Vector-boson pair production

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CERN

Workshop on the physics of HL-LHC, and perspectives at HE-LHC,
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VV production at NNLO

γγ - inclusive and fully differential cross section
[Catani, Cieri, de Florian, Ferrera, Grazzini '12], [Campbell, Ellis, Li, Williams '16]

ZZ - inclusive cross section [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]; see also: [Heinrich et al. ' 17]

- fully differential cross section [Grazzini, Kallweit, Rathlev '15];

Zγ - inclusive and fully differential cross section
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]; see also: [Campbell et al. '17]

Wγ - inclusive and fully differential cross section
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]

WW - inclusive cross section
[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi '14]

- fully differential cross section [Grazzini, Kallweit, Pozzorini, Rathlev, MW '15]

WZ - inclusive cross section [Grazzini, Kallweit, Rathlev, MW '16]

- fully differential cross section [Grazzini, Kallweit, Rathlev, MW '17]

VV production at NNLO

$\gamma\gamma$ - **inclusive and fully differential cross section**
[Catani, Cieri, de Florian, Ferrera, Grazzini '12], [Campbell, Ellis, Li, Williams '16]

ZZ - **inclusive cross section** [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]
- **fully differential cross section** [Grazzini, Kallweit, Rathlev '15];

Zγ - **inclusive and fully differential cross section**
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]

Wγ - **inclusive and fully differential cross section**
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]

WW - **inclusive cross section**
[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi '14]
- **fully differential cross section** [Grazzini, Kallweit, Pozzorini, Rathlev, MW '15]

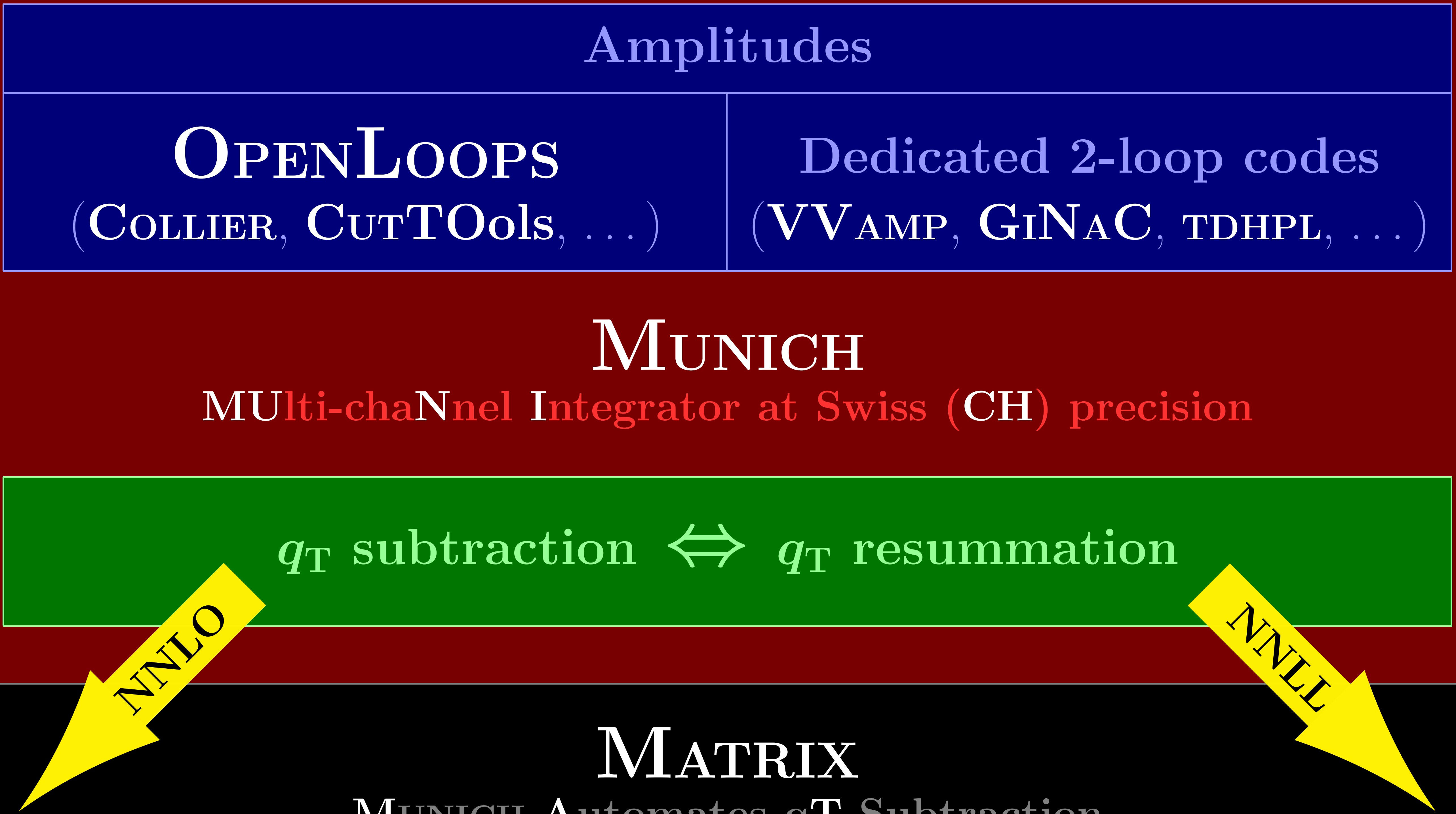
WZ - **inclusive cross section** [Grazzini, Kallweit, Rathlev, MW '16]
- **fully differential cross section** [Grazzini, Kallweit, Rathlev, MW '17]

→ **all done with MATRIX or previous version of the code**

We implemented...

The MATRIX framework

[Grazzini, Kallweit, MW]



Amplitudes

OpenLoops

(**Collier**, **CutTOols**, . . .)

Dedicated 2-loop codes

(**VVamp**, **GiNaC**, **tdhpl**, . . .)

Munich

MUlti-cha**N**nel **I**ntegrator at Swiss (**CH**) precision

q_T subtraction $\Leftrightarrow$ q_T resummation

Matrix

Munich **A**utomates q**T** Subtraction
and **R**esummation to **I**ntegrate **X**-sections.

process	status	comment
$pp\to Z/\gamma^*(\to \ell\ell/\nu\nu)$	✓	**validated analytically + FEWZ**
$pp\to W(\to \ell\nu)$	✓	**validated with FEWZ, NNLOjet**
$pp\to H$	✓	**validated analytically (by SusHi)**
$pp\to \gamma\gamma$	✓	**validated with 2γNNLO**
$pp\to Z\gamma\to \ell\ell\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp\to Z\gamma\to \nu\nu\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp\to W\gamma\to \ell\nu\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp\to ZZ$	✓	[Cascioli et al. '14]
$pp\to ZZ\to \ell\ell\ell\ell$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp\to ZZ\to \ell\ell\ell'\ell'$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp\to ZZ\to \ell\ell\nu'\nu'$	✓	**NEW**
$pp\to ZZ/WW\to \ell\ell\nu\nu$	✓	**NEW**
$pp\to WW$	✓	[Gehrmann et al. '14]
$pp\to WW\to \ell\nu\,\ell'\nu'$	✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
$pp\to WZ$	✓	[Grazzini, Kallweit, Rathlev, MW '16]
$pp\to WZ\to \ell\nu\ell\ell$	✓	[Grazzini, Kallweit, Rathlev, MW '17]
$pp\to WZ\to \ell'\nu'\ell\ell$	✓	[Grazzini, Kallweit, Rathlev, MW '17]
$pp\to HH$	(✓)	**not in first public release**

MATRIX features on one slide

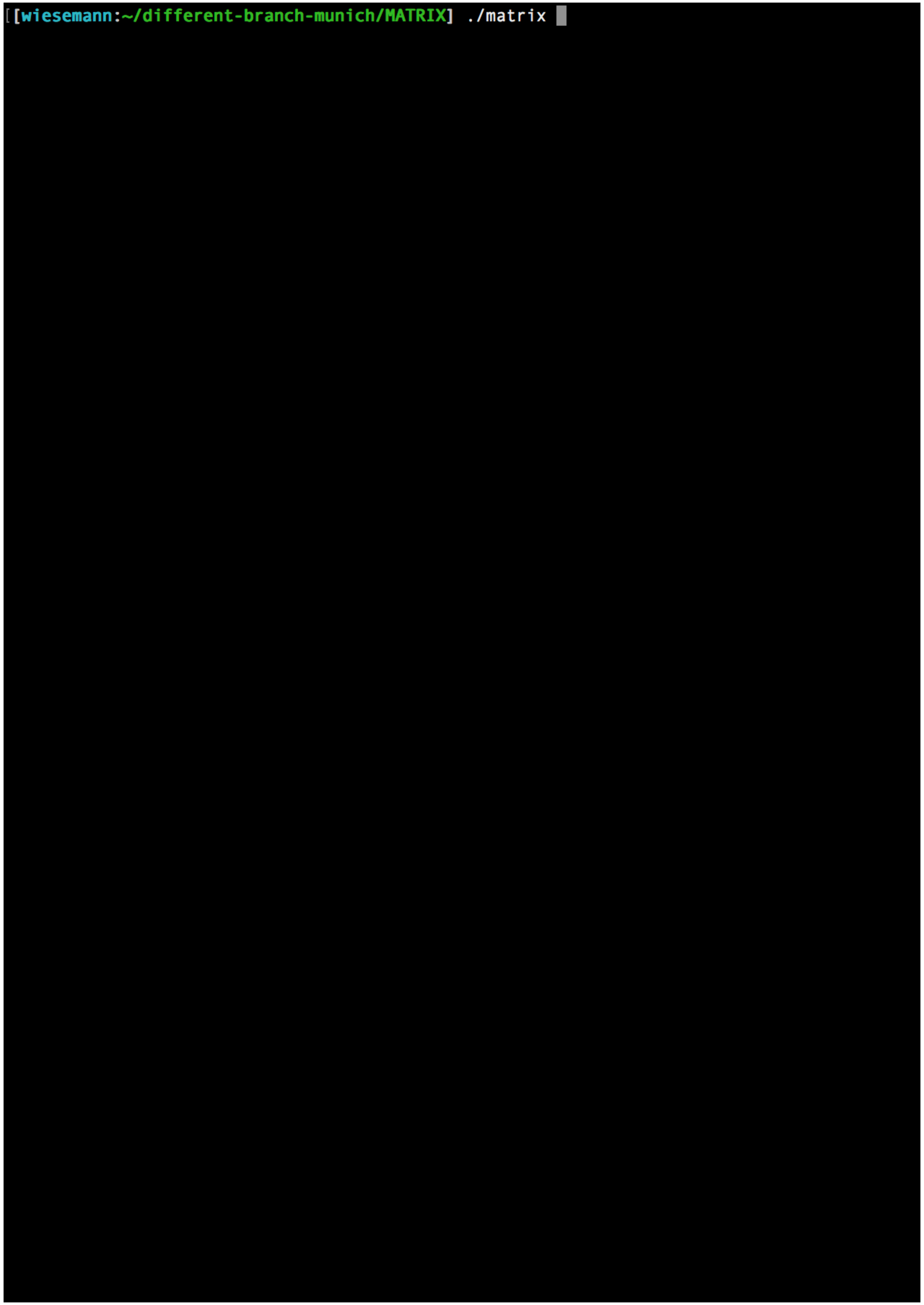
- Colourless 2→1 and 2→2 reactions (decays, off-shell effects, spin correlations; previous slide)
- **physics features:**
  - NNLO accuracy based on q_T subtraction
  - loop-induced gg component part of NNLO cross section (effectively LO accurate)
  - CKM for W-boson production
  - essential fiducial cuts, dynamical scales and distributions already pre-defined for each process
  - final-state particles directly accessible (for distributions, cuts, scales)
  - scale uncertainty estimated automatically estimated (7- or 9-point) with every run
  - **NEW:** automatic extrapolation of q_T-subtraction cut-off to zero (with extrapolation uncertainty)
- **technical features:**
  - Core: C++ code; steered by Python interface (compilation/running/job submission/result collection)
  - **only requirements:** LHAPDF 5 or 6 pre-installed & Python 2.7 with numpy
  - **Otherwise fully automatic!** (download/compilation of external packages; inputs via interface etc.)
  - local and cluster support: LSF (lxplus), HT-Condor (lxplus), condor, SLURM, Torque/PBS, SGE

    → missing your favourite cluster? Let us know!
  - option to reduce workload (output) on slow file systems
  - **all relevant references in CITATION.bib** (provided with every run)
  - comprehensive manual shipped with the code

enter the MATRIX

- After unpacking start MATRIX with:

```
$$ ./matrix
```



```
[[wiesemann:~/different-branch-munich/MATRIX] ./matrix
```

enter the MATRIX

- After unpacking start MATRIX with:

```
$$ ./matrix
```

- Inside the MATRIX compilation shell

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

- lists all process IDs. Select ID, eg:

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

```
[wiesemann:~/different-branch-munich/MATRIX] ./matrix

            /-------------------------------------------------------------------\
            | MATRIX: A fully-differential NNLO(+NNLL) process library          |
            |                                                                   |
            |           __ ___     ___     ____    ___         _     _          |
            |          | _\/_ |   / _ \   |____|  / _ \   ||   \\   //          |
            |          || \/ ||  | |_| |    ||    ||_||   ||    \\ //           |
            |          ||    ||  | ___ |    ||    ||\\    ||    // \\           |
            |          ||    ||  ||   ||    ||    || \\   ||   //   \\          |
            |                                                                   |
            |          Version: 1.0.0.release_candidate4      Aug 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                             (stefan.kallweit@cern.ch) |
            | M. Wiesemann                           (marius.wiesemann@cern.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 with CKM
ppwx01        >>   p p --> W^+                     >>   on-shell W+ production with CKM
ppeex02       >>   p p --> e^- e^+                 >>   Z production with decay
ppnenex02     >>   p p --> v_e^- v_e^+             >>   Z production with decay
ppenex02      >>   p p --> e^- v_e^+               >>   W- production with decay and CKM
ppexne02      >>   p p --> e^+ v_e^-               >>   W+ production with decay and CKM
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
ppenexa03     >>   p p --> e^- v_e^+ gamma         >>   W- gamma production with decay
ppexnea03     >>   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
ppemexmx04    >>   p p --> e^- mu^- e^+ mu^+       >>   ZZ production with decay
ppeeexex04    >>   p p --> e^- e^- e^+ e^+         >>   ZZ production with decay
ppeexnmnmx04  >>   p p --> e^- e^+ v_mu^- v_mu^+   >>   ZZ production with decay
ppemxnmnex04  >>   p p --> e^- mu^+ v_mu^- v_e^+   >>   WW production with decay
ppeexnenex04  >>   p p --> e^- e^+ v_e^- v_e^+     >>   ZZ/WW production with decay
ppemexnmx04   >>   p p --> e^- mu^- e^+ v_mu^+     >>   W-Z production with decay
ppeeexnex04   >>   p p --> e^- e^- e^+ v_e^+       >>   W-Z production with decay
ppeexmxnm04   >>   p p --> e^- e^+ mu^+ v_mu^-     >>   W+Z production with decay
ppeexexne04   >>   p p --> e^- e^+ e^+ v_e^-       >>   W+Z production with decay
[|============>> ppeeexex04
```

enter the MATRIX

- After unpacking start MATRIX with:

```
$$ ./matrix
```

- Inside the MATRIX compilation shell

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

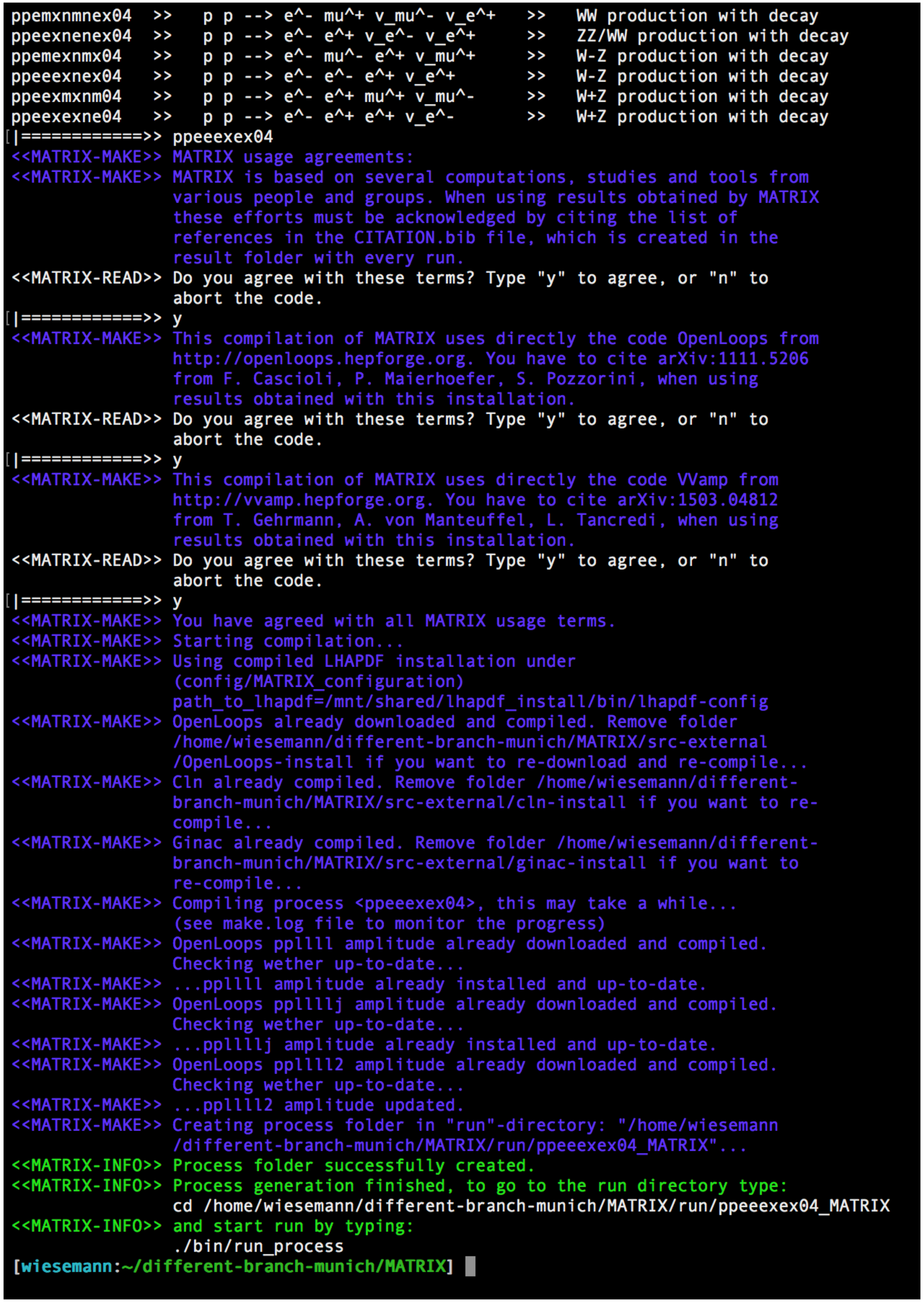
- lists all process IDs. Select ID, eg:

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

- for pp→ZZ→4ℓ. Confirming with

```
|===>> y
```

- the MATRIX usage agreements, the code will automatically start to:
  - dowload/compile of OpenLoops
  - compile of Cln and Ginac
  - compile MATRIX
  - download OpenLoops amplitudes
  - create MATRIX run folder for the process

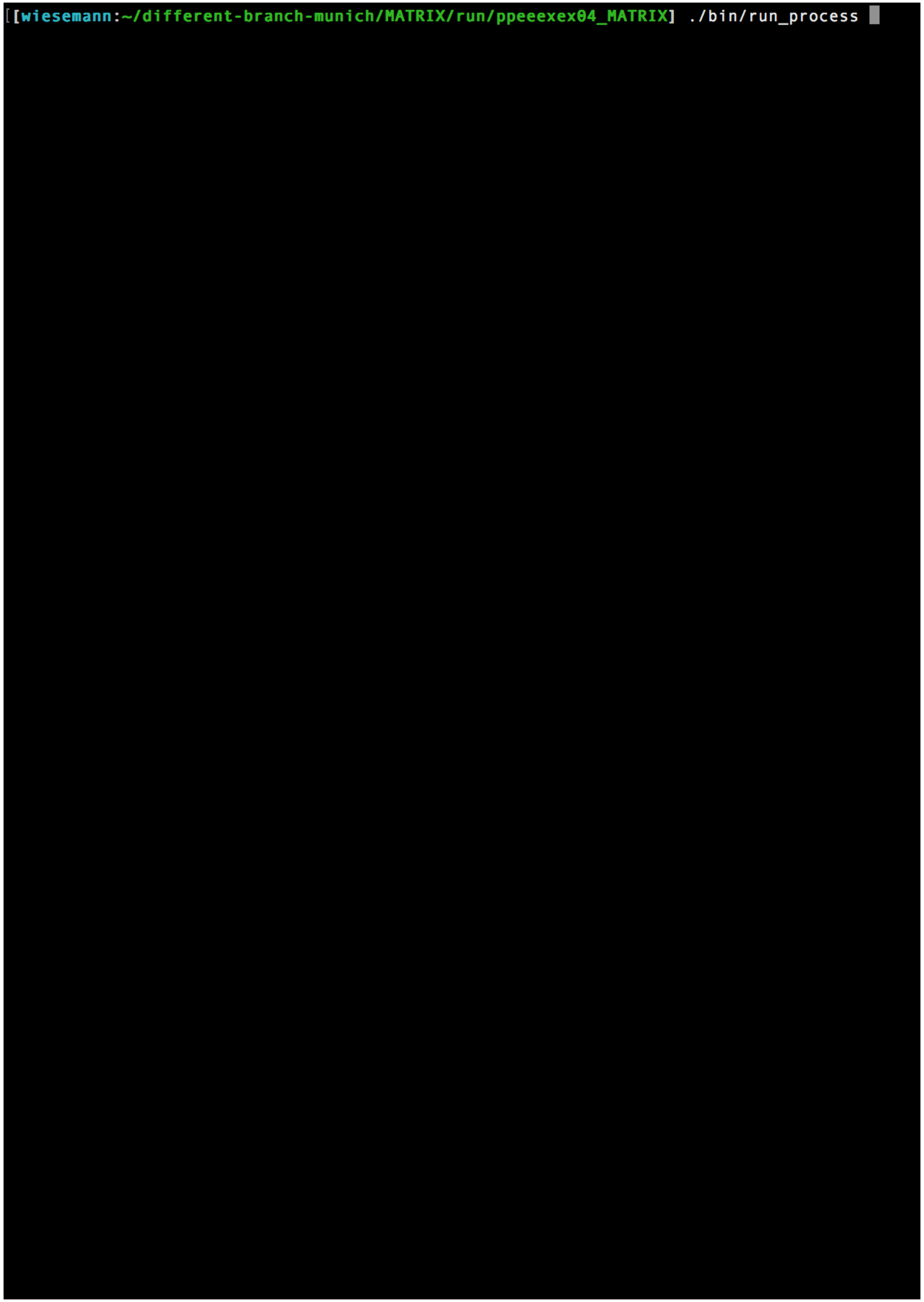


```
ppemxnmnex04  >>   p p --> e^- mu^+ v_mu^- v_e^+   >>   WW production with decay
ppeexnenex04  >>   p p --> e^- e^+ v_e^- v_e^+     >>   ZZ/WW production with decay
ppemexnmx04   >>   p p --> e^- mu^- e^+ v_mu^+     >>   W-Z production with decay
ppeeexnex04   >>   p p --> e^- e^- e^+ v_e^+       >>   W-Z production with decay
ppeexmxnm04   >>   p p --> e^- e^+ mu^+ v_mu^-     >>   W+Z production with decay
ppeexexne04   >>   p p --> e^- e^+ e^+ v_e^-       >>   W+Z production with decay
[|============>> ppeeexex04
<<MATRIX-MAKE>> MATRIX usage agreements:
<<MATRIX-MAKE>> MATRIX is based on several computations, studies and tools from
                various people and groups. When using results obtained by MATRIX
                these efforts must be acknowledged by citing the list of
                references in the CITATION.bib file, which is created in the
                result folder with every run.
<<MATRIX-READ>> Do you agree with these terms? Type "y" to agree, or "n" to
                abort the code.
[|============>> y
<<MATRIX-MAKE>> This compilation of MATRIX uses directly the code OpenLoops from
                http://openloops.hepforge.org. You have to cite arXiv:1111.5206
                from F. Cascioli, P. Maierhoefer, S. Pozzorini, when using
                results obtained with this installation.
<<MATRIX-READ>> Do you agree with these terms? Type "y" to agree, or "n" to
                abort the code.
[|============>> y
<<MATRIX-MAKE>> This compilation of MATRIX uses directly the code VVamp from
                http://vvamp.hepforge.org. You have to cite arXiv:1503.04812
                from T. Gehrmann, A. von Manteuffel, L. Tancredi, when using
                results obtained with this installation.
<<MATRIX-READ>> Do you agree with these terms? Type "y" to agree, or "n" to
                abort the code.
[|============>> y
<<MATRIX-MAKE>> You have agreed with all MATRIX usage terms.
<<MATRIX-MAKE>> Starting compilation...
<<MATRIX-MAKE>> Using compiled LHAPDF installation under
                (config/MATRIX_configuration)
                path_to_lhapdf=/mnt/shared/lhapdf_install/bin/lhapdf-config
<<MATRIX-MAKE>> OpenLoops already downloaded and compiled. Remove folder
                /home/wiesemann/different-branch-munich/MATRIX/src-external
                /OpenLoops-install if you want to re-download and re-compile...
<<MATRIX-MAKE>> Cln already compiled. Remove folder /home/wiesemann/different-
                branch-munich/MATRIX/src-external/cln-install if you want to re-
                compile...
<<MATRIX-MAKE>> Ginac already compiled. Remove folder /home/wiesemann/different-
                branch-munich/MATRIX/src-external/ginac-install if you want to
                re-compile...
<<MATRIX-MAKE>> Compiling process <ppeeexex04>, this may take a while...
                (see make.log file to monitor the progress)
<<MATRIX-MAKE>> OpenLoops pplllll amplitude already downloaded and compiled.
                Checking wether up-to-date...
<<MATRIX-MAKE>> ...pplll amplitude already installed and up-to-date.
<<MATRIX-MAKE>> OpenLoops pplllj amplitude already downloaded and compiled.
                Checking wether up-to-date...
<<MATRIX-MAKE>> ...pplllj amplitude already installed and up-to-date.
<<MATRIX-MAKE>> OpenLoops pplll2 amplitude already downloaded and compiled.
                Checking wether up-to-date...
<<MATRIX-MAKE>> ...pplll2 amplitude updated.
<<MATRIX-MAKE>> Creating process folder in "run"-directory: "/home/wiesemann
                /different-branch-munich/MATRIX/run/ppeeexex04_MATRIX"...
<<MATRIX-INFO>> Process folder successfully created.
<<MATRIX-INFO>> Process generation finished, to go to the run directory type:
                cd /home/wiesemann/different-branch-munich/MATRIX/run/ppeeexex04_MATRIX
<<MATRIX-INFO>> and start run by typing:
                ./bin/run_process
[wiesemann:~/different-branch-munich/MATRIX] 
```

enter the MATRIX

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

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



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

           /-------------------------------------------------------------------\
           | MATRIX: A fully-differential NNLO(+NNLL) process library          |
           |           __  __     ___     ____    ___         _     _          |
           |          | _\/_ |   / _ \   |____|  / _ \   ||   \\   //          |
           |          || \/ ||  | |_| |    ||    ||_||   ||    \\ //           |
           |          ||    ||  | ___ |    ||    ||\\    ||    // \\           |
           |          ||    ||  ||   ||    ||    || \\   ||   //   \\          |
           |                                                                   |
           |          Version: 1.0.0.release_candidate4      Aug 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                             (stefan.kallweit@cern.ch) |
           | M. Wiesemann                           (marius.wiesemann@cern.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:~/different-branch-munich/MATRIX/run/ppeeexex04_MATRIX] ./bin/run_process

           /-------------------------------------------------------------------\
           | MATRIX: A fully-differential NNLO(+NNLL) process library          |
           |           __  __     ___     ____    ___         _     _          |
           |          | _\/_ |   / _ \   |____|  / _ \   ||   \\   //          |
           |          || \/ ||  | |_| |    ||    ||_||   ||    \\ //           |
           |          ||    ||  | ___ |    ||    ||\\    ||    // \\           |
           |          ||    ||  ||   ||    ||    || \\   ||   //   \\          |
           |                                                                   |
           |          Version: 1.0.0.release_candidate4      Aug 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                             (stefan.kallweit@cern.ch) |
           | M. Wiesemann                           (marius.wiesemann@cern.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 fo

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

- The MATRIX run shell
  options, eg, modify inpu

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

```
[wiesemann:~/different-branch-munich/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               =  6500.          #  energy per beam
coll_choice     =  1              #  (1) PP collider; (2) PPbar collider
switch_off_shell = 0              #  switch for effective integration for off-shell Z bosons (eg, Higgs analysis)


#----------------\
# scale settings |
#----------------/
scale_ren       =  91.1876        #  renormalization (muR) scale
scale_fact      =  91.1876        #  factorization (muF) scale
dynamic_scale   =  0              #  dynamic ren./fac. scale
                                  #  0: fixed scale above
                                  #  1: invariant mass (Q) of system (of the colourless final states)
                                  #  2: transverse mass (mT^2=Q^2+pT^2) of system (of the colourless final states)
factor_central_scale = 1          #  relative factor for central scale (important for dynamic scales)
scale_variation  = 1              #  switch for muR/muF uncertainties (0) off; (1) 7-point (default); (2) 9-point va
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
precision_LO    =  1.e-2          #  precision 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
precision_NLO   =  1.e-2          #  precision of NLO cross section
NLO_subtraction_method = 1        #  switch to use (2) qT subtraction (1) Catani-Seymour at NLO

# 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
precision_NNLO  =  1.e-2          #  precision of NNLO cross section
loop_induced    =  1              #  switch to turn on (1) and off (0) loop-induced gg channel


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

# Jet cuts
define_pT jet = 25.               #  requirement on jet transverse momentum (lower cut)
define_eta jet = 4.5              #  requirement on jet pseudo-rapidity (upper cut)
define_y jet = 1.e99              #  requirement on jet rapidity (upper cut)
n_observed_min jet = 0            #  minimal number of observed jets (with cuts above)
n_observed_max jet = 99           #  maximal number of observed jets (with cuts above)

-UU-:----F1  parameter.dat    Top (1,0)     Git-release_candidate  (Fundamental Fld) 8:56AM 4.63 ----------------
Folding buffer... done
```

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
```

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

           /-------------------------------------------------------------------\
           | MATRIX: A fully-differential NNLO(+NNLL) process library          |
           |           __  __     ___     ____    ___         _     _          |
           |          | _\/_ |   / _ \   |____|  / _ \   ||   \\   //          |
           |          || \/ ||  | |_| |    ||    ||_||   ||    \\ //           |
           |          ||    ||  | ___ |    ||    ||\\    ||    // \\           |
           |          ||    ||  ||   ||    ||    || \\   ||   //   \\          |
           |                                                                   |
           |          Version: 1.0.0.release_candidate4      Aug 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                             (stefan.kallweit@cern.ch) |
           | M. Wiesemann                           (marius.wiesemann@cern.ch) |
           |-------------------------------------------------------------------|
           | MATRIX is based on a number of different computations and tools   |
           | from various people and groups. Please acknowledge their efforts  |
           | by citing the list of references which is created with every run. |
           \-------------------------------------------------------------------/

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

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

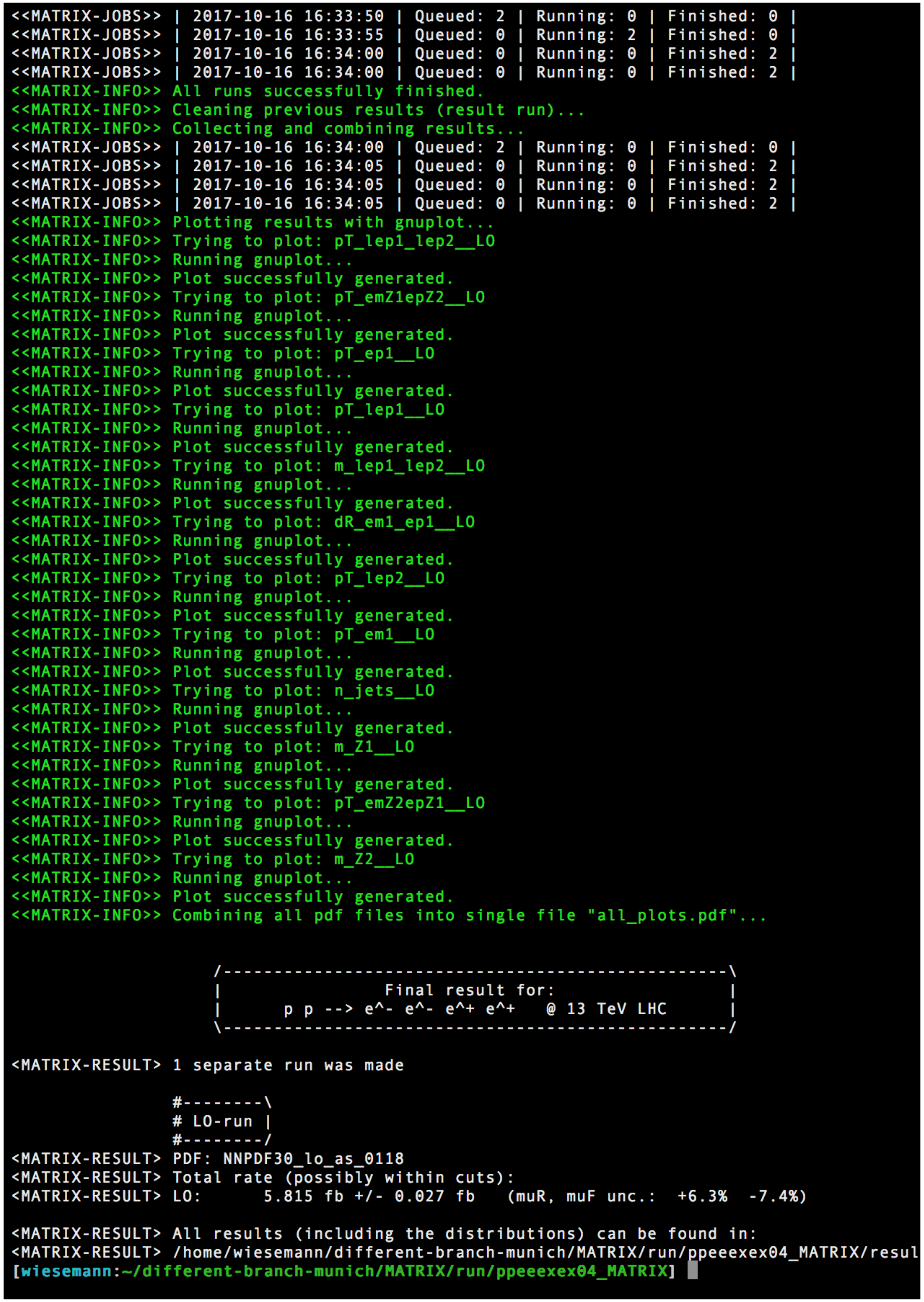
|===>> model

|===>> 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.



