NNLO calculations with MATRIX

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in collaboration with M. Grazzini and S. Kallweit

Outline

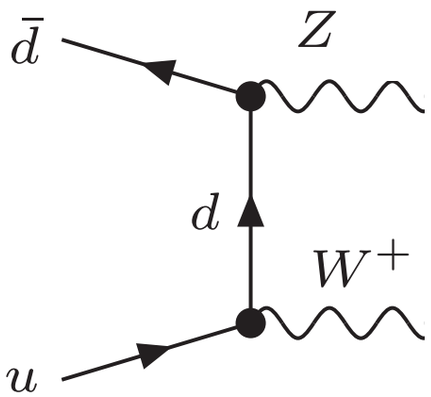
1. Short introduction to precision in diboson computations
2. The MATRIX (public version)
   - available processes
   - NNLO corrections
   - features of the code
   - how to compile/run the code
   - cross sections and CPU budget
3. New developments
   - other corrections
   - combination with resummation
   - Improvements of tails for HL/HE-LHC

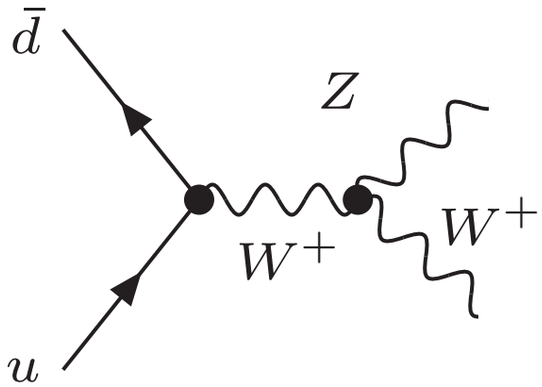
VV production in a nutshell

example: WZ production

VV production in a nutshell

example: WZ production (on-shell)





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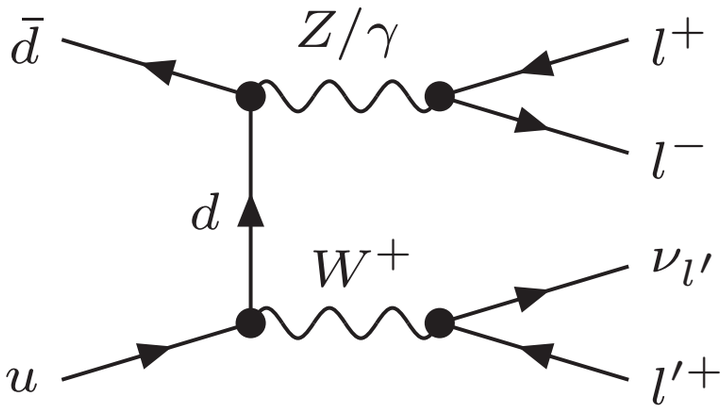

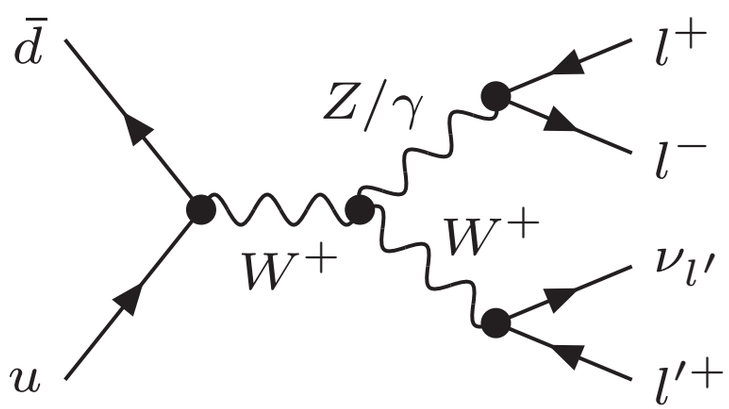

- EW decays of heavy bosons (W, Z, γ*) ✓ (only isolated photons in the final state)

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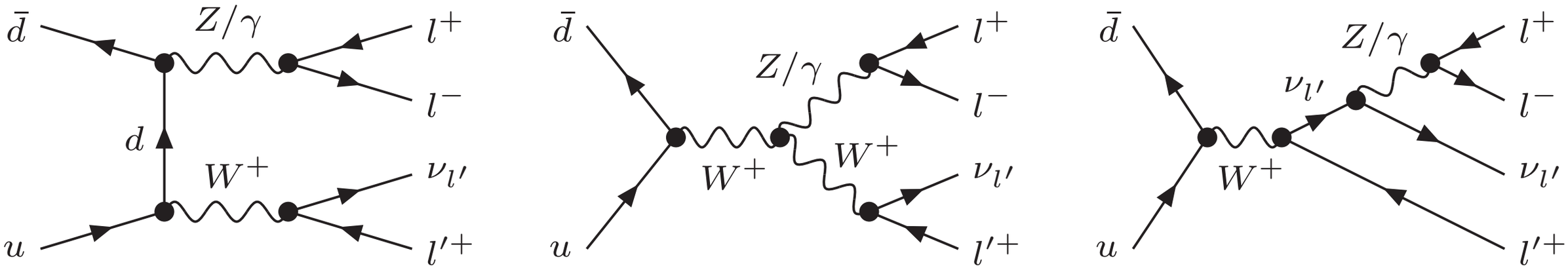

- EW decays of heavy bosons (W, Z, γ*) ✓ (only isolated photons in the final state)
- all topologies to same leptonic final state (with spin correlations & off-shell effects) ✓

VV production in a nutshell

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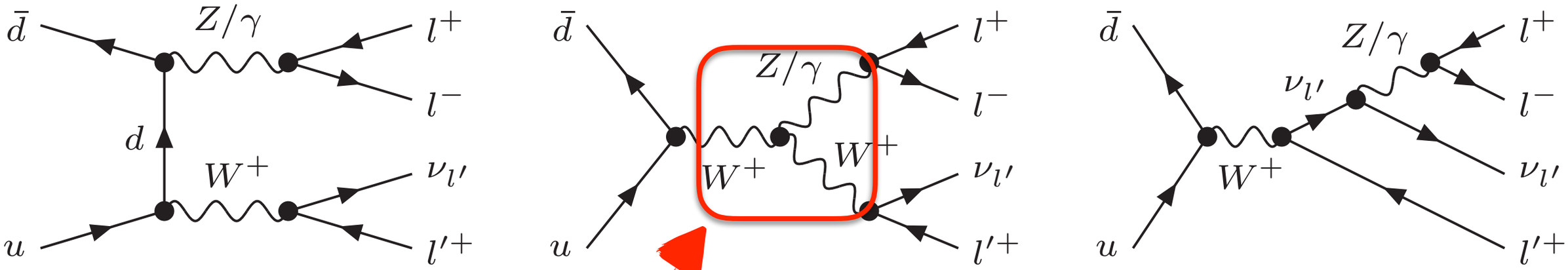

- EW decays of heavy bosons (W, Z, γ*) ✓ (only isolated photons in the final state)
- all topologies to same leptonic final state (with spin correlations & off-shell effects) ✓

