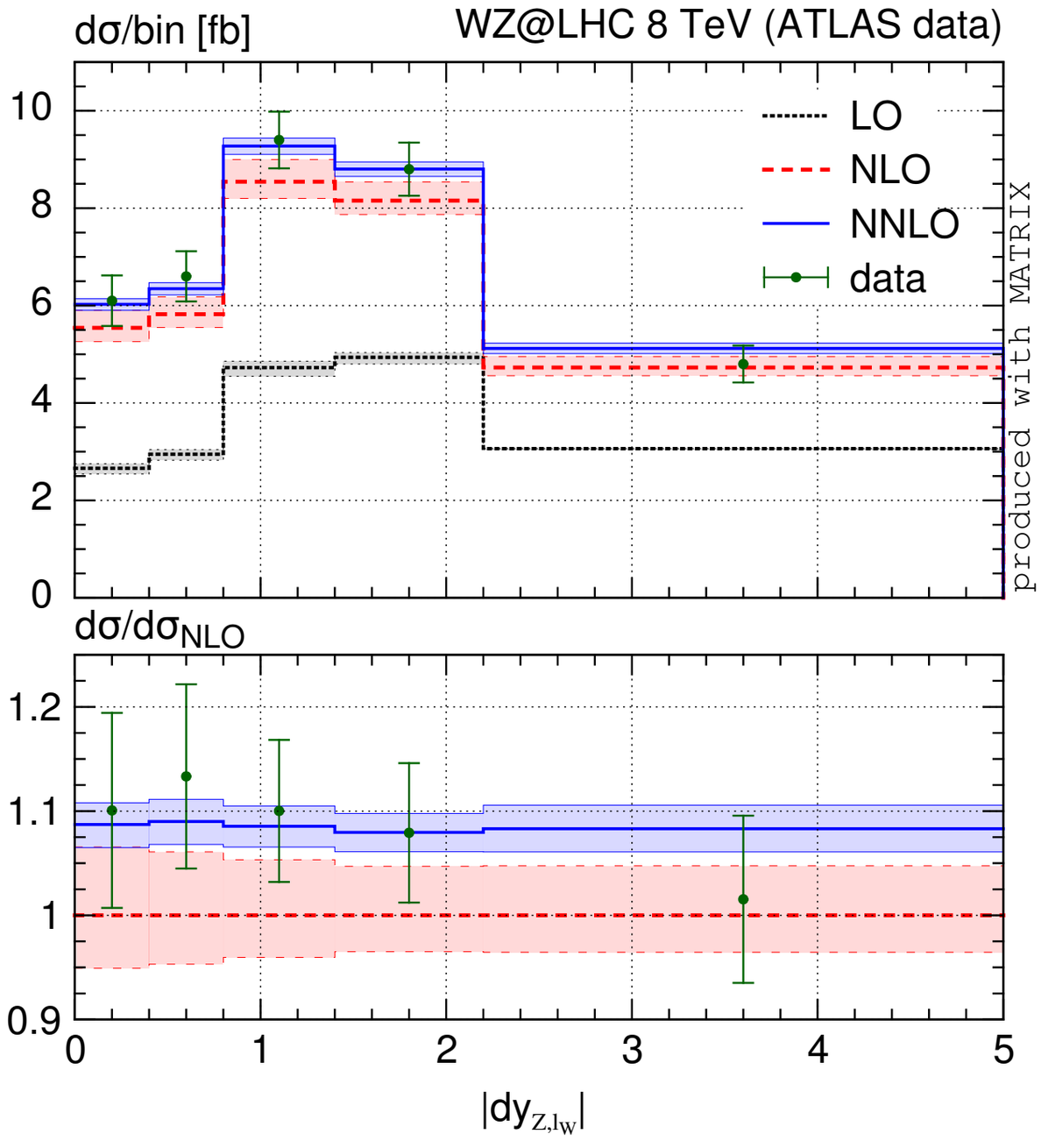


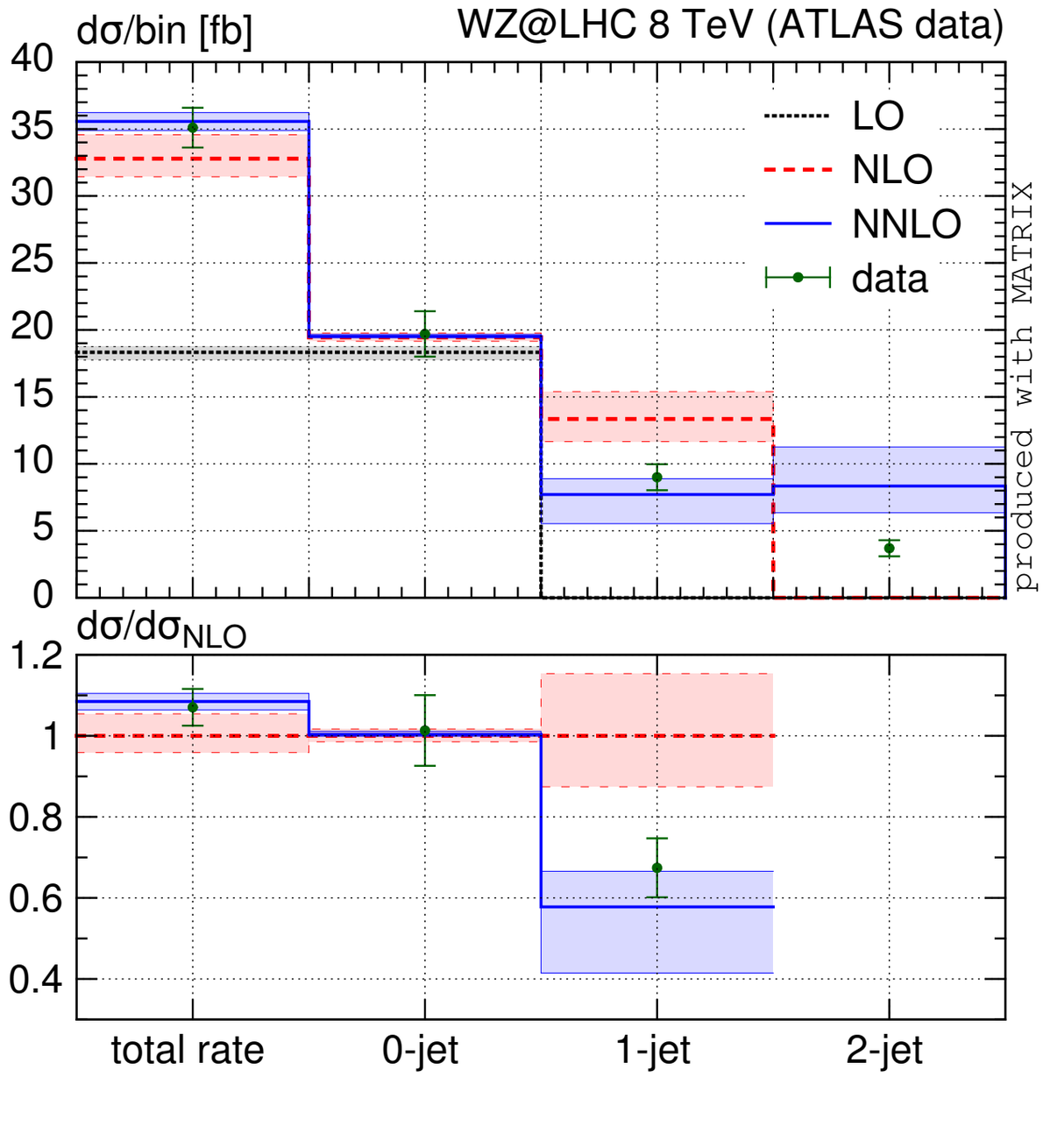


WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

SM measurements

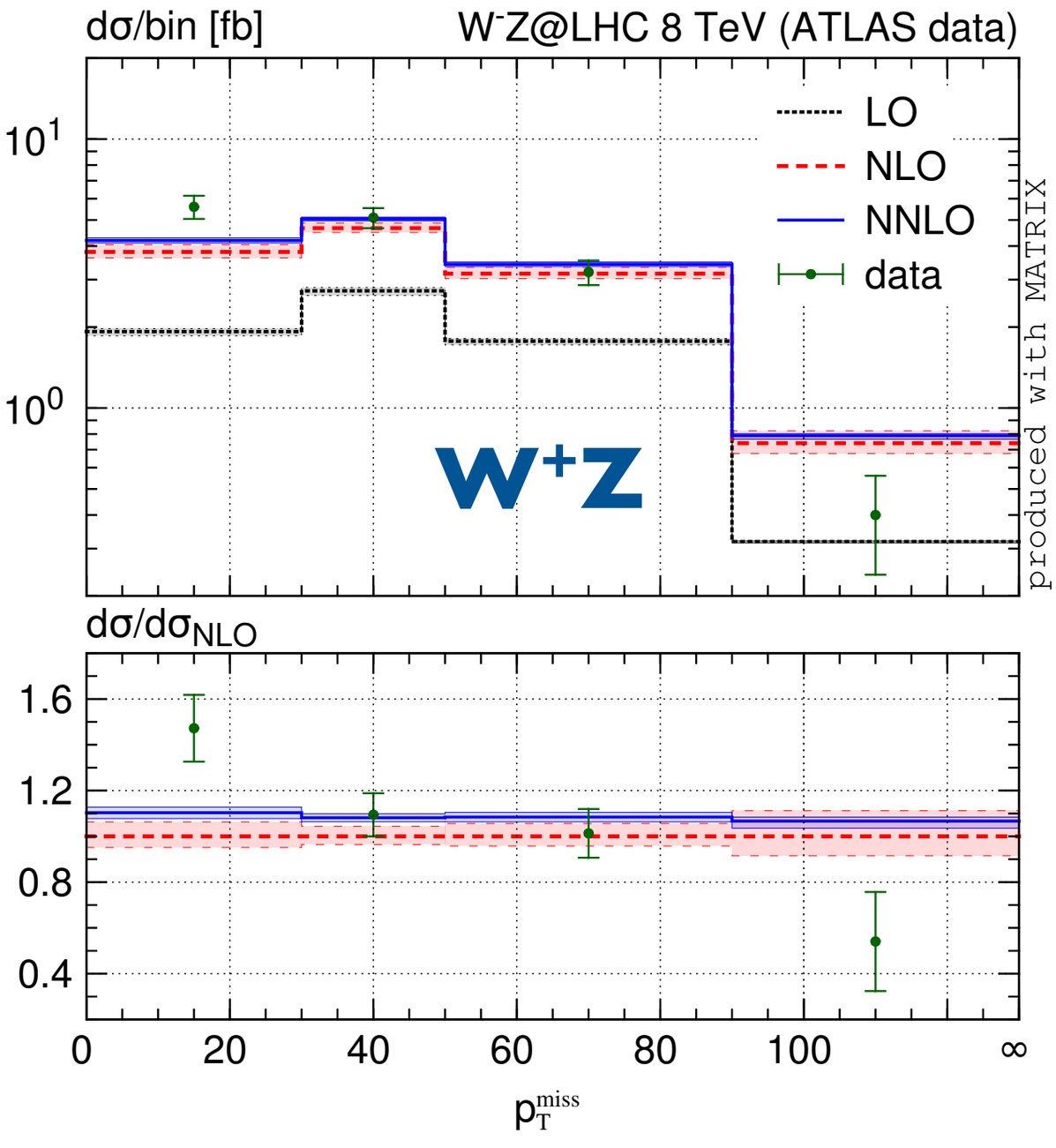


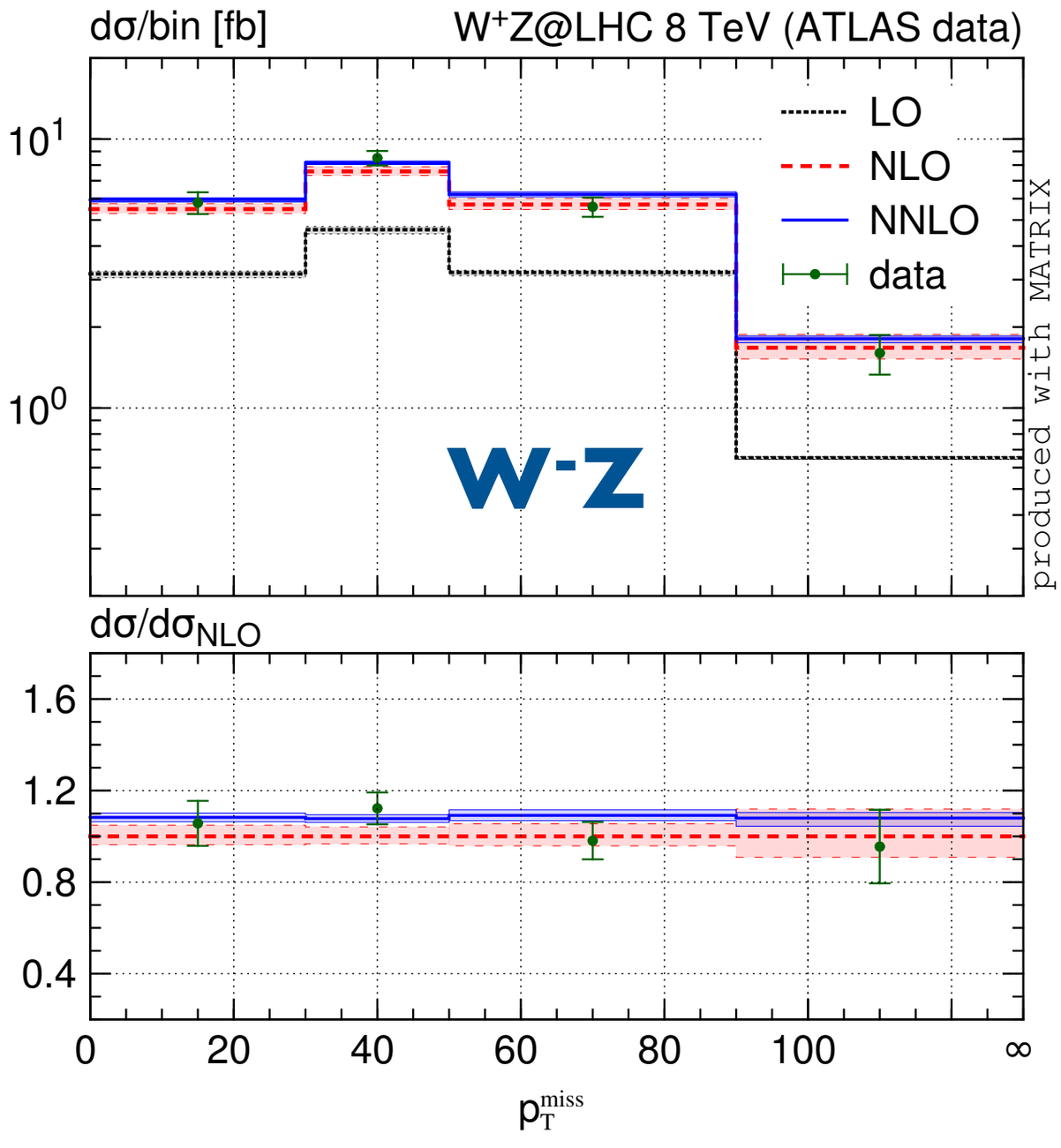


WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

SM measurements

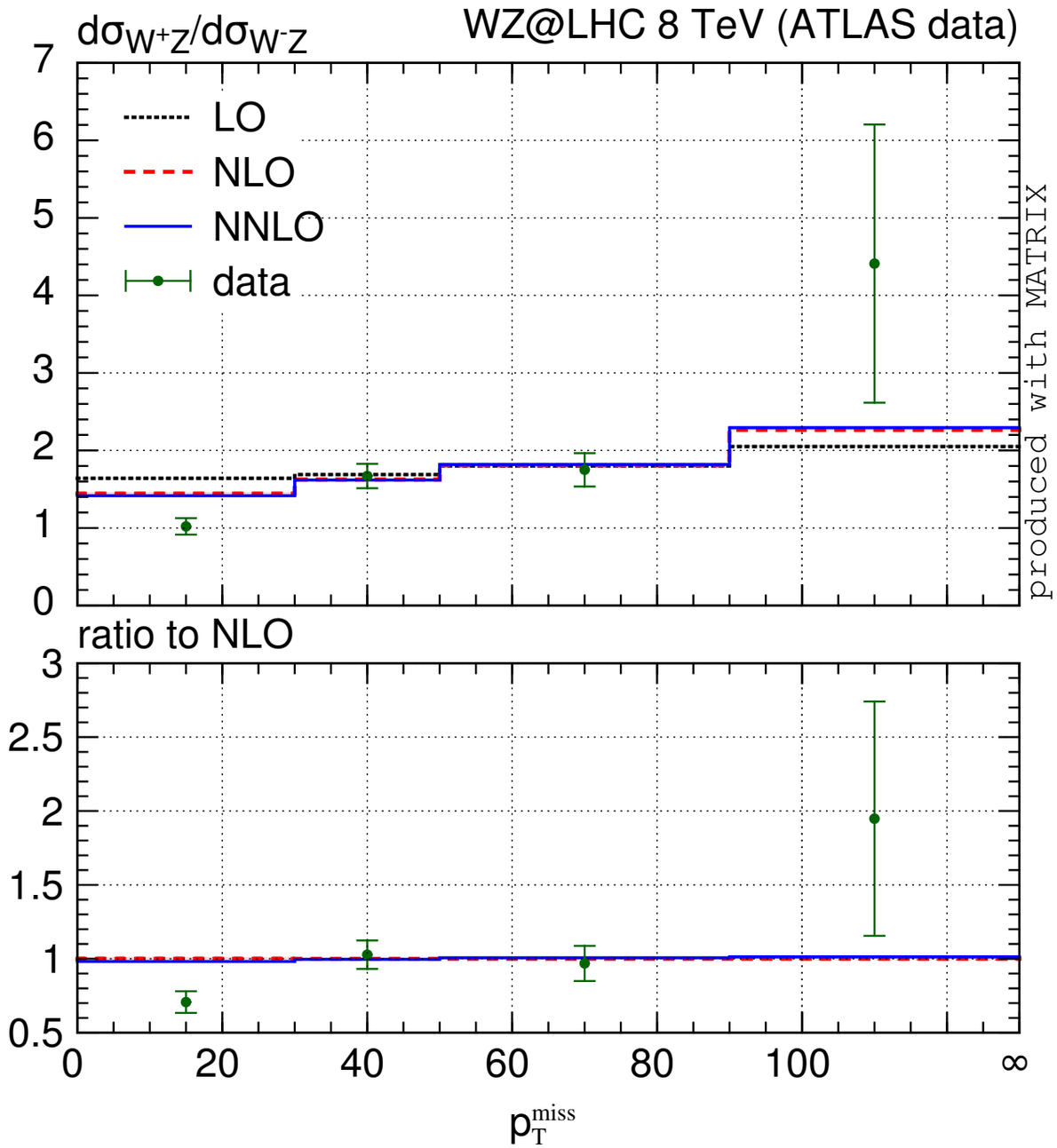


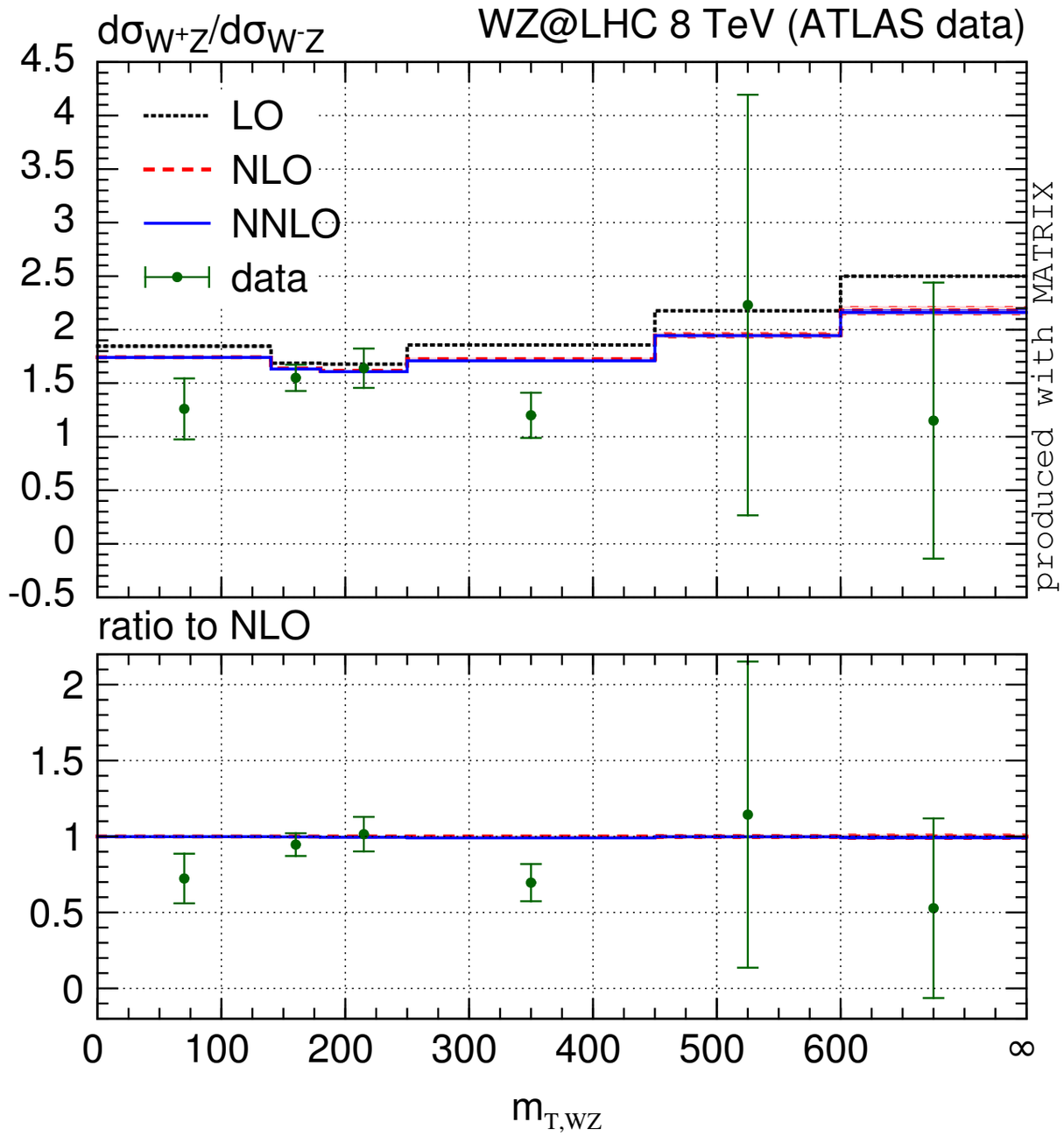


WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

SM measurements





WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

inspired by [CMS-PAS-SUS-16-024]

	definition of the selection cuts for $pp \to \ell_{\rm w}^{\pm}\nu_{\ell_{\rm w}}\ell_{\rm z}^{+}\ell_{\rm z}^{-}, \quad \ell, \ell_{\rm z}, \ell_{\rm w} \in \{e, \mu\}$
CMS 13 TeV (cf. Ref. [63])	$p_{T,\ell_1} > 25(20)\,\text{GeV}$ if $\ell_1 = e(\mu), \quad p_{T,\ell_1} > 25\,\text{GeV}$ if $\ell_1 = \mu$ and $\ell_{\geq 2} \neq \mu$ $p_{T,\ell_{\geq 2}} > 15(10)\,\text{GeV}$ if $\ell_{\geq 2} = e(\mu), \quad \eta_e < 2.5, \quad \eta_\mu < 2.4,$ $\lvert m_{3\ell} - m_Z \rvert > 15\,\text{GeV}, \quad m_{\ell^+\ell^-} > 12\,\text{GeV}$

Category I: no additional cut

Category II: $p_T^{\rm miss} > 200\,\text{GeV}$

Category III: $m_{T,W} > 120\,\text{GeV}$

Category IV: $m_{\ell_{\rm z}\ell_{\rm z}} > 105\,\text{GeV}$

New-physics searches

Category I: no additional cut

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Category IV: $m_{\ell_z\ell_z} > 105\,\text{GeV}$

channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	$\sigma_{\text{NLO}}/\sigma_{\text{LO}}$	$\sigma_{\text{NNLO}}/\sigma_{\text{NLO}}$ [fb]
		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%
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QCD corrections VERY different for various Categories (cuts)

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm NLO}/\sigma_{\rm LO}$	$\sigma_{\rm NNLO}/\sigma_{\rm NLO}$ [fb]
		Category I			
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		Category III			
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		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%
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SF and DF channels different by factor of 3 for $m_{T,W}$>120 GeV

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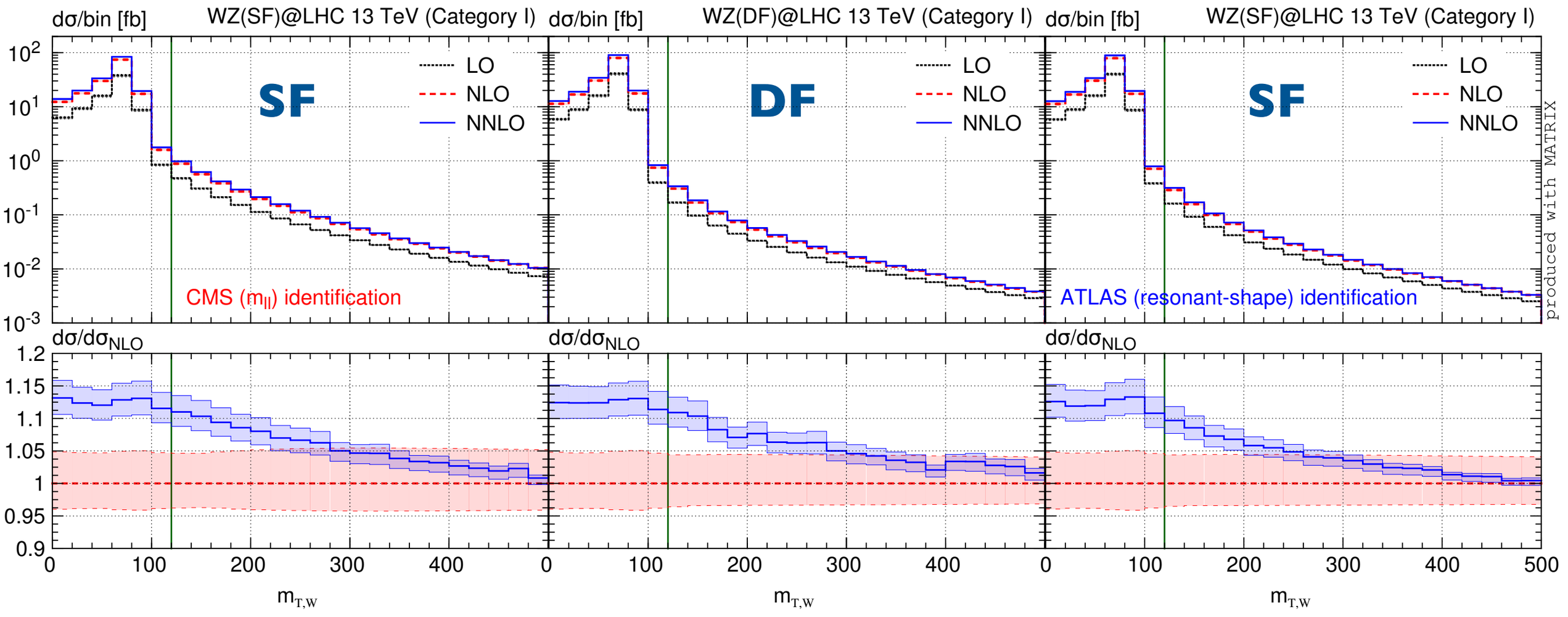
WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category I: no additional cuts



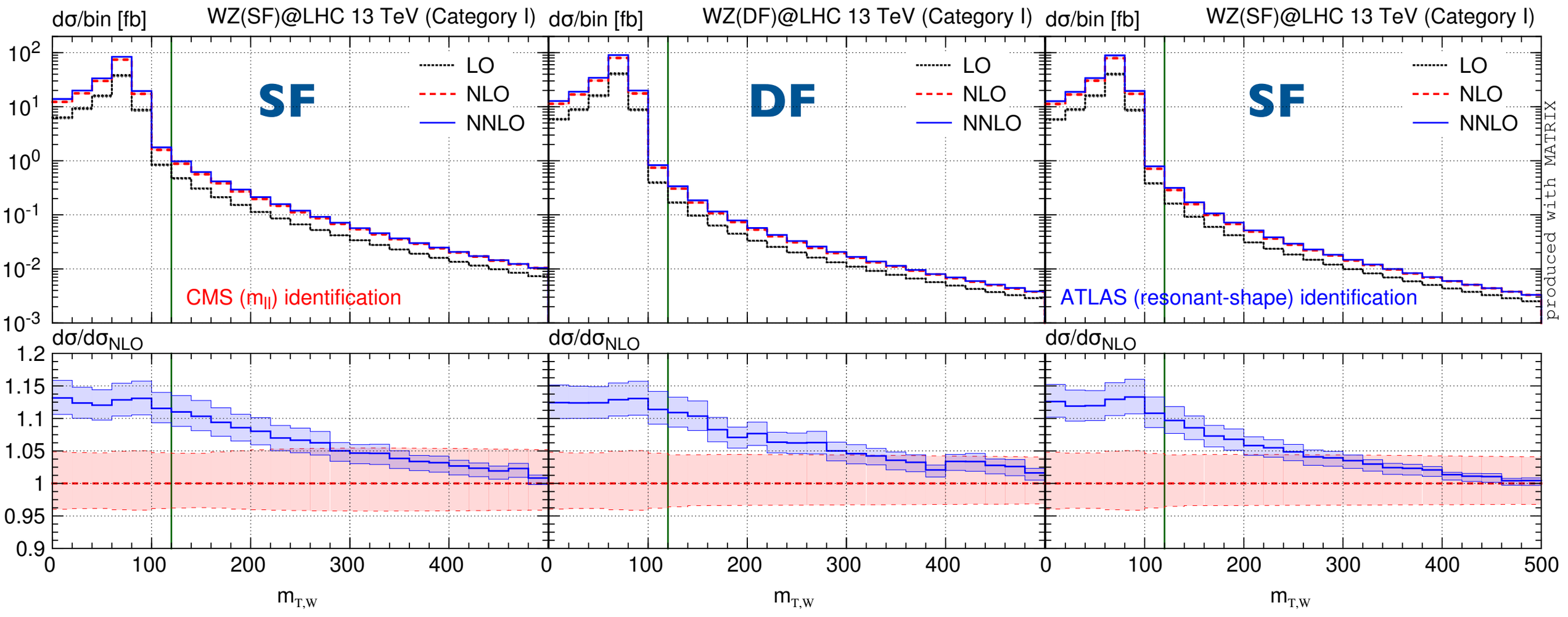
SF and DF channels different by factor of 3 for $m_{T,W}$>120 GeV

WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category I: no additional cuts



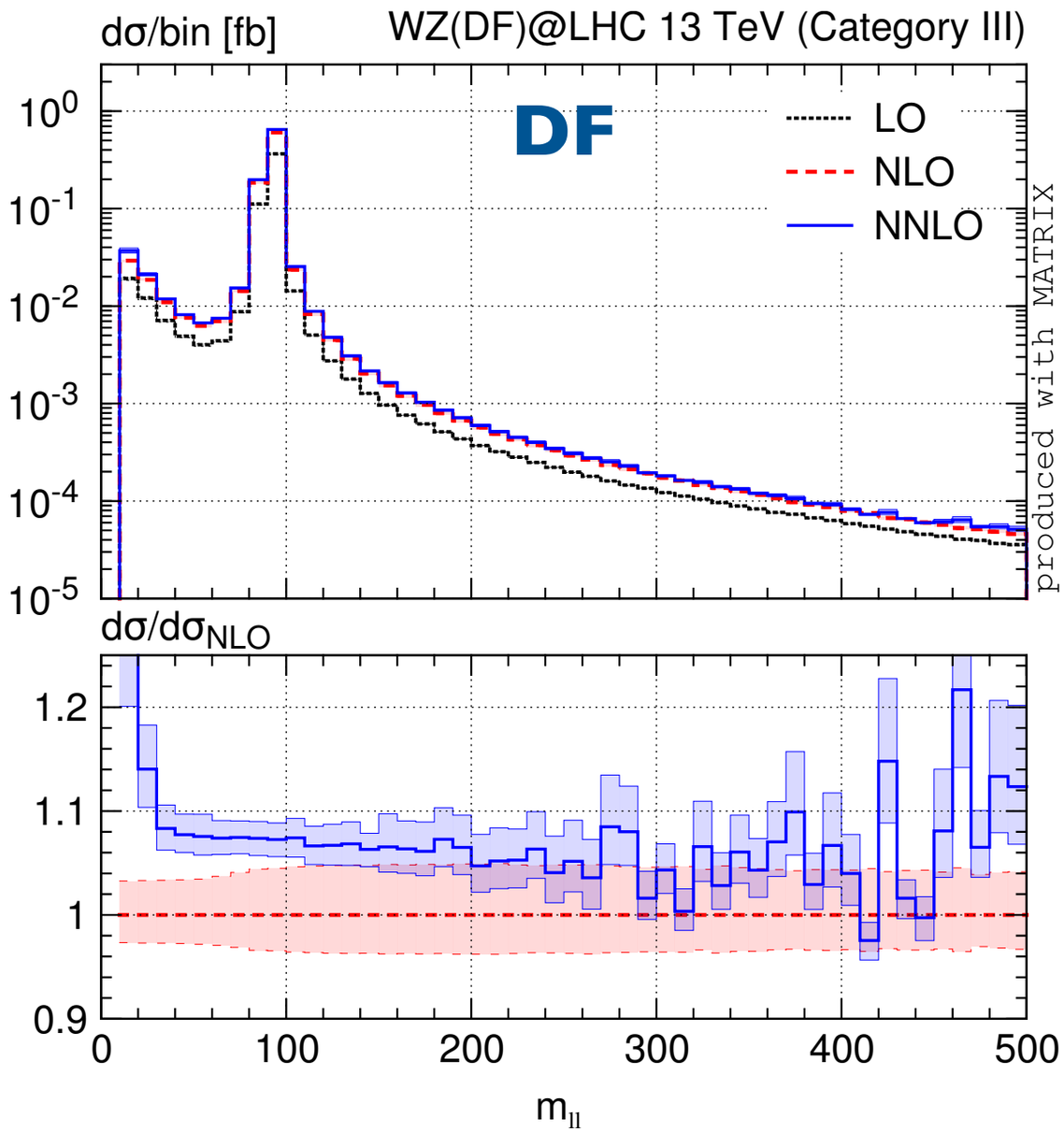
SF and DF channels different by factor of 3 for $m_{T,W}$>120 GeV → **REASON: W/Z identification**

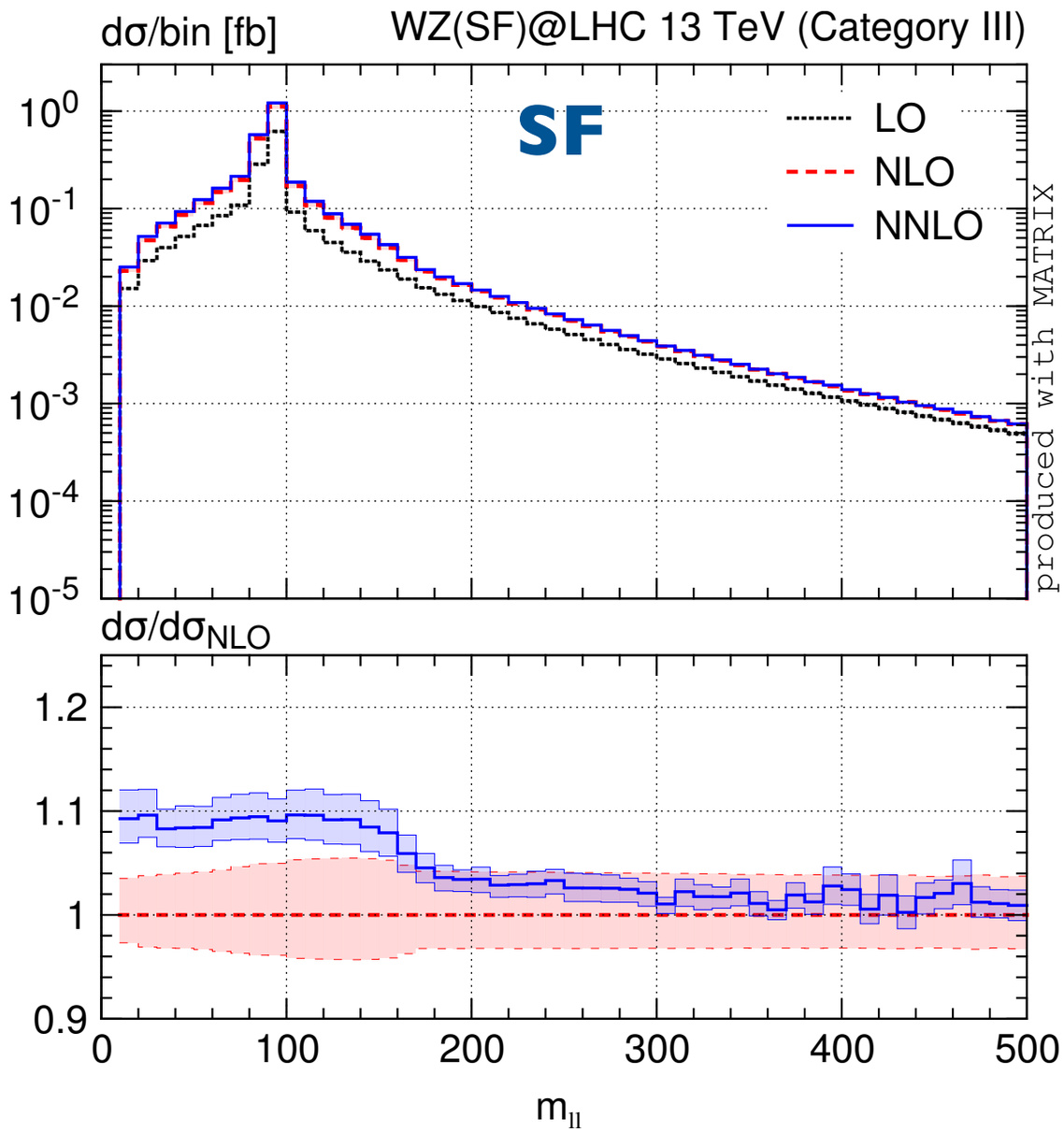
WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category III: $m_{T,W}$>120 GeV