```
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:55 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:34:00 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:34:00 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfuly finished.
<<MATRIX-INFO>> Cleaning previous results (result run)...
<<MATRIX-INFO>> Collecting and combining results...
<<MATRIX-JOBS>> | 2017-10-16 16:34:00 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:34:05 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:34:05 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:34:05 | 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_emZ1epZ2__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.
<<MATRIX-INFO>> Trying to plot: m_Z1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: pT_emZ2epZ1__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Trying to plot: m_Z2__LO
<<MATRIX-INFO>> Running gnuplot...
<<MATRIX-INFO>> Plot successfully generated.
<<MATRIX-INFO>> Combining all pdf files into single file "all_plots.pdf"...


                     /-------------------------------------------------\
                     |                Final result for:                |
                     |      p p --> e^- e^- e^+ e^+   @ 13 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:      5.815 fb +/- 0.027 fb   (muR, muF unc.:  +6.3%  -7.4%)

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

p_T subtraction master formula:

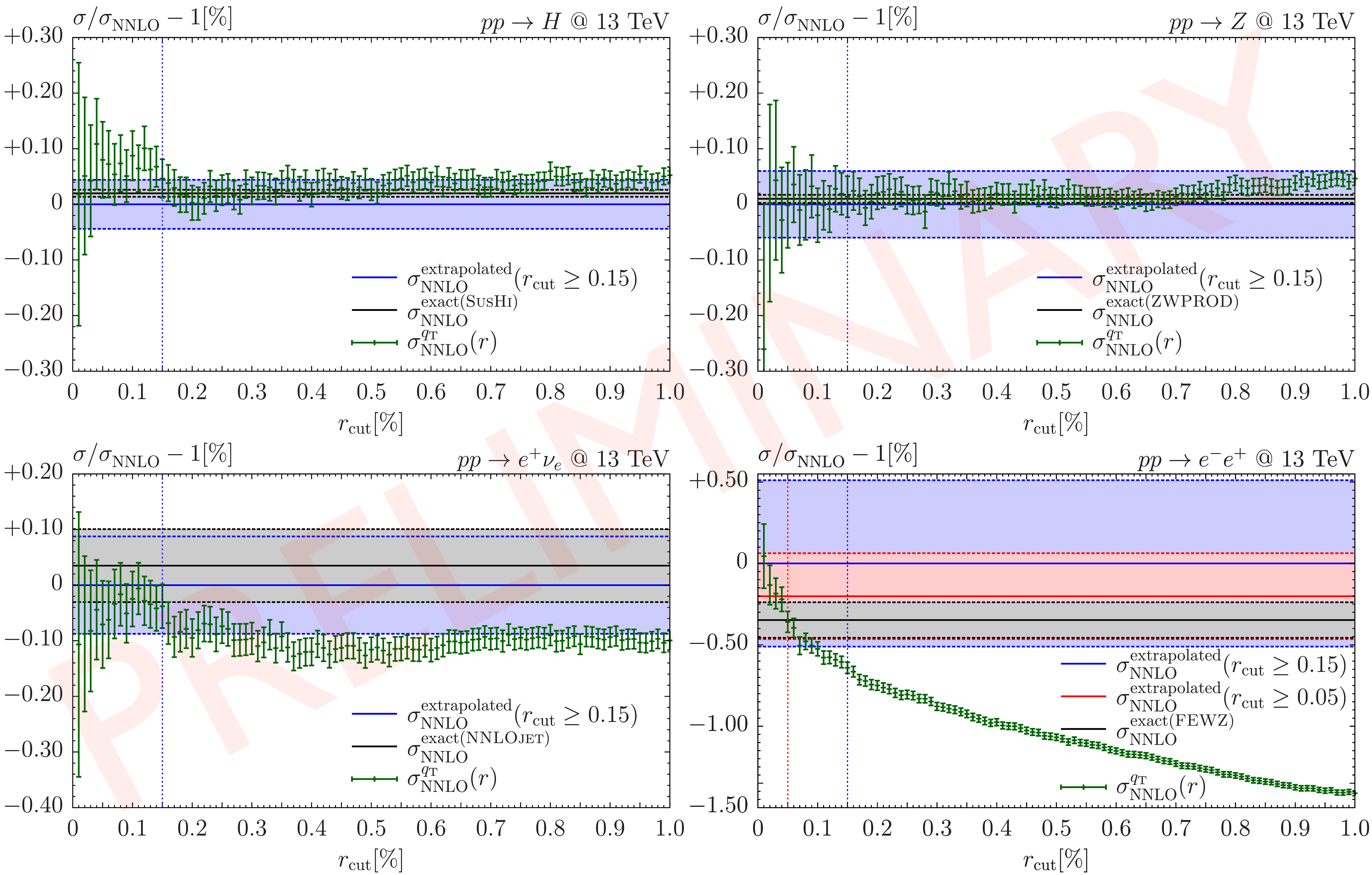
$$d\sigma_{\text{NNLO}} = \left[d\sigma_{\text{NLO}}^{F+1\text{jet}} - \Sigma_{\text{NNLO}} \otimes d\sigma_{\text{LO}} \right] + \mathcal{H}_{\text{NNLO}} \otimes d\sigma_{\text{LO}}$$

[Catani, Grazzini '07]

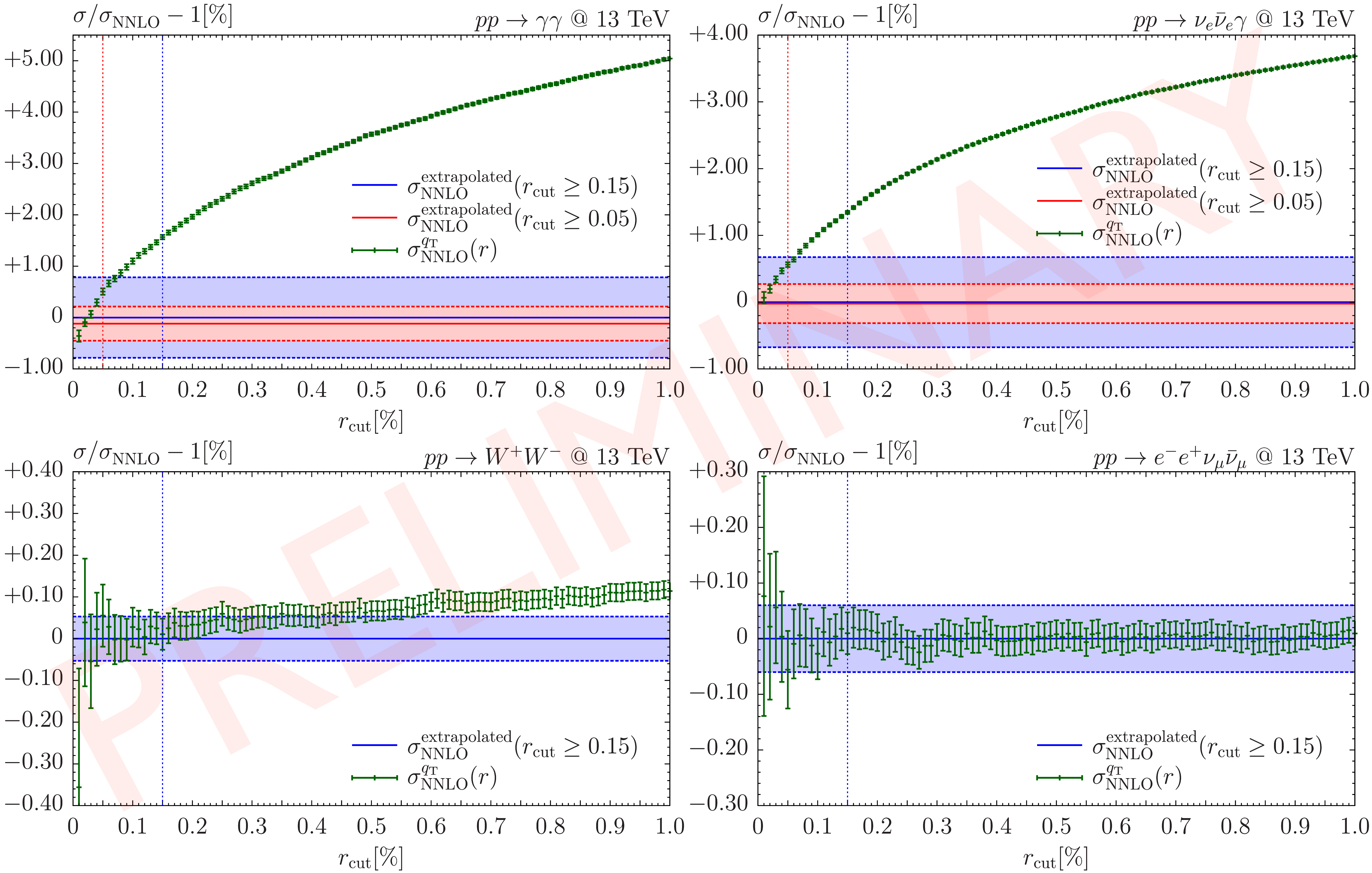
practical implementation:

- subtraction not local
- both terms in squared brackets separately divergent
- introduce lower cut-off r_{cut} on dimensionless quantity $r = p_{T,WW}/m_{WW}$
- use very small r_{cut} value and integrate both terms separately down to $r \geq r_{\text{cut}}$
- assumption: for $r \leq r_{\text{cut}}$ terms cancel (true up to power-suppressed terms)
- numerics forbids arbitrarily small r_{cut} values: use fit towards $r_{\text{cut}} \to 0$ limit
- MATRIX uses extrapolation $r_{\text{cut}} \to 0$ to obtain the final prediction

r_{cut}→0 extrapolation in MATRIX



$r_{\mathrm{cut}} \to 0$ extrapolation in MATRIX



Physics results

MATRIX reference predictions

[Grazzini, Kallweit, MW]

process (`${process_id}`)	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\mathrm{loop}}/\Delta\sigma^{\mathrm{ext}}_{\mathrm{NNLO}})$	$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO}}$	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO}}$	K_{NLO}	K_{NNLO}
$pp \to H$ (`pph21`)	$15.42(0)^{+22\%}_{-17\%}$ pb	$30.26(1)^{+20\%}_{-15\%}$ pb	—	$39.93(3)^{+11\%}_{-10\%}$ pb	$39.93(3)^{+11\%}_{-10\%}$ pb	+96.2%	+32.0%
$pp \to Z$ (`ppz01`)	$43.32(0)^{+12\%}_{-13\%}$ nb	$54.20(1)^{+3.1\%}_{-4.9\%}$ nb	—	$56.01(3)^{+0.84\%}_{-1.1\%}$ nb	$55.99(3)^{+0.84\%}_{-1.1\%}$ nb	+25.1%	+3.31%
$pp \to W^-$ (`ppw01`)	$60.15(0)^{+13\%}_{-14\%}$ nb	$75.95(2)^{+3.3\%}_{-5.3\%}$ nb	—	$78.43(3)^{+0.97\%}_{-1.3\%}$ nb	$78.51(11)^{+0.95\%}_{-1.3\%}$ nb	+26.3%	+3.38%
$pp \to W^+$ (`ppwx01`)	$81.28(1)^{+13\%}_{-14\%}$ nb	$102.2(0)^{+3.4\%}_{-5.3\%}$ nb	—	$105.8(1)^{+0.93\%}_{-1.3\%}$ nb	$105.8(1)^{+0.93\%}_{-1.3\%}$ nb	+25.7%	+3.52%
$pp \to e^-e^+$ (`ppeex02`)	$592.8(1)^{+14\%}_{-14\%}$ pb	$699.7(2)^{+2.9\%}_{-4.5\%}$ pb	—	$728.4(3)^{+0.48\%}_{-0.72\%}$ pb	$732.7(34)^{+0.43\%}_{-0.79\%}$ pb	+18.0%	+4.72%
$pp \to \nu_e\bar{\nu}_e$ (`ppnenex02`)	$2876(0)^{+12\%}_{-13\%}$ pb	$3585(1)^{+3.0\%}_{-4.9\%}$ pb	—	$3705(2)^{+0.86\%}_{-1.1\%}$ pb	$3710(2)^{+0.85\%}_{-1.1\%}$ pb	+24.6%	+3.48%
$pp \to e^-\bar{\nu}_e$ (`ppenex02`)	$2973(0)^{+14\%}_{-15\%}$ pb	$3673(1)^{+3.0\%}_{-5.2\%}$ pb	—	$3773(2)^{+0.89\%}_{-0.94\%}$ pb	$3767(8)^{+0.92\%}_{-0.95\%}$ pb	+23.6%	+2.55%
$pp \to e^+\nu_e$ (`ppexne02`)	$3964(0)^{+14\%}_{-14\%}$ pb	$4855(1)^{+3.0\%}_{-5.1\%}$ pb	—	$4986(2)^{+0.88\%}_{-0.95\%}$ pb	$4986(3)^{+0.88\%}_{-0.95\%}$ pb	+22.5%	+2.70%
$pp \to \gamma\gamma$ (`ppaa02`)	$5592(1)^{+10\%}_{-11\%}$ fb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%
$pp \to e^-e^+\gamma$ (`ppeexa03`)	$1469(0)^{+12\%}_{-12\%}$ fb	$2119(1)^{+2.9\%}_{-4.6\%}$ fb	$16.02(1)^{+24\%}_{-18\%}$ fb (8.14%)	$2326(1)^{+1.2\%}_{-1.3\%}$ fb	$2316(5)^{+1.1\%}_{-1.2\%}$ fb	+44.3%	+9.29%
$pp \to \nu_e\bar{\nu}_e\gamma$ (`ppnenexa03`)	$63.61(1)^{+2.7\%}_{-3.5\%}$ fb	$98.75(2)^{+3.3\%}_{-2.7\%}$ fb	$2.559(2)^{+26\%}_{-19\%}$ fb (17.3%)	$114.7(1)^{+3.2\%}_{-2.6\%}$ fb	$113.5(6)^{+2.9\%}_{-2.4\%}$ fb	+55.2%	+15.0%
$pp \to e^-\bar{\nu}_e\gamma$ (`ppenexa03`)	$726.1(1)^{+11\%}_{-12\%}$ fb	$1850(1)^{+6.6\%}_{-5.3\%}$ fb	—	$2286(1)^{+4.0\%}_{-3.7\%}$ fb	$2256(15)^{+3.7\%}_{-3.5\%}$ fb	+155%	+22.0%
$pp \to e^+\nu_e\gamma$ (`ppexnea03`)	$861.7(1)^{+10\%}_{-11\%}$ fb	$2187(1)^{+6.6\%}_{-5.3\%}$ fb	—	$2707(3)^{+4.1\%}_{-3.8\%}$ fb	$2671(35)^{+3.8\%}_{-3.6\%}$ fb	+154%	+22.1%
$pp \to ZZ$ (`ppzz02`)	$9845(1)^{+5.2\%}_{-6.3\%}$ fb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%
$pp \to W^+W^-$ (`ppwxw02`)	$66.64(1)^{+5.7\%}_{-6.7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%
$pp \to e^-\mu^-e^+\mu^+$ (`ppemexmx04`)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%
$pp \to e^-e^-e^+e^+$ (`ppeeexex04`)	$5.781(1)^{+6.3\%}_{-7.4\%}$ fb	$8.623(3)^{+3.1\%}_{-2.5\%}$ fb	$0.9941(4)^{+25\%}_{-18\%}$ fb (56.9%)	$10.37(1)^{+3.5\%}_{-3.0\%}$ fb	$10.37(1)^{+3.5\%}_{-3.0\%}$ fb	+49.2%	+20.2%
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (`ppeexnmnmx04`)	$22.34(0)^{+5.3\%}_{-6.4\%}$ fb	$33.90(1)^{+3.3\%}_{-2.7\%}$ fb	$3.212(1)^{+25\%}_{-19\%}$ fb (49.6%)	$40.39(2)^{+3.5\%}_{-2.8\%}$ fb	$40.38(2)^{+3.5\%}_{-2.8\%}$ fb	+51.7%	+19.1%
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (`ppemxnmnex04`)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (`ppeexnenex04`)	$115.0(0)^{+6.3\%}_{-7.3\%}$ fb	$203.4(1)^{+4.7\%}_{-3.8\%}$ fb	$12.62(1)^{+26\%}_{-19\%}$ fb (33.8%)	$240.8(1)^{+3.4\%}_{-3.0\%}$ fb	$240.7(1)^{+3.4\%}_{-3.0\%}$ fb	+76.9%	+18.4%
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (`ppemexnmx04`)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%
$pp \to e^-e^-e^+\bar{\nu}_e$ (`ppeeexnex04`)	$11.53(0)^{+5.7\%}_{-6.8\%}$ fb	$23.63(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.26(1)^{+2.3\%}_{-2.1\%}$ fb	$26.26(1)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%
$pp \to e^-e^+\mu^+\nu_\mu$ (`ppeexmxnm04`)	$17.33(0)^{+5.3\%}_{-6.3\%}$ fb	$34.13(1)^{+5.3\%}_{-4.3\%}$ fb	—	$37.75(2)^{+2.3\%}_{-2.0\%}$ fb	$37.76(2)^{+2.2\%}_{-2.0\%}$ fb	+97.0%	+10.6%
$pp \to e^-e^+e^+\nu_e$ (`ppeexexne04`)	$17.37(0)^{+5.3\%}_{-6.3\%}$ fb	$34.20(1)^{+5.3\%}_{-4.3\%}$ fb	—	$37.85(2)^{+2.2\%}_{-2.0\%}$ fb	$37.86(2)^{+2.2\%}_{-2.0\%}$ fb	+96.9%	+10.7%

process (`${process_id}`)	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\text{loop}}/\Delta\sigma^{\text{ext}}_{\text{NNLO}})$	$\sigma^{r_{\text{cut}}}_{\text{NNLO}}$	$\sigma^{\text{extrapolated}}_{\text{NNLO}}$	K_{NLO}	K_{NNLO}	
$pp \to \gamma\gamma$ (ppaa02)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%	**13 TeV**
$pp \to \gamma\gamma$ (ppaa02)	$10.34(0)^{+15\%}_{-15\%}$ pb	$54.63(5)^{+9.9\%}_{-11\%}$ pb	$6701(17)^{+24\%}_{-17\%}$ fb (17.4%)	$88.76(30)^{+9.1\%}_{-7.4\%}$ pb	$88.45(51)^{+9.0\%}_{-7.4\%}$ pb	+428%	+61.9%	**27 TeV**
$pp \to ZZ$ (ppzz02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%	**13 TeV**
$pp \to ZZ$ (ppzz02)	$23.59(1)^{+10\%}_{-11\%}$ pb	$35.56(2)^{+3.2\%}_{-4.1\%}$ pb	$4821(11)^{+25\%}_{-18\%}$ fb (52.9%)	$44.36(17)^{+4.2\%}_{-3.4\%}$ pb	$44.46(33)^{+4.3\%}_{-3.5\%}$ pb	+50.7%	+25.0%	**27 TeV**
$pp \to W^+W^-$ (ppwxw02)	$66.64(1)^{+5.7\%}_{-6.7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%	**13 TeV**
$pp \to W^+W^-$ (ppwxw02)	$152.5(0)^{+10\%}_{-11\%}$ pb	$254.7(2)^{+4.4\%}_{-4.6\%}$ pb	$13.87(3)^{+27\%}_{-19\%}$ pb (29.5%)	$300.4(1.1)^{+3.3\%}_{-3.0\%}$ pb	$299.8(1.3)^{+3.3\%}_{-2.9\%}$ pb	+67.0%	+17.7%	**27 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%	**13 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$22.49(1)^{+11\%}_{-12\%}$ fb	$35.78(3)^{+3.4\%}_{-4.5\%}$ fb	$6.140(20)^{+25\%}_{-18\%}$ fb (57.6%)	$45.78(21)^{+4.6\%}_{-3.8\%}$ fb	$45.28(83)^{+4.4\%}_{-3.6\%}$ fb	+59.1%	+26.6%	**27 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%	**13 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$439.0(1)^{+11\%}_{-12\%}$ fb	$429.0(4)^{+3.5\%}_{-3.2\%}$ fb	$79.19(9)^{+27\%}_{-19\%}$ fb (94.3%)	$507.0(1.4)^{+3.2\%}_{-2.1\%}$ fb	$507.5(1.9)^{+3.3\%}_{-2.1\%}$ fb	−2.27%	+18.3%	**27 TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%	**13TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$23.18(4)^{10.9\%}_{11.5\%}$ fb	$53.21(9)^{+6.1\%}_{-5.3\%}$ fb	—	$62.18(65)^{+2.2\%}_{-3.2\%}$ fb	$62.07(84)^{+2.3\%}_{-3.1\%}$ fb	+129.5%	+16.6%	**27 TeV**

process (${process_id})	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\mathrm{loop}}/\Delta\sigma^{\mathrm{ext}}_{\mathrm{NNLO}})$	$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO}}$	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO}}$	K_{NLO}	K_{NNLO}	
$pp \to \gamma\gamma$ (ppaa02)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%	**13 TeV**
$pp \to \gamma\gamma$ (ppaa02)	$10.34(0)^{+15\%}_{-15\%}$ pb	$54.63(5)^{+9.9\%}_{-11\%}$ pb	$6701(17)^{+24\%}_{-17\%}$ fb (17.4%)	$88.76(30)^{+9.1\%}_{-7.4\%}$ pb	$88.45(51)^{+9.0\%}_{-7.4\%}$ pb	+428%	+61.9%	**27 TeV**
$pp \to ZZ$ (ppzz02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%	**13 TeV**
$pp \to ZZ$ (ppzz02)	$23.59(1)^{+10\%}_{-11\%}$ pb	$35.56(2)^{+3.2\%}_{-4.1\%}$ pb	$4821(11)^{+25\%}_{-18\%}$ fb (52.9%)	$44.36(17)^{+4.2\%}_{-3.4\%}$ pb	$44.46(33)^{+4.3\%}_{-3.5\%}$ pb	+50.7%	+25.0%	**27 TeV**
$pp \to W^+W^-$ (ppwxw02)	$66.64(1)^{+5.7\%}_{-6.7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%	**13 TeV**
$pp \to W^+W^-$ (ppwxw02)	$152.5(0)^{+10\%}_{-11\%}$ pb	$254.7(2)^{+4.4\%}_{-4.6\%}$ pb	$13.87(3)^{+27\%}_{-19\%}$ pb (29.5%)	$300.4(1.1)^{+3.3\%}_{-3.0\%}$ pb	$299.8(1.3)^{+3.3\%}_{-2.9\%}$ pb	+67.0%	+17.7%	**27 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%	**13 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$22.49(1)^{+11\%}_{-12\%}$ fb	$35.78(3)^{+3.4\%}_{-4.5\%}$ fb	$6.140(20)^{+25\%}_{-18\%}$ fb (57.6%)	$45.78(21)^{+4.6\%}_{-3.8\%}$ fb	$45.28(83)^{+4.4\%}_{-3.6\%}$ fb	+59.1%	+26.6%	**27 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%	**13 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$439.0(1)^{+11\%}_{-12\%}$ fb	$429.0(4)^{+3.5\%}_{-3.2\%}$ fb	$79.19(9)^{+27\%}_{-19\%}$ fb (94.3%)	$507.0(1.4)^{+3.2\%}_{-2.1\%}$ fb	$507.5(1.9)^{+3.3\%}_{-2.1\%}$ fb	−2.27%	+18.3%	**27 TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%	**13TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$23.18(4)^{10.9\%}_{11.5\%}$ fb	$53.21(9)^{+6.1\%}_{-5.3\%}$ fb	—	$62.18(65)^{+2.2\%}_{-3.2\%}$ fb	$62.07(84)^{+2.3\%}_{-3.1\%}$ fb	+129.5%	+16.6%	**27 TeV**

YY

~2.2 factor

process (`${process_id}`)	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\mathrm{loop}}/\Delta\sigma^{\mathrm{ext}}_{\mathrm{NNLO}})$	$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO}}$	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO}}$	K_{NLO}	K_{NNLO}	
$pp \to \gamma\gamma$ (ppaa02)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%	13 TeV
$pp \to \gamma\gamma$ (ppaa02)	$10.34(0)^{+15\%}_{-15\%}$ pb	$54.63(5)^{+9.9\%}_{-11\%}$ pb	$6701(17)^{+24\%}_{-17\%}$ fb (17.4%)	$88.76(30)^{+9.1\%}_{-7.4\%}$ pb	$88.45(51)^{+9.0\%}_{-7.4\%}$ pb	+428%	+61.9%	27 TeV
$pp \to ZZ$ (ppzz02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%	13 TeV
$pp \to ZZ$ (ppzz02)	$23.59(1)^{+10\%}_{-11\%}$ pb	$35.56(2)^{+3.2\%}_{-4.1\%}$ pb	$4821(11)^{+25\%}_{-18\%}$ fb (52.9%)	$44.36(17)^{+4.2\%}_{-3.4\%}$ pb	$44.46(33)^{+4.3\%}_{-3.5\%}$ pb	+50.7%	+25.0%	27 TeV
$pp \to W^+W^-$ (ppwxw02)	$66.64(1)^{+5.7\%}_{-6.7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%	13 TeV
$pp \to W^+W^-$ (ppwxw02)	$152.5(0)^{+10\%}_{-11\%}$ pb	$254.7(2)^{+4.4\%}_{-4.6\%}$ pb	$13.87(3)^{+27\%}_{-19\%}$ pb (29.5%)	$300.4(1.1)^{+3.3\%}_{-3.0\%}$ pb	$299.8(1.3)^{+3.3\%}_{-2.9\%}$ pb	+67.0%	+17.7%	27 TeV
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%	13 TeV
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$22.49(1)^{+11\%}_{-12\%}$ fb	$35.78(3)^{+3.4\%}_{-4.5\%}$ fb	$6.140(20)^{+25\%}_{-18\%}$ fb (57.6%)	$45.78(21)^{+4.6\%}_{-3.8\%}$ fb	$45.28(83)^{+4.4\%}_{-3.6\%}$ fb	+59.1%	+26.6%	27 TeV
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%	13 TeV
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$439.0(1)^{+11\%}_{-12\%}$ fb	$429.0(4)^{+3.5\%}_{-3.2\%}$ fb	$79.19(9)^{+27\%}_{-19\%}$ fb (94.3%)	$507.0(1.4)^{+3.2\%}_{-2.1\%}$ fb	$507.5(1.9)^{+3.3\%}_{-2.1\%}$ fb	−2.27%	+18.3%	27 TeV
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%	13TeV
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$23.18(4)^{10.9\%}_{11.5\%}$ fb	$53.21(9)^{+6.1\%}_{-5.3\%}$ fb	—	$62.18(65)^{+2.2\%}_{-3.2\%}$ fb	$62.07(84)^{+2.3\%}_{-3.1\%}$ fb	+129.5%	+16.6%	27 TeV

γγ

~2.2 factor

ZZ (on shell)

~2.7 factor

process `(${process_id})`	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\text{loop}}/\Delta\sigma^{\text{ext}}_{\text{NNLO}})$	$\sigma^{r_{\text{cut}}}_{\text{NNLO}}$	$\sigma^{\text{extrapolated}}_{\text{NNLO}}$	K_{NLO}	K_{NNLO}	
$pp \to \gamma\gamma$ (ppaa02)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%	**13 TeV**
$pp \to \gamma\gamma$ (ppaa02)	$10.34(0)^{+15\%}_{-15\%}$ pb	$54.63(5)^{+9.9\%}_{-11\%}$ pb	$6701(17)^{+24\%}_{-17\%}$ fb (17.4%)	$88.76(30)^{+9.1\%}_{-7.4\%}$ pb	$88.45(51)^{+9.0\%}_{-7.4\%}$ pb	+428%	+61.9%	**27 TeV**
$pp \to ZZ$ (ppzz02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%	**13 TeV**
$pp \to ZZ$ (ppzz02)	$23.59(1)^{+10\%}_{-11\%}$ pb	$35.56(2)^{+3.2\%}_{-4.1\%}$ pb	$4821(11)^{+25\%}_{-18\%}$ fb (52.9%)	$44.36(17)^{+4.2\%}_{-3.4\%}$ pb	$44.46(33)^{+4.3\%}_{-3.5\%}$ pb	+50.7%	+25.0%	**27 TeV**
$pp \to W^+W^-$ (ppwxw02)	$66.64(1)^{+5.7\%}_{-[illegible].7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%	**13 TeV**
$pp \to W^+W^-$ (ppwxw02)	$152.5([illegible])^{+10\%}_{-11\%}$ pb	$254.7(2)^{+4.4\%}_{-4.6\%}$ pb	1[illegible]$.87(3)^{+27\%}_{-19\%}$ pb (29.5%)	$300.4(1.1)^{+3.3\%}_{-3.0\%}$ pb	$299.8(1.3)^{+3.3\%}_{-2.9\%}$ pb	+67.0%	+17.7%	**27 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%	**13 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$22.49(1)^{+11\%}_{-12\%}$ fb	$35.78(3)^{+3.4\%}_{-4.5\%}$ fb	$6.140(20)^{+25\%}_{-18\%}$ fb (57.6%)	$45.78(21)^{+4.6\%}_{-3.8\%}$ fb	$45.28(83)^{+4.4\%}_{-3.6\%}$ fb	+59.1%	+26.6%	**27 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%	**13 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$439.0(1)^{+11\%}_{-12\%}$ fb	$429.0(4)^{+3.5\%}_{-3.2\%}$ fb	$79.19(9)^{+27\%}_{-19\%}$ fb (94.3%)	$507.0(1.4)^{+3.2\%}_{-2.1\%}$ fb	$507.5(1.9)^{+3.3\%}_{-2.1\%}$ fb	−2.27%	+18.3%	**27 TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%	**13TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$23.18(4)^{10.9\%}_{11.5\%}$ fb	$53.21(9)^{+6.1\%}_{-5.3\%}$ fb	—	$62.18(65)^{+2.2\%}_{-3.2\%}$ fb	$62.07(84)^{+2.3\%}_{-3.1\%}$ fb	+129.5%	+16.6%	**27 TeV**

γγ

ZZ (on shell)

WW (on shell)