→ access to triple gauge couplings (TGCs) → high relevance for BSM physics

VV production in a nutshell

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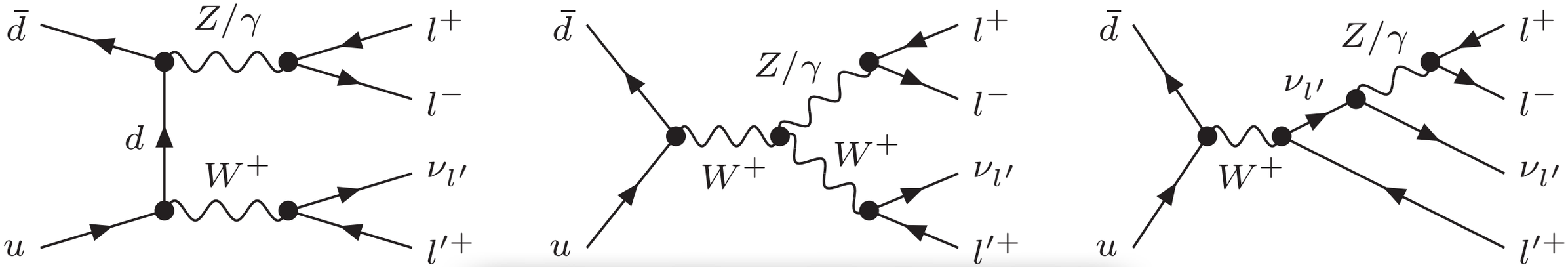
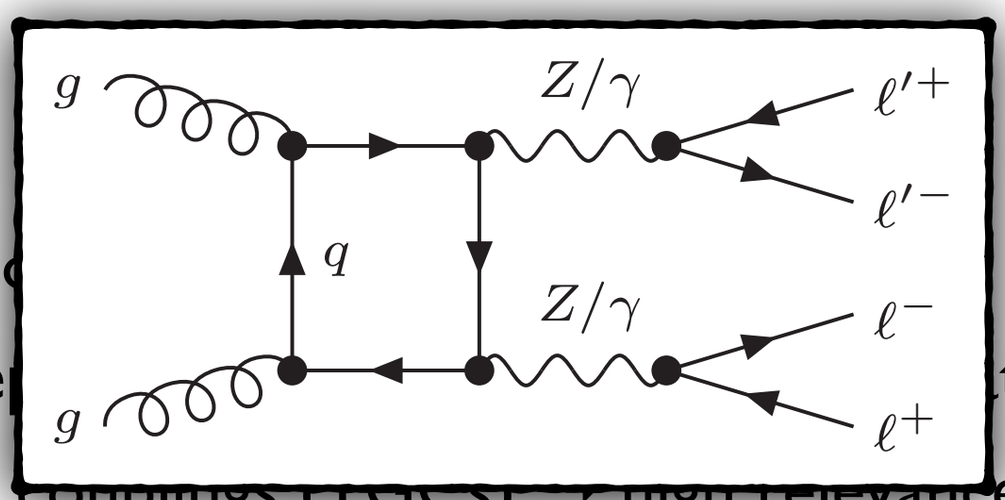


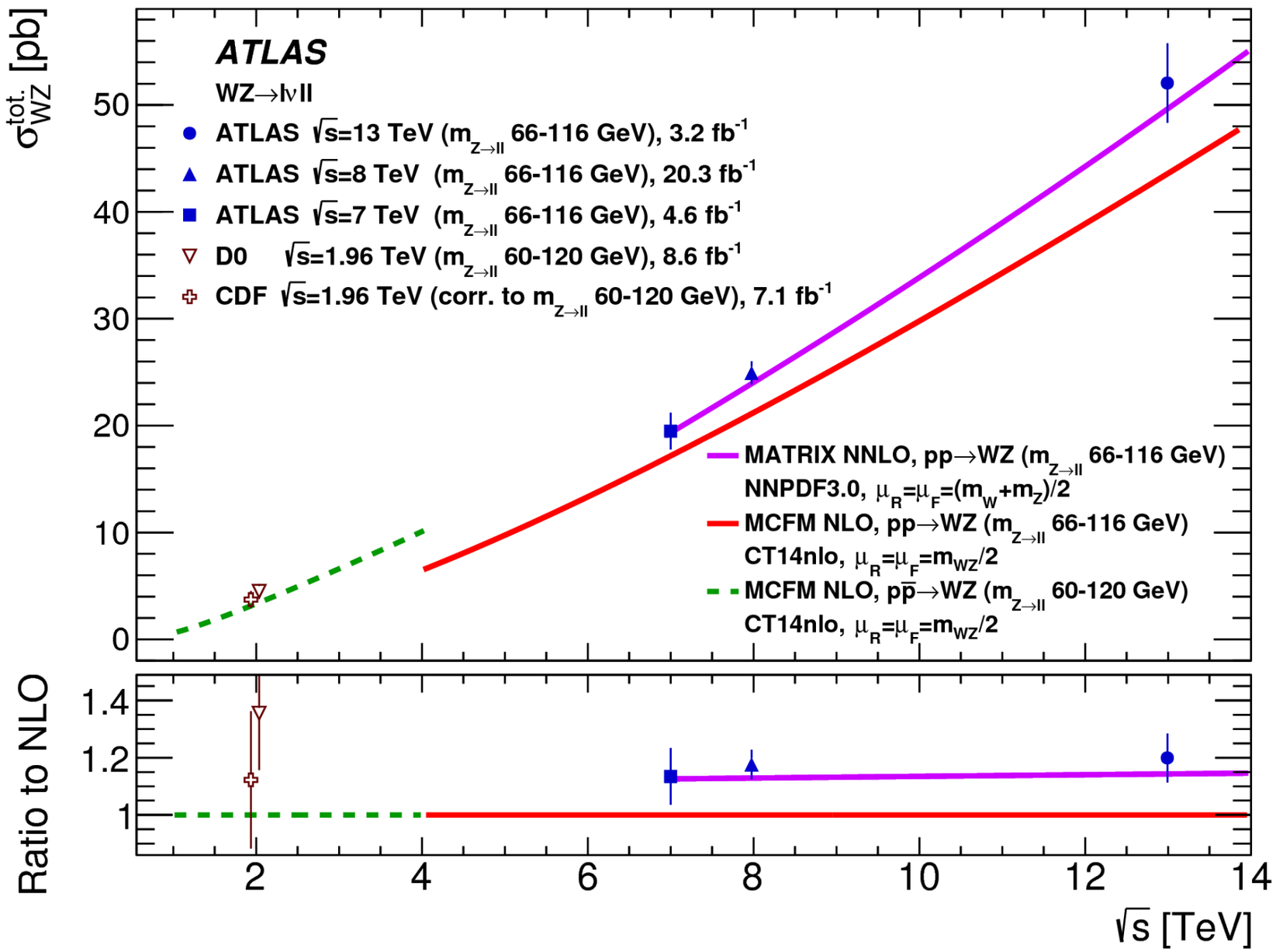


- EW decays of heavy bos photons in the final state)
- all topologies to same le tions & off-shell effects) ✓
  → access to triple gauge couplings (TGCs) → high relevance for BSM physics
- loop-induced gg channel enters NNLO for charge-neutral processes ✓ (eg, for ZZ)

WZ inclusive cross section at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

[ATLAS '16]



We implemented...

The MATRIX framework

[Grazzini, Kallweit, MW '17]

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

Munich

MUlti-chaNnel Integrator at Swiss (CH) precision

q_T subtraction $\Leftrightarrow$ q_T resummation

NNLO

NNLL

Matrix

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

process	status	comment
pp→Z/γ*(→ℓℓ/νν)	✓	**validated analytically + FEWZ**
pp→W(→ℓν)	✓	**validated with FEWZ, NNLOjet**
pp→H	✓	**validated analytically (by SusHi)**
pp→γγ	✓	**validated with 2γNNLO**
pp→Zγ→ℓℓγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→Zγ→ννγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→Wγ→ℓνγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ	✓	[Cascioli et al. '14]
pp→ZZ→ℓℓℓℓ	✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
pp→ZZ→ℓℓℓ'ℓ'	✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
pp→ZZ→ℓℓν'ν'	✓	[Kallweit, MW '18]
pp→ZZ/WW→ℓℓνν	✓	[Kallweit, MW '18]
pp→WW	✓	[Gehrmann et al. '14]
pp→WW→ℓν ℓ'ν'	✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
pp→WZ	✓	[Grazzini, Kallweit, Rathlev, MW '16]
pp→WZ→ℓνℓℓ	✓	[Grazzini, Kallweit, Rathlev, MW '17]
pp→WZ→ℓ'ν'ℓℓ	✓	[Grazzini, Kallweit, Rathlev, MW '17]
pp→HH	(✓)	**not in public release**

process	status	comment
pp→Z/γ*(→ℓℓ/νν)	✓	validated analytically + FEWZ
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pp→γγ	✓	validated with 2γNNLO
pp→Zγ→ℓℓγ	✓	[Grazzini, Kallweit, Rathlev '15]
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pp→HH	(✓)	not in public release