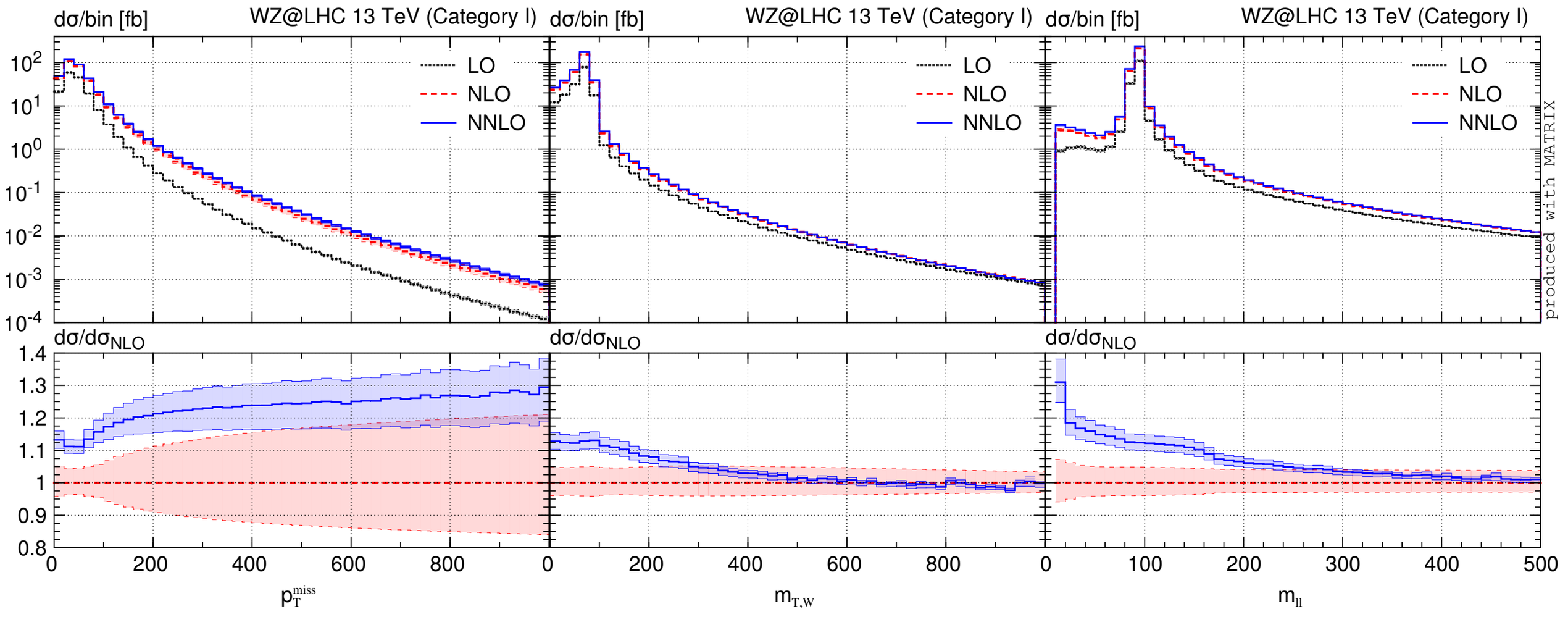


WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category I: no additional cuts



Summary

MATRIX:

- tool for fully-differential NNLO(+NNLL) computations -- flexible, powerful **and** simple!
- **currently:** closed beta
- large list of 2→1, 2→2 Higgs and vector-boson processes
- **includes:** EW decays, **with:** all topologies, off-shell effects, spin correlations

  → realistic computation of cross section in the fiducial phase space

Physics applications:

- **evident:** importance of NNLO for precision and accuracy (to describe data)
- WZ: finalizes diboson processes at NNLO (both: inclusive & differentially)
- NNLO agrees well with data for $\ell\nu\ell\ell$ (SF)+$\ell'\nu'\ell\ell$ (DF) (both: normalization & shapes)
- NP searches: large corrections on relevant observables; SF: strong dependence on identification

Outlook

- **soon:** public version of MATRIX
- NNLO corrections to ZZ with neutrino decay; mixed ZZ/WW→ $\ell\nu\ell\nu$ channel
- **many things to do, include:** p_T resummation, loop-induced gg, NLO EW, ...

FREE YOUR MIND.

THE MATRIX

Thank You !

Back Up

Status of NNLO processes

- All vector-boson pair production processes completed (fully-differential)
- All essential $2\to1$, $2\to2$ process with H, γ, Z, W included (only HZ/HW missing)
- More precisely: We consider the full process with leptonic final states (decays)
  - all leptonic decays with ℓ and ν
  - all resonant and non-resonant structures that lead to the respective final state
  - spin correlations
  - off-shell effects
- loop-induced gg component for electrically neutral processes consistently included up to NNLO (effectively LO accurate)

Running phases

- The running is separated into three main phases, which can be accessed individually by typing "`run_grid`"/"`run_pre`"/"`run_main`" instead of "`run`".
- Each phase requires the previous phases to be successfully done!

```
[|============>> 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
```

Running phases

- The running is separated into three main phases, which can be accessed individually by typing "`run_grid`"/"`run_pre`"/"`run_main`" instead of "`run`".
- Each phase requires the previous phases to be successfully done!
  - warmup ("`run_grid`")
    - generates the integration grids needed for pre and main run.

```
[|============>> 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
```

Running phases

- The running is separated into three main phases, which can be accessed individually by typing "`run_grid`"/"`run_pre`"/"`run_main`" instead of "`run`".
- Each phase requires the previous phases to be successfully done!
  - warmup ("`run_grid`")
    - generates the integration grids needed for pre and main run.
  - runtime extrapolation ("`run_pre`")
    - short test runs to estimate runtime
    - prints preliminary result at the end

```
[|============>> 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
```

Running phases

- The running is separated into three main phases, which can be accessed individually by typing "`run_grid`"/"`run_pre`"/"`run_main`" instead of "`run`".
- Each phase requires the previous phases to be successfully done!
  - warmup ("`run_grid`")
    - generates the integration grids needed for pre and main run.
  - runtime extrapolation ("`run_pre`")
    - short test runs to estimate runtime
    - prints preliminary result at the end
  - x-section computation ("`run_main`")
    - parallelized by runtime from pre run, `max_time_per_job` and `accuracy`
    - starts result combination+gnuplot

```
[|============>> 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
```

Running phases

- The running is separated into three main phases, which can be accessed individually by typing "`run_grid`"/"`run_pre`"/"`run_main`" instead of "`run`".
- Each phase requires the previous phases to be successfully done!
  - warmup ("`run_grid`")
    - generates the integration grids needed for pre and main run.
  - runtime extrapolation ("`run_pre`")
    - short test runs to estimate runtime
    - prints preliminary result at the end
  - x-section computation ("`run_main`")
    - parallelized by runtime from pre run, `max_time_per_job` and `accuracy`
    - starts result combination+gnuplot
    - prints final result at the end

```
                  /-------------------------------------------------\
                  |       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
<<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_fir
[[wiesemann:~/munich-http/MATRIX/run/ppeeexex04_MATRIX]
```

process folder:
`${process_id}_MATRIX`

`input` `log` `result` `bin` `default.MATRIX` `run_XX` ●●●

no need to be touched

`run_XX` ●●●

input (`*.dat`) cards for each run:
- `parameter.dat`
- `model.dat`
- `distribution.dat`

`run_XX` ●●●

`failed`
`successful`
`grid_run`
`pre_main_run`
`main_run`
`saved_log_XX`
●●●

temporary folders indicating status of current jobs

log files for each job separated into the various run phases; each contains also "failed"/"successful"

if indicated in input previous logs are saved before rerun

`run_XX` ●●●

`summary` — various summary information

`gnuplot` — **plots (`*.pdf` and `*.gnu` files)**

`LO-run`
`NLO-run`
`NNLO-run` — result files for ((N)N)LO run:
- total rates (within cuts)
- distributions (separate folder)
- additional combinations with loop-induced component

`input_of_run` — corresponding input

`saved_result_XX` — if indicated in input previous results are saved before rerun

●●●

Additional information

- **`MATRIX_v1.0.0/config/Matrix_configuration`**
  handles configuration, like: **`mode`** to choose local/cluster running,
  `cluster_name` to choose cluster (LSF, slurm, ...)
  (soft link in each **`${process_id}_MATRIX/input/Matrix_configuration`**)
- ma
- eg ue"
- thi
- ./
- ./
- nohup t &
- au
- cr

```
############################
# MATRIX configuration file #
############################
# This file contains all parameters to configure MATRIX
# In the run_folders this is the link to the central configuration file
# in MATRIX/config/; you can replace the link by a copy to have individual
# configurations for the different processes

# Editor to be used to edit input files from MATRIX shell
# (default: use the one specified under environmental variable EDITOR)
#default_editor = emacs  # eg, emacs, vi, nano, ...

# runmode of MATRIX: 0 -- multicore (default)
#                    1 -- cluster
mode = 0

###################
## cluster parameter ##
###################
# Name of cluster currently supported:
#   slurm, LSF (eg, lxplus), condor, qsub (Torque/OpenPBS tested+working; PBS, SGE not tested)
cluster_name = LSF

# Queue/Partition of cluster to be used for running
cluster_queue = 2nw

# Maximal runtime for a single process on a single node,
# too low values may lead failure of the code
#cluster_runtime = 2-00:00:00

# add customizable lines at the beginning of cluster submission file
# this allows to add certain cluster-specific requirements as options to the submission
# eg: cluster_submit_line1 = #SBATCH --mem-per-cpu=4000
#     to increase the memory of a slurm job on certain clusters
#cluster_submit_line1 =
#cluster_submit_line2 =
#cluster_submit_line3 =
```

Additional information

- **`MATRIX_v1.0.0/config/Matrix_configuration`**
  handles configuration, like: **`mode`** to choose local/cluster running,
  `cluster_name` to choose cluster (LSF, slurm, ...)
  (soft link in each **`${process_id}_MATRIX/input/Matrix_configuration`**)
- many additional command-line options, use "**`-h`**" to show all options:

```
./matrix -h
./bin/run_process -h
```

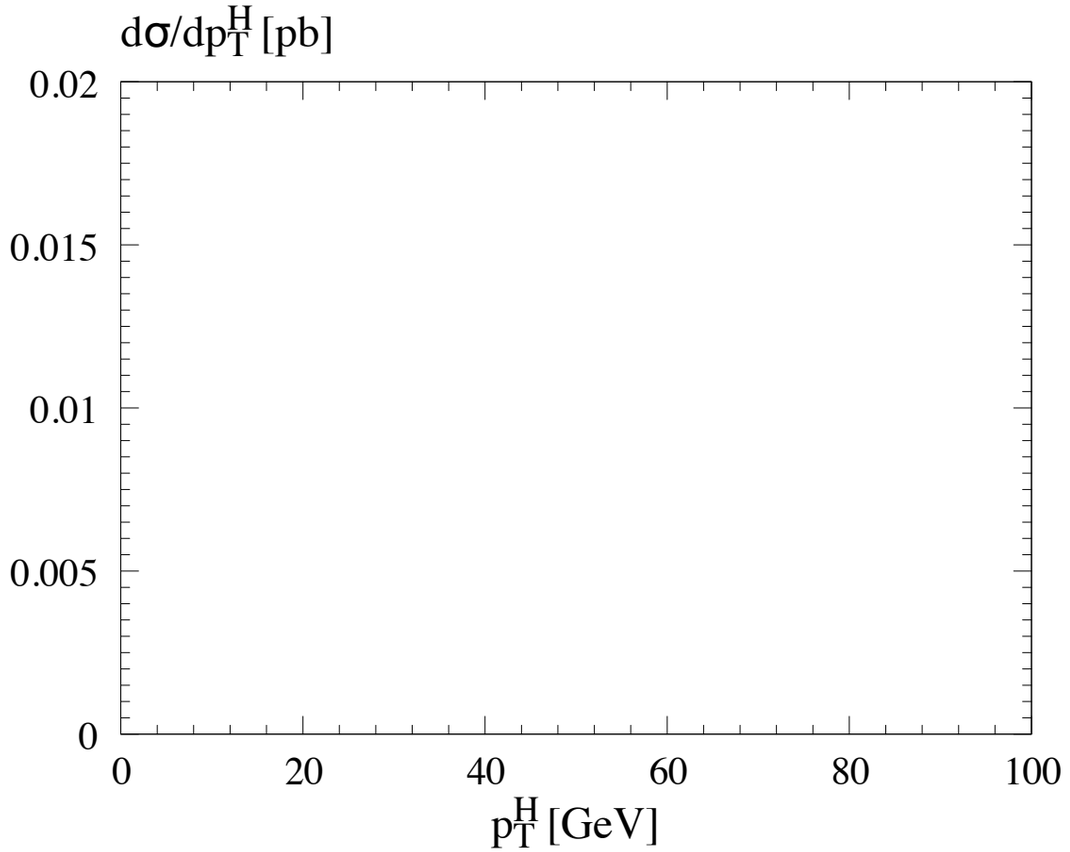
  eg, continue a previous run (all finished jobs will be kept) with "**`--continue`**"
  - this way you can use the code completely without using the shells, eg:

```
./matrix ppeeexex04
./bin/run_process run_my_first_ZZ --run_mode run
nohup ./bin/run_process run_my_first_ZZ --run_mode run > f.out &
```

  - automatic renormalization and factorization scale variations
  - creation of citation file for each run

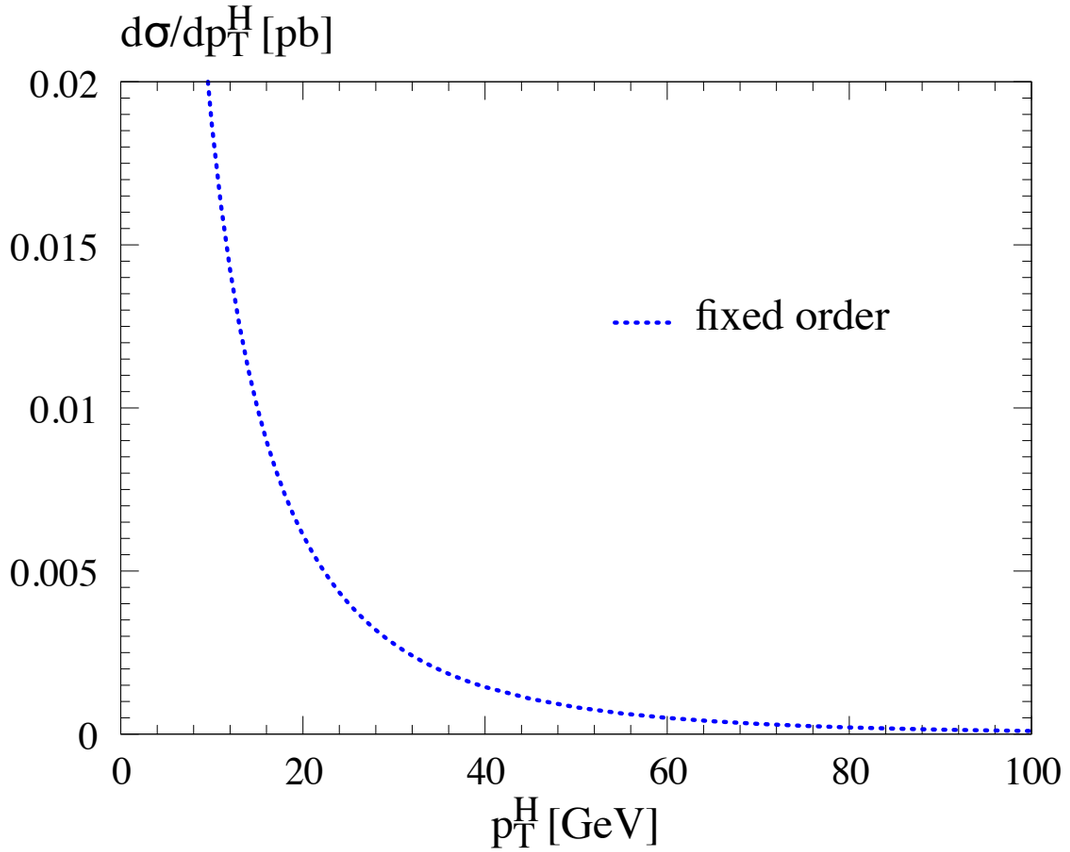
matching: FO+resummation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} =$$