~2.2 factor

~2.7 factor

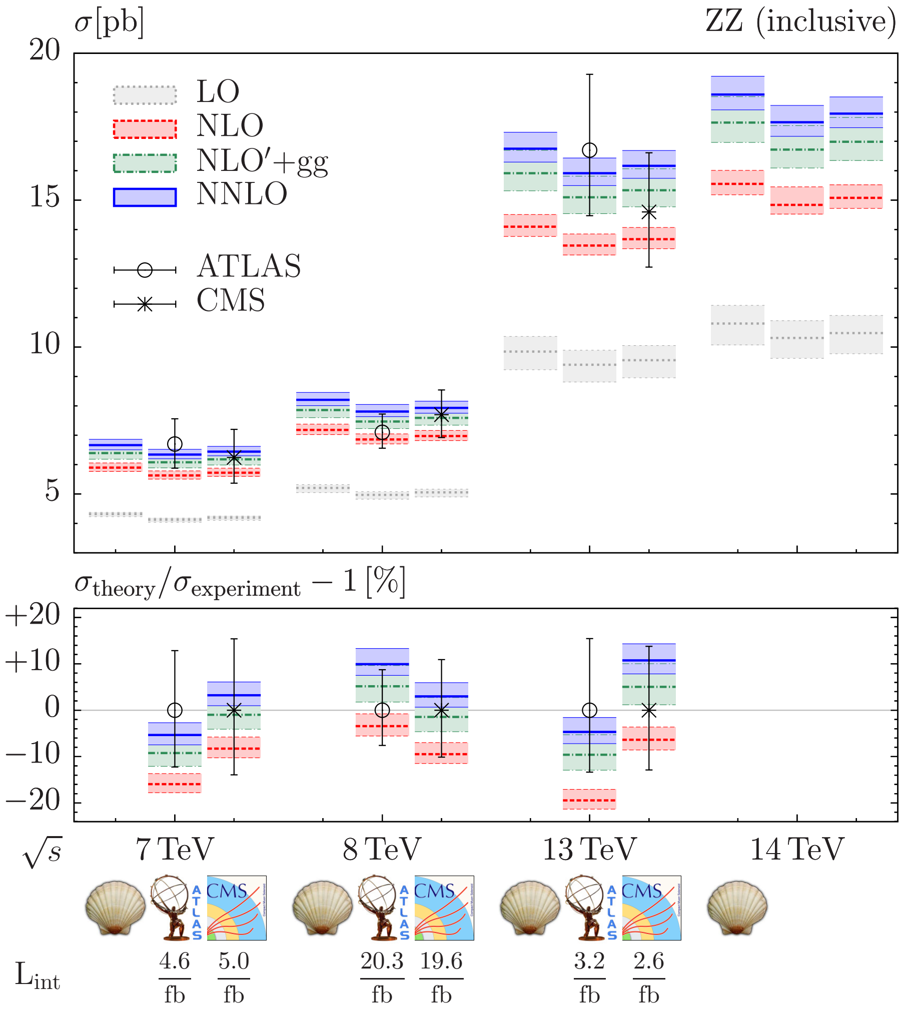
~2.6 factor

process `(${process_id})`	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\mathrm{loop}}/\Delta\sigma^{\mathrm{ext}}_{\mathrm{NNLO}})$	$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO}}$	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO}}$	K_{NLO}	K_{NNLO}	
YY $pp \to \gamma\gamma$ (ppaa02)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%	**13 TeV**
$pp \to \gamma\gamma$ (ppaa02)	$10.34(0)^{+15\%}_{-15\%}$ pb	$54.63(5)^{+9.9\%}_{-11\%}$ pb	$6701(17)^{+24\%}_{-17\%}$ fb (17.4%)	$88.76(30)^{+9.1\%}_{-7.4\%}$ pb	$88.45(51)^{+9.0\%}_{-7.4\%}$ pb	+428%	+61.9%	**~2.2 factor** **27 TeV**
ZZ (on shell) $pp \to ZZ$ (ppzz02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%	**13 TeV**
$pp \to ZZ$ (ppzz02)	$23.59(1)^{+10\%}_{-11\%}$ pb	$35.56(2)^{+3.2\%}_{-4.1\%}$ pb	$4821(11)^{+25\%}_{-18\%}$ fb (52.9%)	$44.36(17)^{+4.2\%}_{-3.4\%}$ pb	$44.46(33)^{+4.3\%}_{-3.5\%}$ pb	+50.7%	+25.0%	**~2.7 factor** **27 TeV**
WW (on shell) $pp \to W^+W^-$ (ppwxw02)	$66.64(1)^{+5.7\%}_{-[illegible].7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%	**13 TeV**
$pp \to W^+W^-$ (ppwxw02)	152.5([illegible])$^{+10\%}_{-11\%}$ pb	$254.7(2)^{+4.4\%}_{-4.6\%}$ pb	1[illegible].87(3)$^{+27\%}_{-19\%}$ pb (29.5%)	$300.4(1.1)^{+3.3\%}_{-3.0\%}$ pb	$299.8(1.3)^{+3.3\%}_{-2.9\%}$ pb	+67.0%	+17.7%	**~2.6 factor** **27 TeV**
ZZ (off shell) $pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%	**13 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$22.49(1)^{+11\%}_{-12\%}$ fb	$35.78(3)^{+3.4\%}_{-4.5\%}$ fb	$6.140(20)^{+25\%}_{-18\%}$ fb (57.6%)	$45.78(21)^{+4.6\%}_{-3.8\%}$ fb	$45.28(83)^{+4.4\%}_{-3.6\%}$ fb	+59.1%	+26.6%	**~2.3 factor** **27 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%	**13 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$439.0(1)^{+11\%}_{-12\%}$ fb	$429.0(4)^{+3.5\%}_{-3.2\%}$ fb	$79.19(9)^{+27\%}_{-19\%}$ fb (94.3%)	$507.0(1.4)^{+3.2\%}_{-2.1\%}$ fb	$507.5(1.9)^{+3.3\%}_{-2.1\%}$ fb	−2.27%	+18.3%	**27 TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%	**13TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$23.18(4)^{10.9\%}_{11.5\%}$ fb	$53.21(9)^{+6.1\%}_{-5.3\%}$ fb	—	$62.18(65)^{+2.2\%}_{-3.2\%}$ fb	$62.07(84)^{+2.3\%}_{-3.1\%}$ fb	+129.5%	+16.6%	**27 TeV**

process (`${process_id}`)	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\mathrm{loop}}/\Delta\sigma^{\mathrm{ext}}_{\mathrm{NNLO}})$	$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO}}$	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO}}$	K_{NLO}	K_{NNLO}	
YY $pp \to \gamma\gamma$ (p[illegible]a[illegible])	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%	**13 TeV**
[illegible] $\to \gamma\gamma$ (ppaa02)	$10.34(0)^{+15\%}_{-15\%}$ pb	$54.63(5)^{+9.9\%}_{-11\%}$ pb	$6701(17)^{+24\%}_{-17\%}$ fb (17.4%)	$88.76(30)^{+9.1\%}_{-7.4\%}$ pb	$88.45(51)^{+9.0\%}_{-7.4\%}$ pb	+428%	+61.9%	**~2.2 factor** **27 TeV**
ZZ (on shell) $pp \to ZZ$ ([illegible]z02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%	**13 TeV**
[illegible] Z[illegible] (ppzz02)	$23.59(1)^{+10\%}_{-11\%}$ pb	$35.56(2)^{+3.2\%}_{-4.1\%}$ pb	$4821(11)^{+25\%}_{-18\%}$ fb (52.9%)	$44.36(17)^{+4.2\%}_{-3.4\%}$ pb	$44.46(33)^{+4.3\%}_{-3.5\%}$ pb	+50.7%	+25.0%	**~2.7 factor** **27 TeV**
WW (on shell) $pp \to W^+W^-$ (pp[illegible]w02)	$66.64(1)^{+5.7\%}_{[illegible].7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%	**13 TeV**
pp [illegible] W[illegible]W^- (ppwxw02)	$152.5([illegible])^{+10\%}_{-11\%}$ pb	$254.7(2)^{+4.4\%}_{-4.6\%}$ pb	1[illegible].87(3)$^{+27\%}_{-19\%}$ pb (29.5%)	$300.4(1.1)^{+3.3\%}_{-3.0\%}$ pb	$299.8(1.3)^{+3.3\%}_{-2.9\%}$ pb	+67.0%	+17.7%	**~2.6 factor** **27 TeV**
ZZ (off shell) $pp \to e^-\mu^-e^+\mu^+$ (pp[illegible]xmx04)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%	**13 TeV**
pp [illegible] (ppemexmx04)	$22.49(1)^{+11\%}_{-12\%}$ fb	$35.78(3)^{+3.4\%}_{-4.5\%}$ fb	$6.140(20)^{+25\%}_{-18\%}$ fb (57.6%)	$45.78(21)^{+4.6\%}_{-3.8\%}$ fb	$45.28(83)^{+4.4\%}_{-3.6\%}$ fb	+59.1%	+26.6%	**~2.3 factor** **27 TeV**
WW (off shell) $pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ ([illegible]em[illegible]ne[illegible]4)	$232.9(0)^{+6.6\%}_{[illegible].6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%	**13 TeV**
pp [illegible] e^- [illegible] $\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	[illegible]39.0([illegible])$^{+11\%}_{-12\%}$ fb	$429.0(4)^{+3.5\%}_{-3.2\%}$ fb	7[illegible].19(9)$^{+27\%}_{-19\%}$ fb (94.3%)	$507.0(1.4)^{+3.2\%}_{-2.1\%}$ fb	$507.5(1.9)^{+3.3\%}_{-2.1\%}$ fb	−2.27%	+18.3%	**~1.9 factor** **27 TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%	**13TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$23.18(4)^{10.9\%}_{11.5\%}$ fb	$53.21(9)^{+6.1\%}_{-5.3\%}$ fb	—	$62.18(65)^{+2.2\%}_{-3.2\%}$ fb	$62.07(84)^{+2.3\%}_{-3.1\%}$ fb	+129.5%	+16.6%	**27 TeV**

process (${process_id})	σ_{LO}	σ_{NLO}	σ_{loop} $(\sigma_{\text{loop}}/\Delta\sigma^{\text{ext}}_{\text{NNLO}})$	$\sigma^{r_{\text{cut}}}_{\text{NNLO}}$	$\sigma^{\text{extrapolated}}_{\text{NNLO}}$	K_{NLO}	K_{NNLO}	
$pp \to \gamma\gamma$ (pp[illegible]a0[illegible])	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2534(1)^{+24\%}_{-17\%}$ fb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	$+361\%$	$+56.4\%$	**13 TeV**
γγ								**~2.2 factor**
[illegible] $\to \gamma\gamma$ (ppaa02)	$10.34(0)^{+15\%}_{-15\%}$ pb	$54.63(5)^{+9.9\%}_{-11\%}$ pb	$6701(17)^{+24\%}_{-17\%}$ fb (17.4%)	$88.76(30)^{+9.1\%}_{-7.4\%}$ pb	$88.45(51)^{+9.0\%}_{-7.4\%}$ pb	$+428\%$	$+61.9\%$	**27 TeV**
$pp \to ZZ$ ([illegible]z02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1361(1)^{+25\%}_{-19\%}$ fb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	$+43.3\%$	$+18.2\%$	**13 TeV**
ZZ (on shell)								**~2.7 factor**
[illegible] Z[illegible] (ppzz02)	$23.59(1)^{+10\%}_{-11\%}$ pb	$35.56(2)^{+3.2\%}_{-4.1\%}$ pb	$4821(11)^{+25\%}_{-18\%}$ fb (52.9%)	$44.36(17)^{+4.2\%}_{-3.4\%}$ pb	$44.46(33)^{+4.3\%}_{-3.5\%}$ pb	$+50.7\%$	$+25.0\%$	**27 TeV**
$pp \to W^+W^-$ (pp[illegible]w02	$66.64(1)^{+5.7\%}_{[illegible].7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4091(3)^{+27\%}_{-19\%}$ fb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$+54.9\%$	$+13.4\%$	**13 TeV**
WW (on shell)								**~2.6 factor**
pp [illegible] W [illegible] V^- (ppwxw02)	[illegible]52.5[illegible])$^{+10\%}_{-11\%}$ pb	$254.7(2)^{+4.4\%}_{-4.6\%}$ pb	1[illegible].87(3)$^{+27\%}_{-19\%}$ pb (29.5%)	$300.4(1.1)^{+3.3\%}_{-3.0\%}$ pb	$299.8(1.3)^{+3.3\%}_{-2.9\%}$ pb	$+67.0\%$	$+17.7\%$	**27 TeV**
$pp \to e^-\mu^-e^+\mu^+$ (pp[illegible]xmx04	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$+48.8\%$	$+20.3\%$	**13 TeV**
ZZ (off shell)								**~2.3 factor**
pp [illegible] $^-$ [illegible] $^-$ [illegible] $^+$ (ppemexmx04)	$22.49(1)^{+11\%}_{-12\%}$ fb	$35.78(3)^{+3.4\%}_{-4.5\%}$ fb	$6.140(20)^{+25\%}_{-18\%}$ fb (57.6%)	$45.78(21)^{+4.6\%}_{-3.8\%}$ fb	$45.28(83)^{+4.4\%}_{-3.6\%}$ fb	$+59.1\%$	$+26.6\%$	**27 TeV**
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ ([illegible]em[illegible]ne[illegible]4)	23[illegible].9(0)$^{+6.6\%}_{[illegible].6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	$+1.34\%$	$+12.1\%$	**13 TeV**
WW (off shell)								**~1.9 factor**
pp [illegible] e^- [illegible] $\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	[illegible]39.0[illegible])$^{+11\%}_{-12\%}$ fb	$429.0(4)^{+3.5\%}_{-3.2\%}$ fb	7[illegible].19(9)$^{+27\%}_{-19\%}$ fb (94.3%)	$507.0(1.4)^{+3.2\%}_{-2.1\%}$ fb	$507.5(1.9)^{+3.3\%}_{-2.1\%}$ fb	-2.27%	$+18.3\%$	**27 TeV**
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ ([illegible]em[illegible]mx[illegible])	11.[illegible]9(0)$^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.15(1)^{+2.2\%}_{-2.1\%}$ fb	$26.15(2)^{+2.3\%}_{-2.1\%}$ fb	$+105\%$	$+11.1\%$	**13TeV**
WZ (off shell)								**~2.4 factor**
pp [illegible] μ [illegible] $^+\bar{\nu}_\mu$ (ppemexnmx04)	[illegible](4)$^{[illegible]10.9\%}_{[illegible]11.5\%}$ fb	$53.21(9)^{+6.1\%}_{-5.3\%}$ fb	—	$62.18(65)^{+2.2\%}_{-3.2\%}$ fb	$62.07(84)^{+2.3\%}_{-3.1\%}$ fb	$+129.5\%$	$+16.6\%$	**27 TeV**

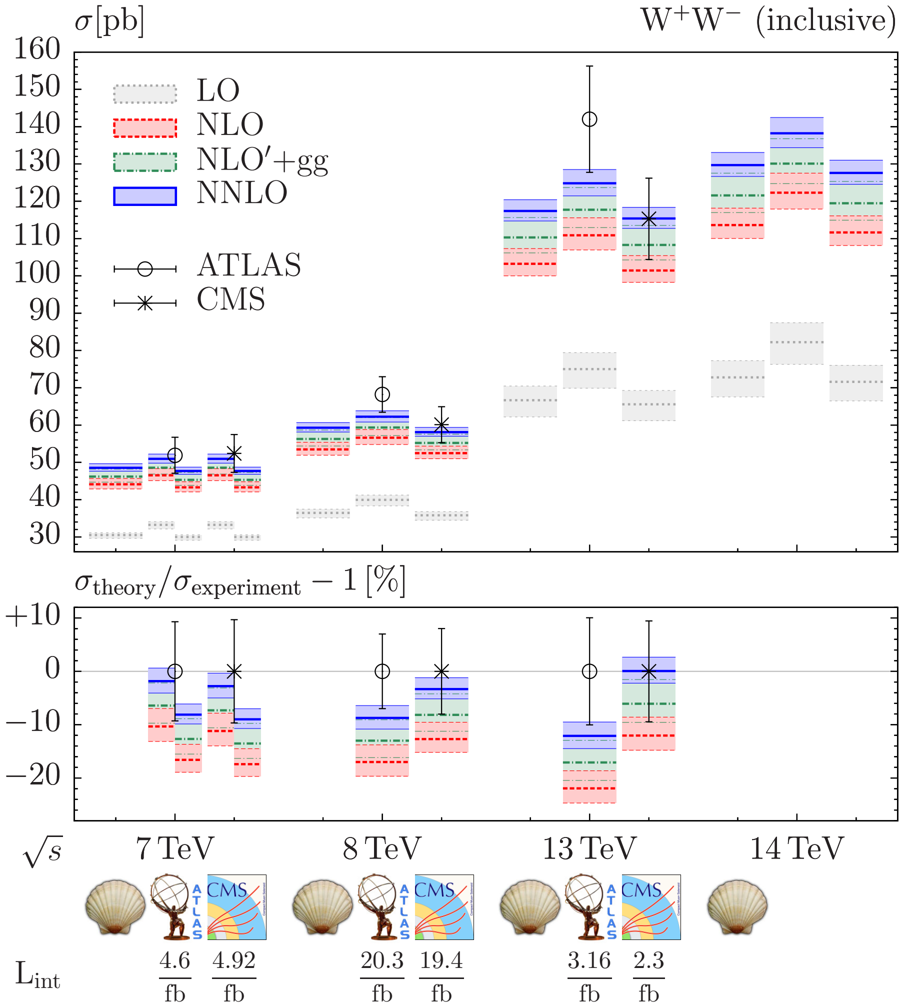
Inclusive diboson results: NNLO vs data

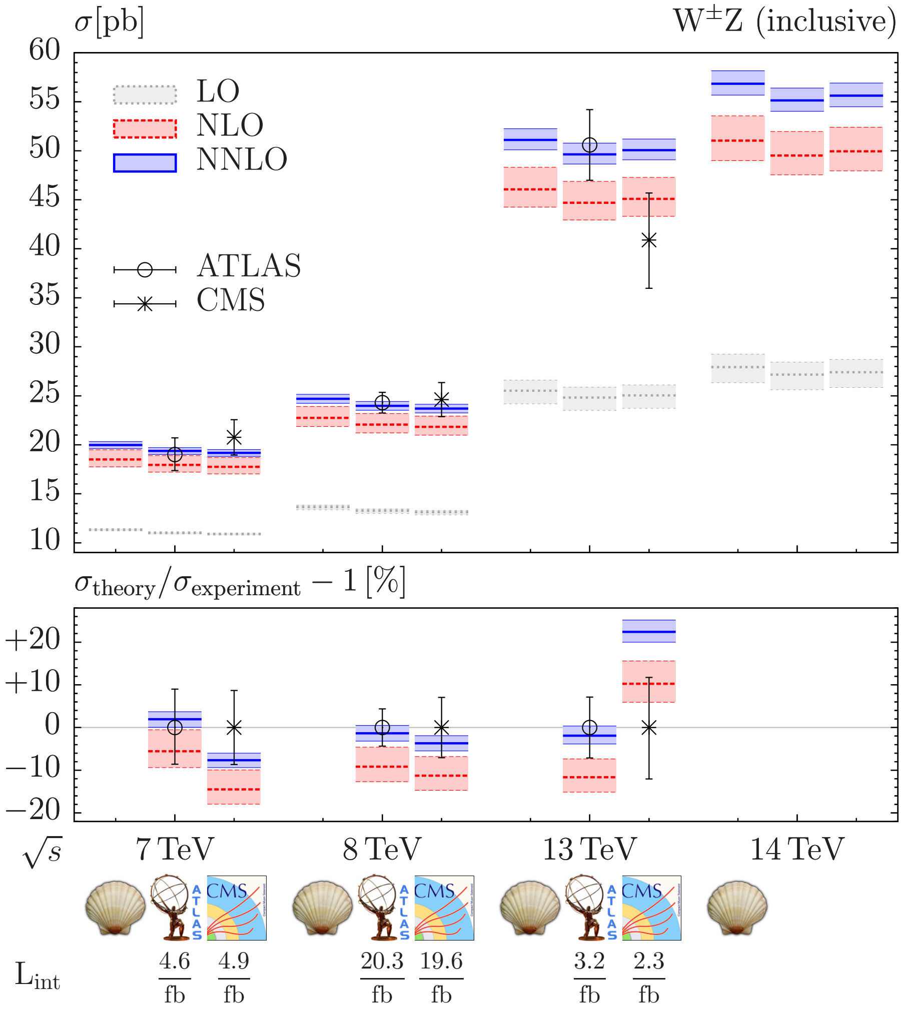


[Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]

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

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

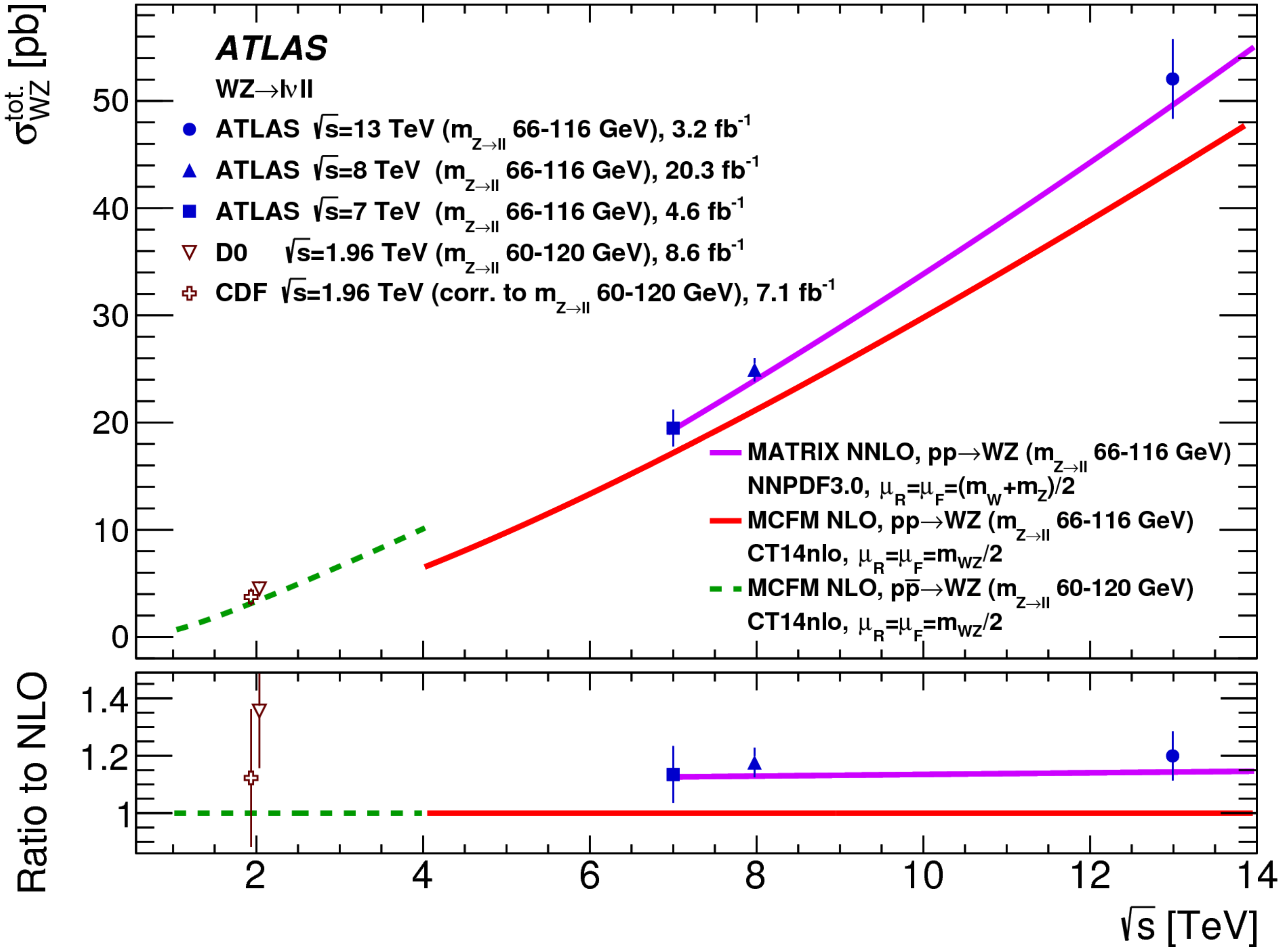




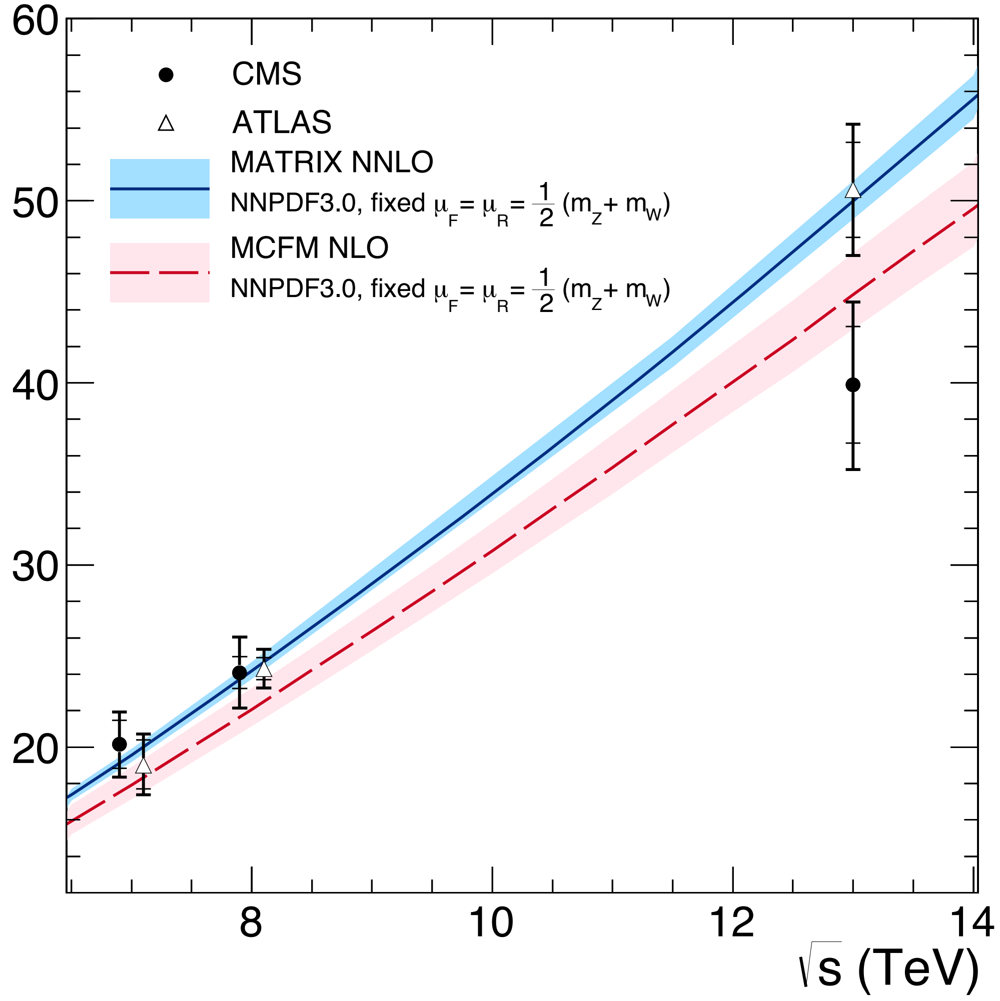
[Grazzini, Kallweit, Rathlev, MW '16]

Inclusive diboson results: NNLO vs data

[ATLAS '16]



[CMS '16]



Recent 13 TeV ATLAS results for ZZ

[ATLAS '17]

measured and predicted fiducial cross sections (36.1 fb^{-1})

Channel	Measurement [fb]	Prediction [fb]
$4e$	$13.7^{+1.1}_{-1.0}$ [± 0.9 (stat.) ±0.4 (syst.) $^{+0.5}_{-0.4}$ (lumi.)]	$10.9^{+0.5}_{-0.4}$
$2e2\mu$	$20.9^{+1.4}_{-1.3}$ [± 1.0 (stat.) ±0.6 (syst.) $^{+0.7}_{-0.6}$ (lumi.)]	$21.2^{+0.9}_{-0.8}$
4μ	$11.5^{+0.9}_{-0.9}$ [± 0.7 (stat.) ±0.4 (syst.) ±0.4 (lumi.)]	$10.9^{+0.5}_{-0.4}$
Combined	$46.2^{+2.5}_{-2.3}$ [± 1.5 (stat.) $^{+1.2}_{-1.1}$(syst.) $^{+1.6}_{-1.4}$ (lumi.)]	$42.9^{+1.9}_{-1.5}$

prediction: NNLO by MATRIX

with global factor 0.95 for NLO EW [Biedermann et al. '16]

and gg-channel times 1.67 [Caola et al. '15]

and 2.5% from EW-ZZjj generated with Sherpa

Recent 13 TeV ATLAS results for ZZ

[ATLAS '17]

measured and predicted fidu (36.1 fb^{-1})

~ 3.25% at 36.1 fb^{-1}

~ 0.35% at 3 ab^{-1}

Channel	Measurement [fb]	Prediction [fb]
$4e$	$13.7^{+1.1}_{-1.0}$ [± 0.9 (stat.) ±0.4 (syst.) $^{+0.5}_{-0.4}$ (lumi.)]	$10.9^{+0.5}_{-0.4}$
$2e2\mu$	$20.9^{+1.4}_{-1.3}$ [± 1.0 (stat.) ±0.6 (syst.) $^{+0.7}_{-0.6}$ (lumi.)]	$21.2^{+0.9}_{-0.8}$
4μ	$11.5^{+0.9}_{-0.9}$ [± 0.7 (stat.) ±0.4 (syst.) ±0.4 (lumi.)]	$10.9^{+0.5}_{-0.4}$
Combined	$46.2^{+2.5}_{-2.3}$ [± 1.5 (stat.) $^{+1.2}_{-1.1}$(syst.) $^{+1.6}_{-1.4}$ (lumi.)]	$42.9^{+1.9}_{-1.5}$

prediction: NNLO by MATRIX

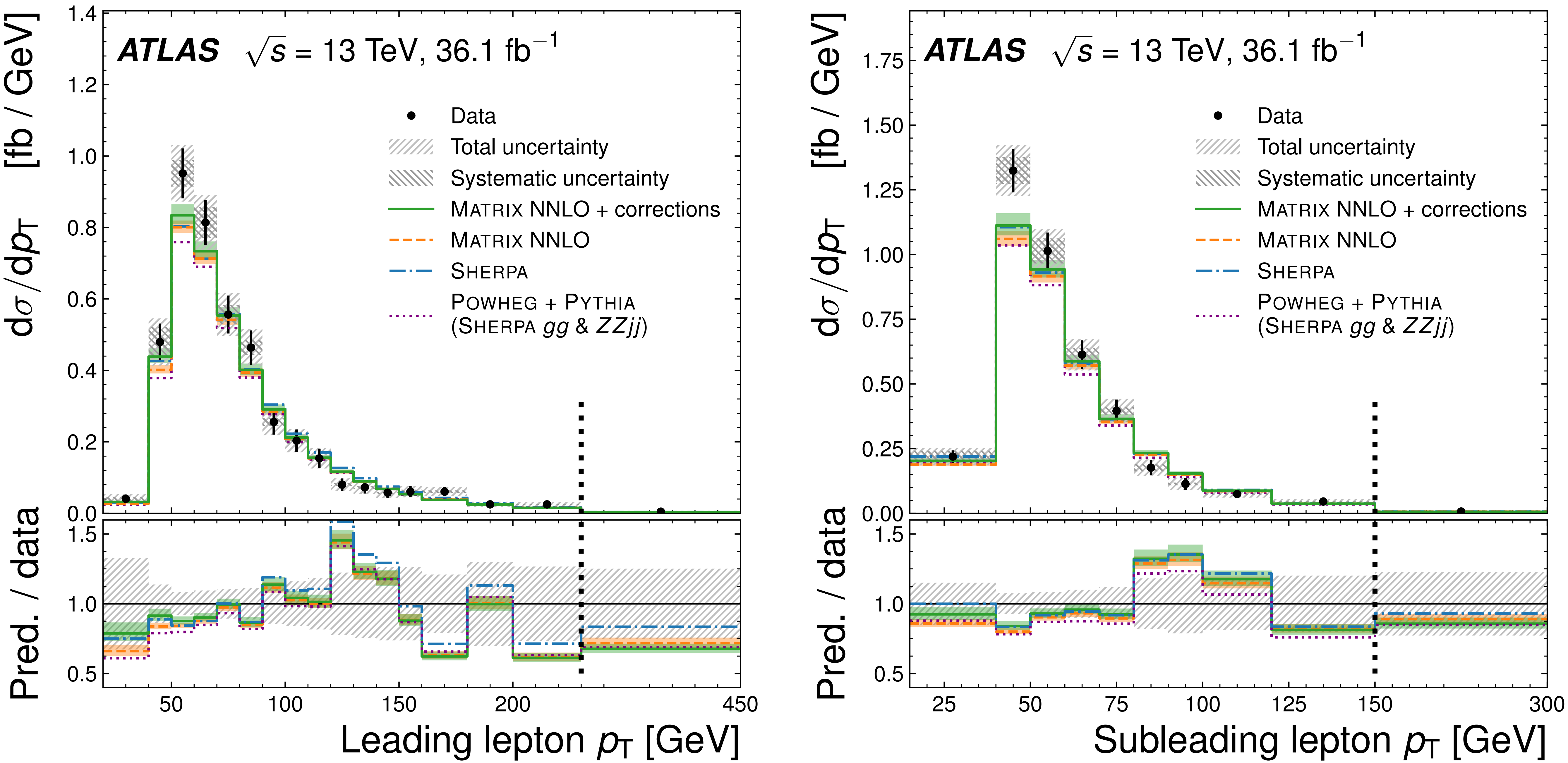
with global factor 0.95 for NLO EW [Biedermann et al. '16]

and gg-channel times 1.67 [Caola et al. '15]