single boson processes

process		status	comment
pp→Z/γ*(→ℓℓ/νν)	single boson processes	✓	validated analytically + FEWZ
pp→W(→ℓν)		✓	validated with FEWZ, NNLOjet
pp→H		✓	validated analytically (by SusHi)
pp→γγ	photon processes	✓	validated with 2γNNLO
pp→Zγ→ℓℓγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→Zγ→ννγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→Wγ→ℓνγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ		✓	[Cascioli et al. '14]
pp→ZZ→ℓℓℓℓ		✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
pp→ZZ→ℓℓℓ'ℓ'		✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
pp→ZZ→ℓℓν'ν'		✓	[Kallweit, MW '18]
pp→ZZ/WW→ℓℓνν		✓	[Kallweit, MW '18]
pp→WW		✓	[Gehrmann et al. '14]
pp→WW→ℓν ℓ'ν'		✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
pp→WZ		✓	[Grazzini, Kallweit, Rathlev, MW '16]
pp→WZ→ℓνℓℓ		✓	[Grazzini, Kallweit, Rathlev, MW '17]
pp→WZ→ℓ'ν'ℓℓ		✓	[Grazzini, Kallweit, Rathlev, MW '17]
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process		status	comment
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pp→Zγ→ℓℓγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→Zγ→ννγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→Wγ→ℓνγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ	massive diboson processes	✓	[Cascioli et al. '14]
pp→ZZ→ℓℓℓℓ		✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
pp→ZZ→ℓℓℓ'ℓ'		✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]
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pp→ZZ/WW→ℓℓνν		✓	[Kallweit, MW '18]
pp→WW		✓	[Gehrmann et al. '14]
pp→WW→ℓν ℓ'ν'		✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
pp→WZ		✓	[Grazzini, Kallweit, Rathlev, MW '16]
pp→WZ→ℓνℓℓ		✓	[Grazzini, Kallweit, Rathlev, MW '17]
pp→WZ→ℓ'ν'ℓℓ		✓	[Grazzini, Kallweit, Rathlev, MW '17]
pp→HH		(✓)	not in public release

p_T subtraction master formula:

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

[Catani, Grazzini '07]

subtraction terms known from resummation:

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

NNLO accuracy consequence of unitarity:

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

Resummation formula:

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

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

p_T subtraction master formula:

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

[Catani, Grazzini '07]

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 $r \geq r_{cut}$
- assumption: for $r \leq r_{cut}$ terms cancel (true up to power-suppressed terms)
- numerics forbids arbitrarily small r_{cut} values: use fit towards $r_{cut} \rightarrow 0$ limit
- MATRIX uses extrapolation $r_{cut} \rightarrow 0$ to obtain the final prediction

p_T subtraction master formula:

$$d\sigma_{\mathrm{NNLO}} = \Big[\underbrace{d\sigma_{\mathrm{NLO}}^{F+1\mathrm{jet}}}_{(r > r_{cut})} - \underbrace{\Sigma_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}}_{(r > r_{cut})} \Big] + \mathcal{H}_{\mathrm{NNLO}} \otimes d\sigma_{\mathrm{LO}}$$

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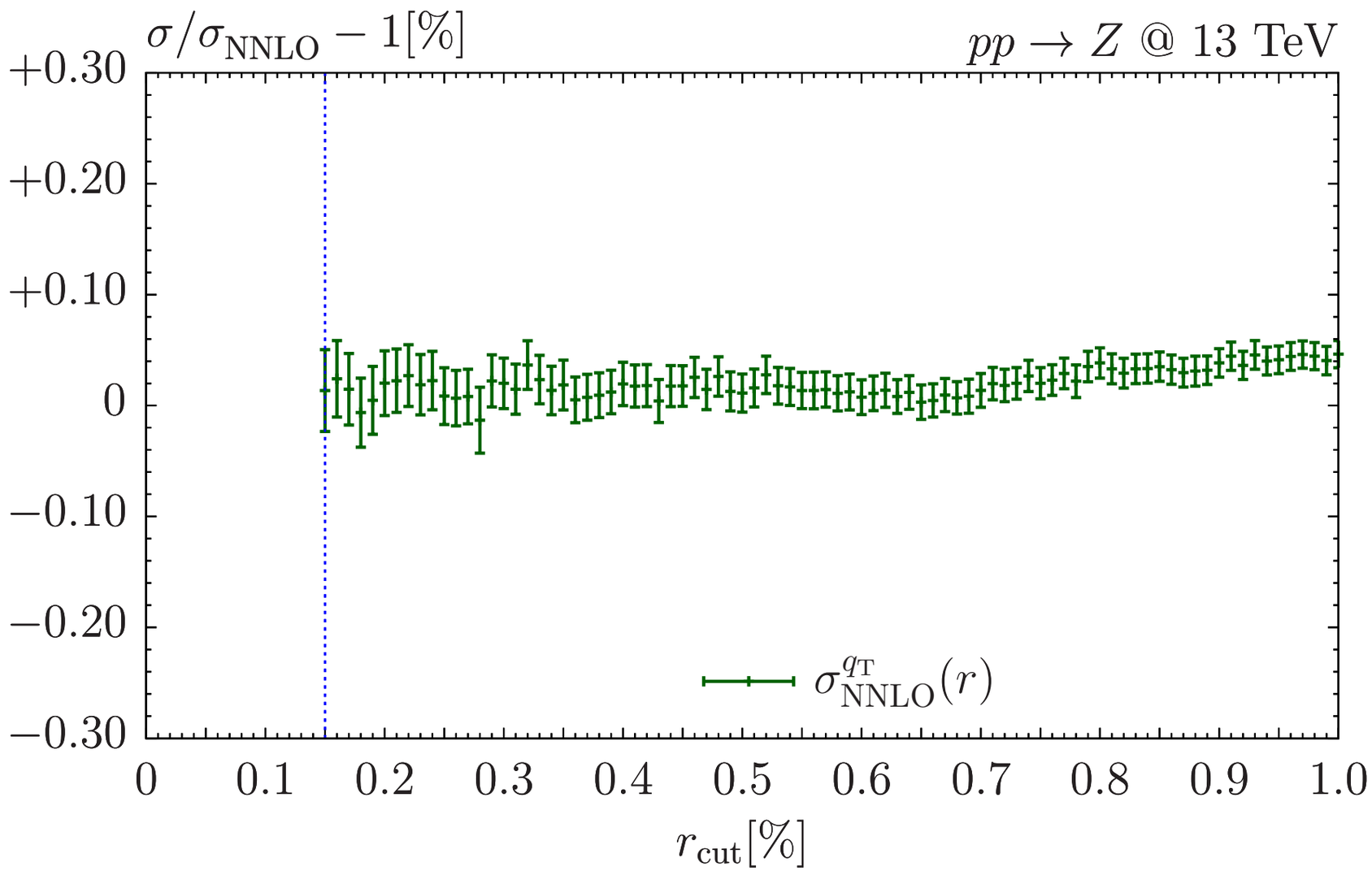
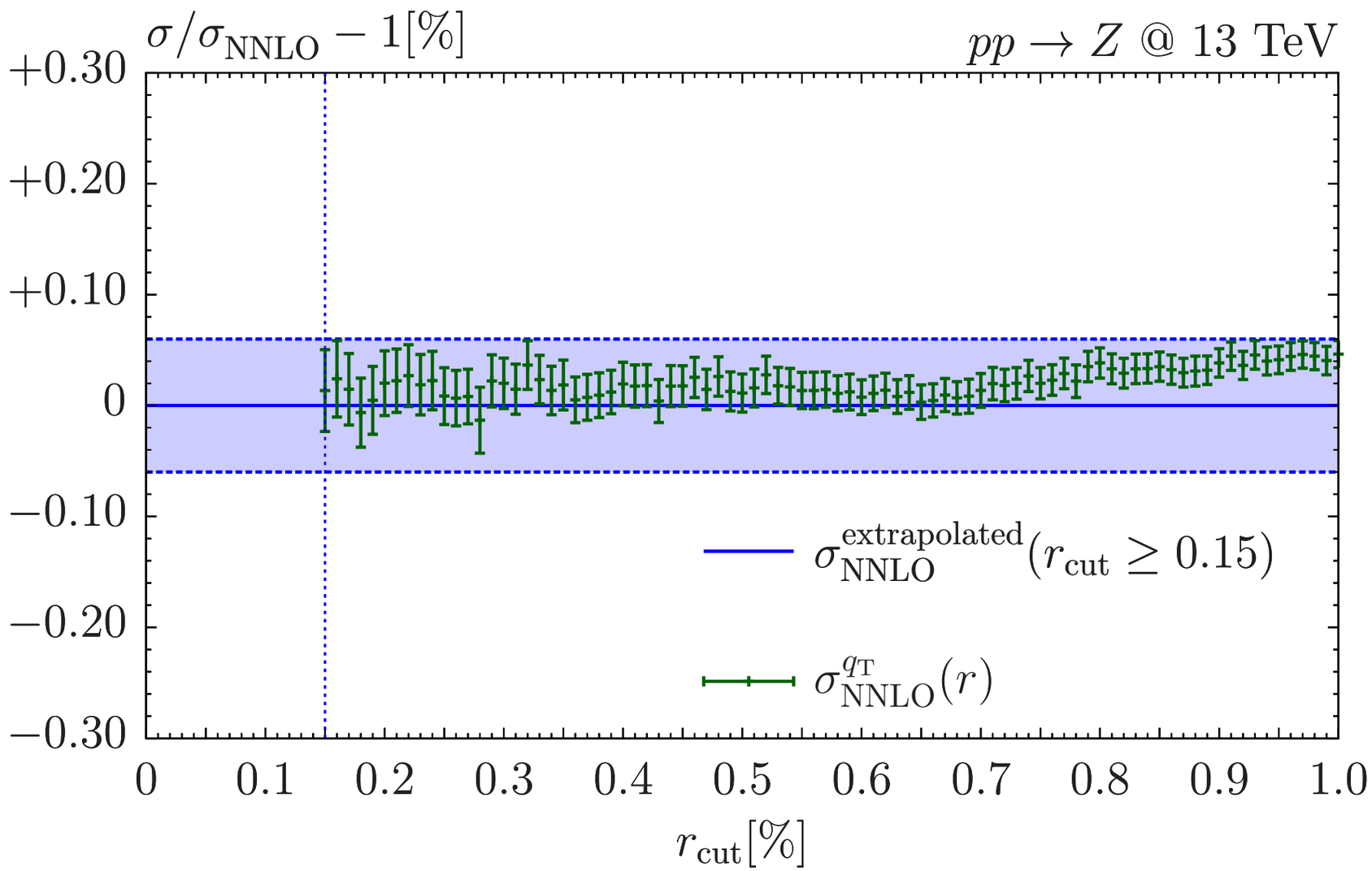
$r_{cut} \to 0$ extrapolation in MATRIX