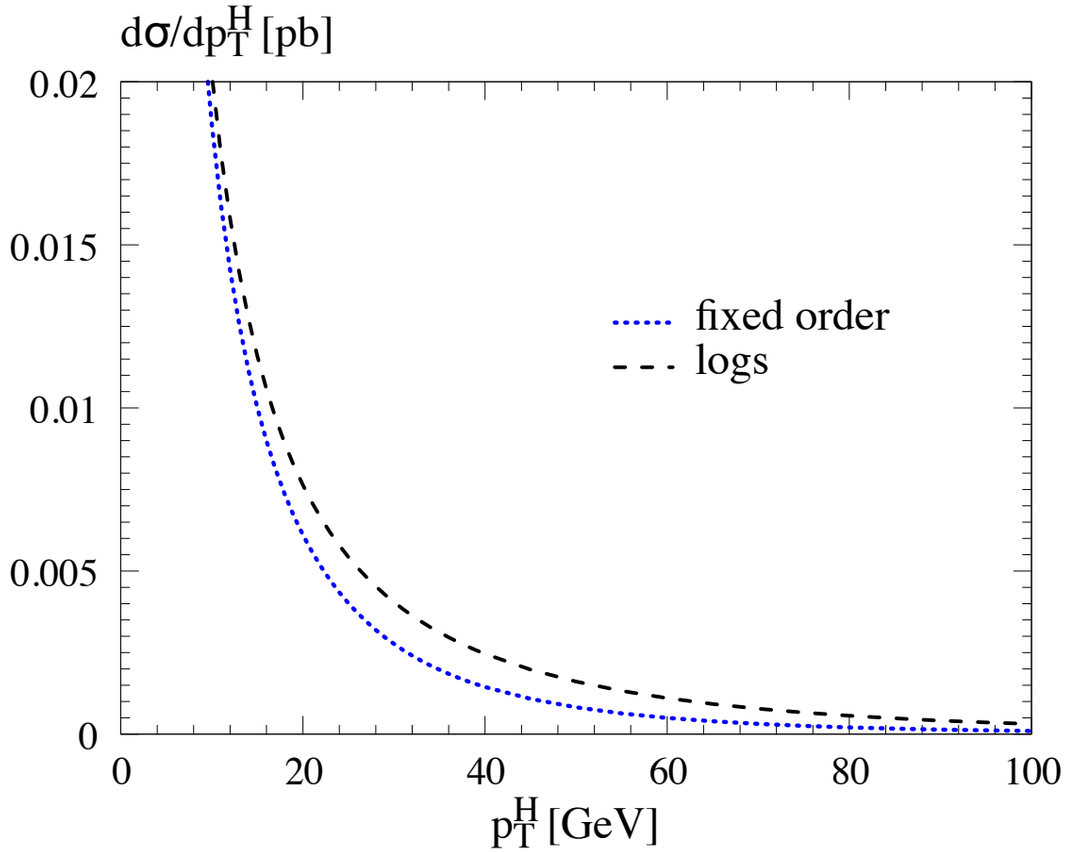
matching: FO+resummation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



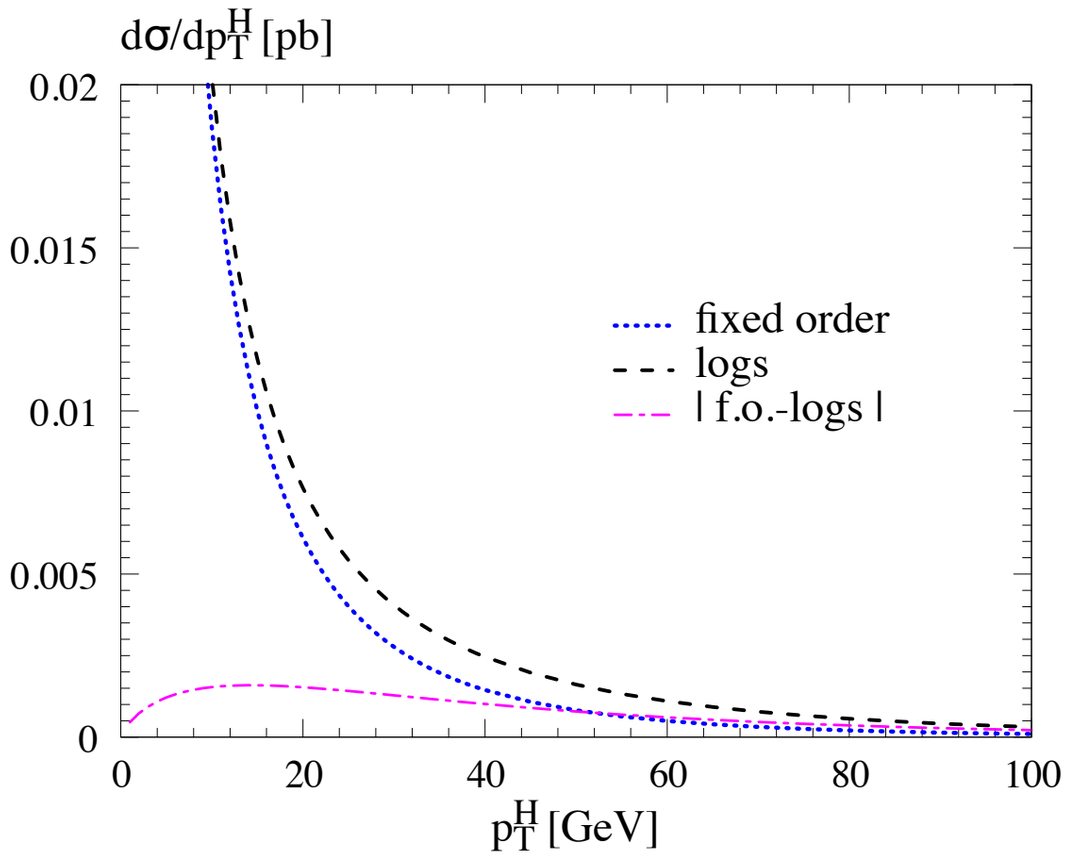
matching: FO+resummation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



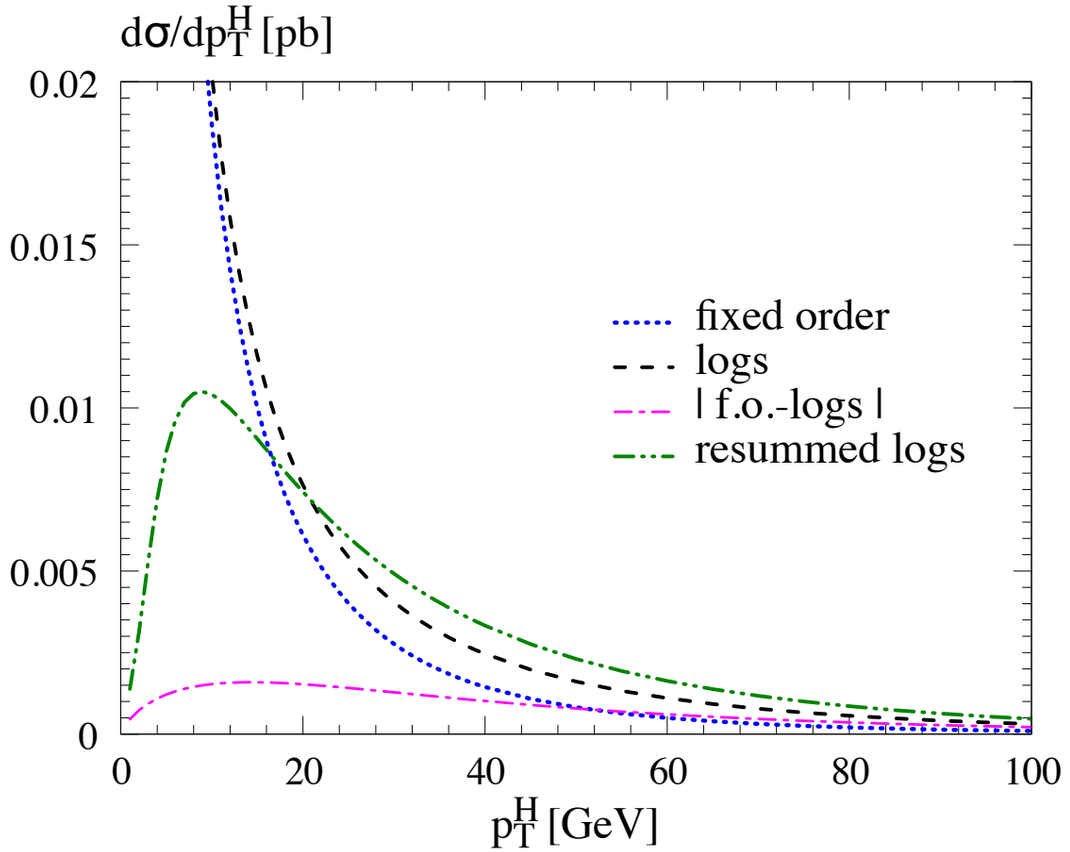
matching: FO+resummation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



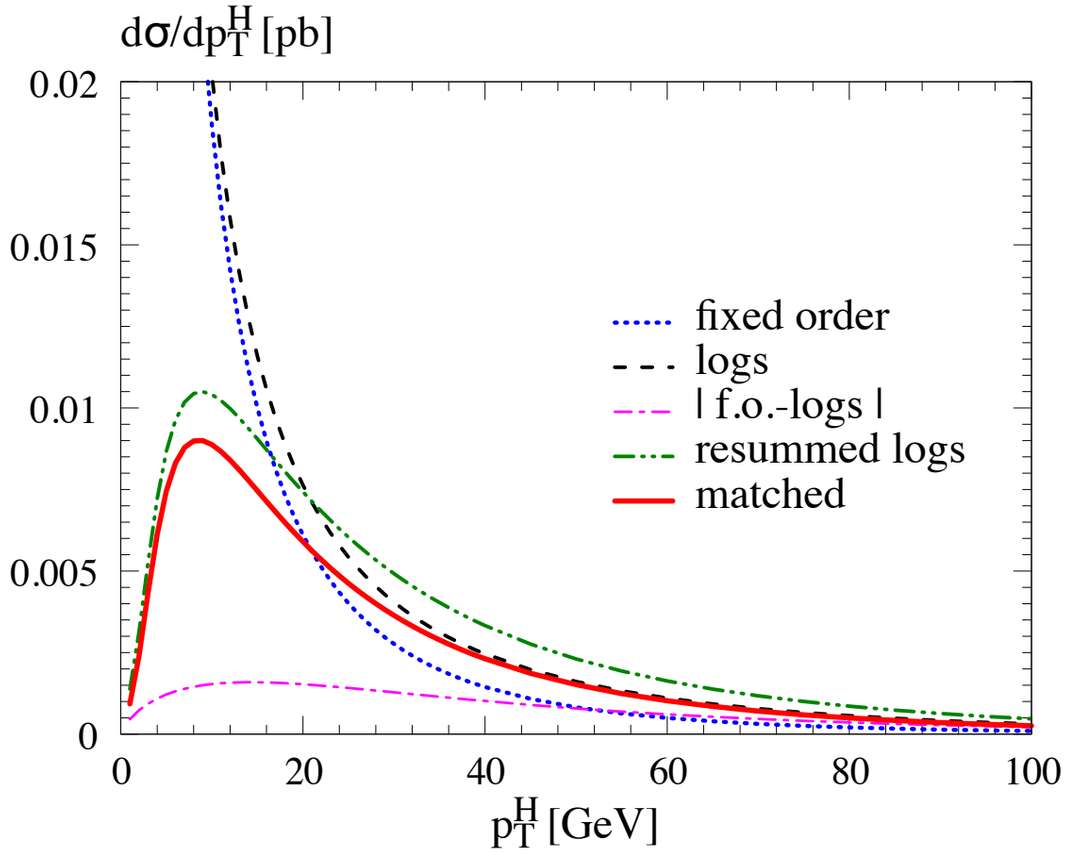
matching: FO+resummation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} + \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{l.a.}}$$



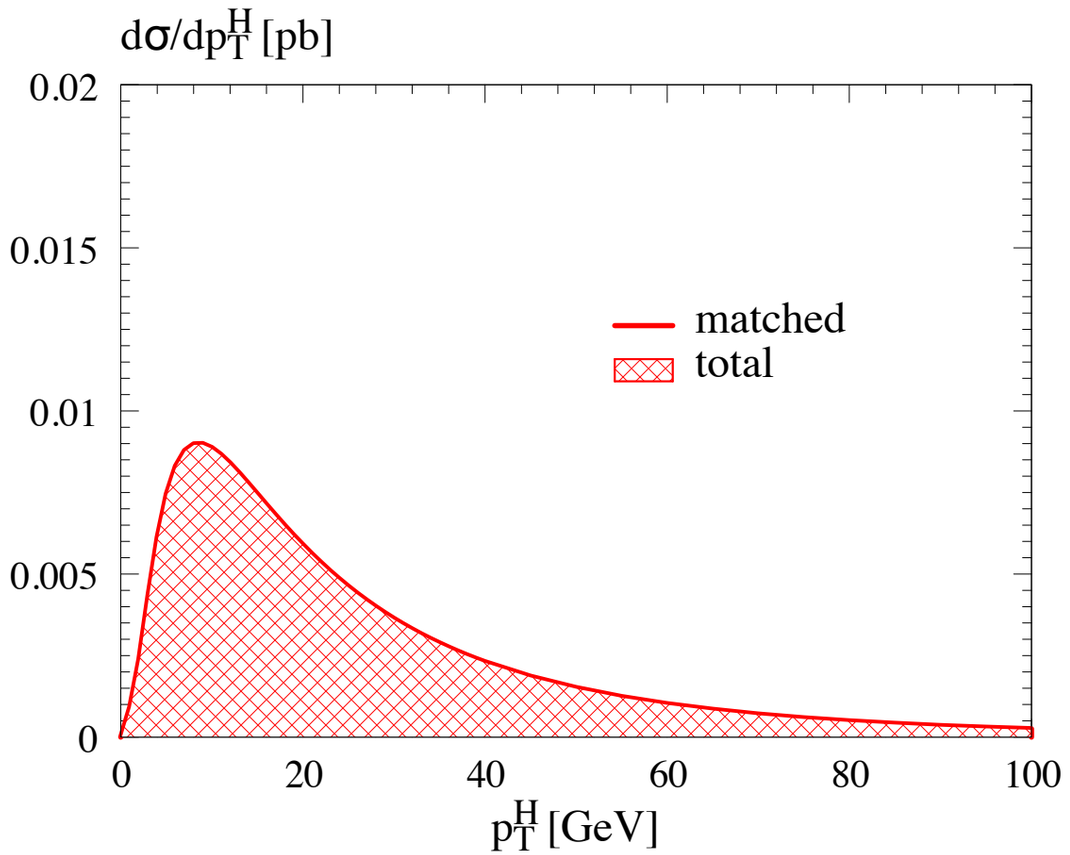
matching: FO+resummation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} + \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{l.a.}}$$



matching: FO+resummation

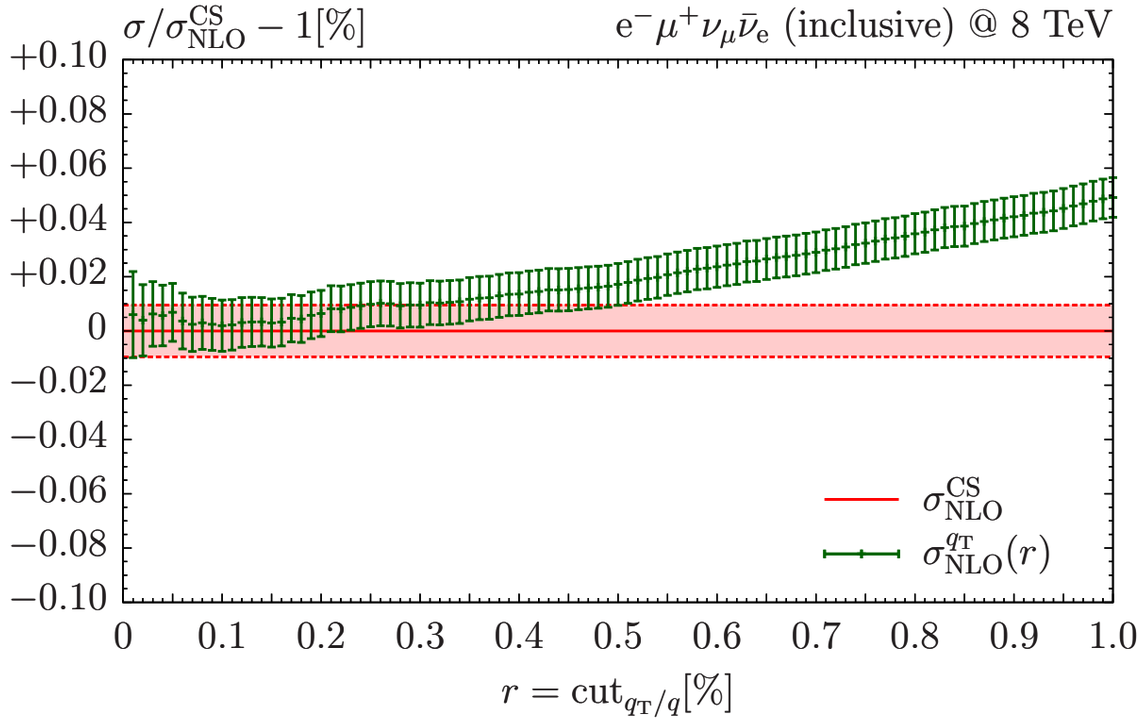
$$\int \mathrm{d}p_T^2 \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} \equiv \left[\sigma^{(\text{tot})}\right]_{\text{f.o.}} .$$