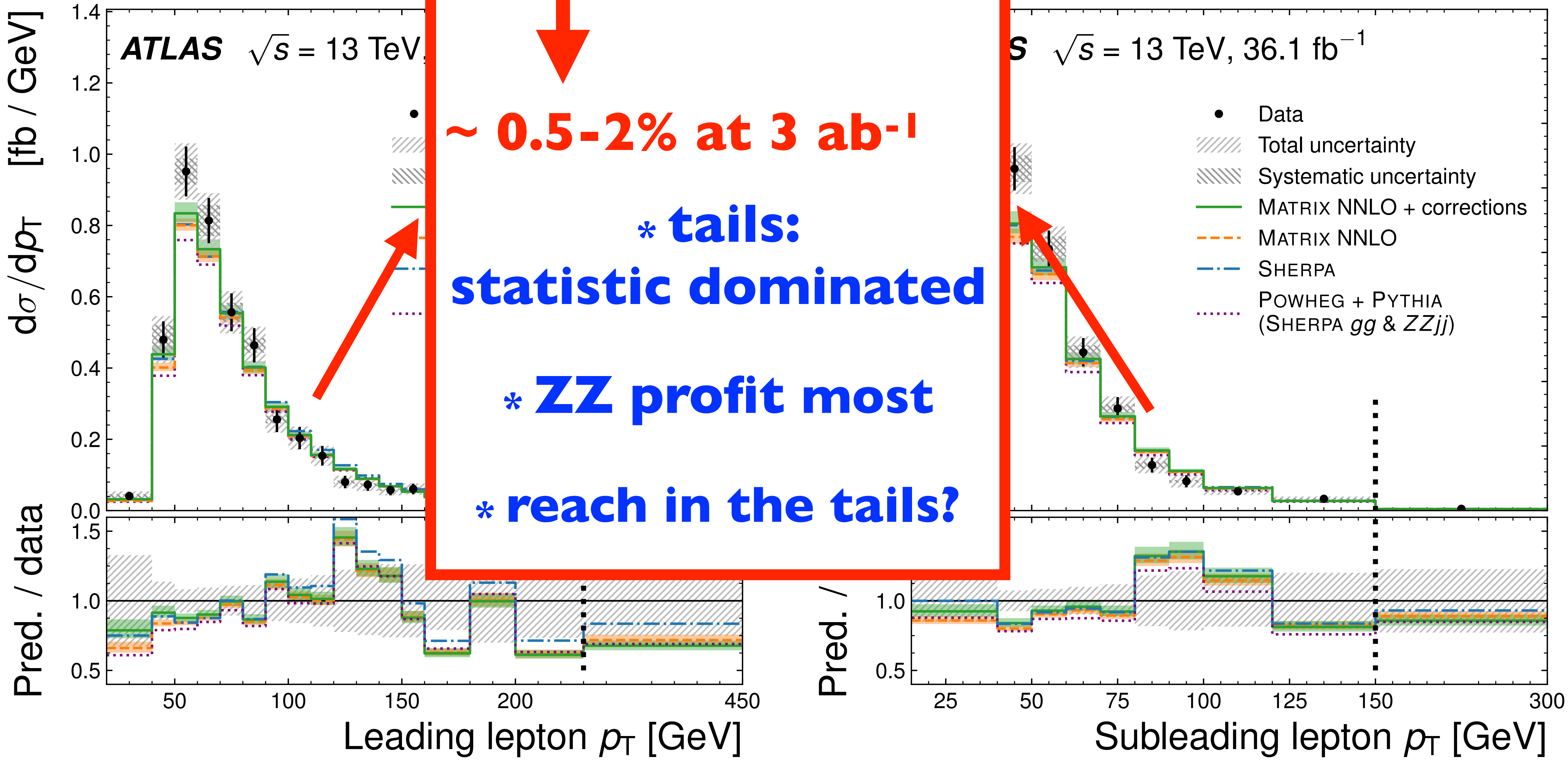
and 2.5% from EW-ZZjj generated with Sherpa

Recent 13 TeV ATLAS results for ZZ

[ATLAS '17]



Recent 13 TeV ATLAS results for ZZ



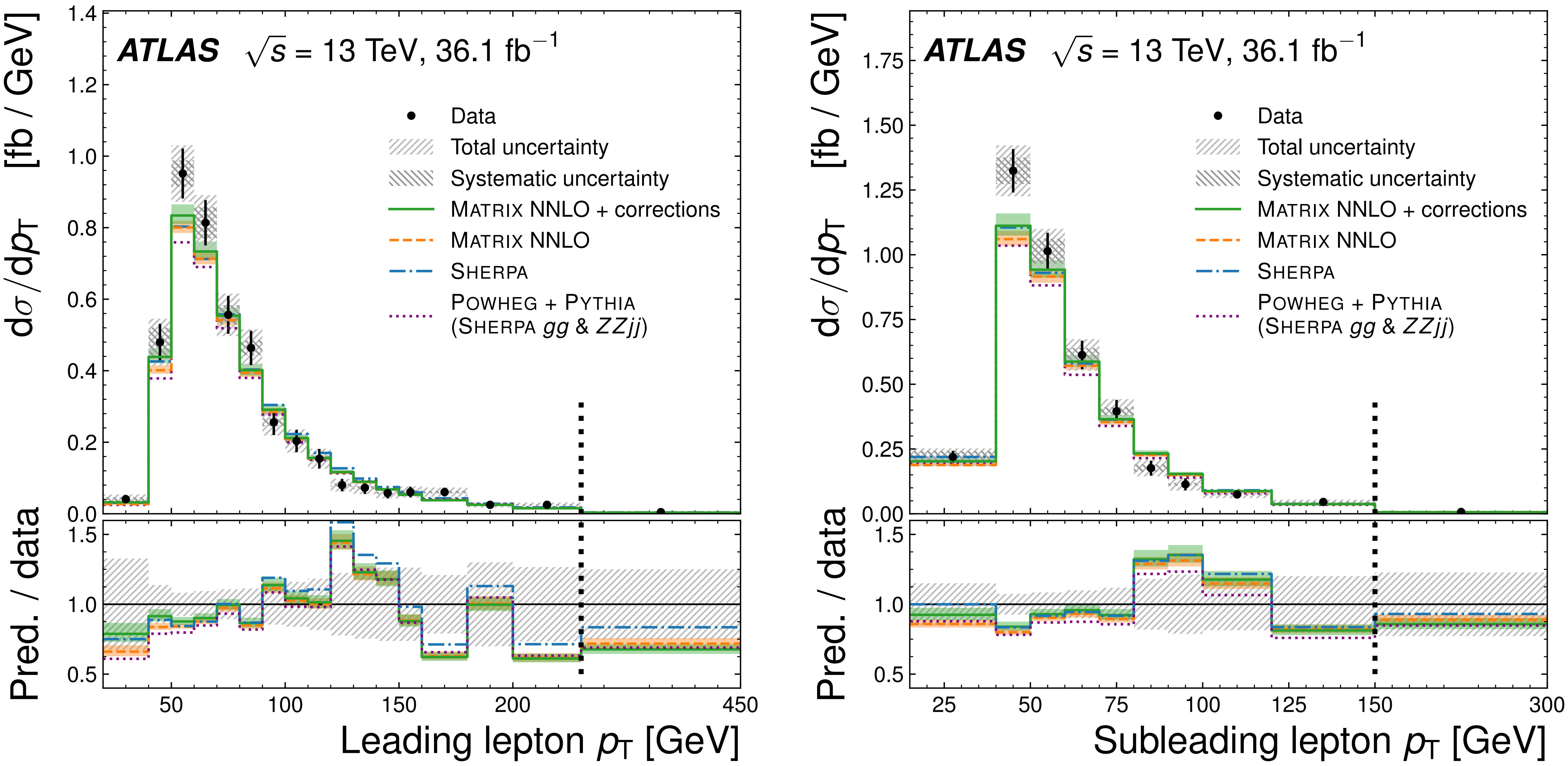
~ 5-20% at 36.1 fb^{-1}

~ 0.5-2% at 3 ab^{-1}

- * **tails: statistic dominated**
- * **ZZ profit most**
- * **reach in the tails?**

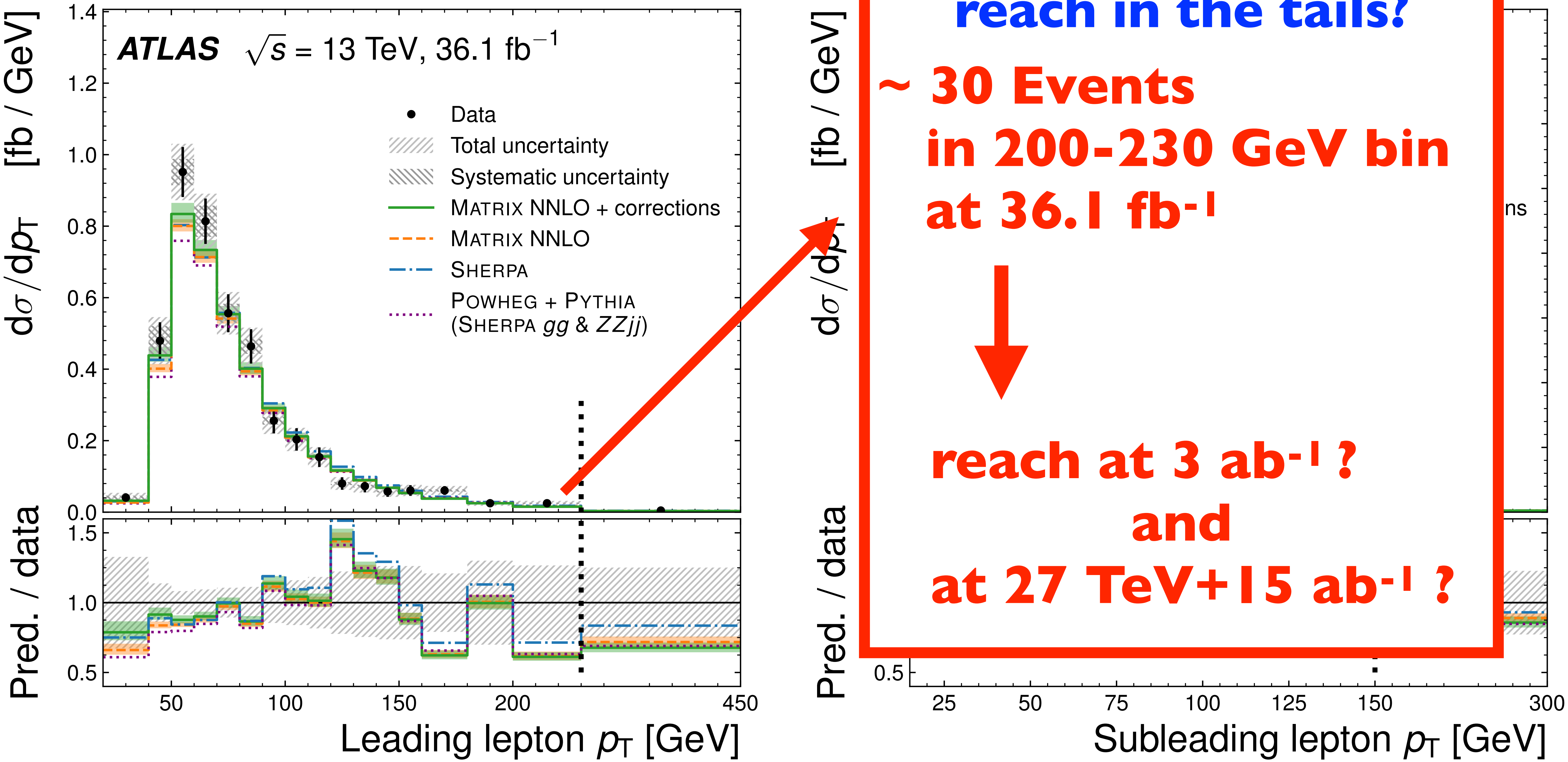
Recent 13 TeV ATLAS results for ZZ

[ATLAS '17]



Recent 13 TeV ATLAS results for ZZ

[ATLAS '17]



reach in the tails?

~ 30 Events in 200-230 GeV bin at 36.1 fb^{-1}

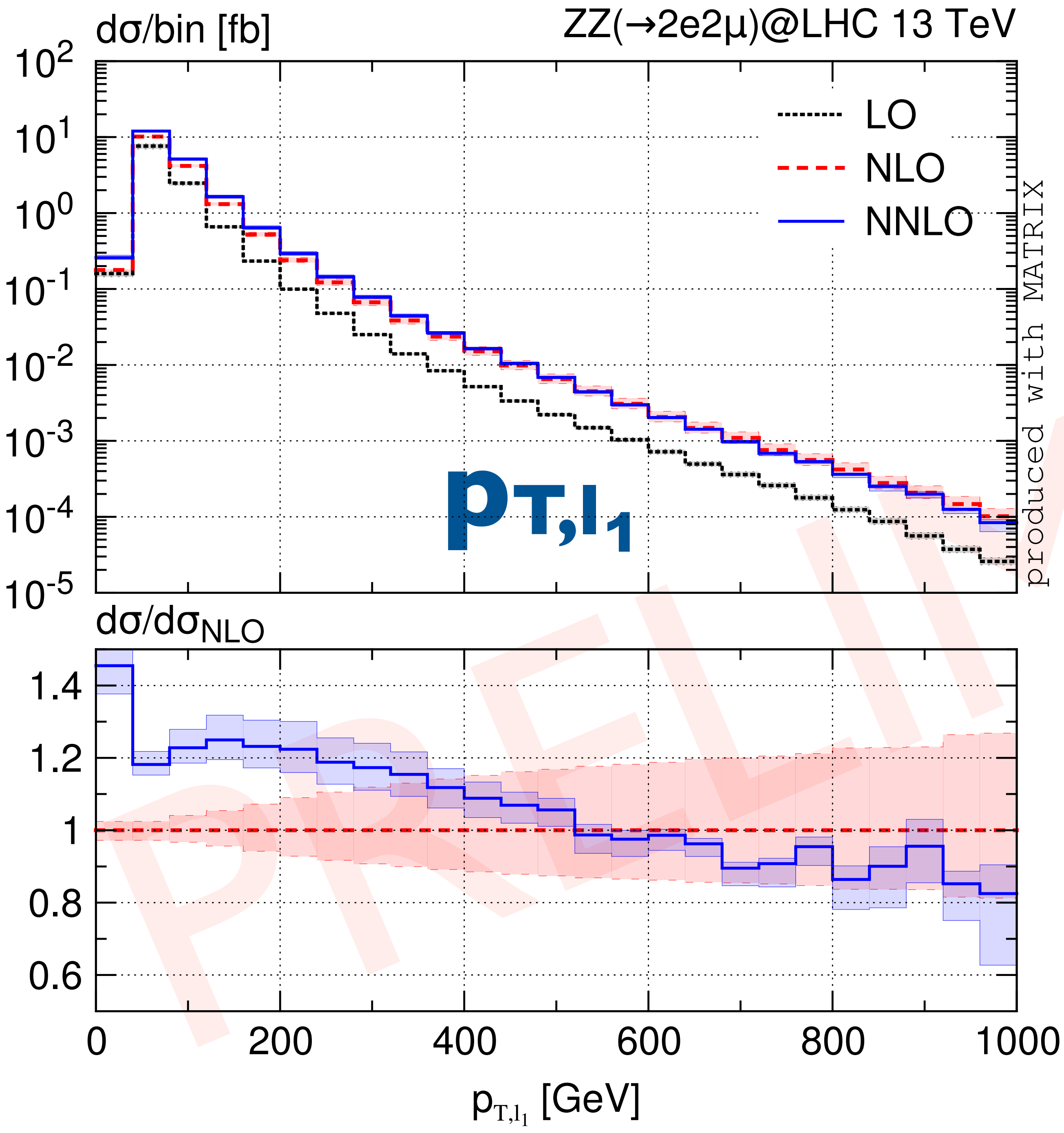
reach at 3 ab^{-1} ?

and

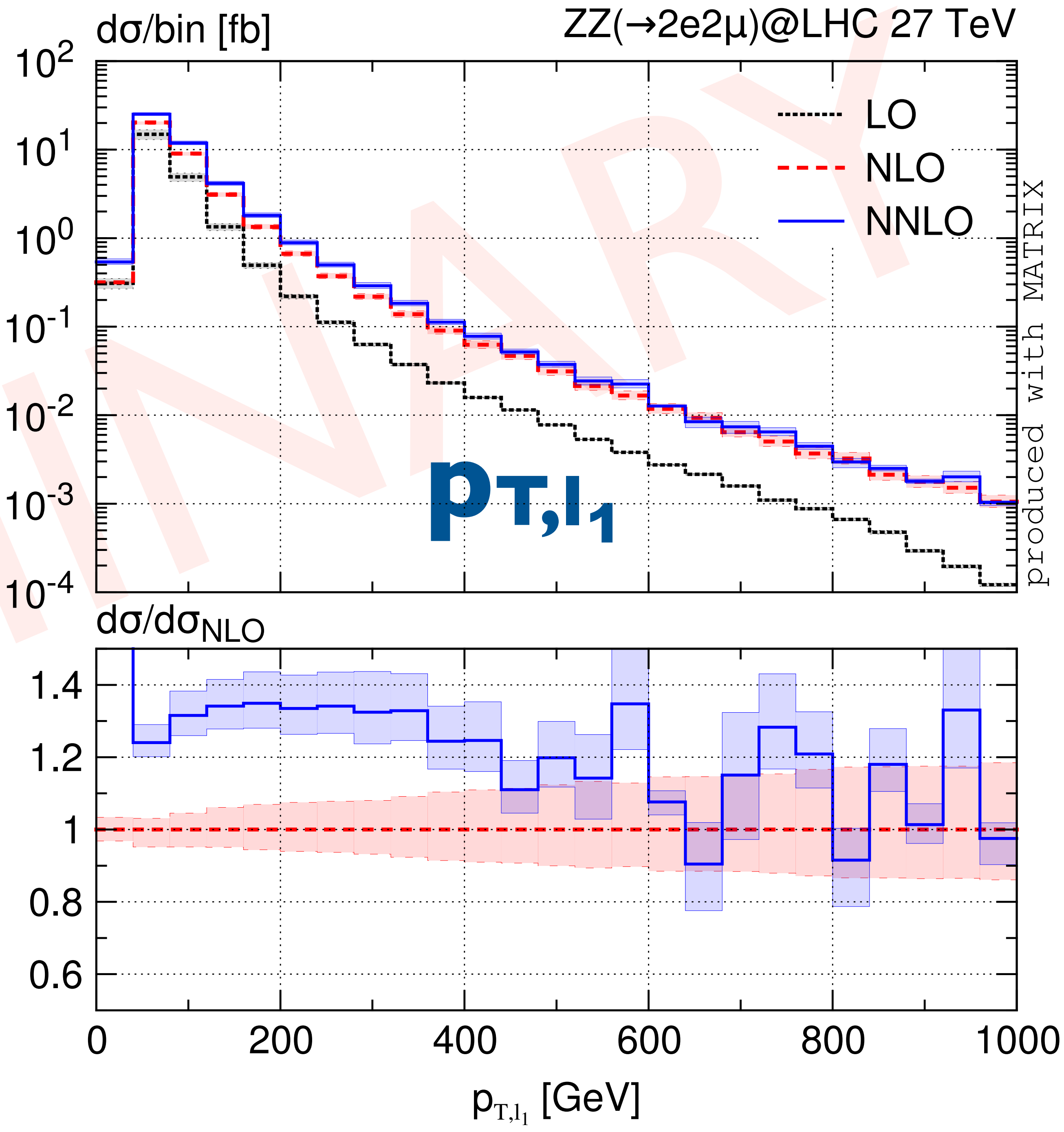
at 27 TeV+15 ab^{-1} ?

Reach in the tails for ZZ

13 TeV



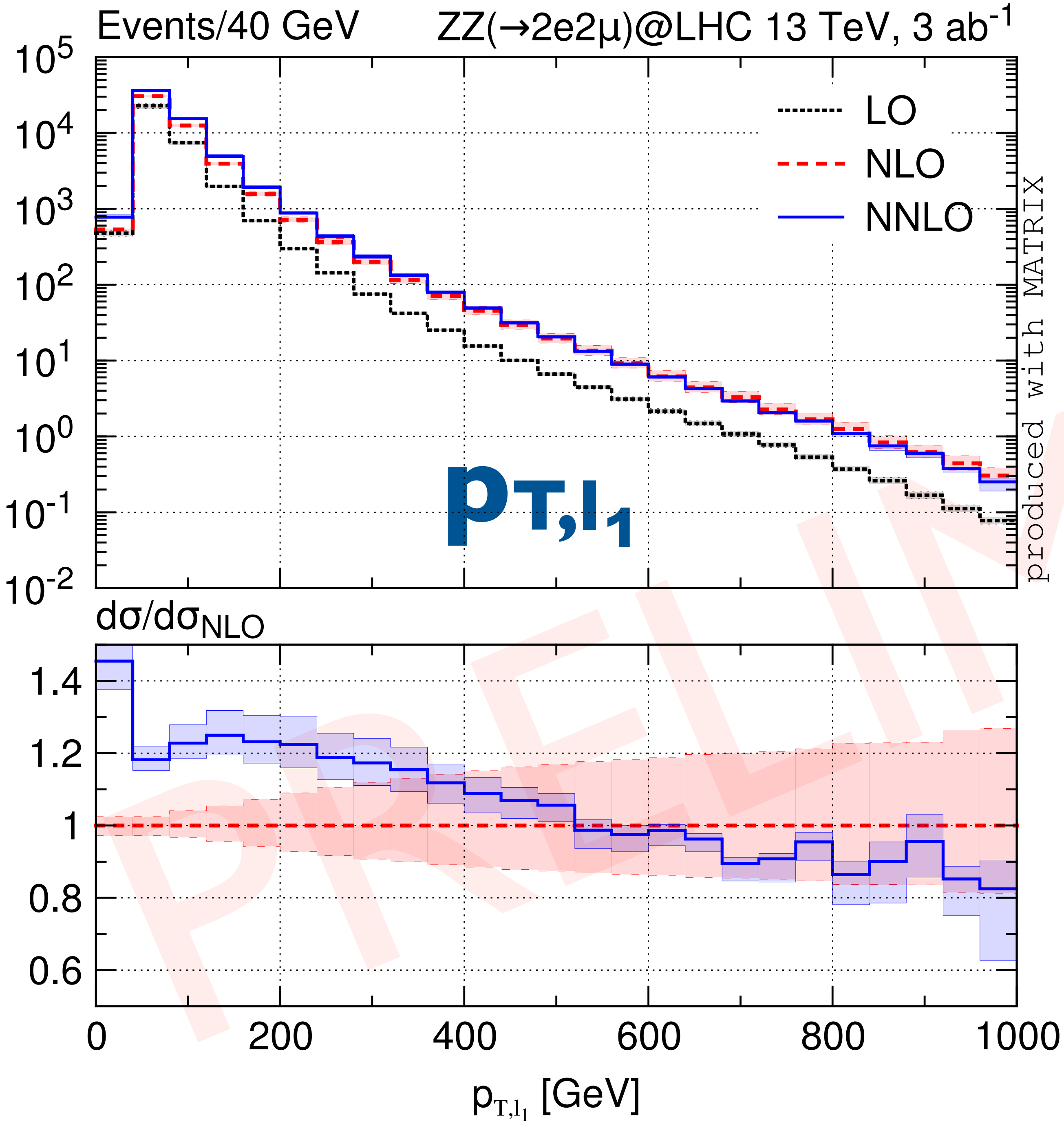
27 TeV

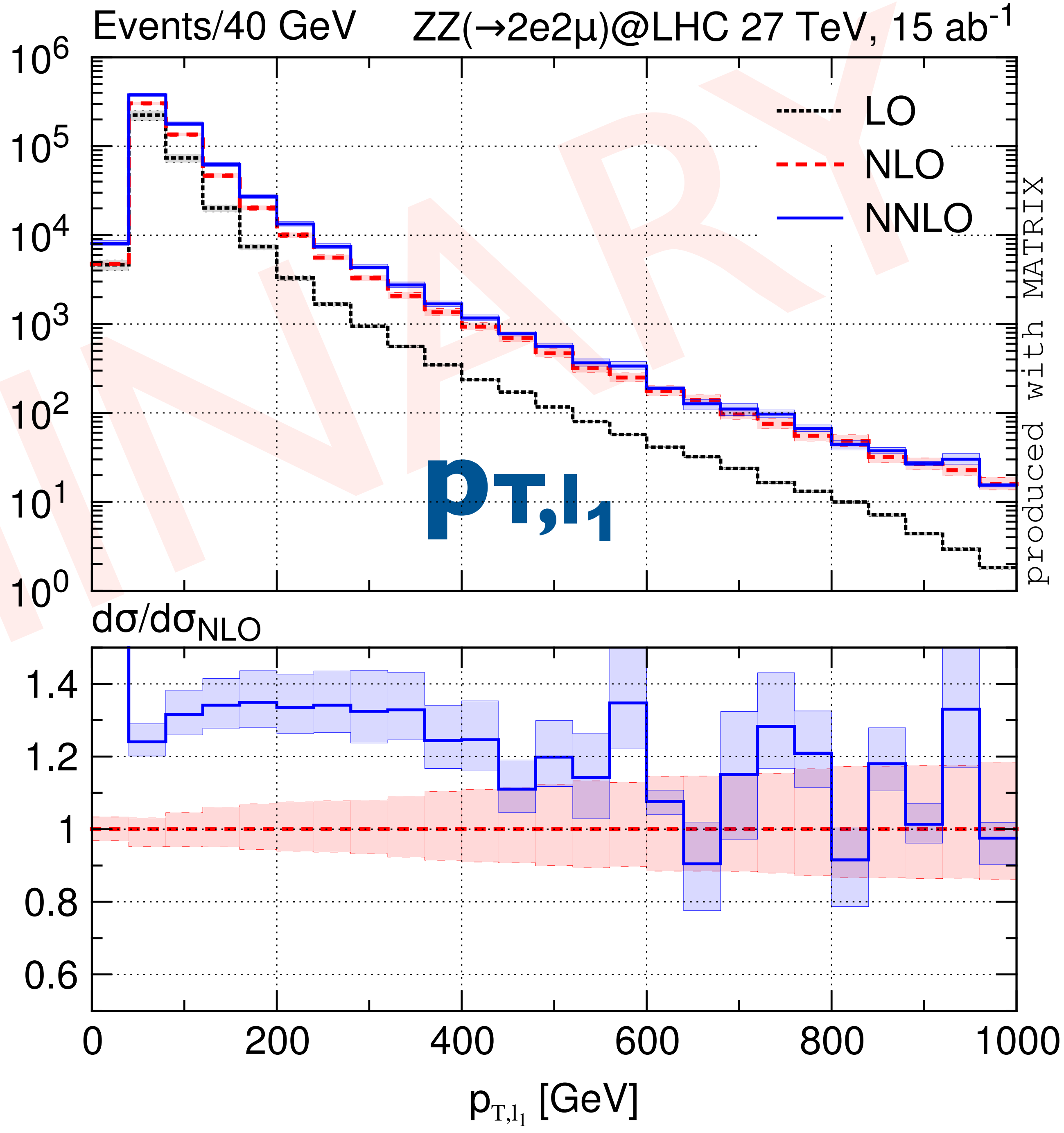


Reach in the tails for ZZ

13 TeV, 3 ab^{-1}

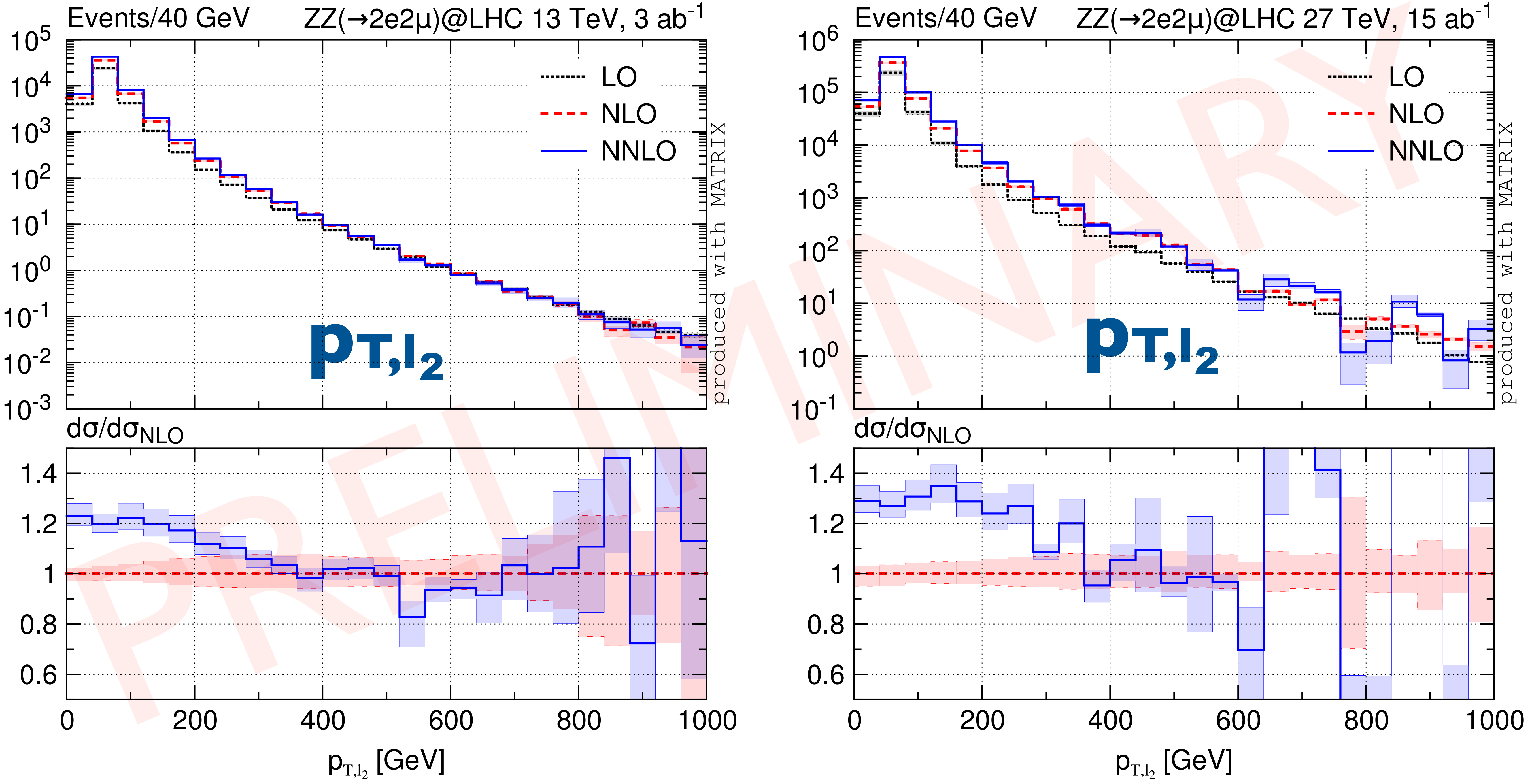
27 TeV, 15 ab^{-1}





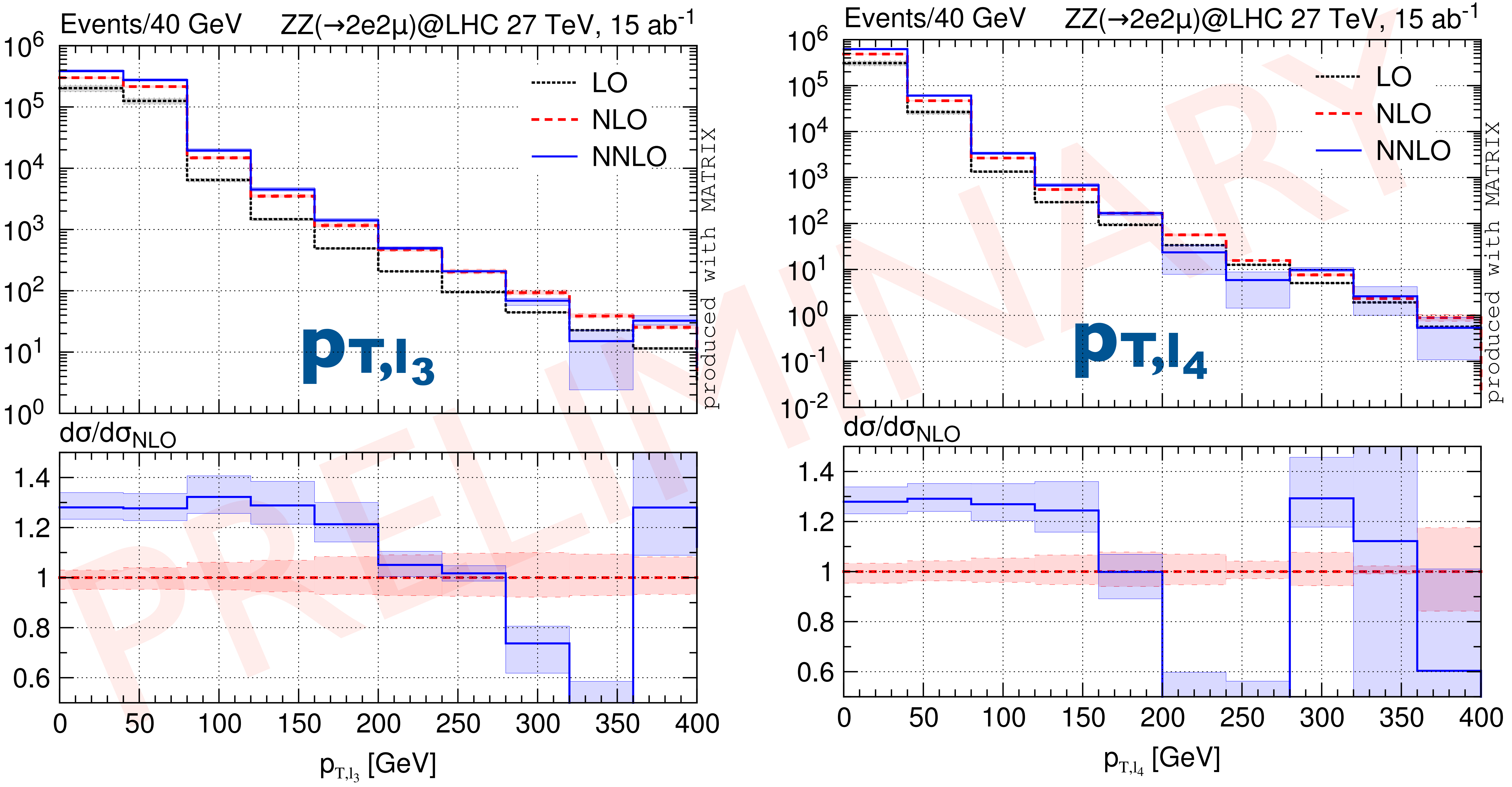
Reach in the tails for ZZ

13 TeV, 3 ab^{-1} **27 TeV, 15 ab^{-1}**



Reach in the tails for ZZ

27 TeV, 15 ab^{-1}



WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements

ATLAS (8 TeV):

channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{ATLAS} [fb]
$\mu^\pm e^+ e^-$	$18.32(0)^{+2.3\%}_{-3.2\%}$	$32.76(1)^{+5.4\%}_{-4.1\%}$	$35.53(2)^{+1.8\%}_{-1.9\%}$	$36.3 \pm 5.4\%(\text{stat}) \pm 2.6\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm \mu^+ \mu^-$				$35.7 \pm 5.3\%(\text{stat}) \pm 3.7\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm e^+ e^-$	$18.37(0)^{+2.3\%}_{-3.2\%}$	$32.85(1)^{+5.4\%}_{-4.1\%}$	$35.64(2)^{+1.8\%}_{-1.9\%}$	$38.1 \pm 6.2\%(\text{stat}) \pm 4.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^\pm \mu^+ \mu^-$				$33.3 \pm 4.7\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
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):

channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{ATLAS} [fb]
$\mu^\pm e^+ e^-$	$28.83(0)^{+5.4\%}_{-6.5\%}$	$57.69(1)^{+5.4\%}_{-4.3\%}$	$63.93(3)^{+2.3\%}_{-2.1\%}$	$55.1 \pm 11.1\%(\text{stat}) \pm 5.1\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$e^\pm \mu^+ \mu^-$				$75.2 \pm 9.5\%(\text{stat}) \pm 5.3\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^\pm e^+ e^-$	$28.90(0)^{+5.4\%}_{-6.5\%}$	$57.84(1)^{+5.4\%}_{-4.3\%}$	$64.09(3)^{+2.2\%}_{-2.1\%}$	$50.5 \pm 14.2\%(\text{stat}) \pm 10.6\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$\mu^\pm \mu^+ \mu^-$				$63.6 \pm 8.9\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.3\%(\text{lumi})$
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, Rathlev, MW '17]