automatically computed in every single MATRIX NNLO run

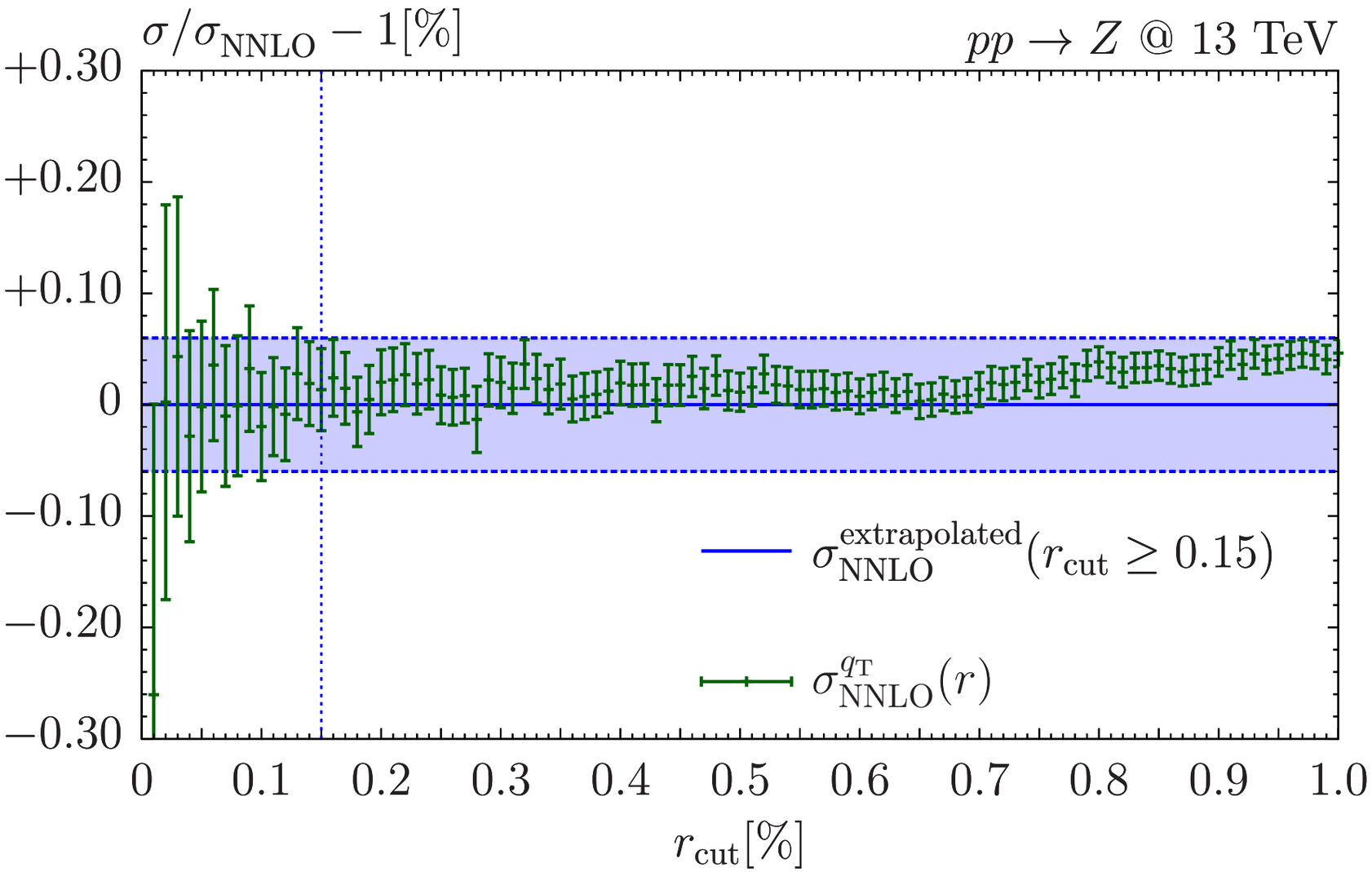


$r_{cut} \rightarrow 0$ extrapolation in MATRIX

simple quadratic fit ($A * r_{cut}^2 + B * r_{cut} + C$) to extrapolate to $r_{cut}=0$