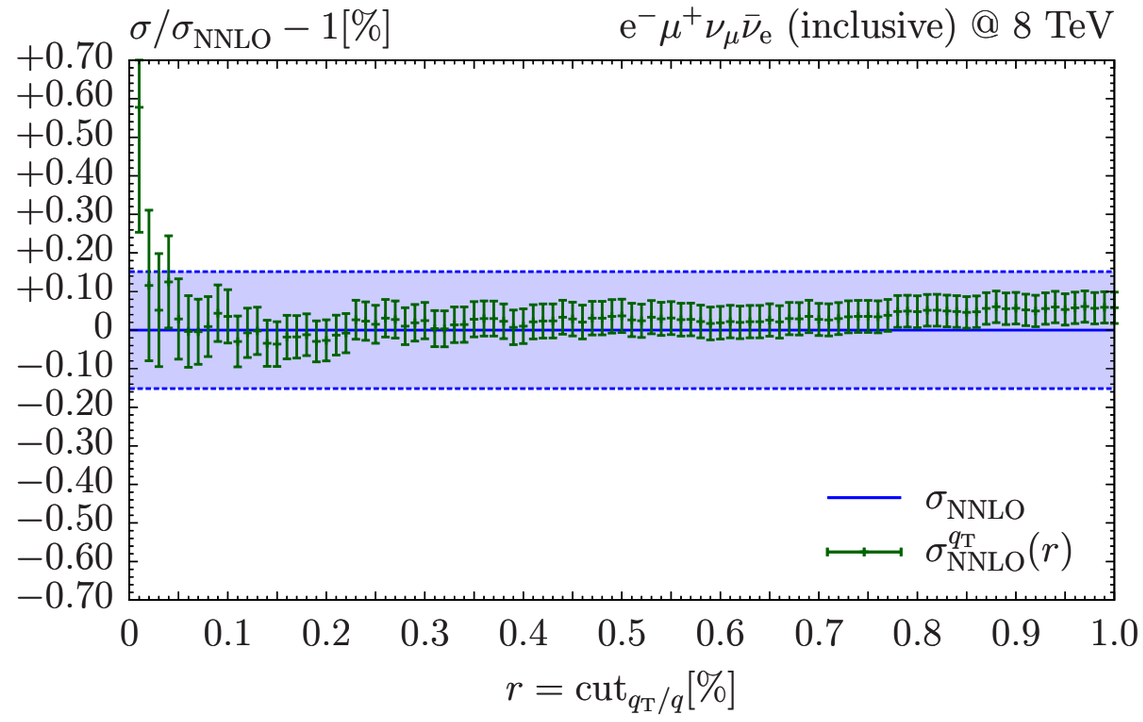


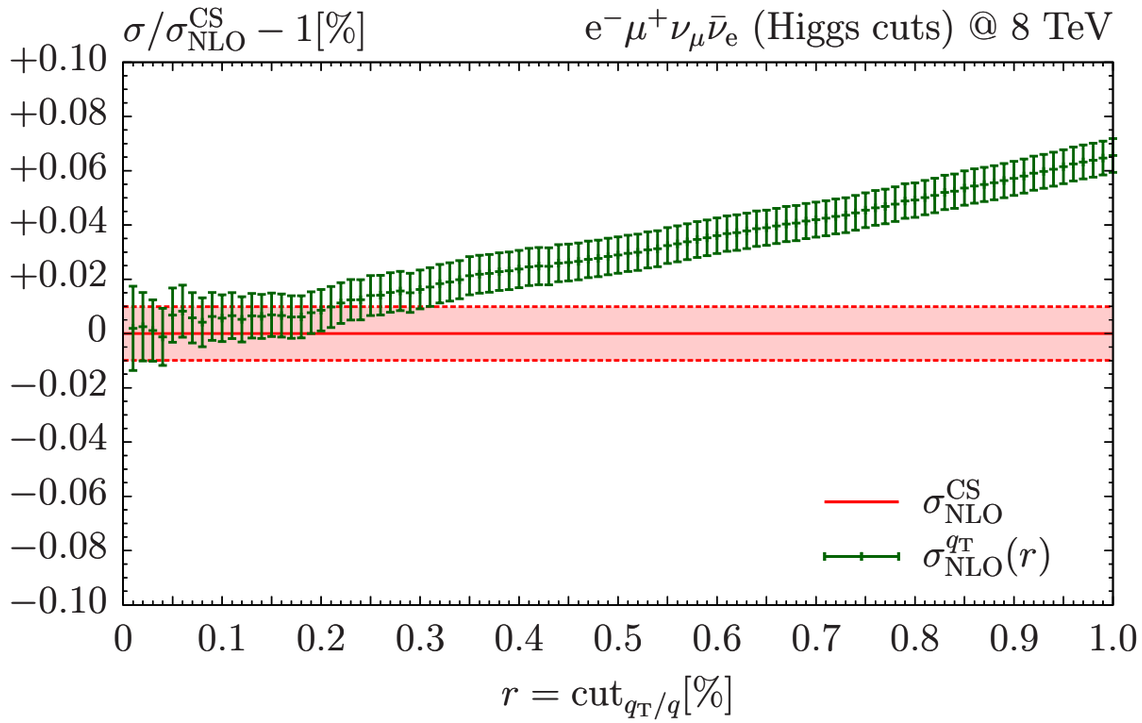
WW fully differential at NNLO

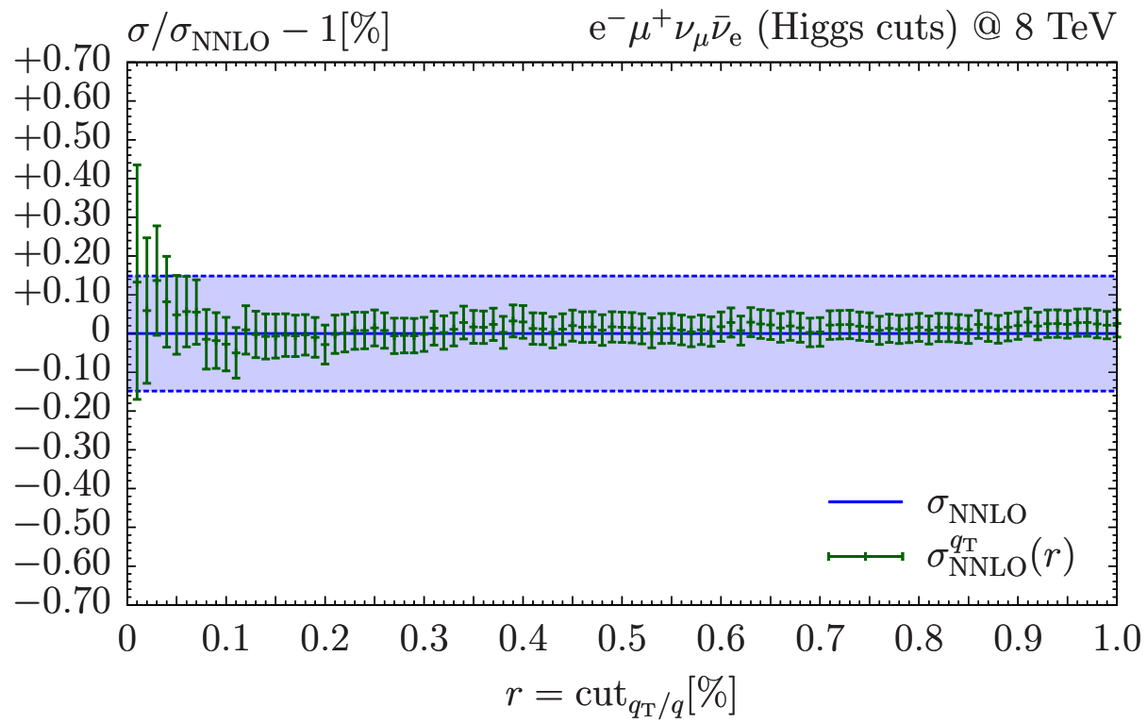
[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

stability of r_{cut} dependence









Theoretical status of WW production

fixed-order:

- NNLO corrections to inclusive [Gehrmann, Grazzini, Kallweit, P. Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi '14]

  and differential cross sections [Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

- NLO corrections to gg channel
  [Caola, Melnikov, Röntsch, Tancredi '15], second one for Higgs interference?

- NLO EW corrections
  [Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder '16]

resummation:

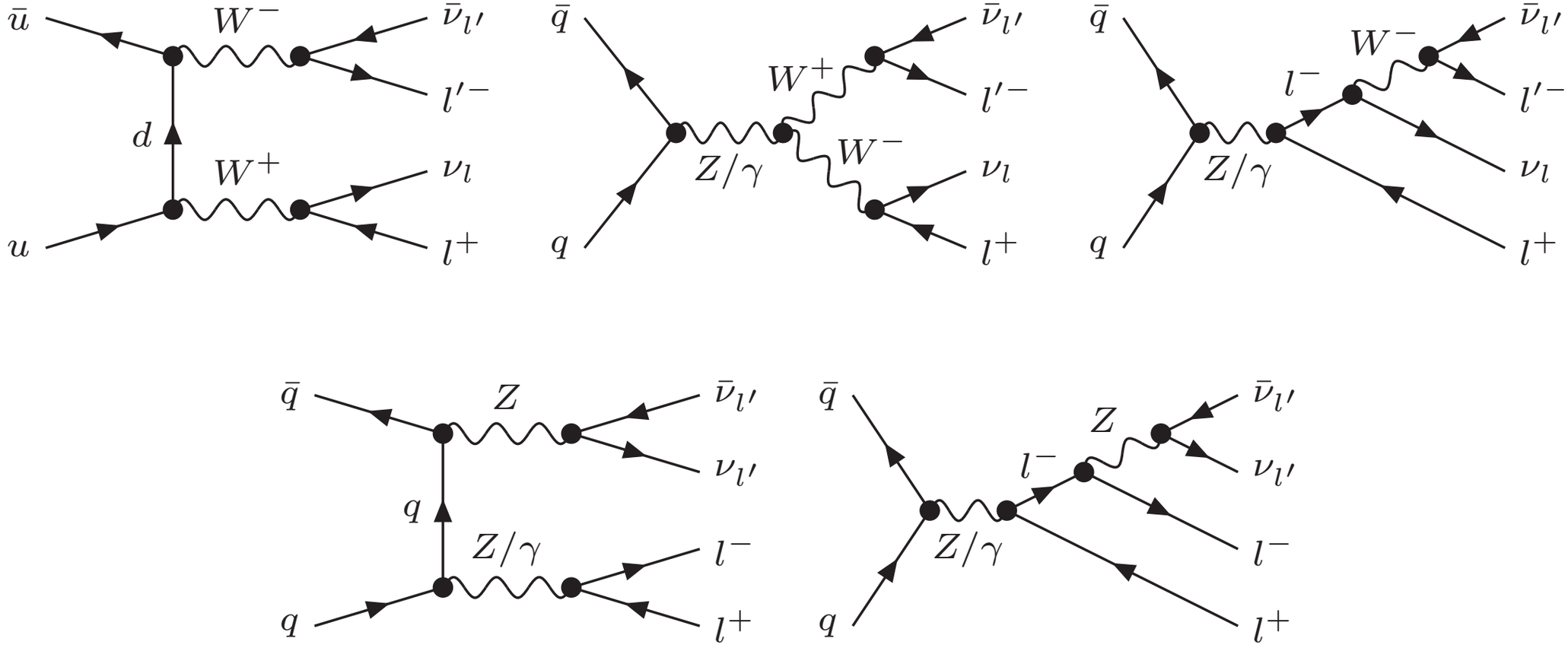
- NNLO+NNLL pT resummation of WW pair
  [Grazzini, Kallweit, Rathlev, MW '15]

- **recently:** NNLO+NNLL jet-veto resummation
  [Dawson, Jaiswal, Li, Ramani, Zeng '16]

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

- all $pp \to WW \to \ell\nu\,\ell'\nu'$ processes, including:
  - double-resonant W decays
  - single-resonant Z/γ* decays ($pp \to Z/\gamma^* \to WW^*/\ell\nu W \to \ell\nu\,\ell'\nu'$)
  - double(single)-resonant $pp \to ZZ/Z\gamma^* \to \ell\nu\ell\nu$($pp \to Z/\gamma^* \to \ell\nu\ell\nu$) in SF



WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

- all $pp \to WW \to \ell\nu\,\ell'\nu'$ processes, including:
  - double-resonant W decays
  - single-resonant Z/γ* decays ($pp \to Z/\gamma^* \to WW^*/\ell\nu W \to \ell\nu\,\ell'\nu'$)
  - double(single)-resonant $pp \to ZZ/Z\gamma^* \to \ell\nu\ell\nu$($pp \to Z/\gamma^* \to \ell\nu\ell\nu$) in SF
- HERE: different-flavour channel $pp \to WW \to e\nu_e\,\mu\nu_\mu$ (for simplicity):
- inclusive results
- WW signal cuts:

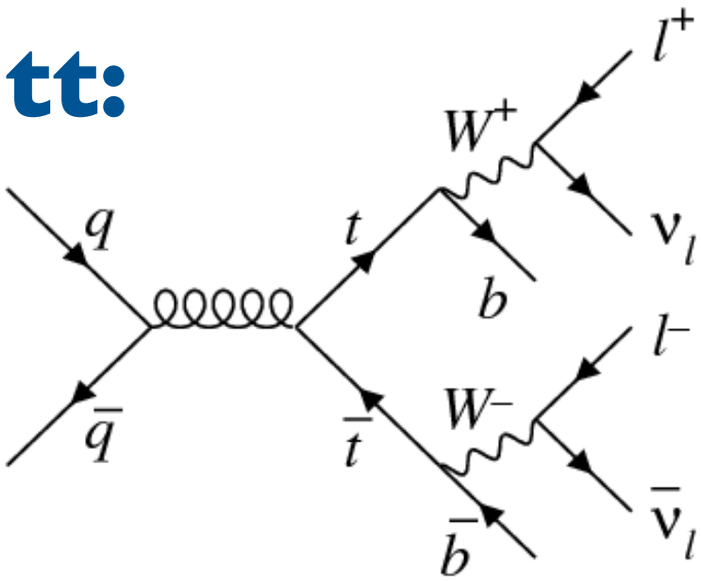
$m_{ll} > 10\,\text{GeV}, \quad \Delta R_{ll} > 0.1, \quad p_T^{\text{miss}} > 15\ \text{GeV}, \quad p_T^{\text{miss, rel}} > 20\,\text{GeV}$
jet veto $\quad$ (anti-k_T, $R = 0.4$, $p_{T,j} > 25\,\text{GeV}$, $\lvert y_j\rvert < 4.5$)
lepton cuts $\quad$ ($p_{T,l_1} > 25\,\text{GeV}$, $p_{T,l_2} > 20\,\text{GeV}$, $\lvert y_\mu\rvert < 2.4$, $\lvert y_e\rvert < 1.37$ or $1.52 < \lvert y_e\rvert < 2.47$)

WW fully differential at NNLO

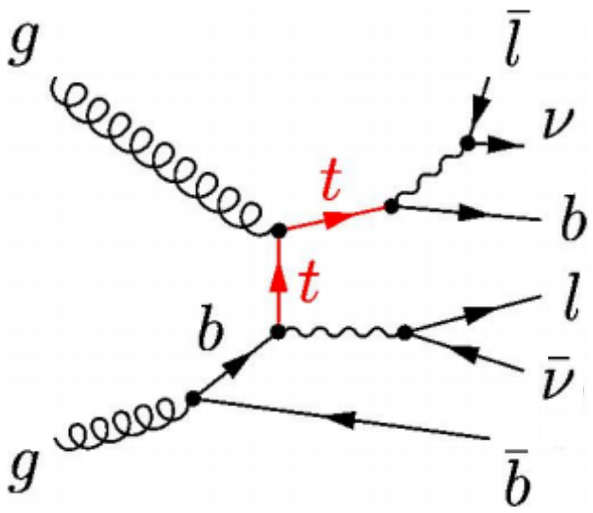
[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

top-quark contamination

tt:



Wt:



how to avoid tt/Wt contributions in computation:

four-flavour scheme (4FS)

- diagrams with final-state b-quarks finite subgroup (b massive)
- remove top-quark contamination by dropping such diagrams
- default choice in our computation

five-flavour scheme (5FS)

- b-quark contributions not finite (b massless, clustered in jets)
- use resonance structure with respect to top-quark width:

$$\sigma = A \cdot \frac{1}{\Gamma_t^2} + B \cdot \frac{1}{\Gamma_t} + C$$

- fit coefficients for different Γ_t → C: top-subtracted c.s.
- used as cross check (agreement for fiducial rates ~1%)

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

σ [fb]	8 TeV	13 TeV
LO	$425.41(4)\,^{+2.8\%}_{-3.6\%}$	$778.99\ (8)\,^{+5.7\%}_{-6.7\%}$
NLO	$623.47(6)\,^{+3.6\%}_{-2.9\%}$	$1205.11(12)\,^{+3.9\%}_{-3.1\%}$
NLO′+gg	$655.83(8)\,^{+4.3\%}_{-3.3\%}$	$1286.81(13)\,^{+4.8\%}_{-3.7\%}$
NNLO	$690.4(5)\,^{+2.2\%}_{-1.9\%}$	$1370.9(11)\,^{+2.6\%}_{-2.3\%}$

fiducial rates (WW cuts)

8 TeV	13 TeV
$147.23(2)\,^{+3.4\%}_{-4.4\%}$	$233.04(2)\,^{+6.6\%}_{-7.6\%}$
$153.07(2)\,^{+1.9\%}_{-1.6\%}$	$236.19(2)\,^{+2.8\%}_{-2.4\%}$
$166.41(3)\,^{+1.3\%}_{-1.3\%}$	$267.31(4)\,^{+1.5\%}_{-2.1\%}$
$164.1\ (1)\,^{+1.3\%}_{-0.8\%}$	$261.5(2)\,^{+1.9\%}_{-1.2\%}$

NLO'+gg = NLO+gg BOTH with NNLO PDFs

→ acceptances (WW cuts)

$A = \sigma^{\text{cuts}}/\sigma^{\text{inclusive}}$	8 TeV	13 TeV
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	$0.29915(6)^{+0.8\%}_{-1.0\%}$
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	$0.19599(4)^{+4.4\%}_{-4.7\%}$
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	$0.20773(5)^{+3.2\%}_{-3.1\%}$
NNLO	$0.2378(4)\,^{+1.3\%}_{-0.9\%}$	$0.1907(3)\,^{+1.2\%}_{-0.9\%}$

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

fiducial rates (WW cuts)

σ [fb]	8 TeV		13 TeV	
LO	$425.41(4)^{+2.8\%}_{-3.6\%}$	+47%	$778.99\ (8)^{+5.7\%}_{-6.7\%}$	+55%
NLO	$623.47(6)^{+3.6\%}_{-2.9\%}$	+5.2%	$1205.11(12)^{+3.9\%}_{-3.1\%}$	+6.8%
NLO′+gg	$655.83(8)^{+4.3\%}_{-3.3\%}$	+5.3%	$1286.81(13)^{+4.8\%}_{-3.7\%}$	+6.5%
NNLO	$690.4(5)^{+2.2\%}_{-1.9\%}$		$1370.9(11)^{+2.6\%}_{-2.3\%}$	

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$166.41(3)^{+1.3\%}_{-1.3\%}$	$267.31(4)^{+1.5\%}_{-2.1\%}$
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WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

fiducial rates (WW cuts)

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NLO	$623.47(6)^{+3.6\%}_{-2.9\%}$	+5.2%	$1205.11(12)^{+3.9\%}_{-3.1\%}$	+6.8%
NLO′+gg	$655.83(8)^{+4.3\%}_{-3.3\%}$	+5.3%	$1286.81(13)^{+4.8\%}_{-3.7\%}$	+6.5%
NNLO	$690.4(5)\ ^{+2.2\%}_{-1.9\%}$		$1370.9(11)\ ^{+2.6\%}_{-2.3\%}$	