SM measurements

ATLAS (8 TeV):

perfect agreement at NNLO

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

ATLAS (13 TeV):

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

CMS (13 TeV):

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

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements

ATLAS (8 TeV):

perfect agreement at NNLO

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

ATLAS (13 TeV):

perfect agreement at NNLO

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

CMS (13 TeV):

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

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements

ATLAS (8 TeV):

channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{ATLAS} [fb]
$\mu^\pm e^+ e^-$	$18.32(0)^{+2.3\%}_{-3.2\%}$	$32.76(1)^{+5.4\%}_{-4.1\%}$	$35.53(2)^{+1.8\%}_{-1.9\%}$	$36.3\ \pm 5.4\%(\mathrm{stat}) \pm 2.6\%(\mathrm{syst}) \pm 2.2\%(\mathrm{lumi})$
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perfect agreement at NNLO

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$\mu^\pm \mu^+ \mu^-$				$63.6\ \pm 8.9\%(\mathrm{stat}) \pm 4.1\%(\mathrm{syst}) \pm 2.3\%(\mathrm{lumi})$
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perfect agreement at NNLO

CMS (13 TeV):

2.6σ, BUT low statistics

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

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements

ATLAS (8 TeV):

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm ATLAS}$ [fb]
$\mu^\pm e^+ e^-$	$18.32(0)^{+2.3\%}_{-3.2\%}$	$32.76(1)^{+5.4\%}_{-4.1\%}$	$35.53(2)^{+1.8\%}_{-1.9\%}$	$36.3 \pm 5.4\%({\rm stat}) \pm 2.6\%({\rm syst}) \pm 2.2\%({\rm lumi})$
$e^\pm \mu^+ \mu^-$				$35.7 \pm 5.3\%({\rm stat}) \pm 3.7\%({\rm syst}) \pm 2.2\%({\rm lumi})$
			$5.64(2)^{+1.8\%}_{-1.9\%}$	$38.1 \pm 6.2\%({\rm stat}) \pm 4.5\%({\rm syst}) \pm 2.2\%({\rm lumi})$
				$33.3 \pm 4.7\%({\rm stat}) \pm 2.5\%({\rm syst}) \pm 2.2\%({\rm lumi})$
			$5.59(2)^{+1.8\%}_{-1.9\%}$	$35.1 \pm 2.7\%({\rm stat}) \pm 2.4\%({\rm syst}) \pm 2.2\%({\rm lumi})$

perfect agreement at NNL

~ 5.2% at 3.2 fb^{-1}

~ 0.2% at 3 ab^{-1}

ATLAS (13 TeV):

			$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm ATLAS}$ [fb]
			$.93(3)^{+2.3\%}_{-2.1\%}$	$55.1 \pm 11.1\%({\rm stat}) \pm 5.1\%({\rm syst}) \pm 2.4\%({\rm lumi})$
				$75.2 \pm 9.5\%({\rm stat}) \pm 5.3\%({\rm syst}) \pm 2.3\%({\rm lumi})$
$e^\pm e^+ e^-$	$28.90(0)^{+5.4\%}_{-6.5\%}$	$57.84(1)^{+5.4\%}_{-4.3\%}$	$64.09(3)^{+2.2\%}_{-2.1\%}$	$50.5 \pm 14.2\%({\rm stat}) \pm 10.6\%({\rm syst}) \pm 2.4\%({\rm lumi})$
$\mu^\pm \mu^+ \mu^-$				$63.6 \pm 8.9\%({\rm stat}) \pm 4.1\%({\rm syst}) \pm 2.3\%({\rm lumi})$
combined	$28.86(0)^{+5.4\%}_{-6.5\%}$	$57.76(1)^{+5.4\%}_{-4.3\%}$	$64.01(3)^{+2.3\%}_{-2.1\%}$	$63.2 \pm 5.2\%({\rm stat}) \pm 4.1\%({\rm syst}) \pm 2.4\%({\rm lumi})$

perfect agreement at NNLO

CMS (13 TeV):

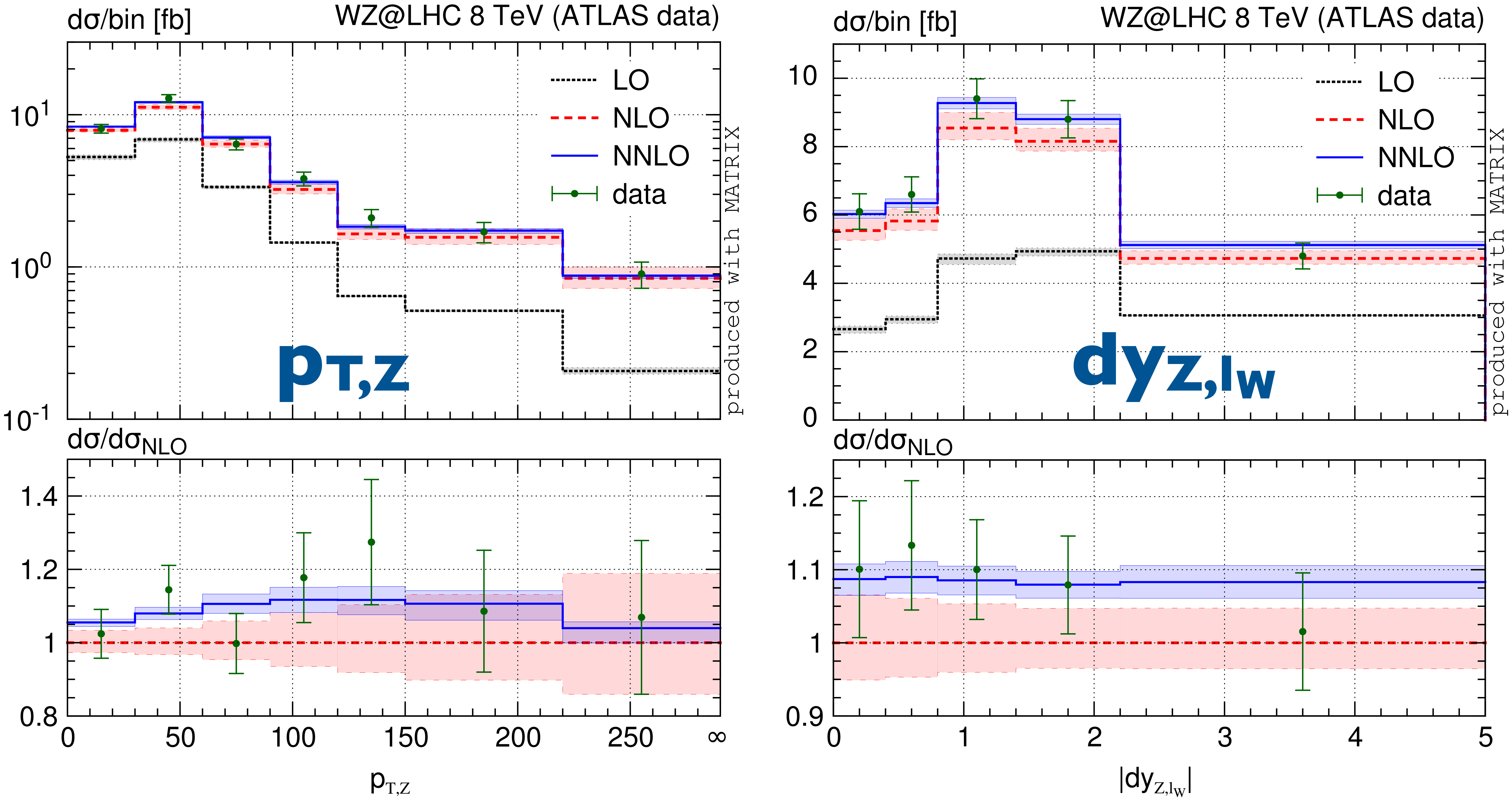
2.6σ, BUT low statistics

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

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

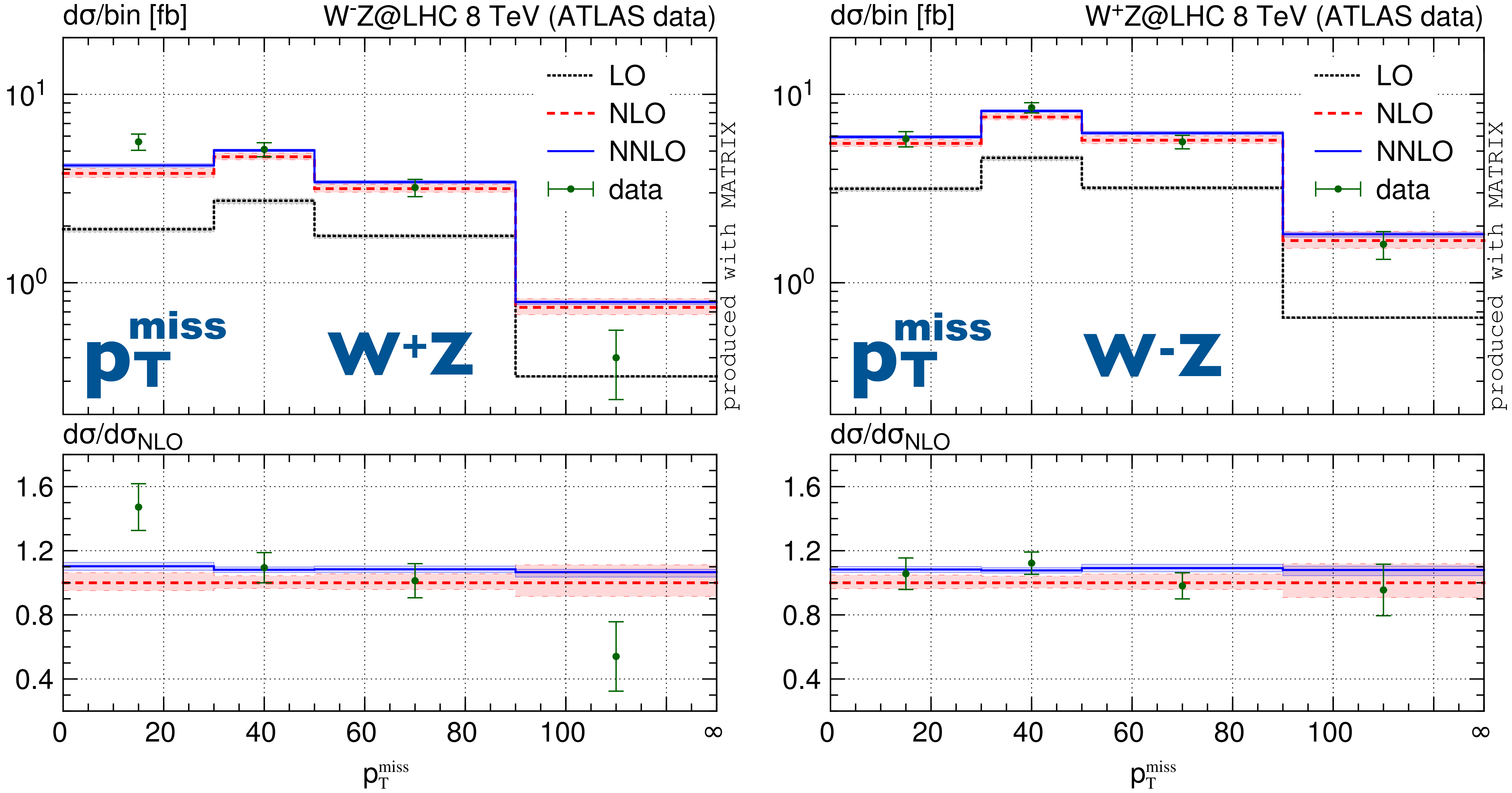
SM measurements (ATLAS 8 TeV, 20.3 fb^{-1})



WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements (ATLAS 8 TeV, 20.3 fb^{-1})



WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

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

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

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

New-physics searches

Category I: no additional cut

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

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

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

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%
combined	$7.540(1)^{+3.4\%}_{-4.2\%}$	$13.44(0)^{+4.4\%}_{-3.6\%}$	$14.80(1)^{+1.9\%}_{-1.8\%}$	78.2%	10.2%

New-physics searches

Category I: no additional cut

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

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

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

QCD corrections VERY different for various Categories (cuts)

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%
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$\ell^-\ell^+\ell^-$	$31.74(0)^{+5.3\%}_{-6.3\%}$	$63.00(2)^{+5.0\%}_{-4.1\%}$	$71.13(4)^{+2.2\%}_{-2.2\%}$	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%
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$\ell'^-\ell^+\ell^-$	$1.603(0)^{+3.4\%}_{-4.4\%}$	$2.805(1)^{+4.2\%}_{-3.5\%}$	$3.058(1)^{+1.7\%}_{-1.6\%}$	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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Category III: $m_{T,W} > 120\,\mathrm{GeV}$

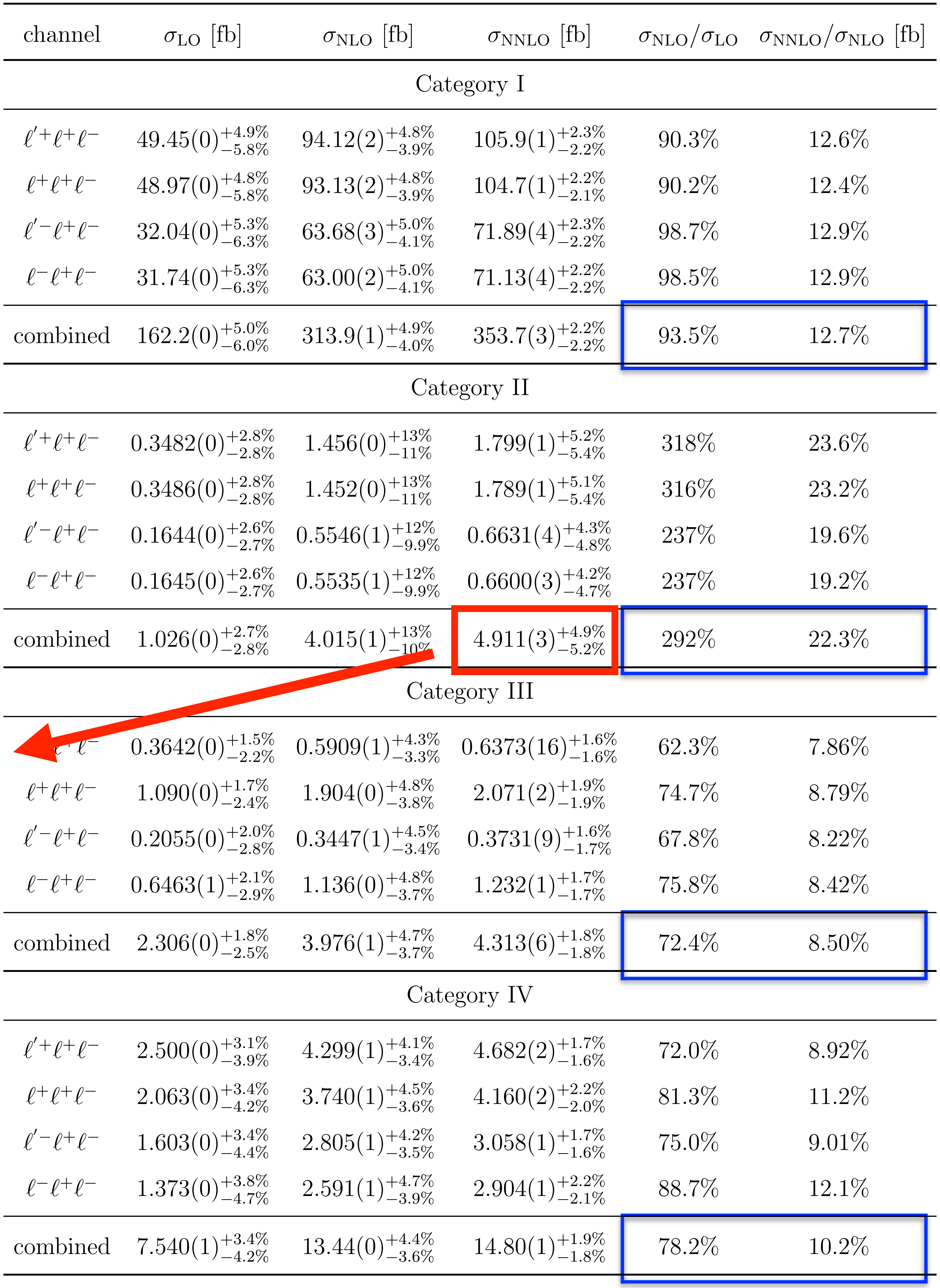
Category IV: $m_{\ell_z\ell_z} > 105\,\mathrm{GeV}$

QCD corrections VERY different for various Categories (cuts)

~ 200 Events at 40 fb^{-1}

↓

~ 15000 Events at 3 ab^{-1}



channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	$\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	$\sigma_{\mathrm{NNLO}}/\sigma_{\mathrm{NLO}}$ [fb]
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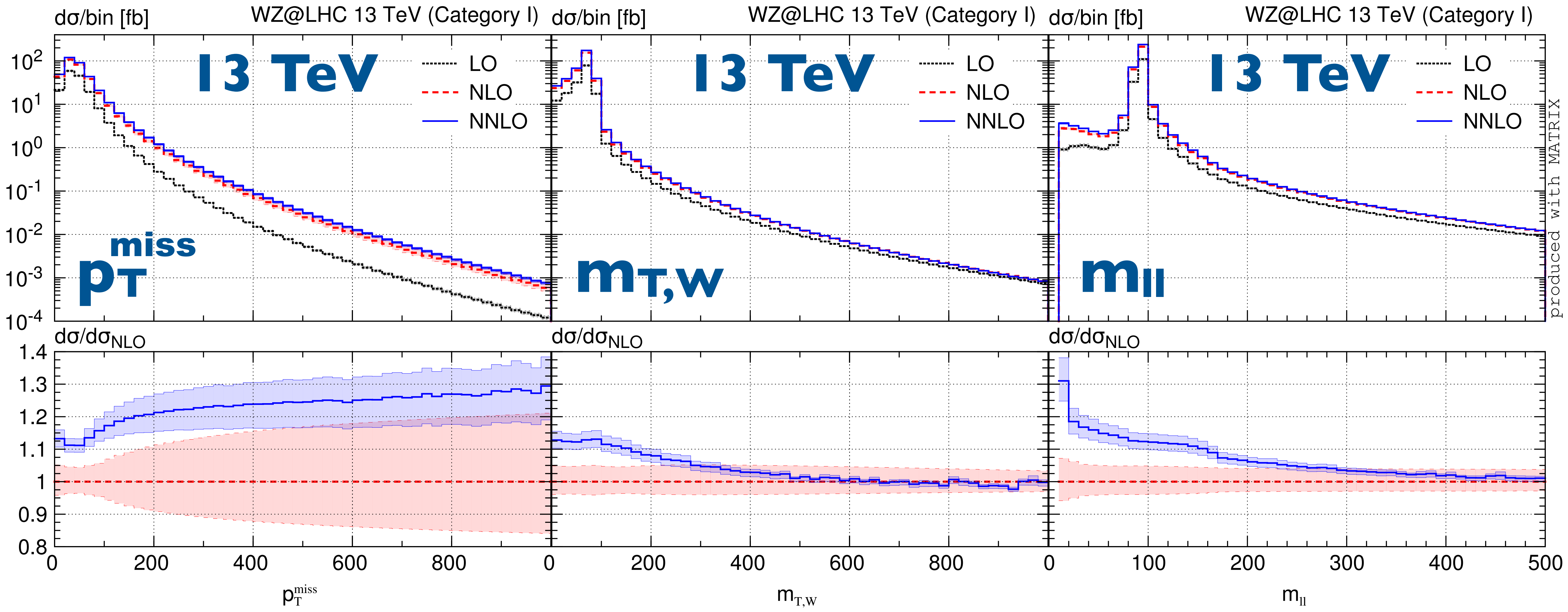
Category II					
$\ell'^+\ell^+\ell^-$	$0.3482(0)^{+2.8\%}_{-2.8\%}$	$1.456(0)^{+13\%}_{-11\%}$	$1.799(1)^{+5.2\%}_{-5.4\%}$	318%	23.6%
$\ell^+\ell^+\ell^-$	$0.3486(0)^{+2.8\%}_{-2.8\%}$	$1.452(0)^{+13\%}_{-11\%}$	$1.789(1)^{+5.1\%}_{-5.4\%}$	316%	23.2%
$\ell'^-\ell^+\ell^-$	$0.1644(0)^{+2.6\%}_{-2.7\%}$	$0.5546(1)^{+12\%}_{-9.9\%}$	$0.6631(4)^{+4.3\%}_{-4.8\%}$	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					
$\ell^+\ell^-$	$0.3642(0)^{+1.5\%}_{-2.2\%}$	$0.5909(1)^{+4.3\%}_{-3.3\%}$	$0.6373(16)^{+1.6\%}_{-1.6\%}$	62.3%	7.86%
$\ell^+\ell^+\ell^-$	$1.090(0)^{+1.7\%}_{-2.4\%}$	$1.904(0)^{+4.8\%}_{-3.8\%}$	$2.071(2)^{+1.9\%}_{-1.9\%}$	74.7%	8.79%
$\ell'^-\ell^+\ell^-$	$0.2055(0)^{+2.0\%}_{-2.8\%}$	$0.3447(1)^{+4.5\%}_{-3.4\%}$	$0.3731(9)^{+1.6\%}_{-1.7\%}$	67.8%	8.22%
$\ell^-\ell^+\ell^-$	$0.6463(1)^{+2.1\%}_{-2.9\%}$	$1.136(0)^{+4.8\%}_{-3.7\%}$	$1.232(1)^{+1.7\%}_{-1.7\%}$	75.8%	8.42%
combined	$2.306(0)^{+1.8\%}_{-2.5\%}$	$3.976(1)^{+4.7\%}_{-3.7\%}$	$4.313(6)^{+1.8\%}_{-1.8\%}$	72.4%	8.50%
Category IV					
$\ell'^+\ell^+\ell^-$	$2.500(0)^{+3.1\%}_{-3.9\%}$	$4.299(1)^{+4.1\%}_{-3.4\%}$	$4.682(2)^{+1.7\%}_{-1.6\%}$	72.0%	8.92%
$\ell^+\ell^+\ell^-$	$2.063(0)^{+3.4\%}_{-4.2\%}$	$3.740(1)^{+4.5\%}_{-3.6\%}$	$4.160(2)^{+2.2\%}_{-2.0\%}$	81.3%	11.2%
$\ell'^-\ell^+\ell^-$	$1.603(0)^{+3.4\%}_{-4.4\%}$	$2.805(1)^{+4.2\%}_{-3.5\%}$	$3.058(1)^{+1.7\%}_{-1.6\%}$	75.0%	9.01%
$\ell^-\ell^+\ell^-$	$1.373(0)^{+3.8\%}_{-4.7\%}$	$2.591(1)^{+4.7\%}_{-3.9\%}$	$2.904(1)^{+2.2\%}_{-2.1\%}$	88.7%	12.1%
combined	$7.540(1)^{+3.4\%}_{-4.2\%}$	$13.44(0)^{+4.4\%}_{-3.6\%}$	$14.80(1)^{+1.9\%}_{-1.8\%}$	78.2%	10.2%

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

Category I: no additional cuts



WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

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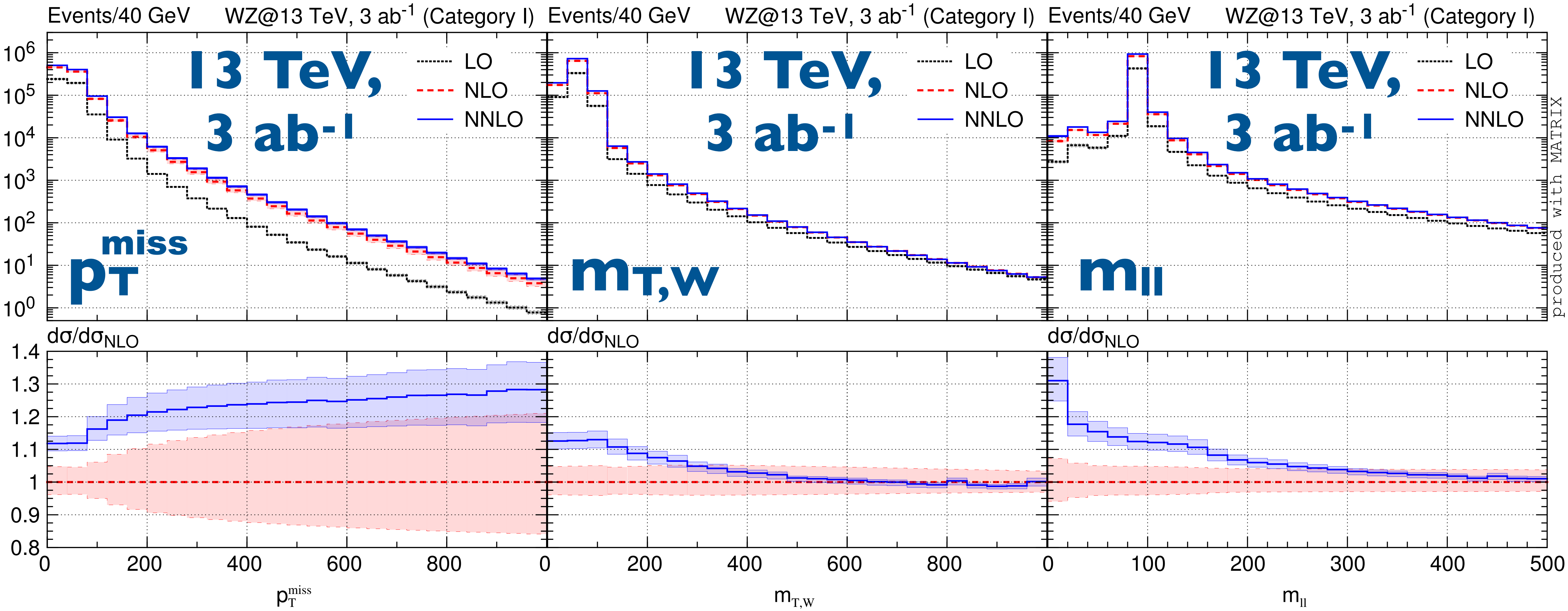
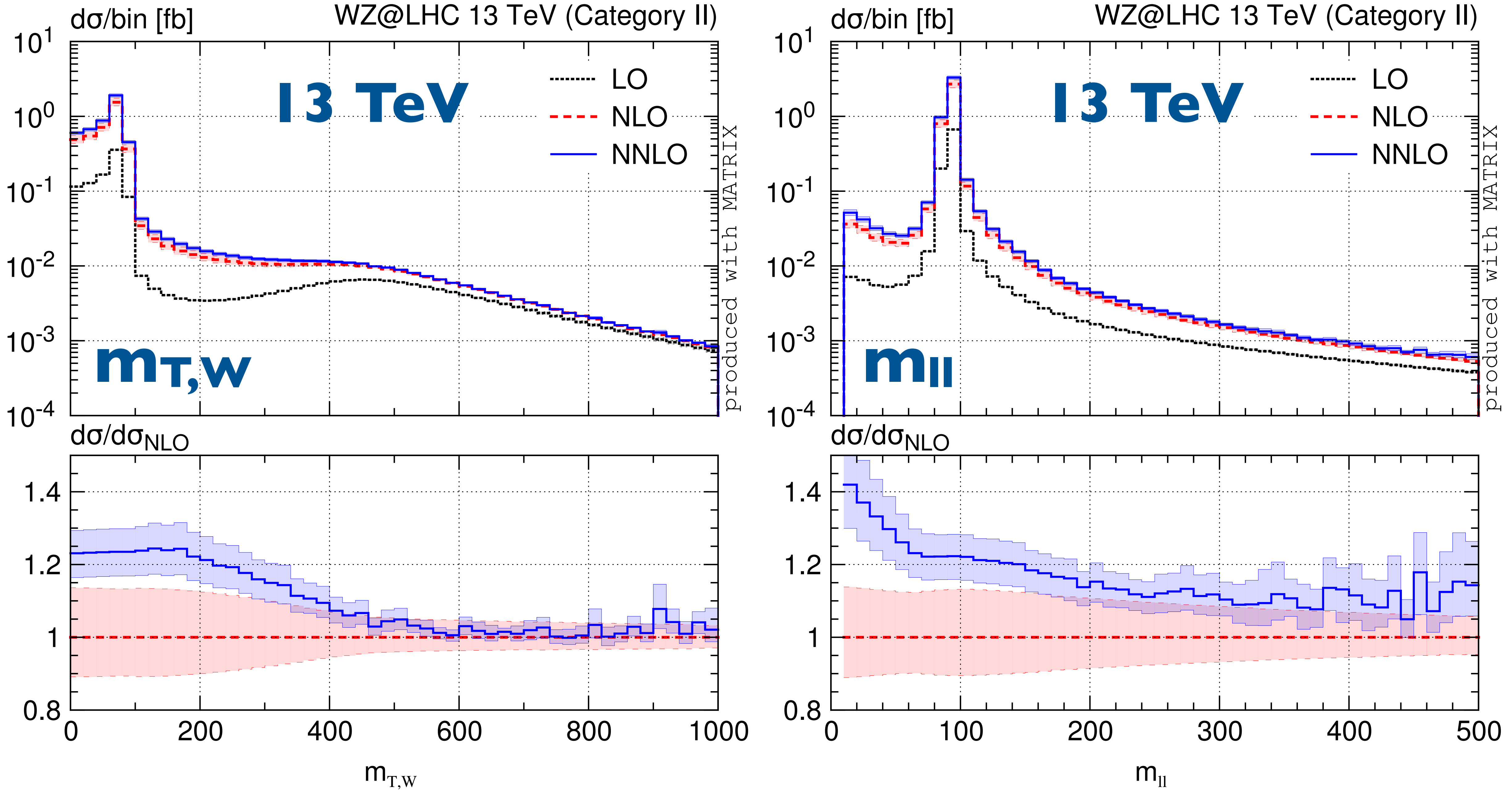


WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

Category II: p_T^{miss}>200 GeV

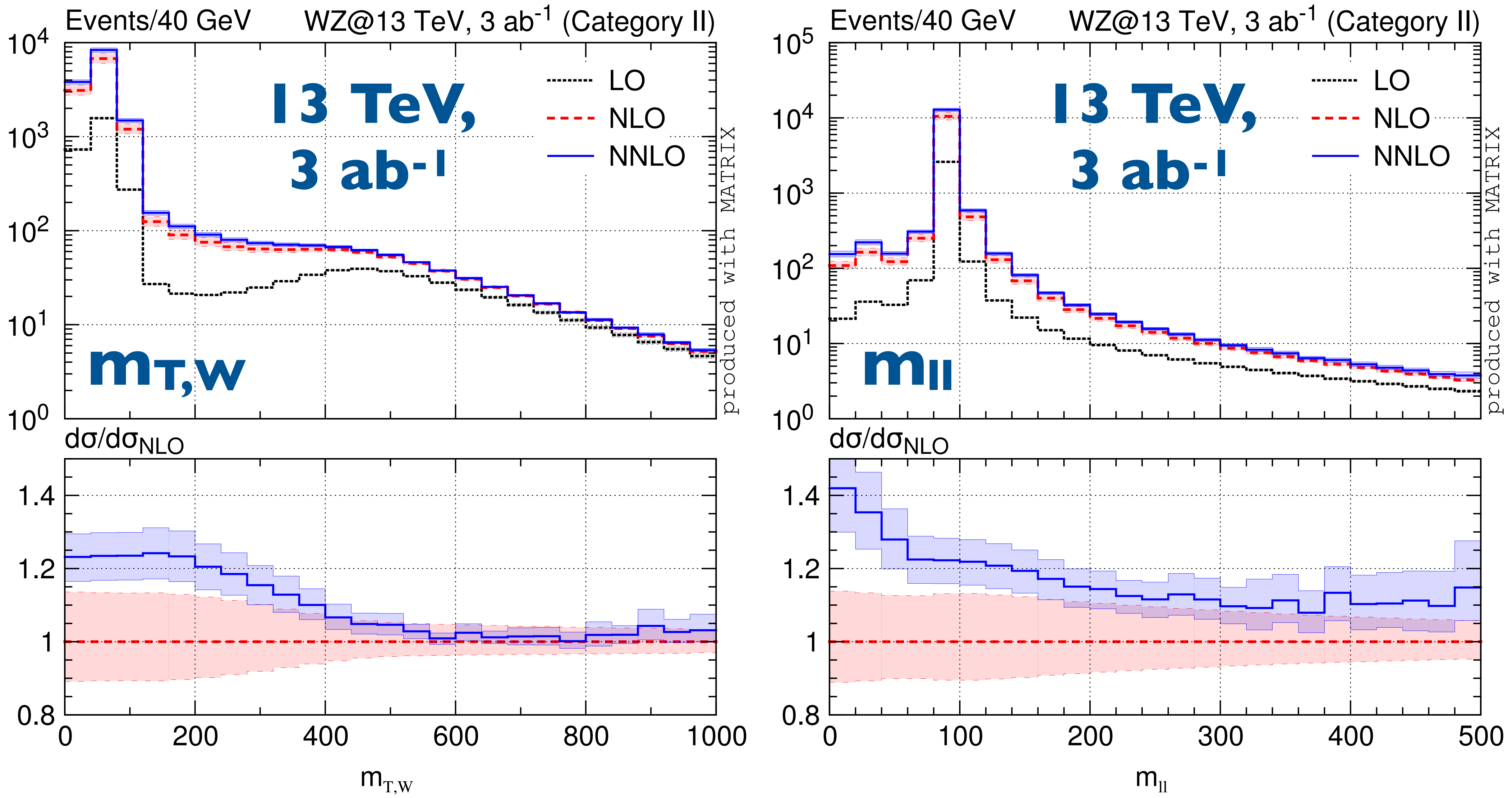


WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

Category II: p_T^{miss}>200 GeV

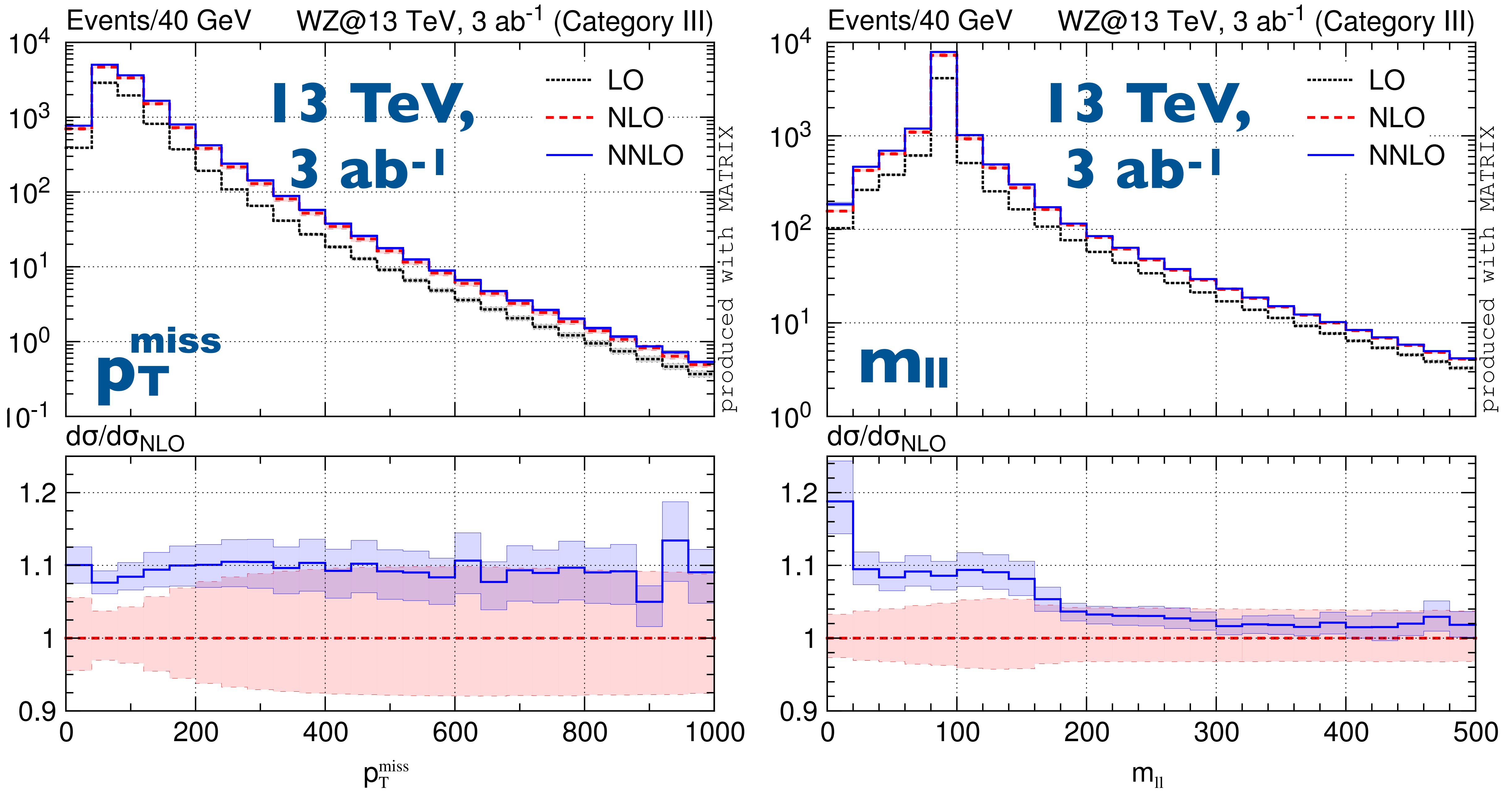


WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

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

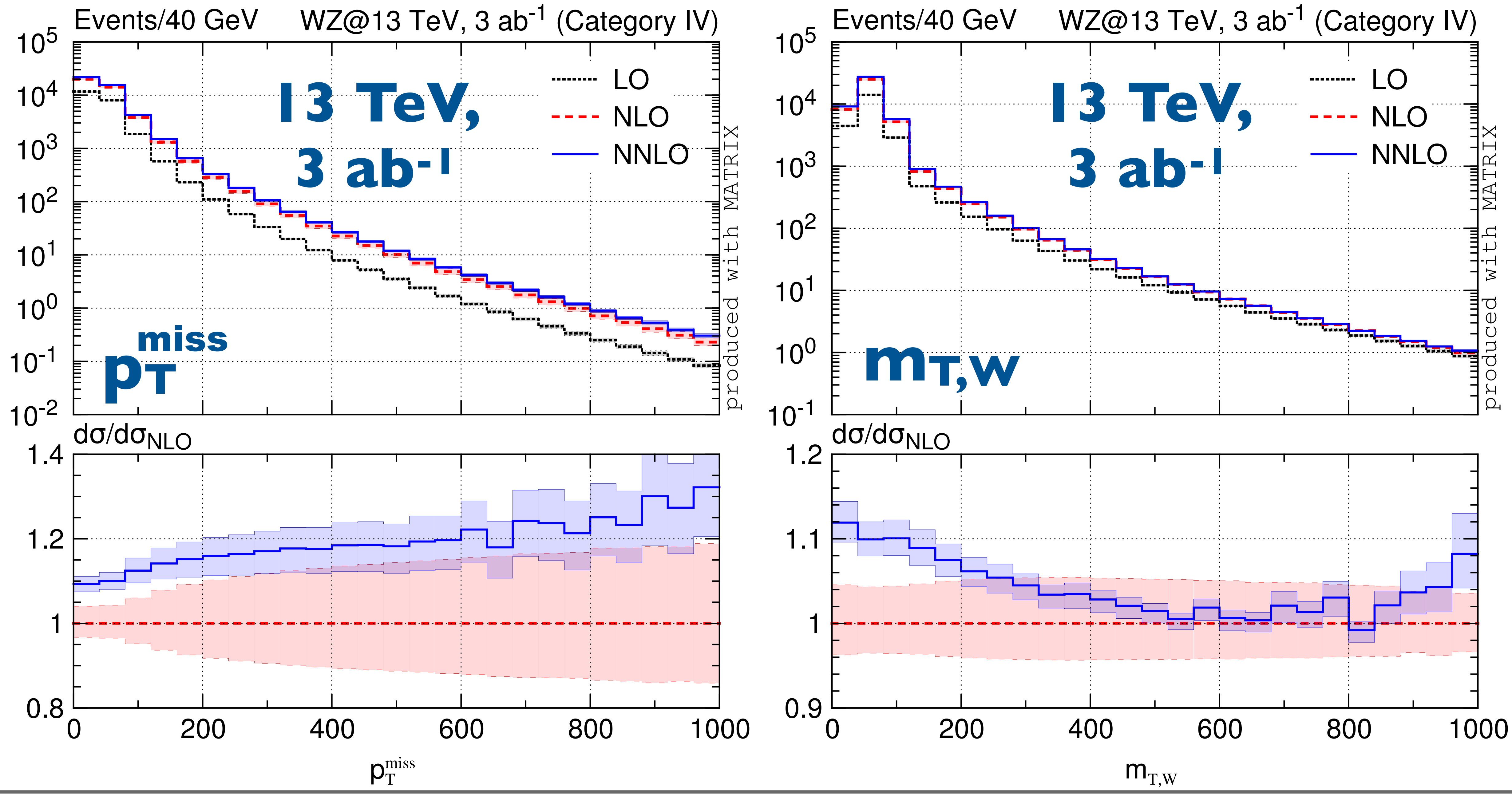


WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

Category IV: m_{ll}>105 GeV



Summary

MATRIX: **(public release in preparation!)**

- tool for fully-differential NNLO(+NNLL) computations -- flexible, powerful **and** simple!
- large list of 2→1, 2→2 Higgs and vector-boson processes
- **includes:** full leptonic (2→4) processes, **with:** all topologies, off-shell effects, spin correlations
  - → realistic computation of cross section in the fiducial phase space

Physics applications:

- All diboson processes available now at NNLO (both: inclusive & differentially; WZ was the last)
- Very good agreement of theory and data for VV processes (shown for ZZ and WZ)
- **evident:** importance of NNLO for precision and accuracy (to describe data)

Prospects at the HL/HE LHC:

- Statistical error subleading for integrated (inclusive & fiducial) rates (reduce systematics?)
- Far reach in tails of kinematical distributions for VV processes:
  - → up to $\mathcal{O}$(1 TeV) for p_T and invariant-mass distributions at 13 TeV, 3 ab^{-1}
  - → well beyond $\mathcal{O}$(1 TeV) for p_T and invariant-mass distributions at 27 TeV, 15 ab^{-1}

Outlook

- ZZ with neutrino decay at NNLO; mixed ZZ/WW→$\ell\nu\ell\nu$ channel
- **beyond MATRIX release:** p_T resummation, NLO gg, NLO EW, ...

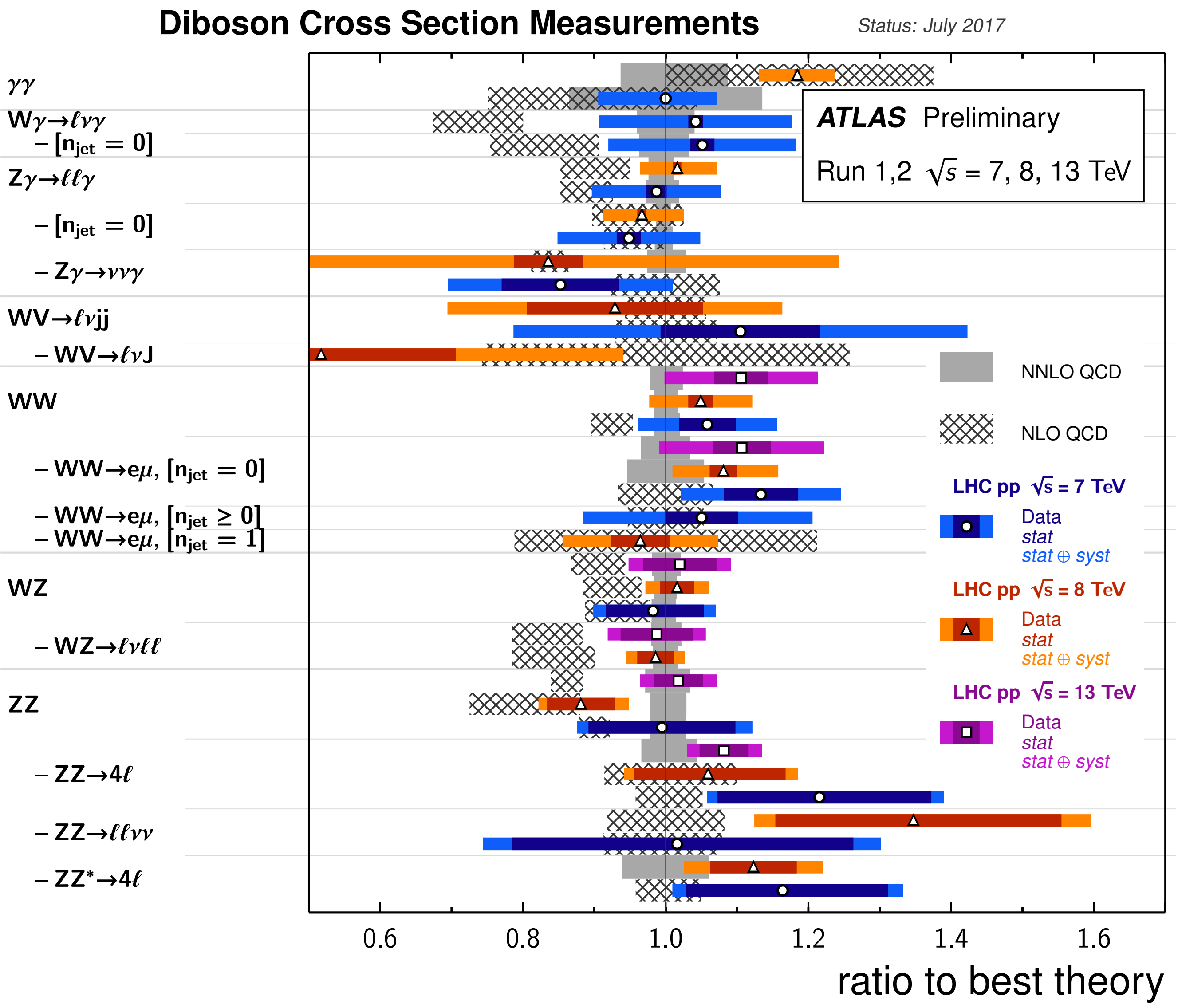

FREE YOUR MIND.
THE MATRIX

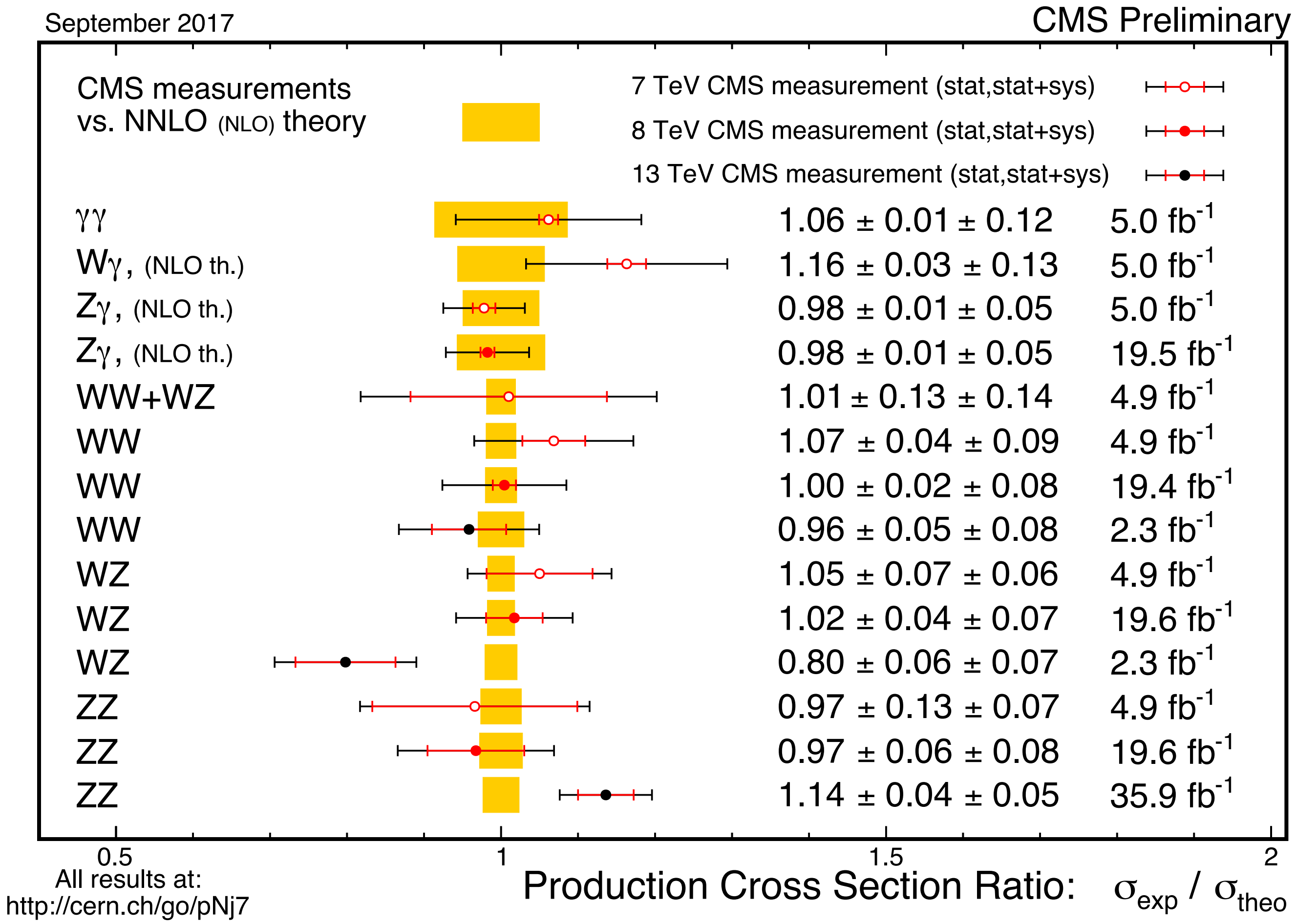
Thank You !

Back Up

Introduction

Vector-boson pair production: Data vs. Theory





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]

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:

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

[Catani, Grazzini '07]

subtraction terms known from resummation:

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

NNLO accuracy consequence of unitarity:

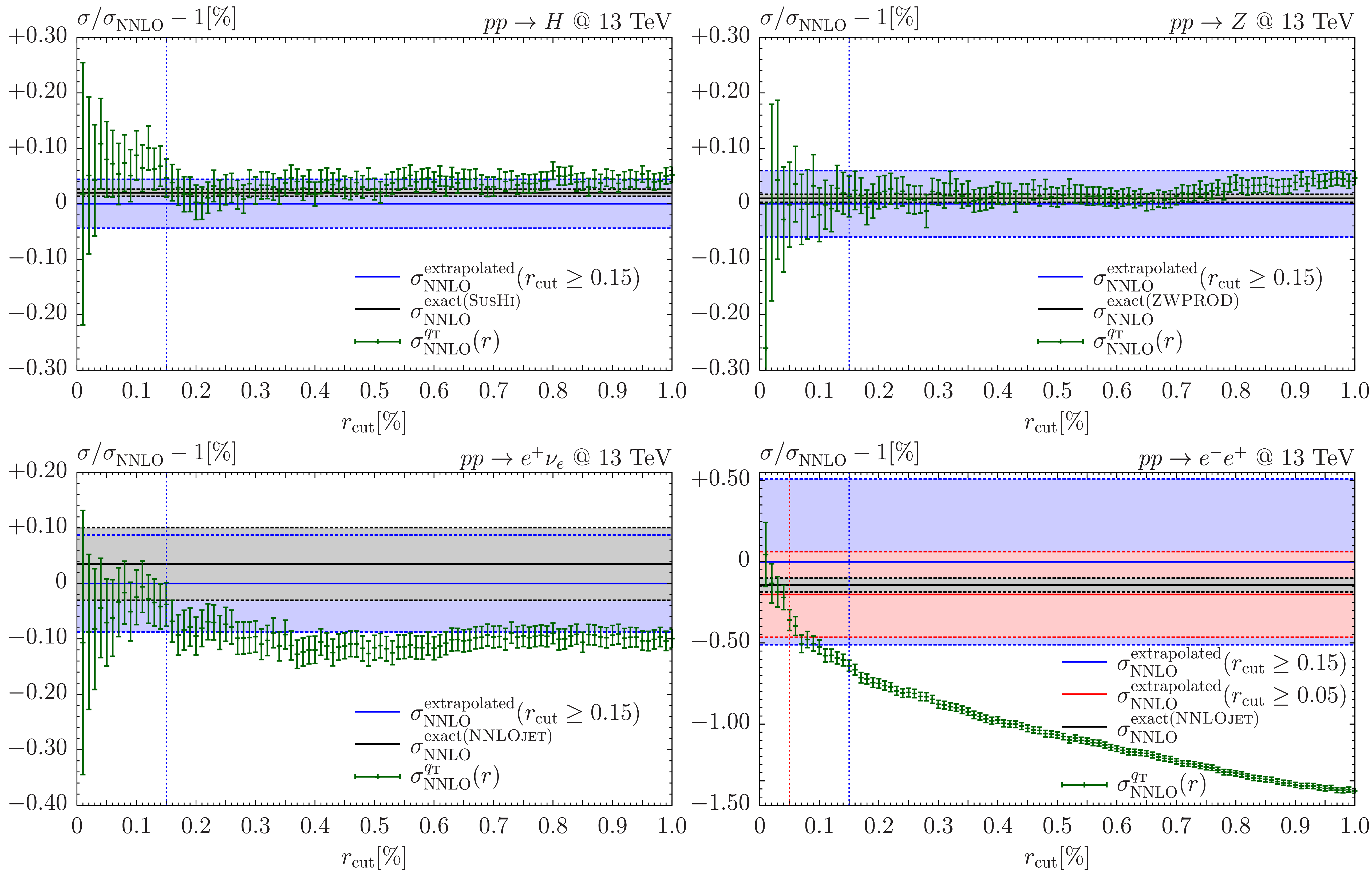
$$\int dp_T^2 \, \frac{d\sigma^{(\text{res})}}{dp_T^2 \, dy \, dM \, d\Omega} = \mathcal{H} \otimes d\sigma_{\text{LO}} \qquad \left(\ln(Q^2b^2/b_0^2) \to \ln(Q^2b^2/b_0^2 + 1)\right)$$

Resummation formula:

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

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

$r_{\text{cut}}\rightarrow 0$ extrapolation in MATRIX



Status of p_T resummation

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

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

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 $\longleftrightarrow$ p_T resummation: all NNLO directly also at NNLL

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

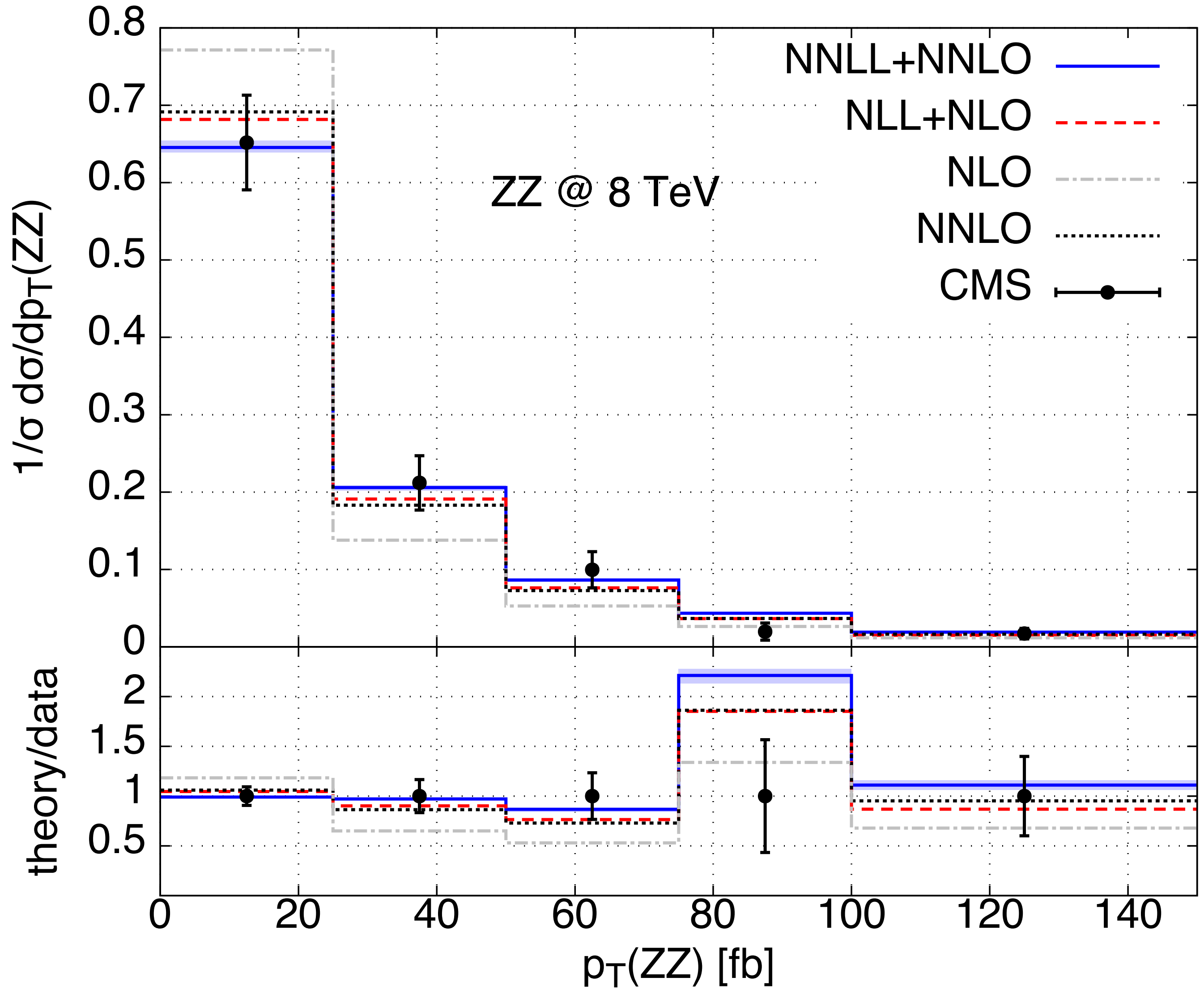
$$\frac{d\sigma^{(\text{res})}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$

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

Status of p_T resummation

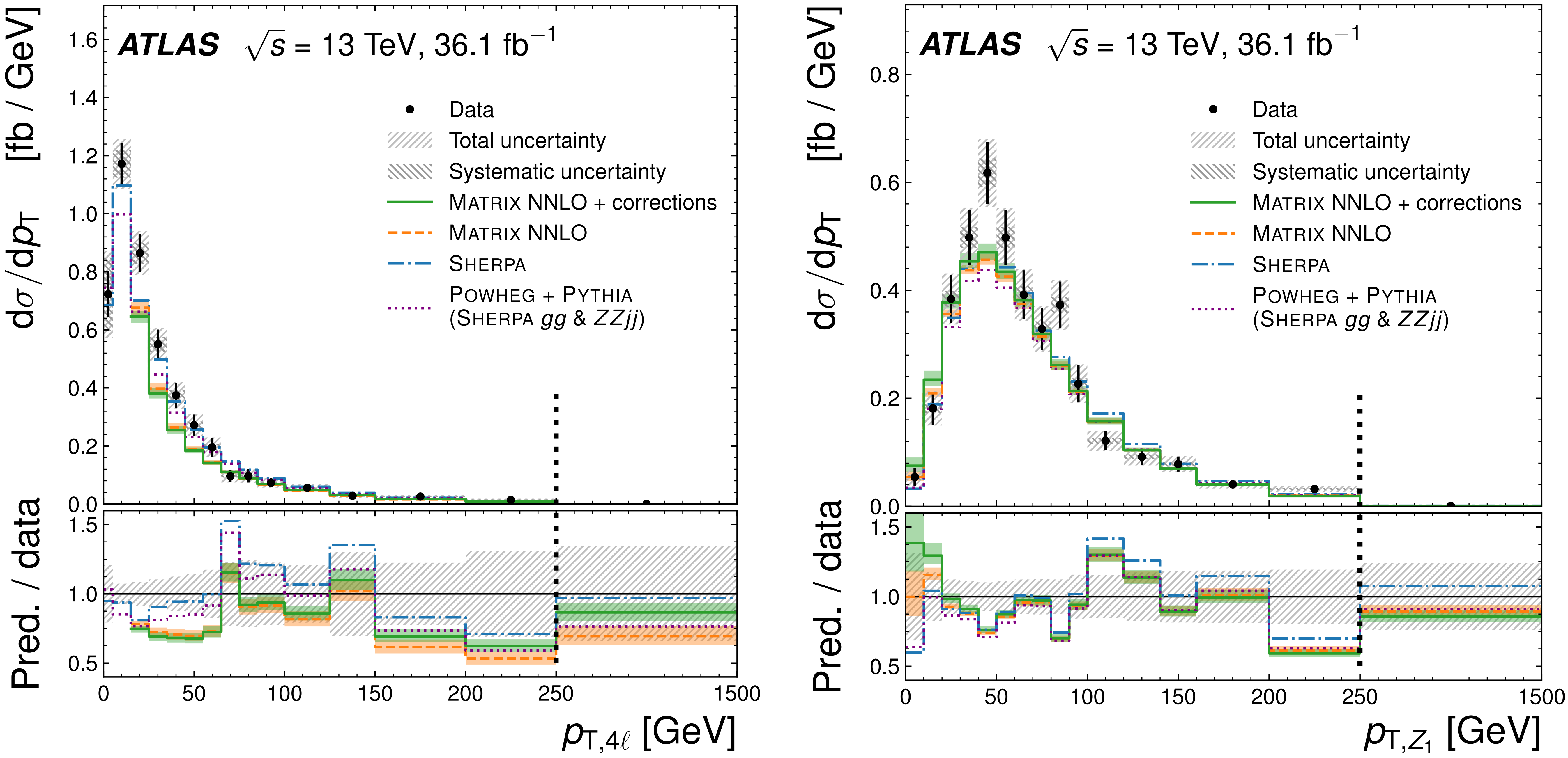
- p_T = transverse momentum of Born-level system, eg: $p_{T,4\ell}$ in pp→ZZ→4ℓ
- Why resummation? Observable divergent for p_T→0 at fixed order!
- p_T subtraction ⟷ p_T resummation: all NNLO directly also at NNLL
- currently restricted to a charge-neutral final-state system (ie, no W and WZ)
- will **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]