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



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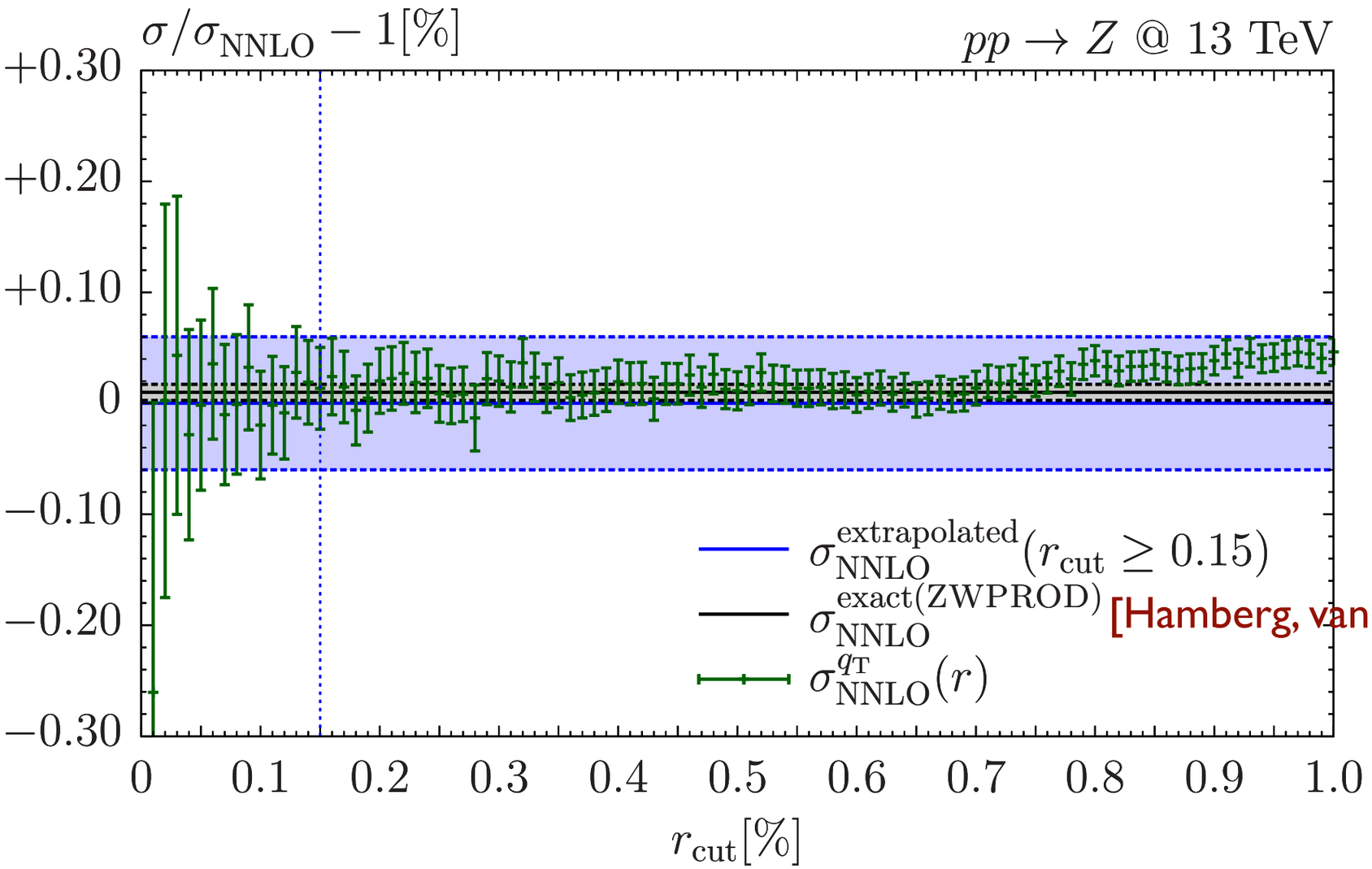
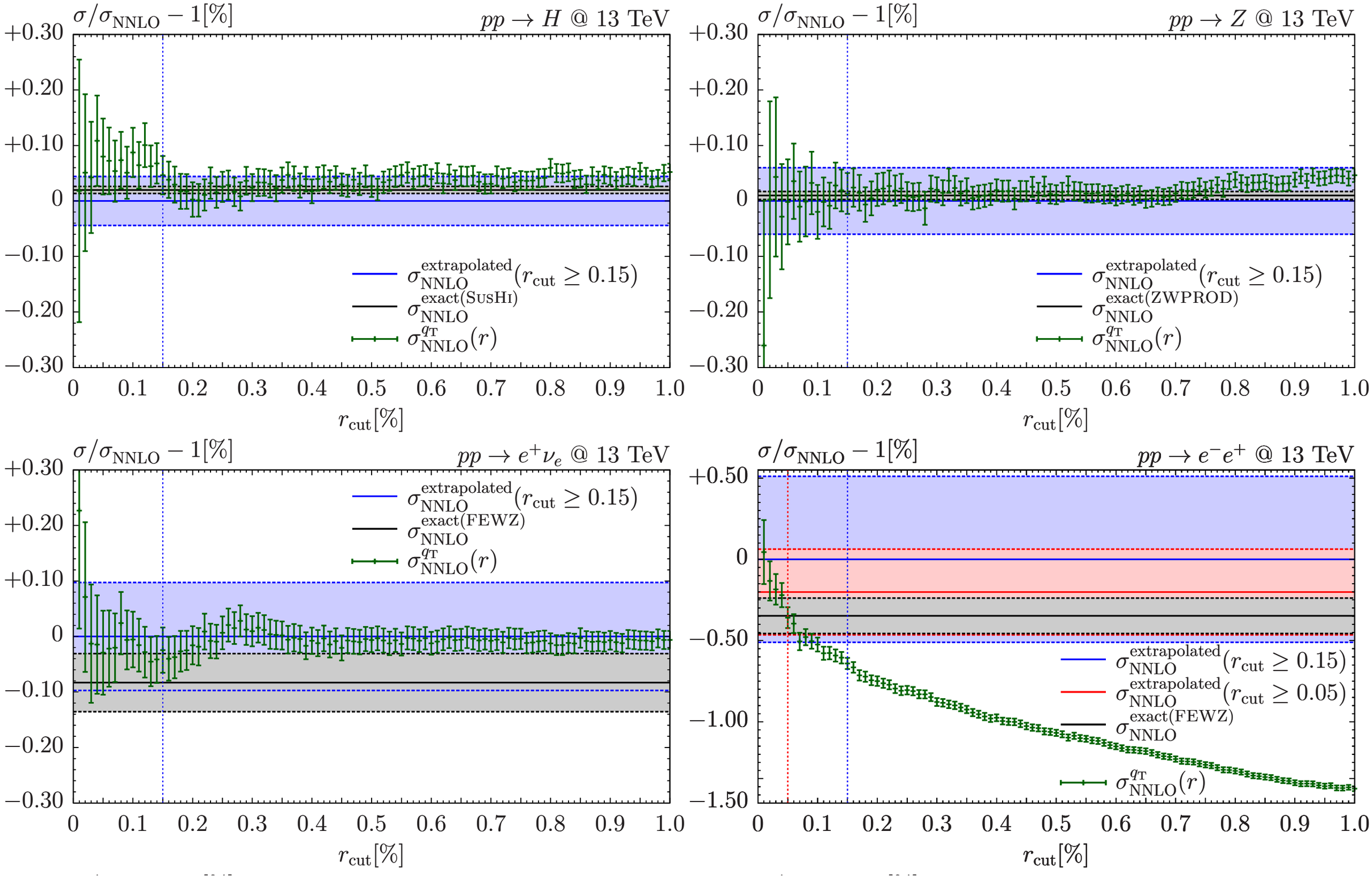


[Hamberg, van Neerven, Matsuura '91]