	8 TeV		13 TeV	
LO	$147.23(2)^{+3.4\%}_{-4.4\%}$	+4%	$233.04(2)^{+6.6\%}_{-7.6\%}$	+1.3%
NLO	$153.07(2)^{+1.9\%}_{-1.6\%}$	+8.7%	$236.19(2)^{+2.8\%}_{-2.4\%}$	+13%
NLO′+gg	$166.41(3)^{+1.3\%}_{-1.3\%}$	-1.4%	$267.31(4)^{+1.5\%}_{-2.1\%}$	-2.2%
NNLO	$164.1\ (1)^{+1.3\%}_{-0.8\%}$		$261.5(2)\ ^{+1.9\%}_{-1.2\%}$	

NLO'+gg = NLO+gg BOTH with NNLO PDFs

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NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	$0.19599(4)^{+4.4\%}_{-4.7\%}$
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	$0.20773(5)^{+3.2\%}_{-3.1\%}$
NNLO	$0.2378(4)\ ^{+1.3\%}_{-0.9\%}$	$0.1907(3)\ ^{+1.2\%}_{-0.9\%}$

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive rates

fiducial rates (WW cuts)

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NNLO	$690.4(5)\ ^{+2.2\%}_{-1.9\%}$		$1370.9(11)\ ^{+2.6\%}_{-2.3\%}$	

	8 TeV		13 TeV	
LO	$147.23(2)^{+3.4\%}_{-4.4\%}$	+4%	$233.04(2)^{+6.6\%}_{-7.6\%}$	+1.3%
NLO	$153.07(2)^{+1.9\%}_{-1.6\%}$	+8.7%	$236.19(2)^{+2.8\%}_{-2.4\%}$	+13%
NLO′+gg	$166.41(3)^{+1.3\%}_{-1.3\%}$	-1.4%	$267.31(4)^{+1.5\%}_{-2.1\%}$	-2.2%
NNLO	$164.1\ (1)^{+1.3\%}_{-0.8\%}$		$261.5(2)\ ^{+1.9\%}_{-1.2\%}$	

NLO'+gg = NLO+gg BOTH with NNLO PDFs

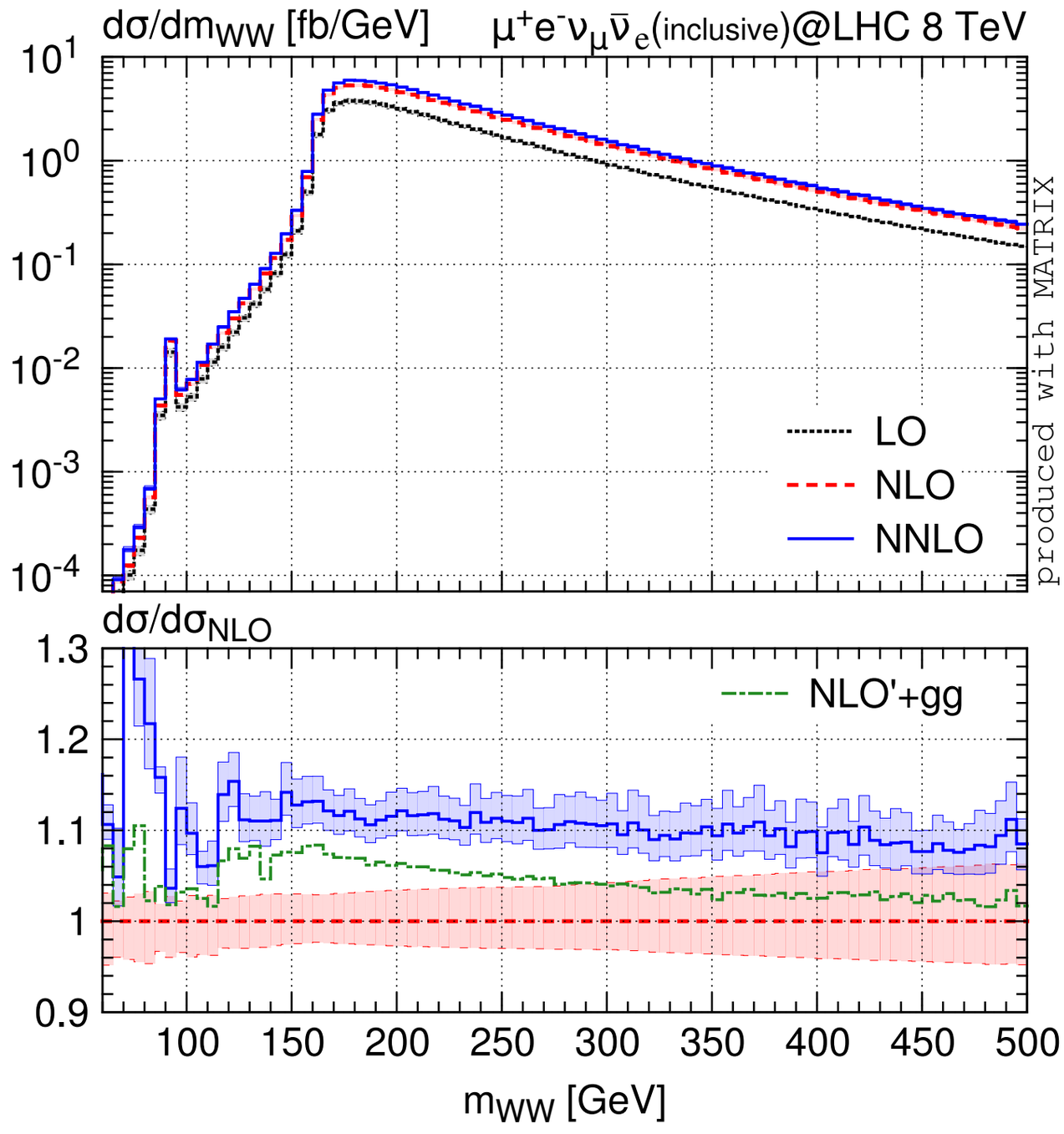
→ acceptances (WW cuts)

$A = \sigma^{\text{cuts}}/\sigma^{\text{inclusive}}$	8 TeV		13 TeV	
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	+29%	$0.29915(6)^{+0.8\%}_{-1.0\%}$	+34%
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	+3.3%	$0.19599(4)^{+4.4\%}_{-4.7\%}$	+6%
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	-6.3%	$0.20773(5)^{+3.2\%}_{-3.1\%}$	-8.2%
NNLO	$0.2378(4)\ ^{+1.3\%}_{-0.9\%}$		$0.1907(3)\ ^{+1.2\%}_{-0.9\%}$	

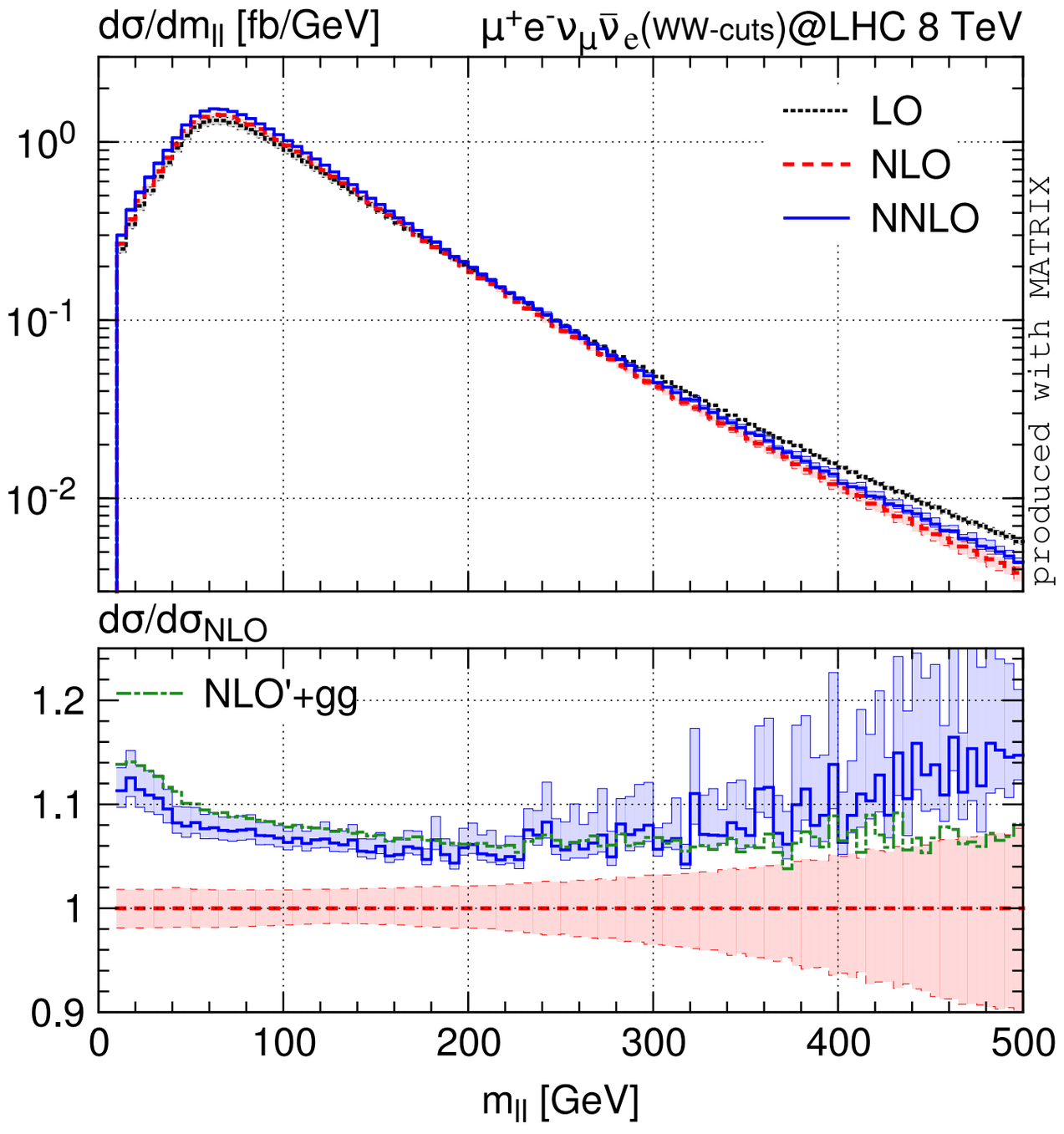
WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive



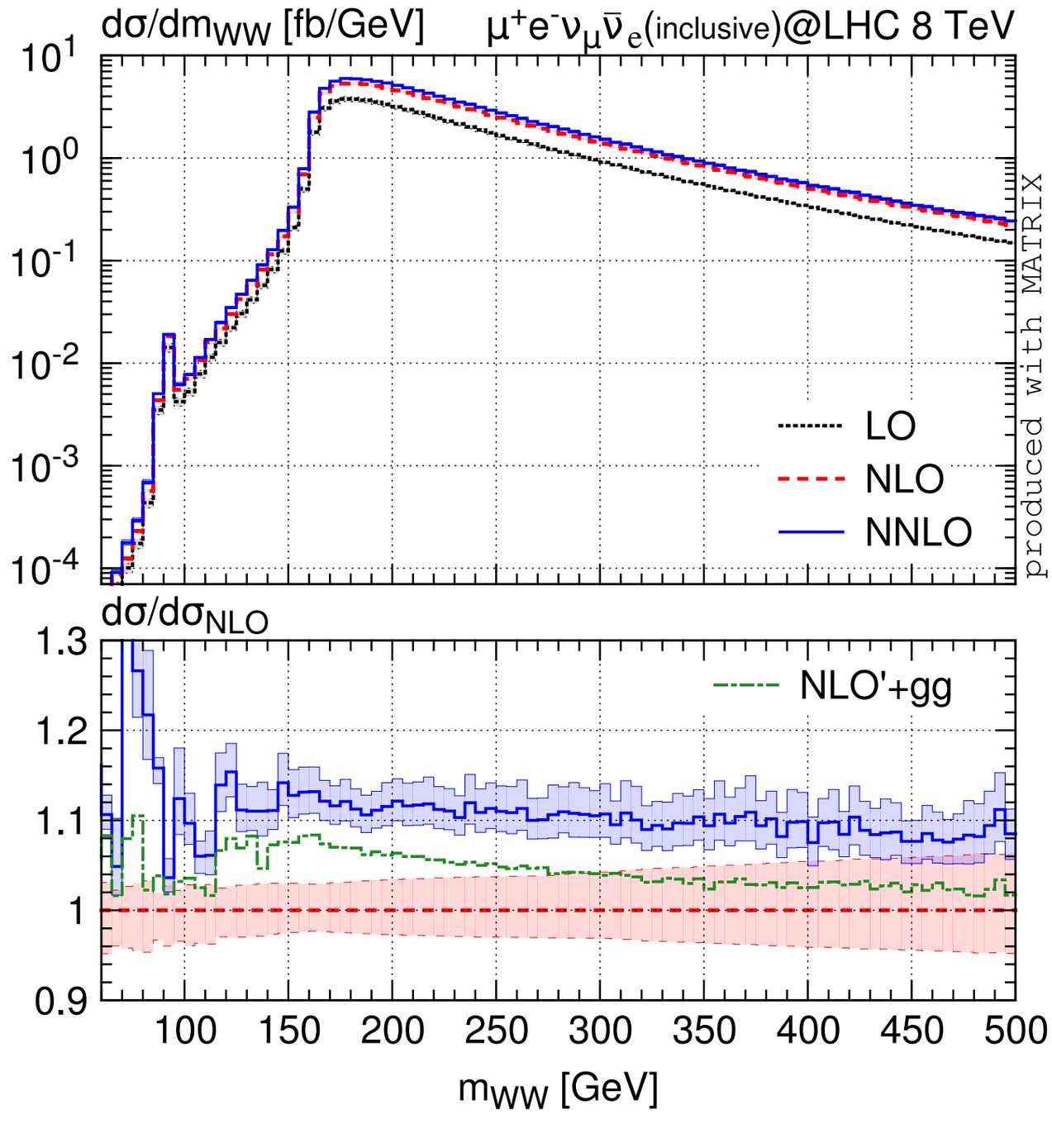
WW cuts

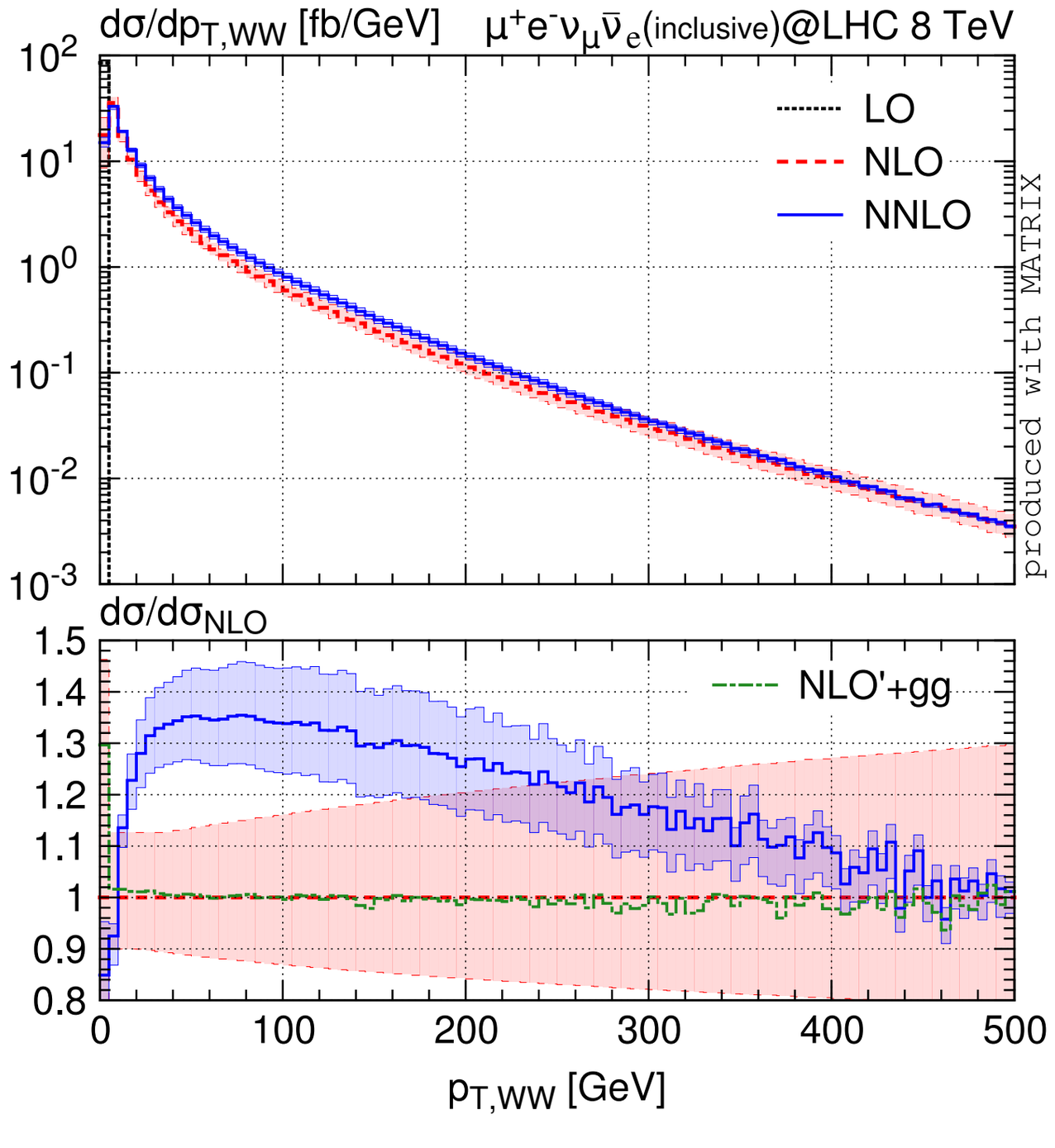


WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

inclusive: distributions (8 TeV)





WZ fully differential at NNLO [Grazzini, Kallweit, MW]

SM measurements

ATLAS (8 TeV):