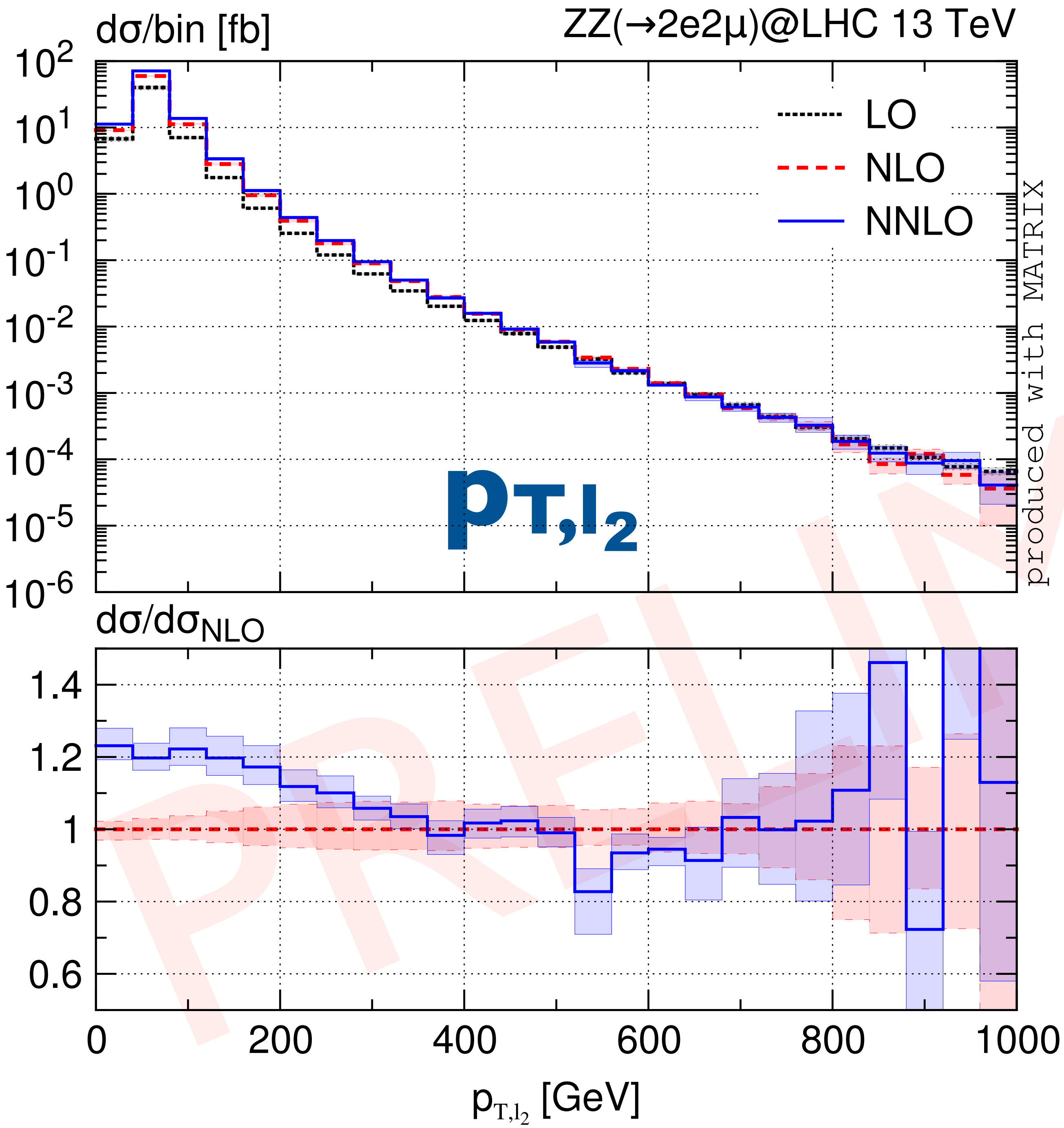
Recent 13 TeV ATLAS results for ZZ

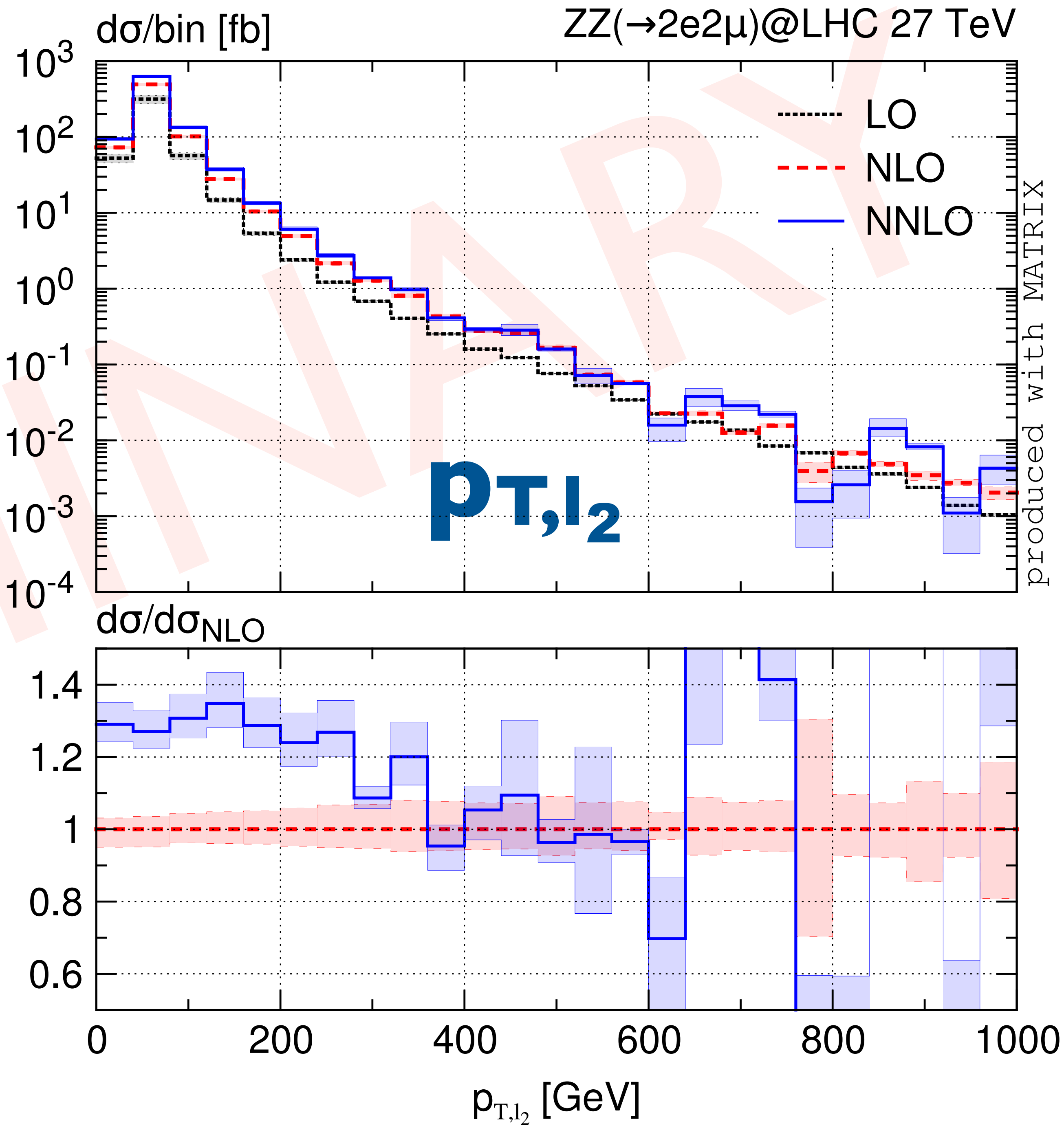
[ATLAS '17]