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



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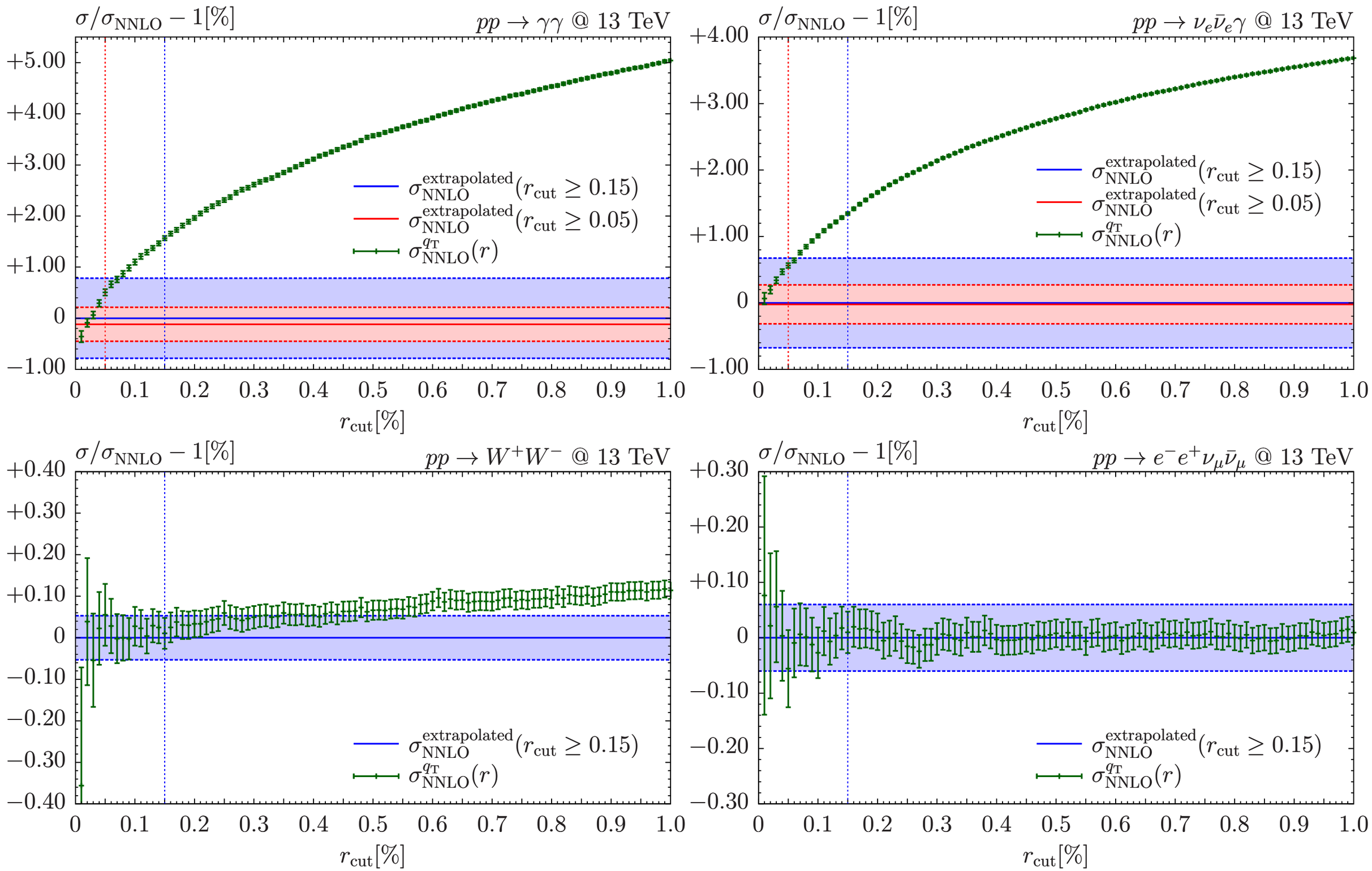


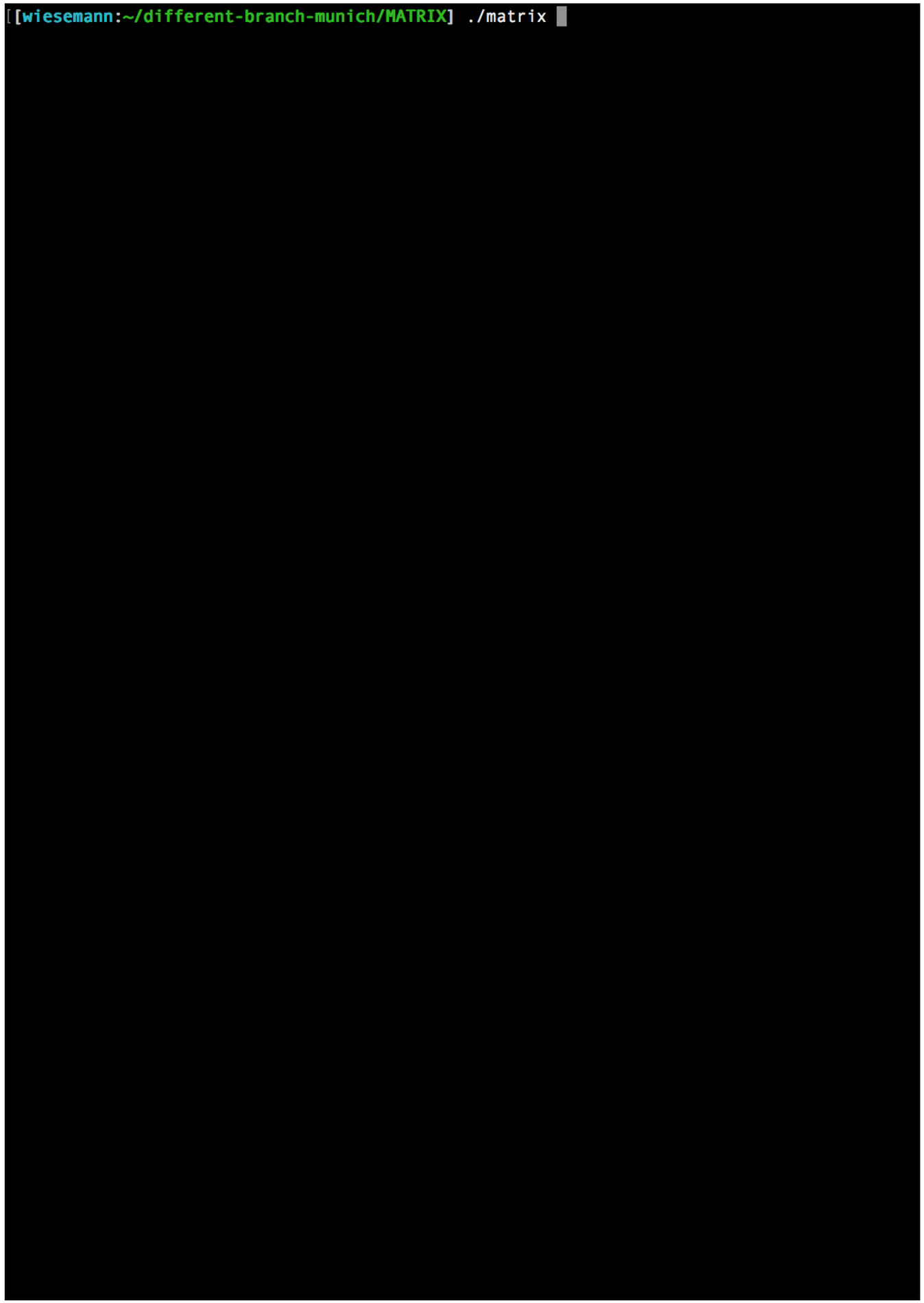
MATRIX features on one slide

- 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
  - 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

How to compile

- After unpacking start MATRIX with:

```
$$ ./matrix
```



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- After unpacking start MATRIX with:

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```

- Inside the MATRIX compilation shell

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

- lists all process IDs. Select ID, eg:

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

- for pp→ZZ→4ℓ.

```
[[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
```

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|===>> ppeeexex04
```

- for pp→ZZ→4ℓ. Confirming with

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

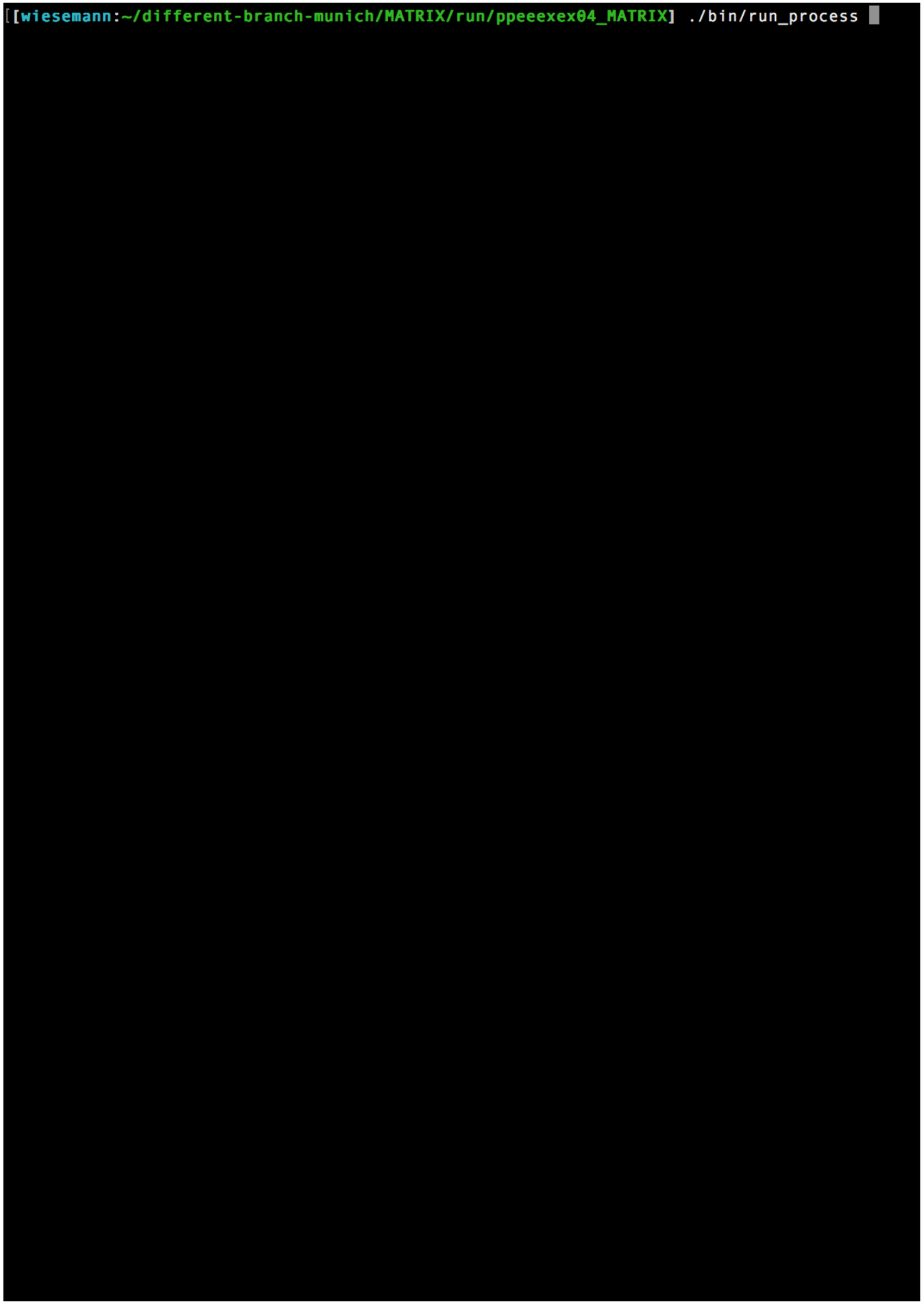
- the MATRIX usage agreements, the code will automatically start to:
  - dowload/compile of OpenLoops
  - compile of Cln and Ginac
  - compile MATRIX
  - download OpenLoops amplitudes
  - create MATRIX run folder for the process

```
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 pplll amplitude already downloaded and compiled.
                Checking wether up-to-date...
<<MATRIX-MAKE>> ...pplll amplitude already installed and up-to-date.
<<MATRIX-MAKE>> OpenLoops pllllj amplitude already downloaded and compiled.
                Checking wether up-to-date...
<<MATRIX-MAKE>> ...pllllj amplitude already installed and up-to-date.
<<MATRIX-MAKE>> OpenLoops pllll2 amplitude already downloaded and compiled.
                Checking wether up-to-date...
<<MATRIX-MAKE>> ...pllll2 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]
```

How to run

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

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



How to run

- 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
```

How to run

- 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
```

How to run

- After changing into the directory we start the r

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

- First, choose a name for

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

- The MATRIX run shell options, eg, modify 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
```

How to run

- 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
```

How to run

- 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 successfully 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]
```

Running phases

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

```
|============>> run
<<MATRIX-INFO>> New Run folder created: /home/wiesemann/different-branch-
                munich/MATRIX/run/ppeeexex04_MATRIX/run_my_first_ZZ.
<<MATRIX-INFO>> Using LHAPDF version 6.1.6...
<<MATRIX-INFO>> Now it's time for running...
<<MATRIX-INFO>> Running in multicore mode...
<<MATRIX-INFO>> Starting grid setup (warmup)...
<<MATRIX-JOBS>> | 2017-10-16 16:30:15 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:30:20 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:25 | Queued: 0 | Running: 1 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Starting runs to extrapolate runtimes from accuracy (pre run)...
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:40 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Extrapolating runtimes...
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 1 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |

                    /-----------------------------------------------\
                    |       Preliminary (inaccurate) result for:    |
                    |      p p --> e^- e^- e^+ e^+   @ 13 TeV LHC   |
                    \-----------------------------------------------/
                #--------\
                # LO-run |
                #--------/
<MATRIX-RESULT> PDF: NNPDF30_lo_as_0118
<MATRIX-RESULT> Total rate (possibly within cuts):
<MATRIX-RESULT> LO:      5.829 fb +/- 0.042 fb   (muR, muF unc.:  +6.3%  -7.4%)
<MATRIX-RESULT> This result is very inaccurate and only a rough estimate!
<MATRIX-RESULT> Wait until the main run finishes to get the final result!

<<MATRIX-INFO>> Starting cross section computation (main run)...
<<MATRIX-JOBS>> | 2017-10-16 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 successfully 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...
```

Running phases

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

```
[|============>> run
<<MATRIX-INFO>> New Run folder created: /home/wiesemann/different-branch-
                munich/MATRIX/run/ppeeexex04_MATRIX/run_my_first_ZZ.
<<MATRIX-INFO>> Using LHAPDF version 6.1.6...
<<MATRIX-INFO>> Now it's time for running...
<<MATRIX-INFO>> Running in multicore mode...
<<MATRIX-INFO>> Starting grid setup (warmup)...
<<MATRIX-JOBS>> | 2017-10-16 16:30:15 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:30:20 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:25 | Queued: 0 | Running: 1 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Starting runs to extrapolate runtimes from accuracy (pre run)...
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:40 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Extrapolating runtimes...
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 1 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |

                    /-----------------------------------------------\
                    |       Preliminary (inaccurate) result for:    |
                    |      p p --> e^- e^- e^+ e^+   @ 13 TeV LHC   |
                    \-----------------------------------------------/
                #--------\
                # LO-run |
                #--------/
<MATRIX-RESULT> PDF: NNPDF30_lo_as_0118
<MATRIX-RESULT> Total rate (possibly within cuts):
<MATRIX-RESULT> LO:      5.829 fb +/- 0.042 fb   (muR, muF unc.:  +6.3%  -7.4%)
<MATRIX-RESULT> This result is very inaccurate and only a rough estimate!
<MATRIX-RESULT> Wait until the main run finishes to get the final result!

<<MATRIX-INFO>> Starting cross section computation (main run)...
<<MATRIX-JOBS>> | 2017-10-16 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 successfully 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...
```

Running phases

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

```
[|============>> run
<<MATRIX-INFO>> New Run folder created: /home/wiesemann/different-branch-
                munich/MATRIX/run/ppeeexex04_MATRIX/run_my_first_ZZ.
<<MATRIX-INFO>> Using LHAPDF version 6.1.6...
<<MATRIX-INFO>> Now it's time for running...
<<MATRIX-INFO>> Running in multicore mode...
<<MATRIX-INFO>> Starting grid setup (warmup)...
<<MATRIX-JOBS>> | 2017-10-16 16:30:15 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:30:20 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:25 | Queued: 0 | Running: 1 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Starting runs to extrapolate runtimes from accuracy (pre run)...
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:40 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Extrapolating runtimes...
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 1 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |

                    /-----------------------------------------------\
                    |       Preliminary (inaccurate) result for:    |
                    |      p p --> e^- e^- e^+ e^+   @ 13 TeV LHC   |
                    \-----------------------------------------------/
                  #--------\
                  # LO-run |
                  #--------/
<MATRIX-RESULT> PDF: NNPDF30_lo_as_0118
<MATRIX-RESULT> Total rate (possibly within cuts):
<MATRIX-RESULT> LO:      5.829 fb +/- 0.042 fb   (muR, muF unc.:  +6.3%  -7.4%)
<MATRIX-RESULT> This result is very inaccurate and only a rough estimate!
<MATRIX-RESULT> Wait until the main run finishes to get the final result!

<<MATRIX-INFO>> Starting cross section computation (main run)...
<<MATRIX-JOBS>> | 2017-10-16 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 successfully 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...
```