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm ATLAS}$ [fb]
$\mu^+e^+e^-$	$11.59(0)^{+2.2\%}_{-3.0\%}$	$20.42(0)^{+5.3\%}_{-4.0\%}$	$22.11(1)^{+1.8\%}_{-1.9\%}$	$23.9 \pm 6.5\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^+\mu^+\mu^-$				$19.9 \pm 7.2\%(\text{stat}) \pm 3.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^+e^+e^-$	$11.62(0)^{+2.2\%}_{-3.0\%}$	$20.48(0)^{+5.3\%}_{-4.0\%}$	$22.17(1)^{+1.8\%}_{-1.9\%}$	$22.6 \pm 8.0\%(\text{stat}) \pm 4.4\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^+\mu^+\mu^-$				$19.8 \pm 6.0\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
combined	$11.60(0)^{+2.2\%}_{-3.0\%}$	$20.45(0)^{+5.3\%}_{-4.0\%}$	$22.14(1)^{+1.8\%}_{-1.9\%}$	$21.2 \pm 3.4\%(\text{stat}) \pm 2.3\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^-e^+e^-$	$6.732(1)^{+2.4\%}_{-3.4\%}$	$12.35(0)^{+5.7\%}_{-4.3\%}$	$13.42(1)^{+1.9\%}_{-1.9\%}$	$12.4 \pm 9.5\%(\text{stat}) \pm 3.1\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^-\mu^+\mu^-$				$15.7 \pm 7.5\%(\text{stat}) \pm 2.8\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^-e^+e^-$	$6.750(1)^{+2.4\%}_{-3.4\%}$	$12.38(0)^{+5.7\%}_{-4.3\%}$	$13.47(1)^{+1.9\%}_{-2.0\%}$	$15.4 \pm 9.8\%(\text{stat}) \pm 5.0\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$\mu^-\mu^+\mu^-$				$13.4 \pm 7.5\%(\text{stat}) \pm 2.8\%(\text{syst}) \pm 2.3\%(\text{lumi})$
combined	$6.741(1)^{+2.4\%}_{-3.4\%}$	$12.36(0)^{+5.7\%}_{-4.3\%}$	$13.45(1)^{+1.9\%}_{-2.0\%}$	$14.0 \pm 4.3\%(\text{stat}) \pm 2.8\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$\mu^\pm e^+e^-$	$18.32(0)^{+2.3\%}_{-3.2\%}$	$32.76(1)^{+5.4\%}_{-4.1\%}$	$35.53(2)^{+1.8\%}_{-1.9\%}$	$36.3 \pm 5.4\%(\text{stat}) \pm 2.6\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm\mu^+\mu^-$				$35.7 \pm 5.3\%(\text{stat}) \pm 3.7\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm e^+e^-$	$18.37(0)^{+2.3\%}_{-3.2\%}$	$32.85(1)^{+5.4\%}_{-4.1\%}$	$35.64(2)^{+1.8\%}_{-1.9\%}$	$38.1 \pm 6.2\%(\text{stat}) \pm 4.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^\pm\mu^+\mu^-$				$33.3 \pm 4.7\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
combined	$18.35(0)^{+2.3\%}_{-3.2\%}$	$32.81(1)^{+5.4\%}_{-4.1\%}$	$35.59(2)^{+1.8\%}_{-1.9\%}$	$35.1 \pm 2.7\%(\text{stat}) \pm 2.4\%(\text{syst}) \pm 2.2\%(\text{lumi})$

WZ fully differential at NNLO [Grazzini, Kallweit, MW]

CMS (13 TeV):

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm CMS}$ [fb]
combined	$148.4(0)^{+5.4\%}_{-6.4\%}$	$301.4(1)^{+5.5\%}_{-4.5\%}$	$334.3(2)^{+2.3\%}_{-2.1\%}$	$258 \pm 8.1\%(\text{stat})^{+7.4\%}_{-7.7\%}(\text{syst}) \pm 3.1(\text{lumi})$

ATLAS (13 TeV):

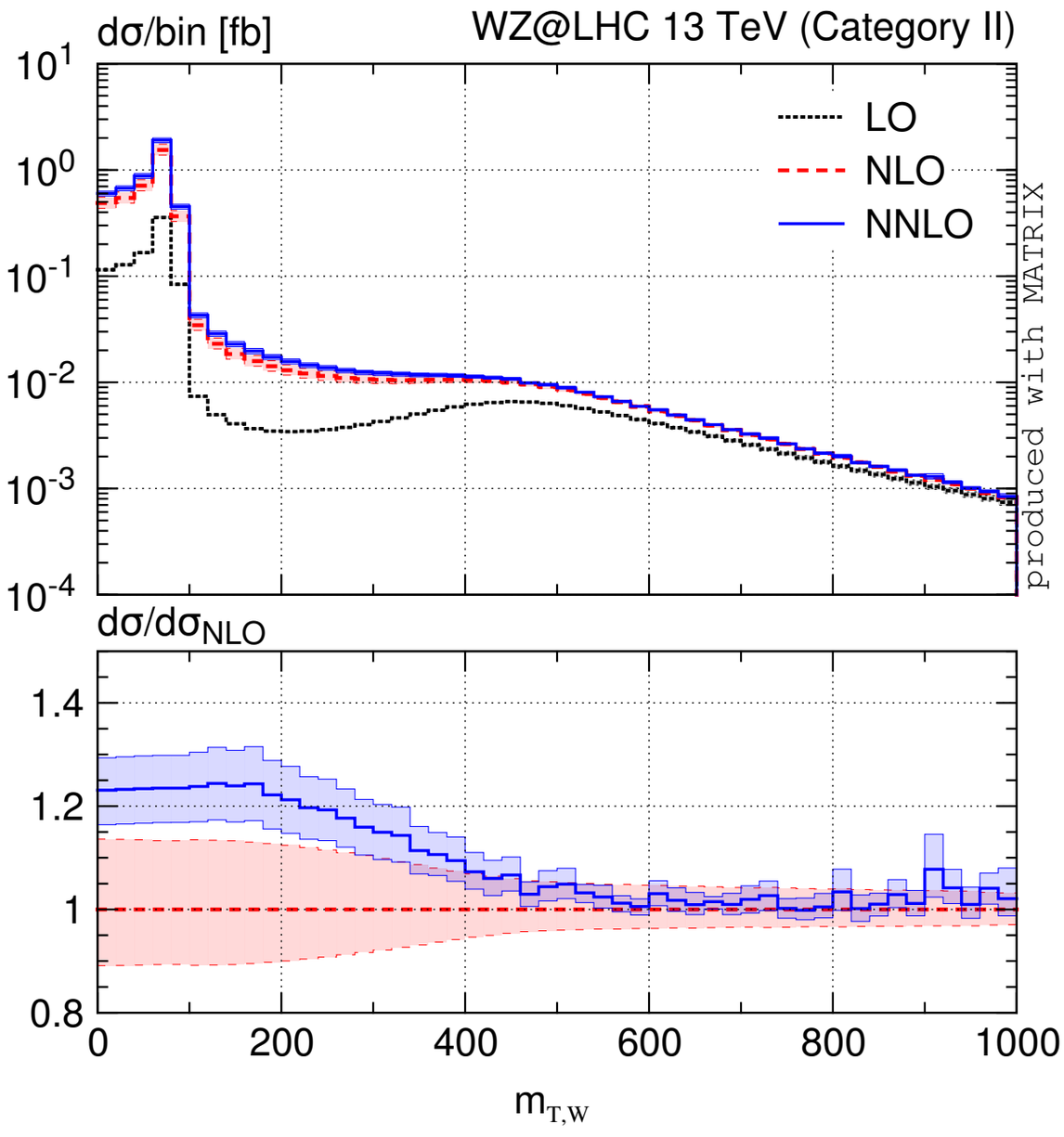
channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm ATLAS}$ [fb]
$\mu^+e^+e^-$	$17.33(0)^{+5.3\%}_{-6.3\%}$	$34.12(1)^{+5.3\%}_{-4.3\%}$	$37.75(2)^{+2.3\%}_{-2.0\%}$	$32.2 \pm 14.4\%(\text{stat}) \pm 5.0\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$e^+\mu^+\mu^-$				$45.0 \pm 12.1\%(\text{stat}) \pm 4.6\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^+e^+e^-$	$17.37(0)^{+5.3\%}_{-6.3\%}$	$34.21(1)^{+5.3\%}_{-4.3\%}$	$37.84(2)^{+2.2\%}_{-2.0\%}$	$28.0 \pm 19.2\%(\text{stat}) \pm 11.2\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$\mu^+\mu^+\mu^-$				$36.5 \pm 11.6\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.3\%(\text{lumi})$
combined	$17.35(0)^{+5.3\%}_{-6.3\%}$	$34.16(1)^{+5.3\%}_{-4.3\%}$	$37.80(2)^{+2.2\%}_{-2.0\%}$	$36.7 \pm 6.7\%(\text{stat}) \pm 3.9\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$\mu^-e^+e^-$	$11.50(0)^{+5.7\%}_{-6.8\%}$	$23.57(1)^{+5.5\%}_{-4.5\%}$	$26.18(1)^{+2.3\%}_{-2.1\%}$	$22.9 \pm 17.5\%(\text{stat}) \pm 5.8\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$e^-\mu^+\mu^-$				$30.2 \pm 15.2\%(\text{stat}) \pm 6.9\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^-e^+e^-$	$11.53(0)^{+5.7\%}_{-6.8\%}$	$23.63(0)^{+5.5\%}_{-4.5\%}$	$26.25(1)^{+2.2\%}_{-2.1\%}$	$22.5 \pm 21.0\%(\text{stat}) \pm 10.5\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$\mu^-\mu^+\mu^-$				$27.1 \pm 13.7\%(\text{stat}) \pm 5.0\%(\text{syst}) \pm 2.4\%(\text{lumi})$
combined	$11.51(0)^{+5.7\%}_{-6.8\%}$	$23.60(1)^{+5.5\%}_{-4.5\%}$	$26.22(1)^{+2.3\%}_{-2.1\%}$	$26.1 \pm 8.1\%(\text{stat}) \pm 4.7\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$\mu^\pm e^+e^-$	$28.83(0)^{+5.4\%}_{-6.5\%}$	$57.69(1)^{+5.4\%}_{-4.3\%}$	$63.93(3)^{+2.3\%}_{-2.1\%}$	$55.1 \pm 11.1\%(\text{stat}) \pm 5.1\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$e^\pm\mu^+\mu^-$				$75.2 \pm 9.5\%(\text{stat}) \pm 5.3\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^\pm e^+e^-$	$28.90(0)^{+5.4\%}_{-6.5\%}$	$57.84(1)^{+5.4\%}_{-4.3\%}$	$64.09(3)^{+2.2\%}_{-2.1\%}$	$50.5 \pm 14.2\%(\text{stat}) \pm 10.6\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$\mu^\pm\mu^+\mu^-$				$63.6 \pm 8.9\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.3\%(\text{lumi})$
combined	$28.86(0)^{+5.4\%}_{-6.5\%}$	$57.76(1)^{+5.4\%}_{-4.3\%}$	$64.01(3)^{+2.3\%}_{-2.1\%}$	$63.2 \pm 5.2\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.4\%(\text{lumi})$

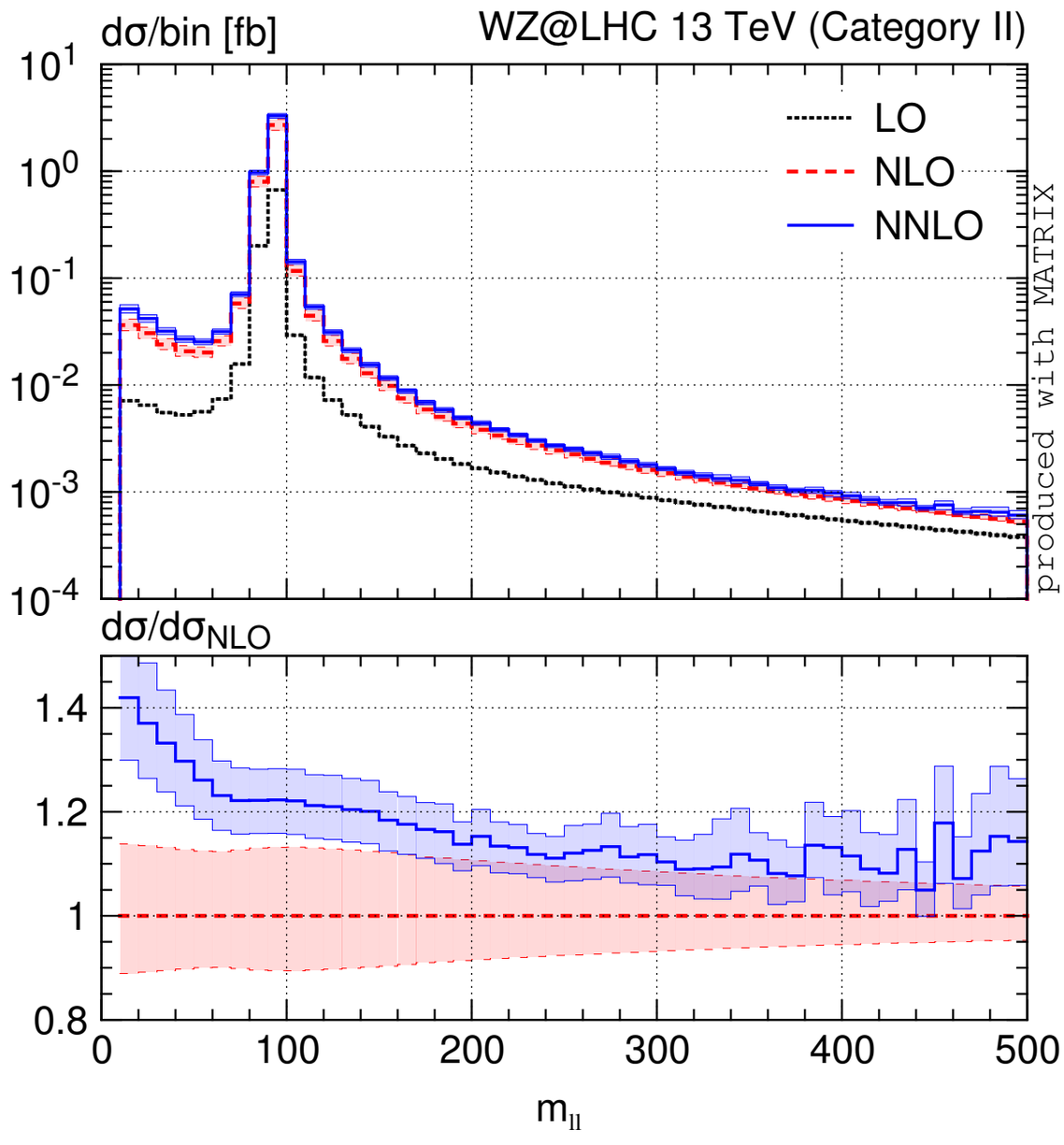
WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category II: p_T^{miss}>200 GeV