Reach in the tails for ZZ

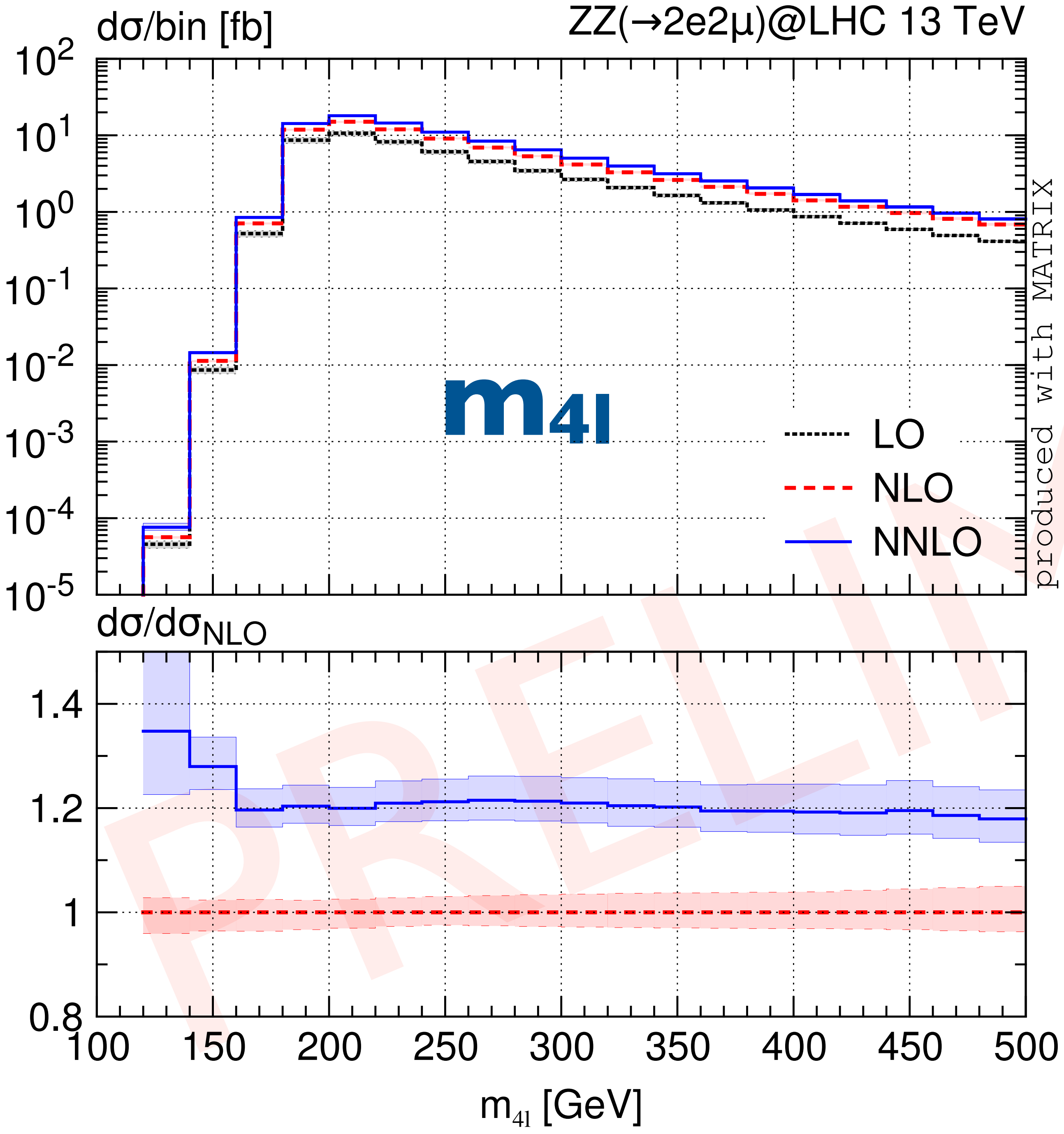
13 TeV **27 TeV**



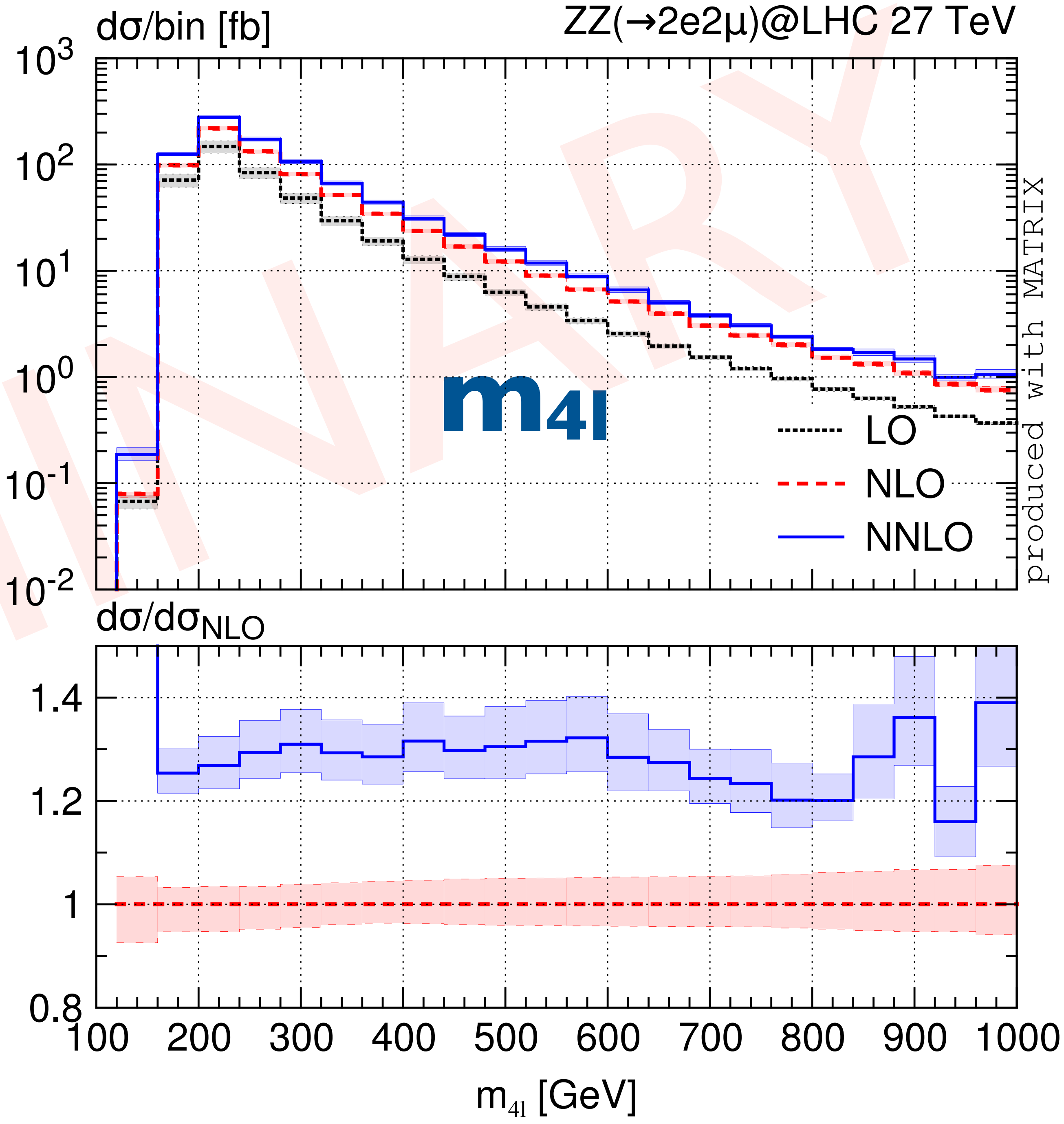


Reach in the tails for ZZ

13 TeV

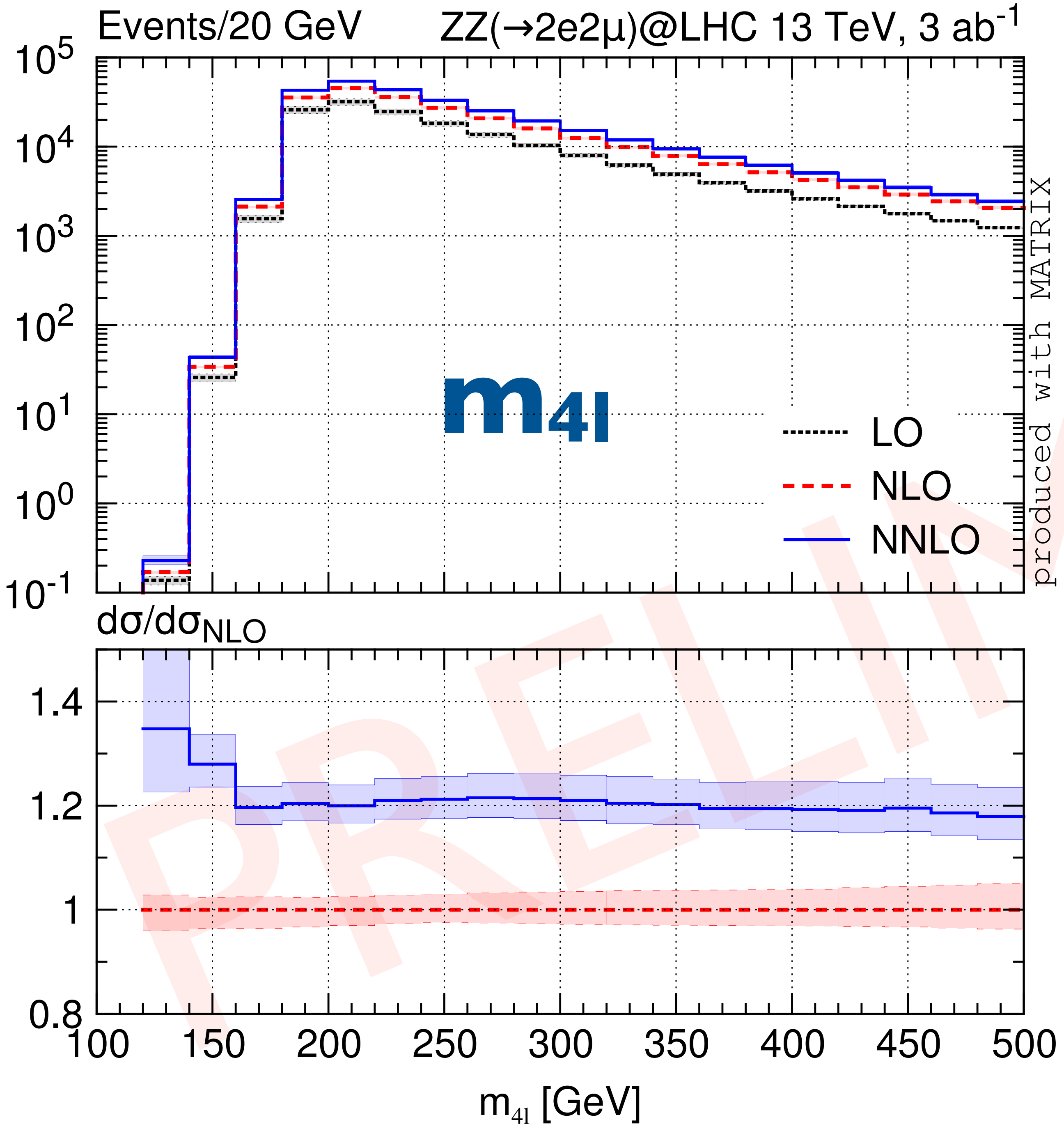


27 TeV

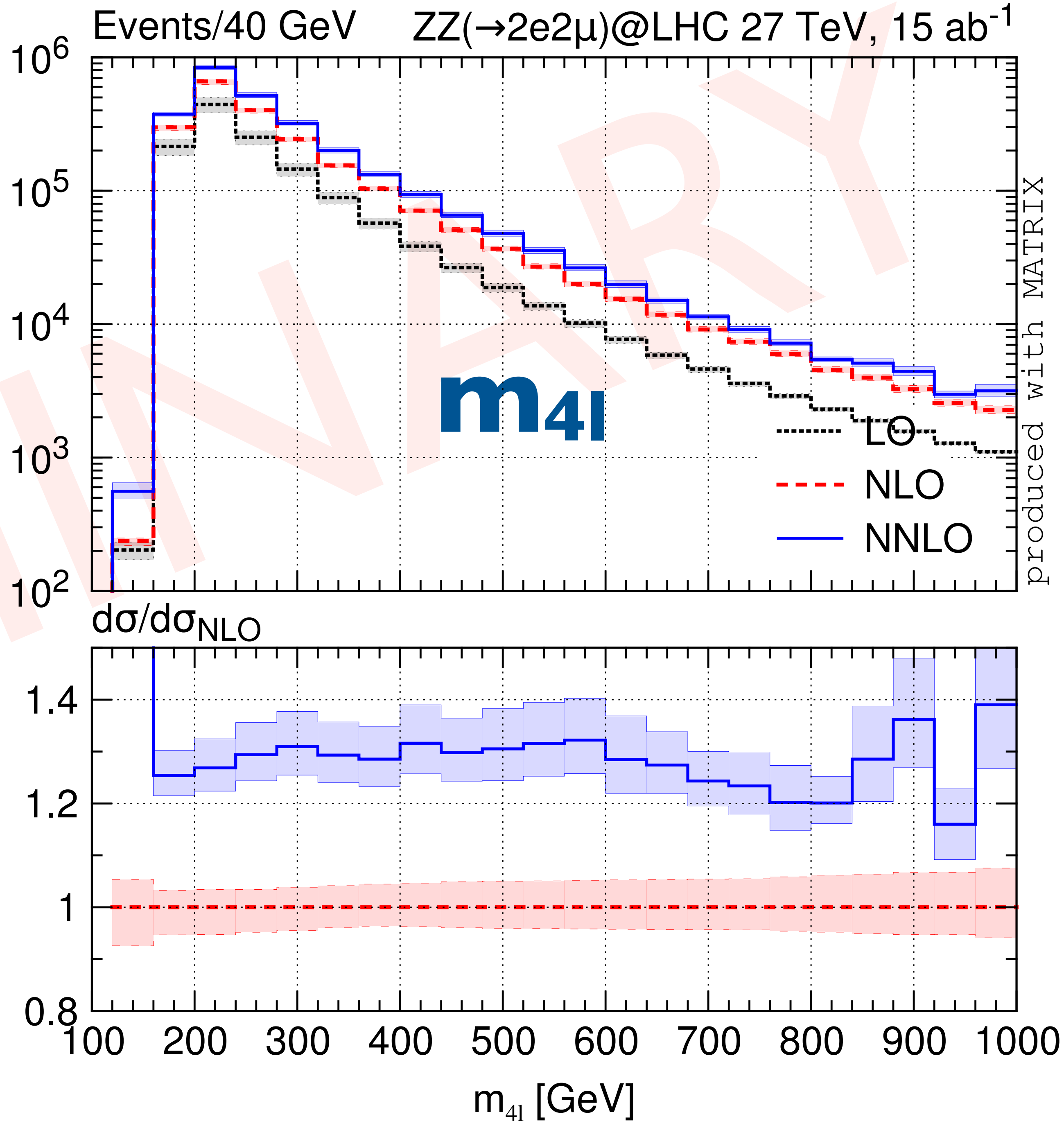


Reach in the tails for ZZ

13 TeV, 3 ab^{-1}

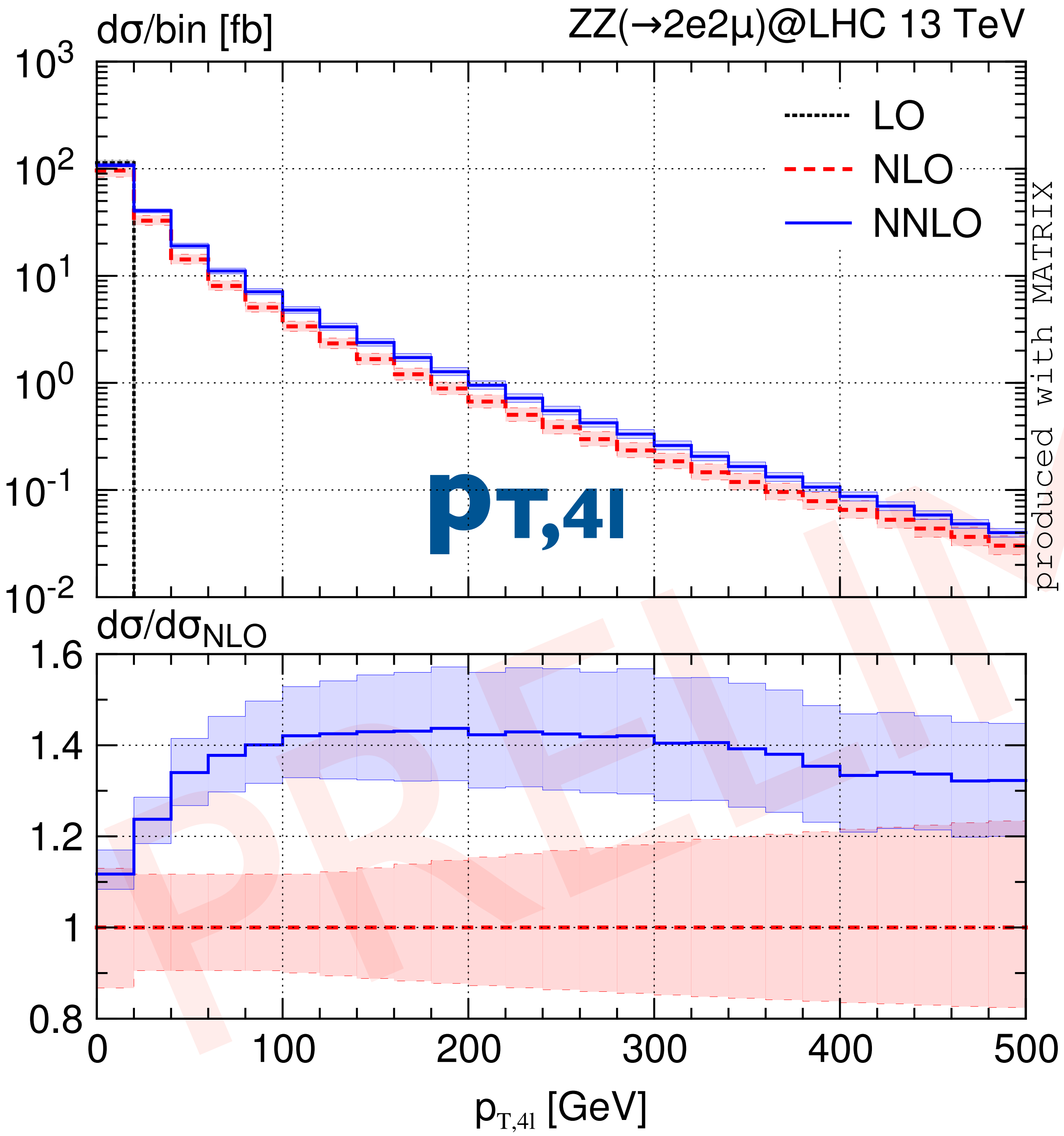


27 TeV, 15 ab^{-1}

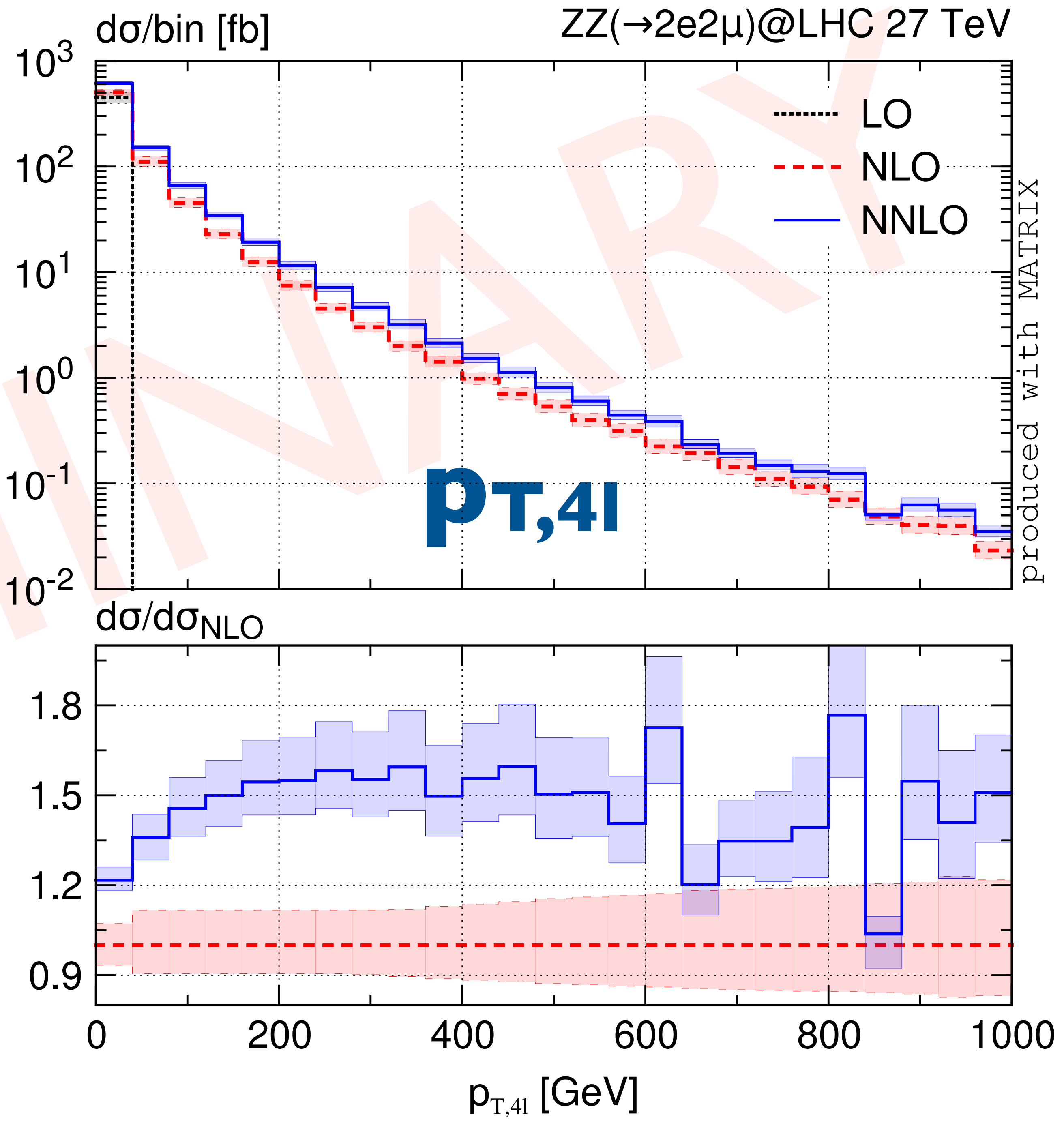


Reach in the tails for ZZ

13 TeV

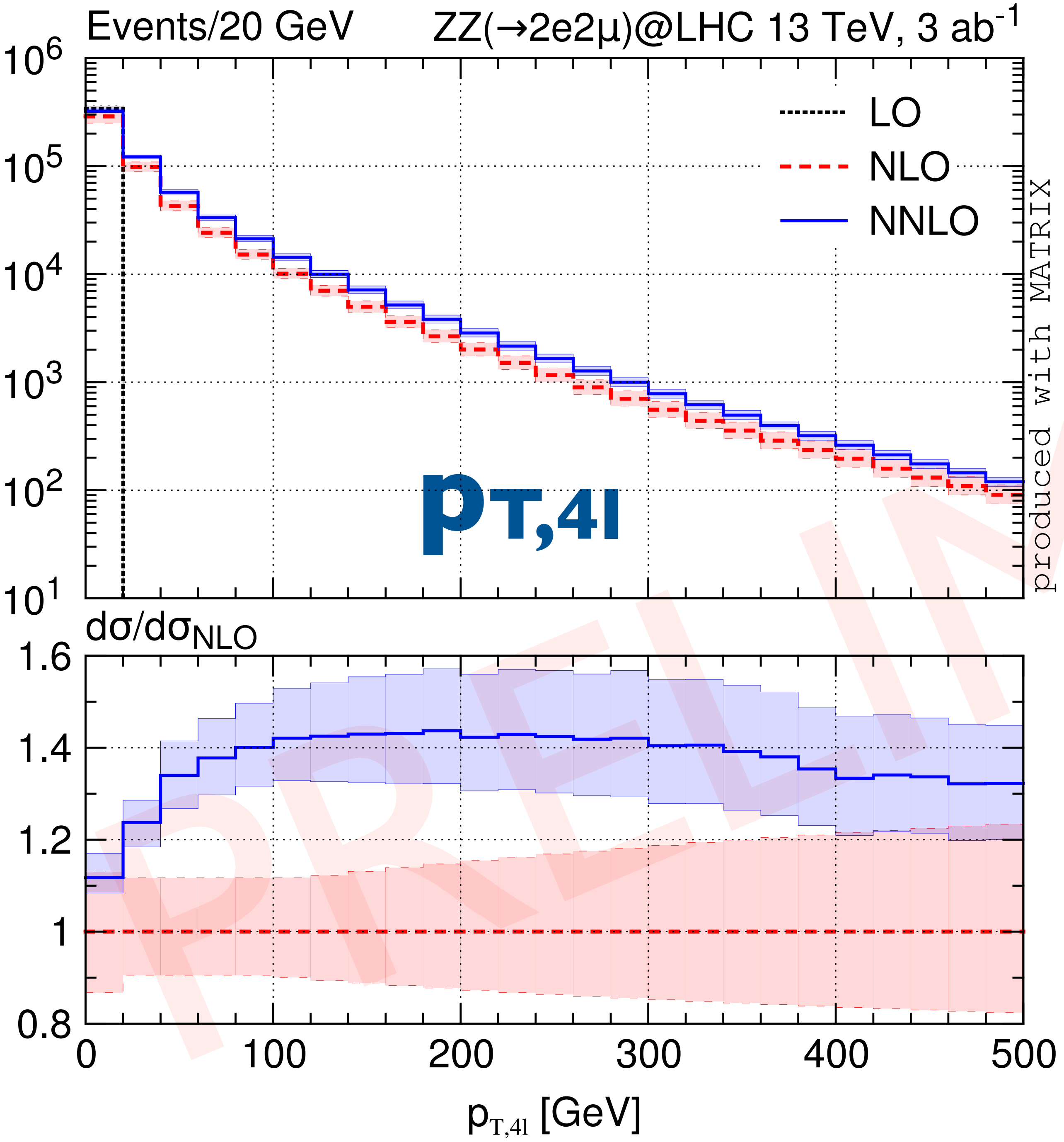


27 TeV

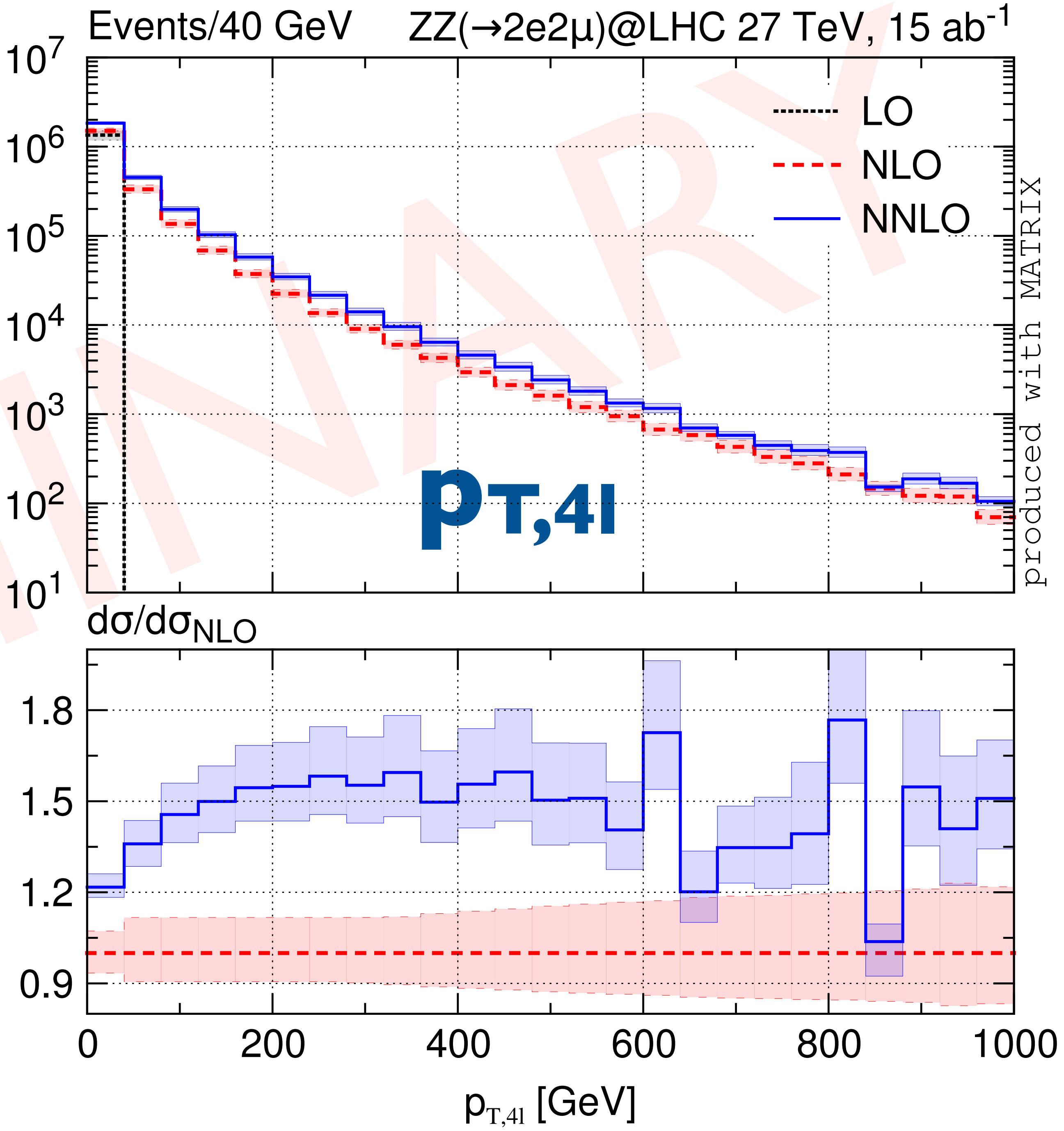


Reach in the tails for ZZ

13 TeV, 3 ab^{-1}

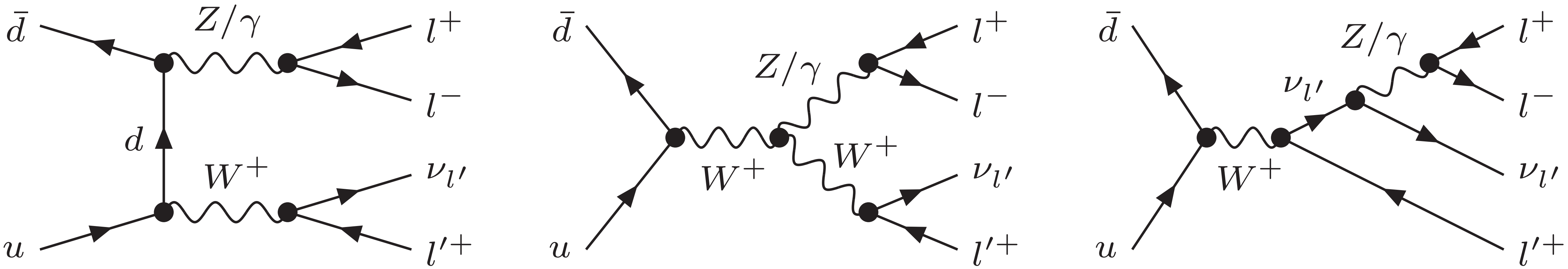


27 TeV, 15 ab^{-1}



WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]



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

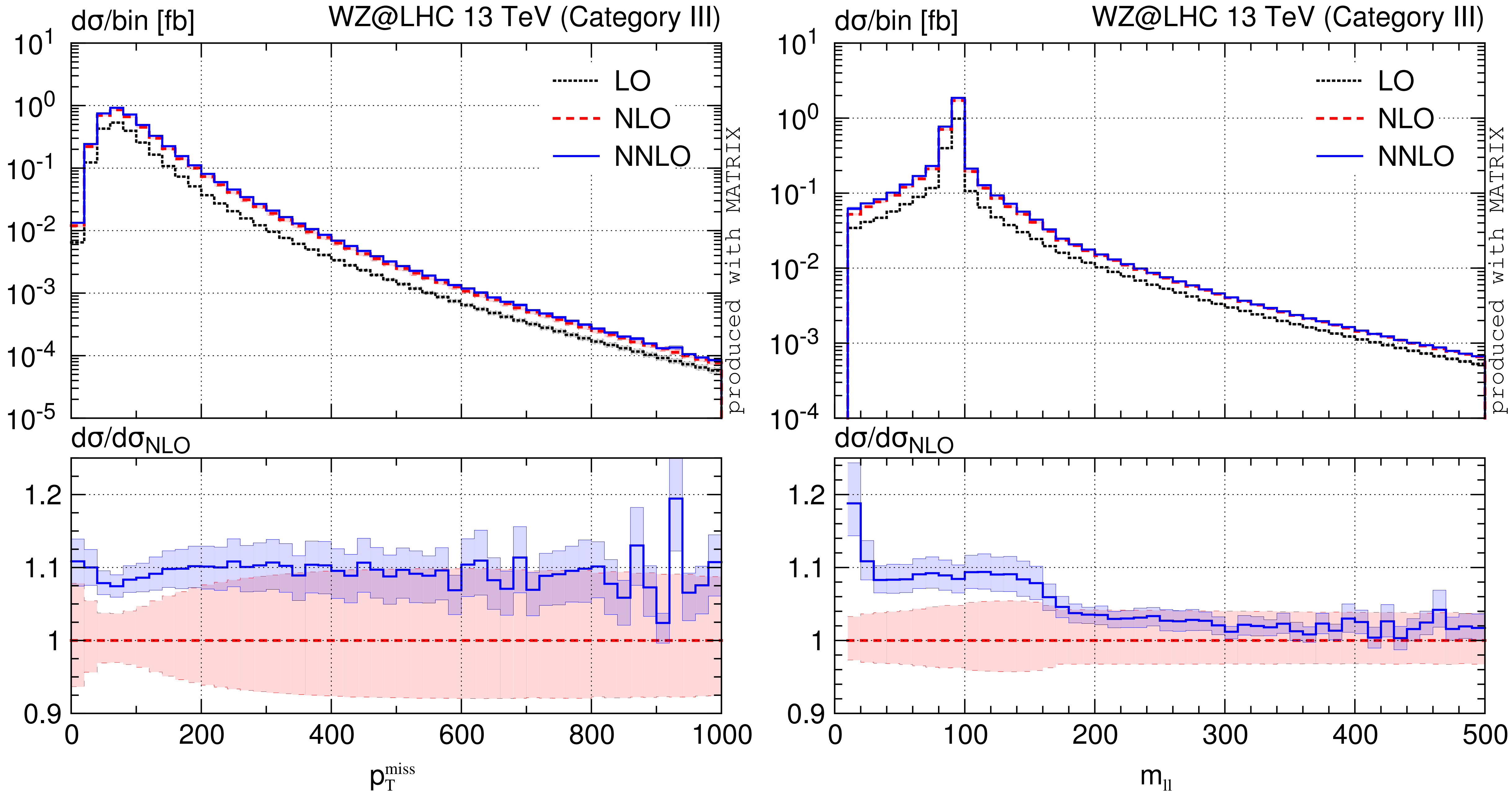
W, Z identification different	definition of the fiducial volume for $pp \to \ell_{\mathrm{w}}^{\pm}\nu_{\ell_{\mathrm{w}}}\ell_{\mathrm{z}}^{+}\ell_{\mathrm{z}}^{-}$, $\ell, \ell_{\mathrm{w}}, \ell_{\mathrm{z}} \in \{e, \mu\}$
ATLAS 8/13 TeV (cf. Ref. [5,6])	$p_{T,\ell_{\mathrm{z}}} > 15\,\mathrm{GeV}$,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

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

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

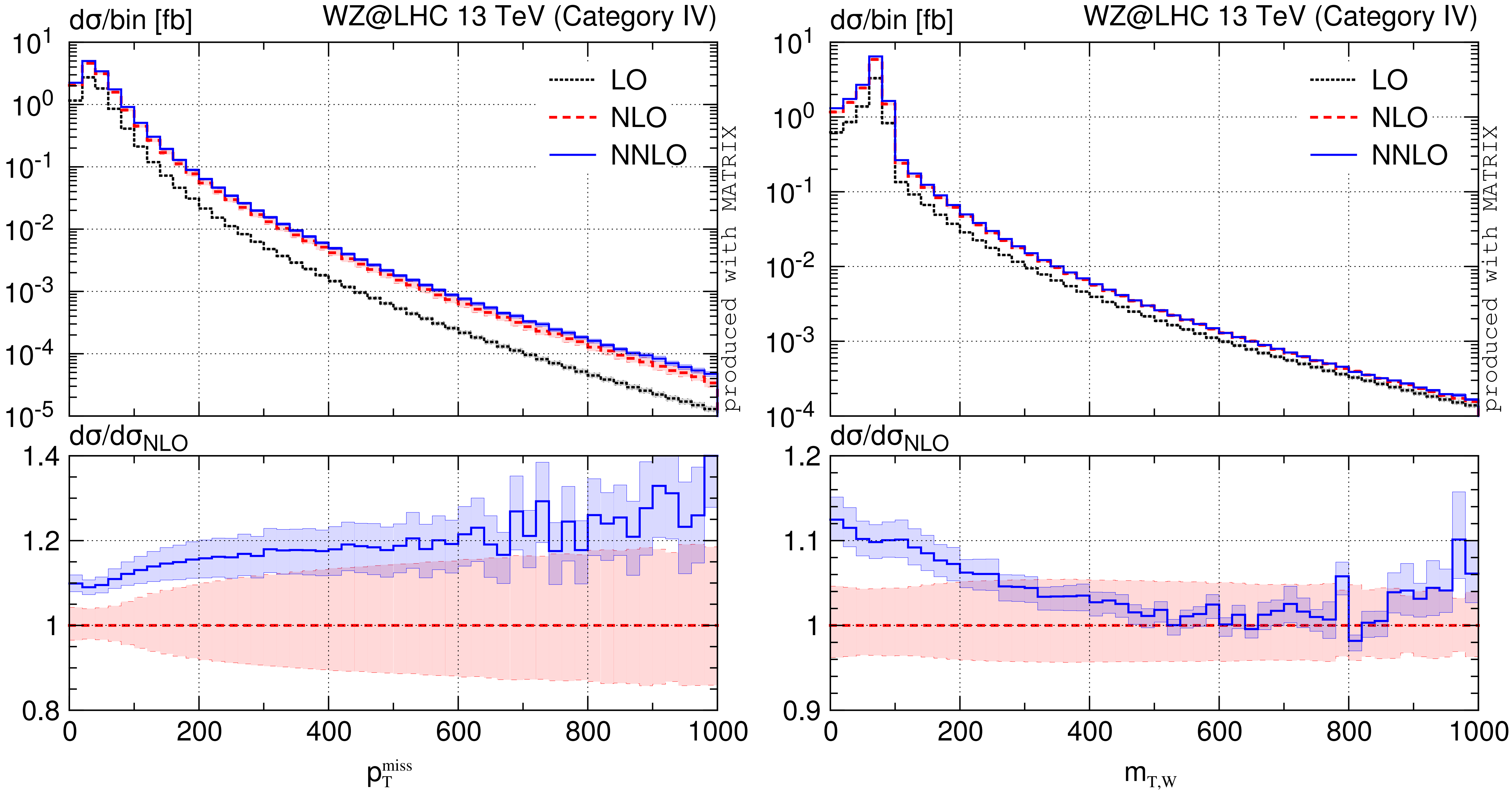


WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

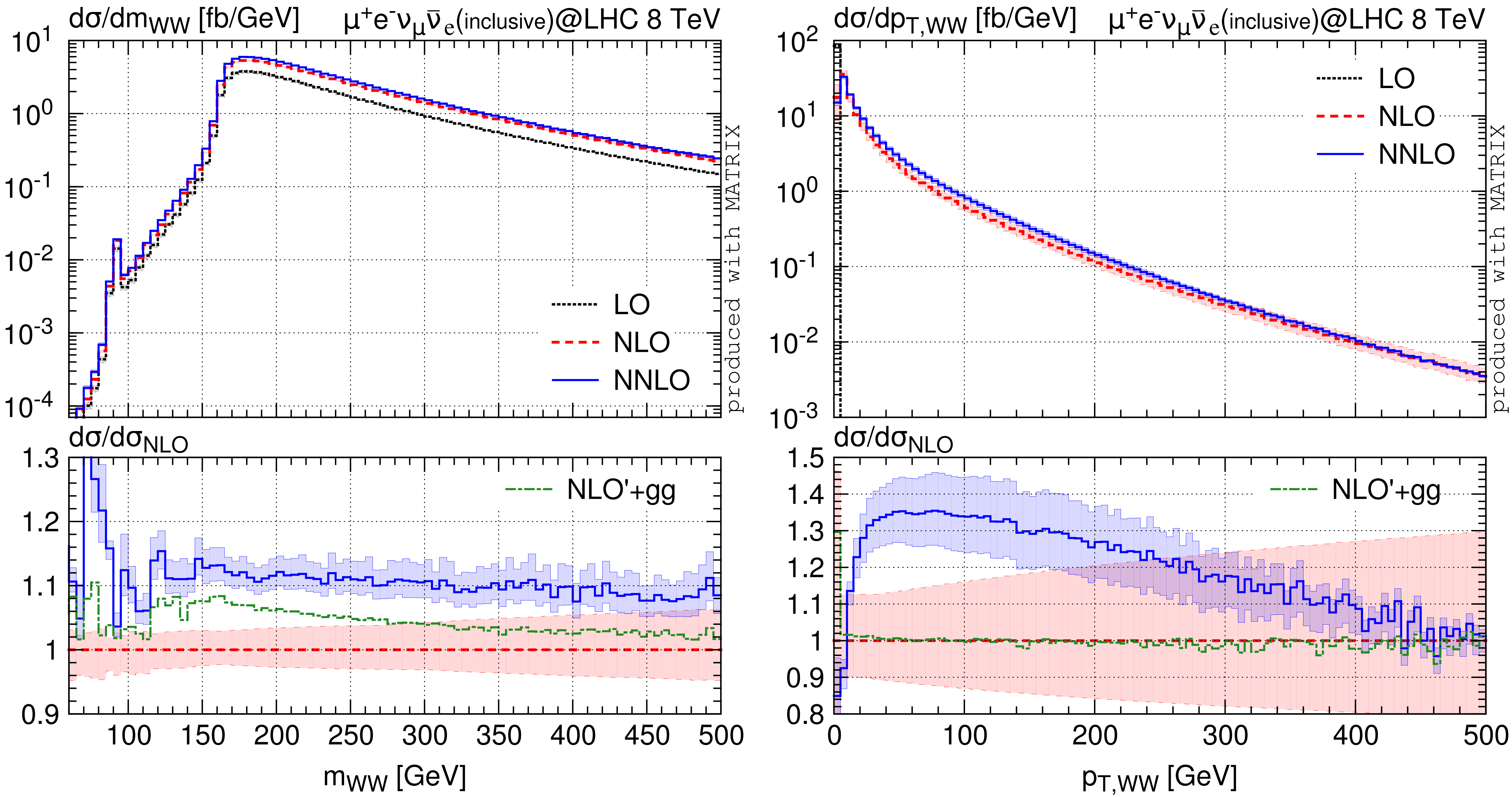
Category IV: $m_{ll}>105$ GeV



WW fully differential at NNLO

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

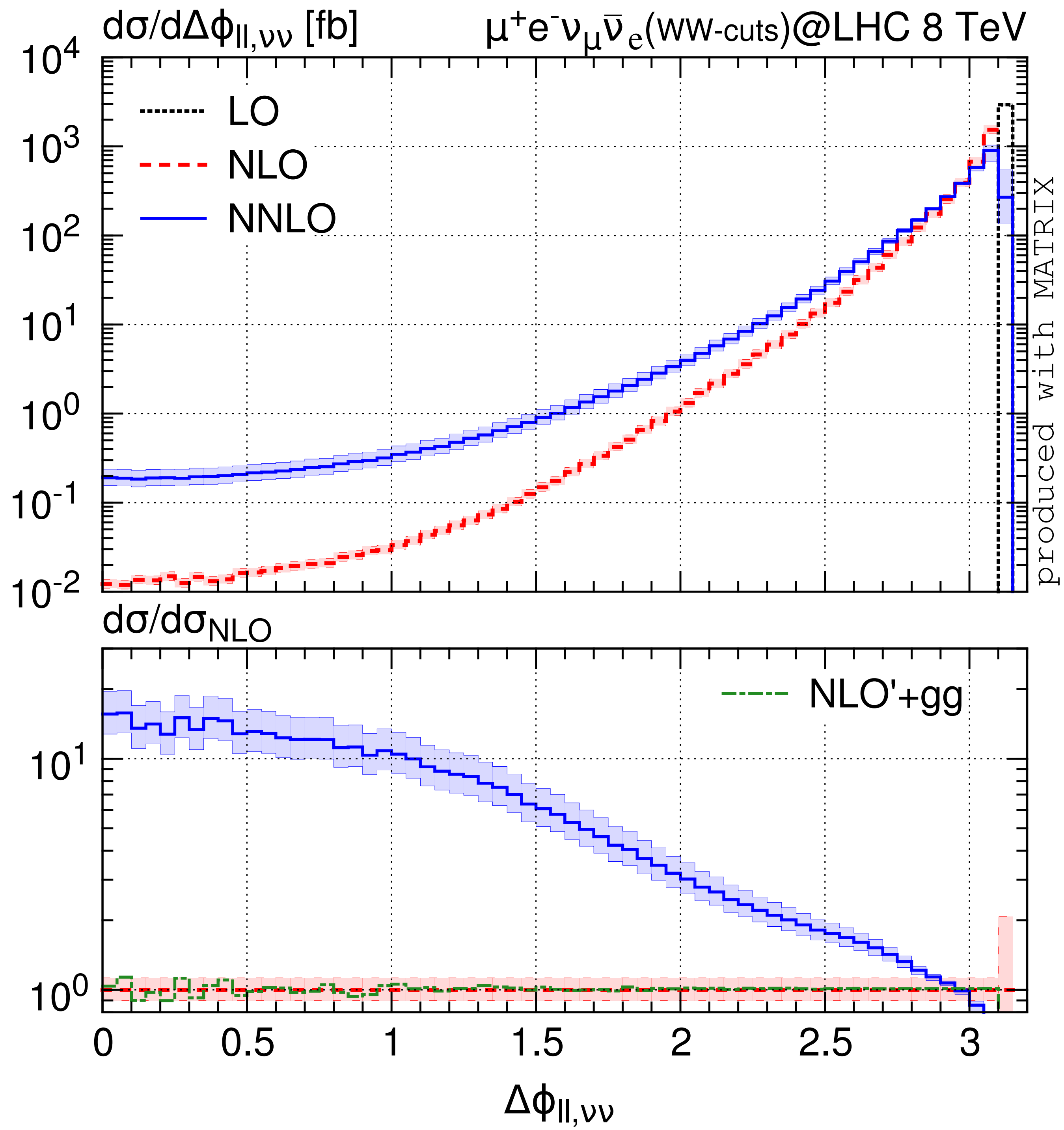
inclusive: distributions (8 TeV)

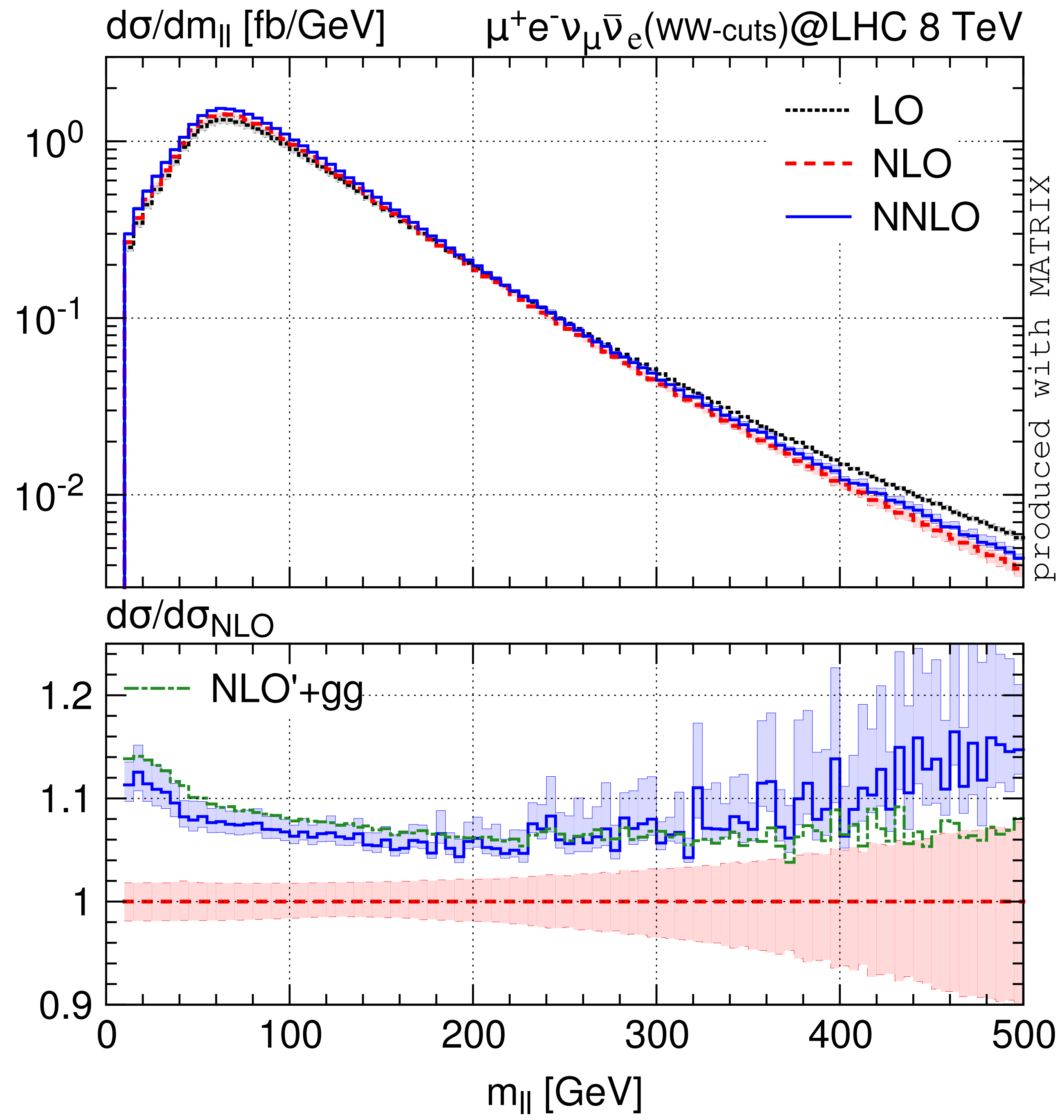


WW fully differential at NNLO

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

WW signal cuts: distributions (8 TeV)



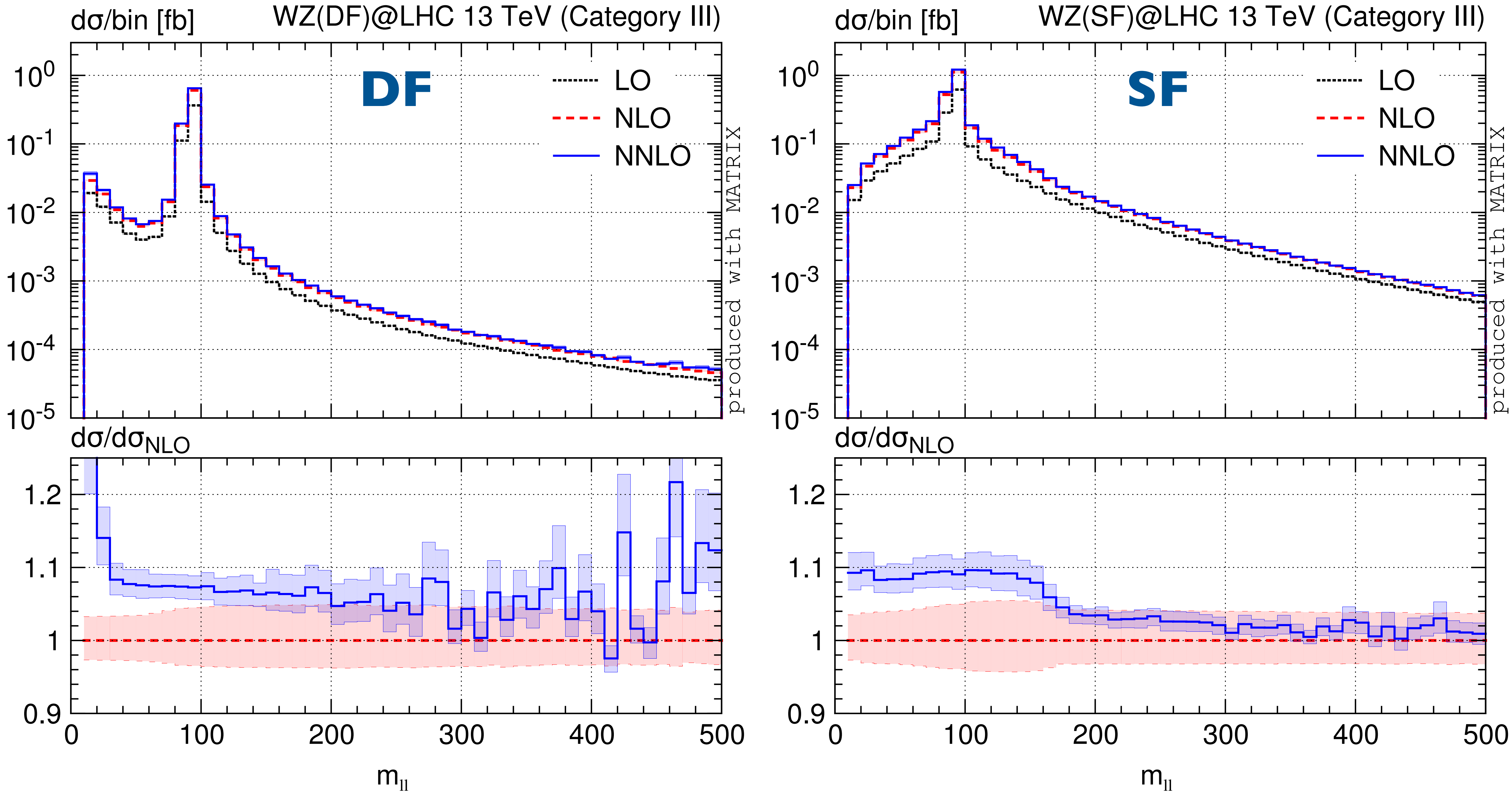


WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

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



WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements

- various channels:
  - different-flavour (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-flavour (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

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

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

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements

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

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

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

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

    pp → $e^-\nu_e\, e^+e^-$, pp → $\mu^-\nu_\mu\, \mu^+\mu^-$ (identical for massless fermions)
- fiducial phase space (ATLAS/CMS) for pp → $l'\nu_{l'}\, l\,l$ $(l,l' \in \{e,\mu\})$
  - 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 $pp \to \ell_{\rm w}^{\pm}\nu_{\ell_{\rm w}}\ell_{\rm z}^{+}\ell_{\rm z}^{-}$, $\ell, \ell_{\rm w}, \ell_{\rm z} \in \{e,\mu\}$
ATLAS 8/13 TeV (cf. Ref. [5,6])	$p_{T,\ell_{\rm z}} > 15\,\text{GeV}$, $p_{T,\ell_{\rm w}} > 20\,\text{GeV}$, $\eta_\ell < 2.5$, $\lvert m_{\ell_{\rm z}\ell_{\rm z}} - m_Z\rvert < 10\,\text{GeV}$, $m_{T,W} > 30\,\text{GeV}$, $\Delta R_{\ell_{\rm z}\ell_{\rm z}} > 0.2$, $\Delta R_{\ell_{\rm z}\ell_{\rm w}} > 0.3$
CMS 13 TeV (cf. Ref. [7])	$p_{T,\ell_{\rm z,1}} > 20\,\text{GeV}$, $p_{T,\ell_{\rm z,2}} > 10\,\text{GeV}$, $p_{T,\ell_{\rm w}} > 20\,\text{GeV}$, $\eta_\ell < 2.5$, $60\,\text{GeV} < m_{\ell_{\rm z}\ell_{\rm z}} < 120\,\text{GeV}$, $m_{\ell^+\ell^-} > 4\,\text{GeV}$

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

New-physics searches

Category I: no additional cuts