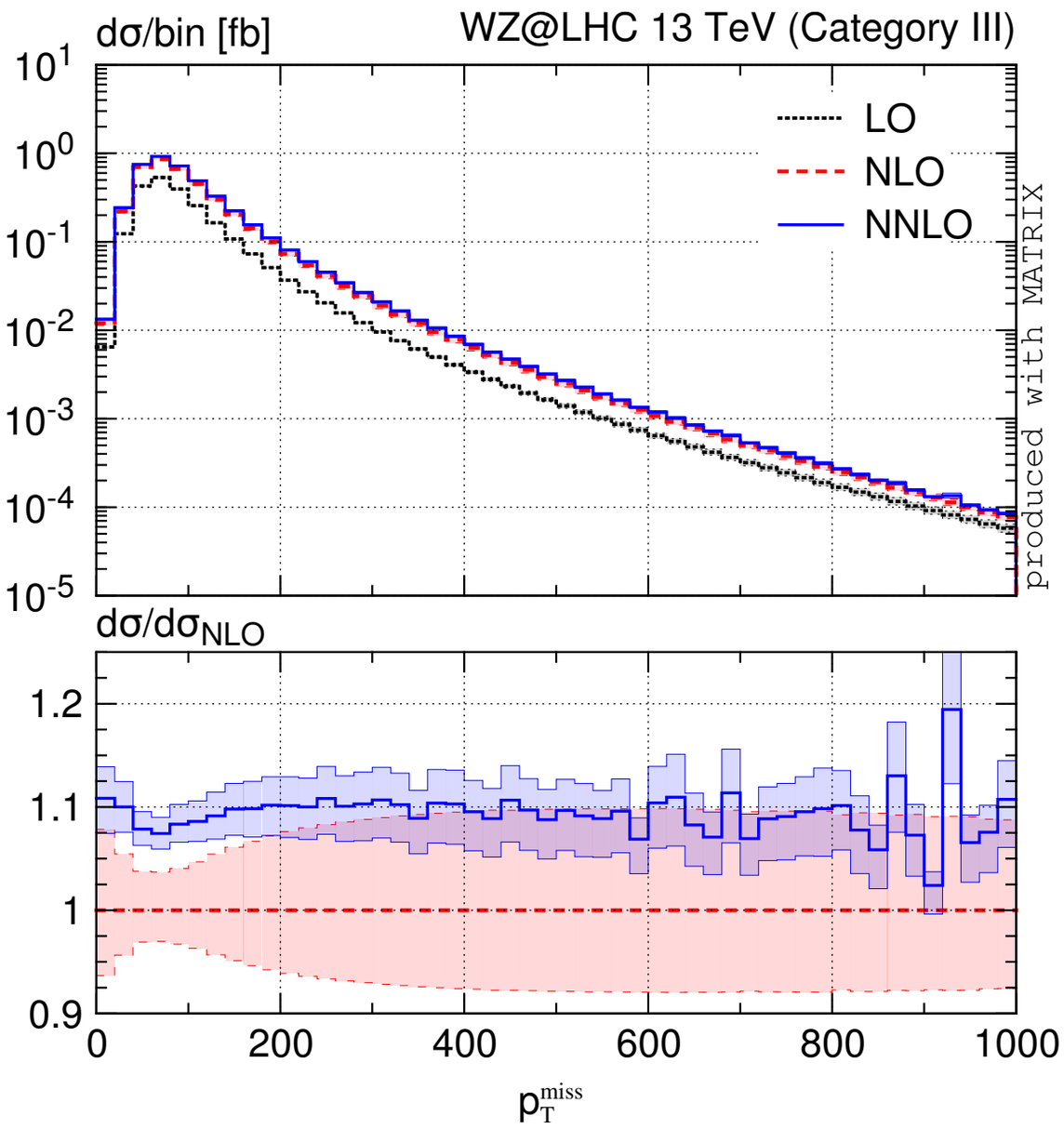


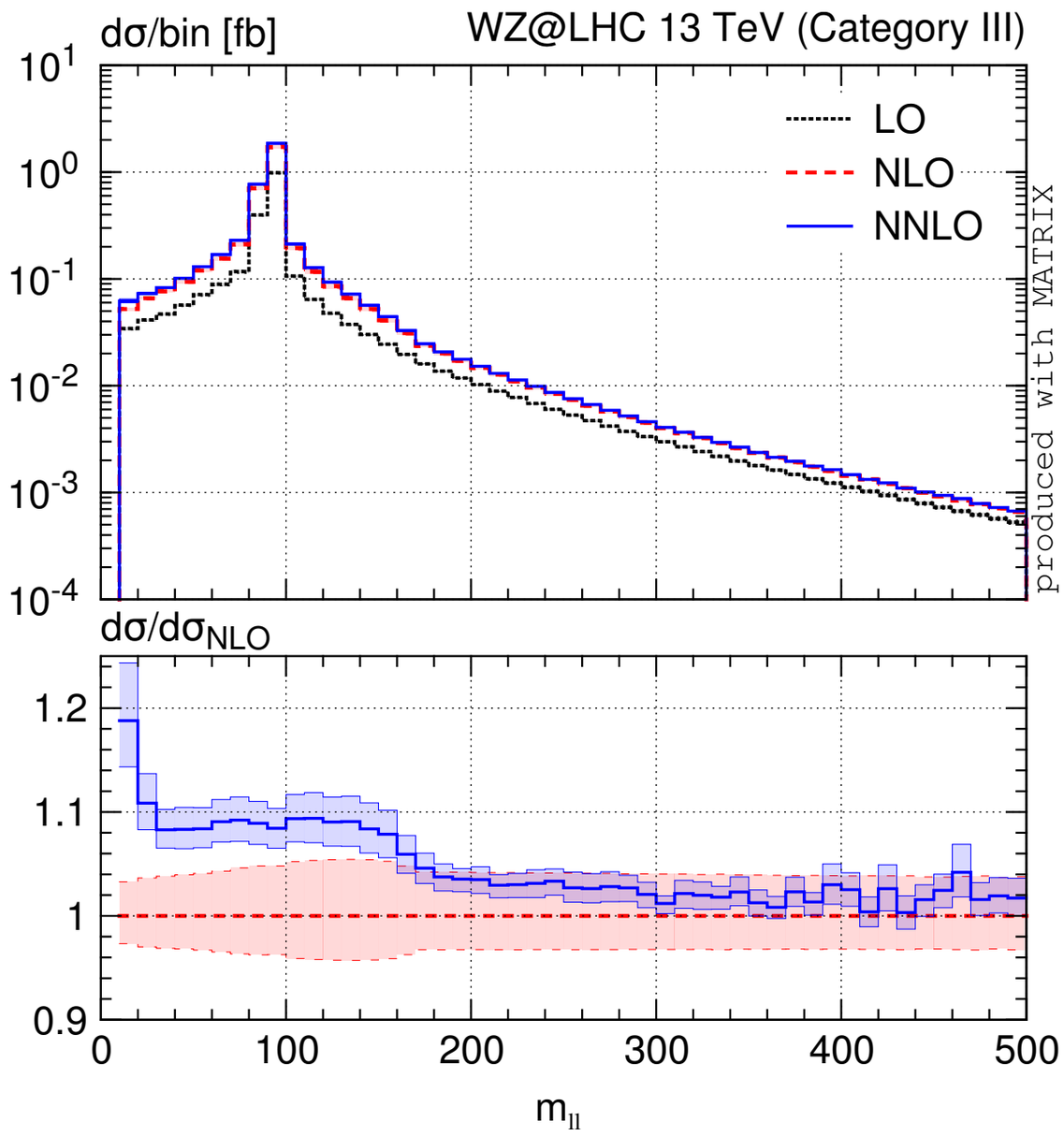
WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category III: $m_{T,W}$>120 GeV



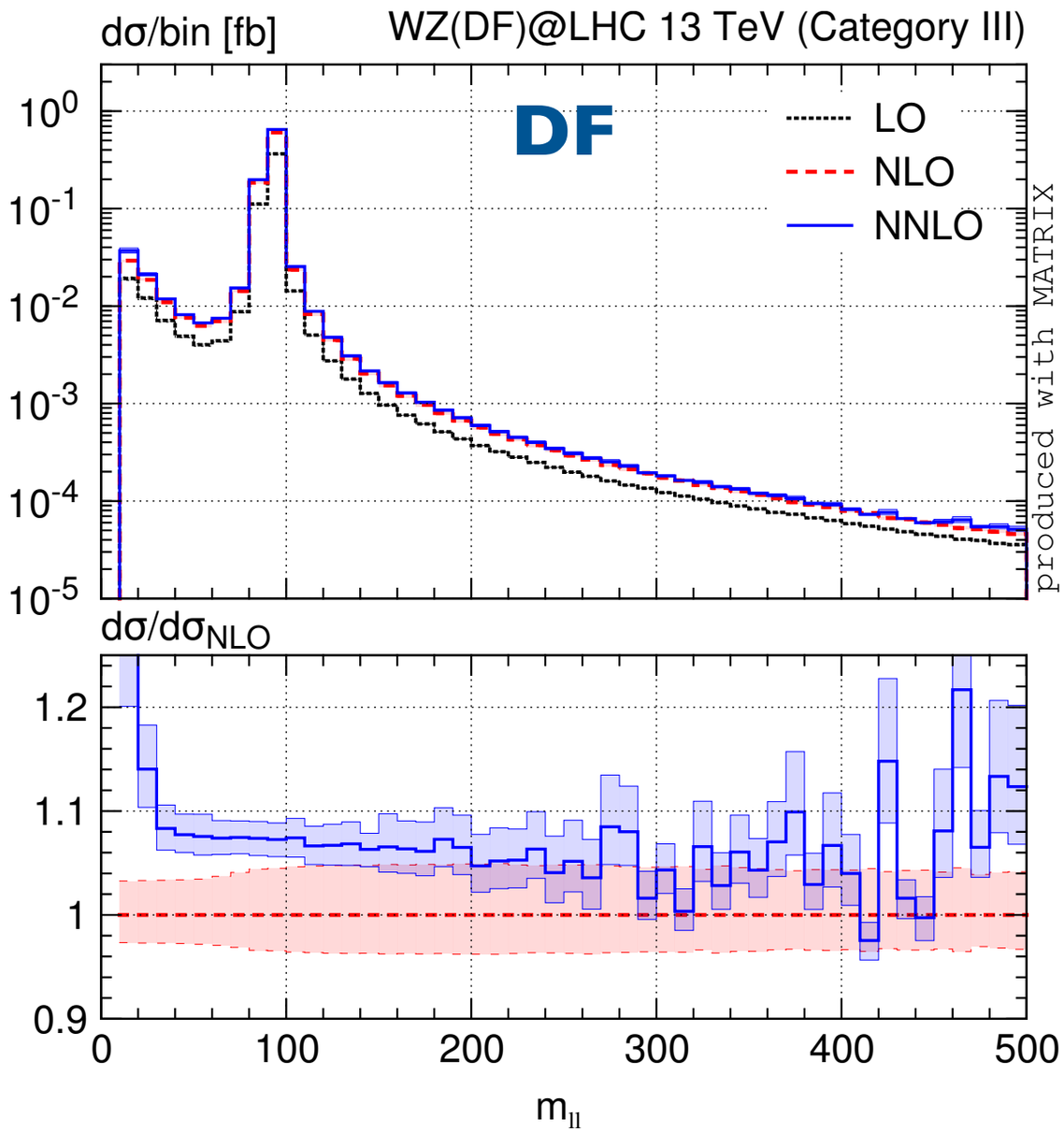


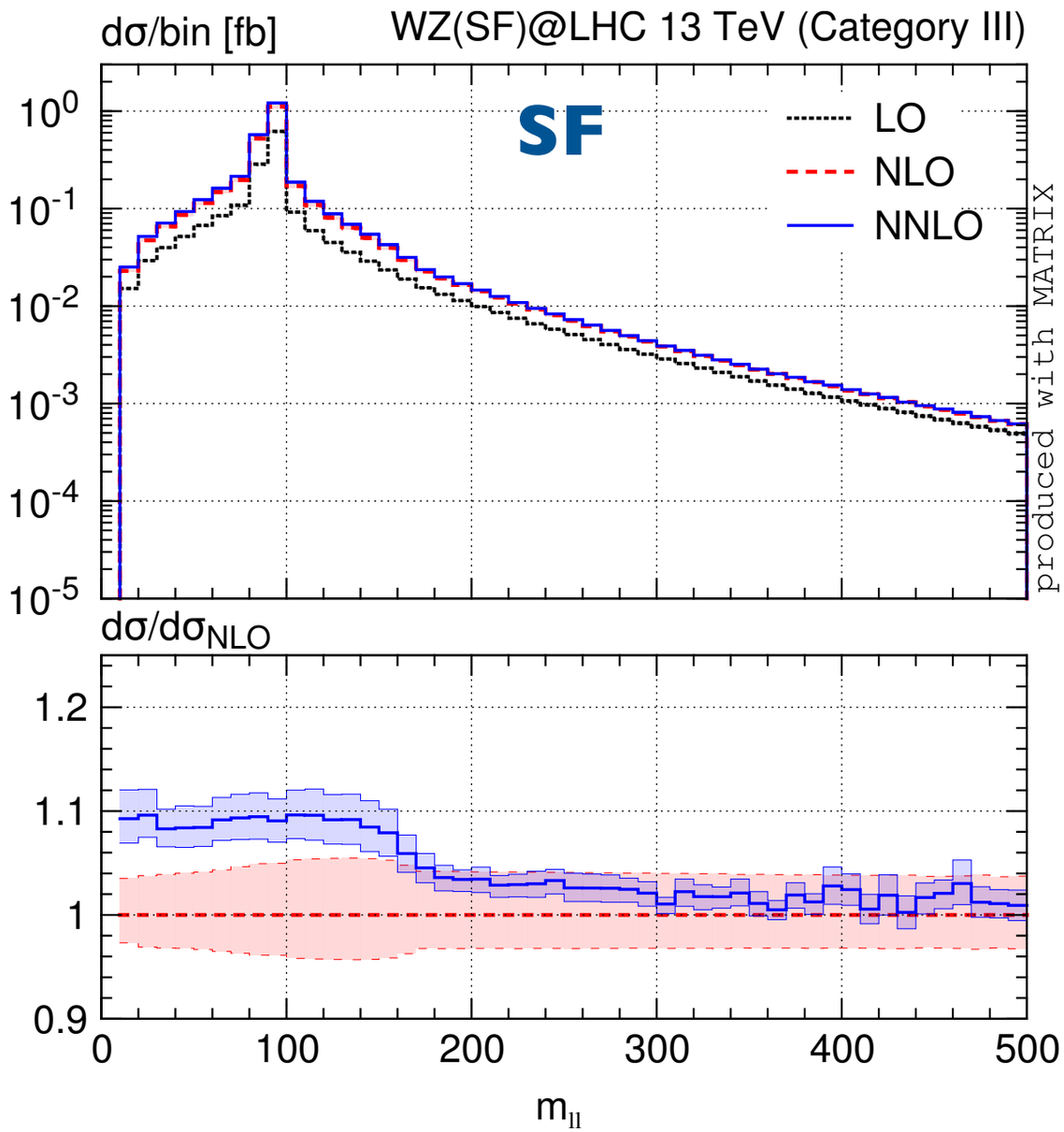
WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category III: $m_{T,W}$>120 GeV



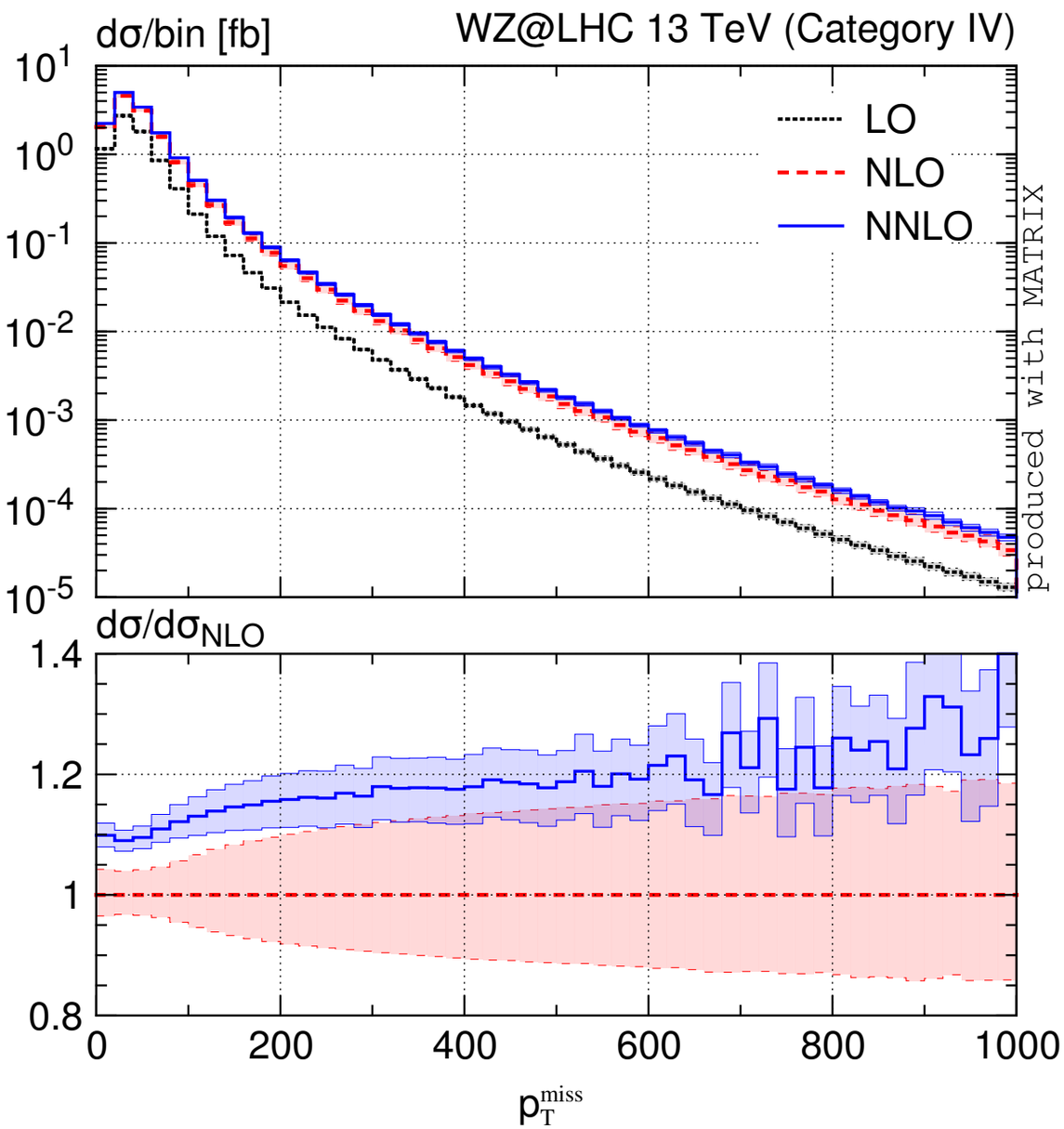


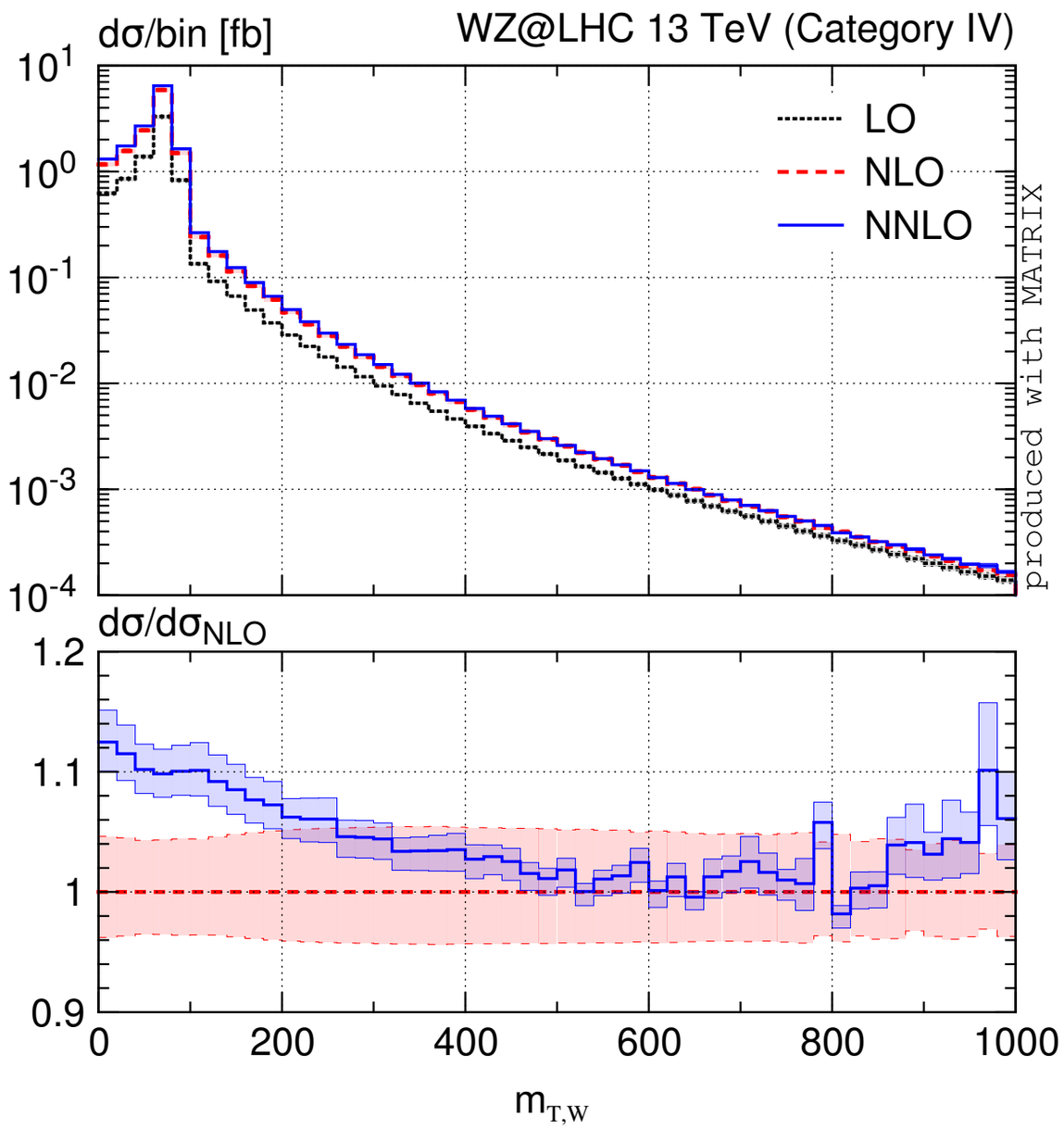
WZ fully differential at NNLO

[Grazzini, Kallweit, MW]

New-physics searches

Category IV: m_{ll}>105 GeV





WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

WW signal cuts: distributions (8 TeV)