Running phases

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

```
[|============>> run
<<MATRIX-INFO>> New Run folder created: /home/wiesemann/different-branch-
                munich/MATRIX/run/ppeeexex04_MATRIX/run_my_first_ZZ.
<<MATRIX-INFO>> Using LHAPDF version 6.1.6...
<<MATRIX-INFO>> Now it's time for running...
<<MATRIX-INFO>> Running in multicore mode...
<<MATRIX-INFO>> Starting grid setup (warmup)...
<<MATRIX-JOBS>> | 2017-10-16 16:30:15 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:30:20 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:25 | Queued: 0 | Running: 1 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Starting runs to extrapolate runtimes from accuracy (pre run)...
<<MATRIX-JOBS>> | 2017-10-16 16:33:35 | Queued: 2 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:40 | Queued: 0 | Running: 2 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 0 | Running: 0 | Finished: 2 |
<<MATRIX-INFO>> All runs successfully finished.
<<MATRIX-INFO>> Extrapolating runtimes...
<<MATRIX-JOBS>> | 2017-10-16 16:33:45 | Queued: 1 | Running: 0 | Finished: 0 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |
<<MATRIX-JOBS>> | 2017-10-16 16:33:50 | Queued: 0 | Running: 0 | Finished: 1 |

                    /-----------------------------------------------\
                    |       Preliminary (inaccurate) result for:    |
                    |      p p --> e^- e^- e^+ e^+   @ 13 TeV LHC   |
                    \-----------------------------------------------/
                #--------\
                # LO-run |
                #--------/
<MATRIX-RESULT> PDF: NNPDF30_lo_as_0118
<MATRIX-RESULT> Total rate (possibly within cuts):
<MATRIX-RESULT> LO:      5.829 fb +/- 0.042 fb   (muR, muF unc.:  +6.3%  -7.4%)
<MATRIX-RESULT> This result is very inaccurate and only a rough estimate!
<MATRIX-RESULT> Wait until the main run finishes to get the final result!

<<MATRIX-INFO>> Starting cross section computation (main run)...
<<MATRIX-JOBS>> | 2017-10-16 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 successfully 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 reference predictions

[Grazzini, Kallweit, MW '17]

process (${process_id})	$\sigma_{\rm LO}$	$\sigma_{\rm NLO}$	$\sigma_{\rm loop}$ ($\sigma_{\rm loop}/\Delta\sigma^{\rm ext}_{\rm NNLO}$)	$\sigma^{r_{\rm cut}}_{\rm NNLO}$	$\sigma^{\rm extrapolated}_{\rm NNLO}$	$K_{\rm NLO}$	$K_{\rm NNLO}$
$pp \to H$ (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	—	$78.36(3)^{+0.98\%}_{-1.2\%}$ nb	$78.33(8)^{+0.98\%}_{-1.2\%}$ nb	+26.3%	+3.14%
$pp \to W^+$ (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	$732.7(3.4)^{+0.43\%}_{-0.79\%}$ 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)	$2972(0)^{+14\%}_{-15\%}$ pb	$3674(1)^{+3.1\%}_{-5.2\%}$ pb	—	$3772(2)^{+0.89\%}_{-0.94\%}$ pb	$3768(3)^{+0.90\%}_{-0.93\%}$ pb	+23.6%	+2.57%
$pp \to e^+\nu_e$ (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)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2.534(1)^{+24\%}_{-17\%}$ pb (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)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1.361(1)^{+25\%}_{-19\%}$ pb (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	$4.091(3)^{+27\%}_{-19\%}$ pb (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	—	$26.17(1)^{+2.2\%}_{-2.1\%}$ fb	$26.17(2)^{+2.2\%}_{-2.1\%}$ 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	—	$26.27(1)^{+2.3\%}_{-2.1\%}$ fb	$26.25(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	$17.33(0)^{+5.3\%}_{-6.3\%}$ fb	$34.14(1)^{+5.3\%}_{-4.3\%}$ fb	—	$37.74(2)^{+2.2\%}_{-2.0\%}$ fb	$37.74(4)^{+2.2\%}_{-2.0\%}$ fb	+97.0%	+10.6%
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	$17.37(0)^{+5.3\%}_{-6.3\%}$ fb	$34.21(2)^{+5.3\%}_{-4.3\%}$ fb	—	$37.85(2)^{+2.3\%}_{-2.0\%}$ fb	$37.84(3)^{+2.3\%}_{-2.0\%}$ fb	+96.9%	+10.6%

MATRIX reference predictions

[Grazzini, Kallweit, MW '17]

process (${process_id})	$\sigma_{\rm LO}$	$\sigma_{\rm NLO}$	$\sigma_{\rm loop}$ ($\sigma_{\rm loop}/\Delta\sigma^{\rm ext}_{\rm NNLO}$)	$\sigma^{r_{\rm cut}}_{\rm NNLO}$	$\sigma^{\rm extrapolated}_{\rm NNLO}$	$K_{\rm NLO}$	$K_{\rm NNLO}$
$pp \to H$ (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	—	$78.36(3)^{+0.98\%}_{-1.2\%}$ nb	$78.33(8)^{+0.98\%}_{-1.2\%}$ nb	+26.3%	+3.14%
$pp \to W^+$ (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	$732.7(3.4)^{+0.43\%}_{-0.79\%}$ 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)	$2972(0)^{+14\%}_{-15\%}$ pb	$3674(1)^{+3.1\%}_{-5.2\%}$ pb	—	$3772(2)^{+0.89\%}_{-0.94\%}$ pb	$3768(3)^{+0.90\%}_{-0.93\%}$ pb	+23.6%	+2.57%
$pp \to e^+\nu_e$ (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)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2.534(1)^{+24\%}_{-17\%}$ pb (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)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1.361(1)^{+25\%}_{-19\%}$ pb (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	$4.091(3)^{+27\%}_{-19\%}$ pb (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	—	$26.17(1)^{+2.2\%}_{-2.1\%}$ fb	$26.17(2)^{+2.2\%}_{-2.1\%}$ 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	—	$26.27(1)^{+2.3\%}_{-2.1\%}$ fb	$26.25(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	$17.33(0)^{+5.3\%}_{-6.3\%}$ fb	$34.14(1)^{+5.3\%}_{-4.3\%}$ fb	—	$37.74(2)^{+2.2\%}_{-2.0\%}$ fb	$37.74(4)^{+2.2\%}_{-2.0\%}$ fb	+97.0%	+10.6%
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	$17.37(0)^{+5.3\%}_{-6.3\%}$ fb	$34.21(2)^{+5.3\%}_{-4.3\%}$ fb	—	$37.85(2)^{+2.3\%}_{-2.0\%}$ fb	$37.84(3)^{+2.3\%}_{-2.0\%}$ fb	+96.9%	+10.6%

loop-induced gg can be significant fraction of NNLO correction (process dependent)

MATRIX reference predictions

[Grazzini, Kallweit, MW '17]

process (${process_id})	$\sigma_{\rm LO}$	$\sigma_{\rm NLO}$	$\sigma_{\rm loop}$ ($\sigma_{\rm loop}/\Delta\sigma^{\rm ext}_{\rm NNLO}$)	$\sigma^{r_{\rm cut}}_{\rm NNLO}$	$\sigma^{\rm extrapolated}_{\rm NNLO}$	$K_{\rm NLO}$	$K_{\rm NNLO}$
$pp \to H$ (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	—	$78.36(3)^{+0.98\%}_{-1.2\%}$ nb	$78.33(8)^{+0.98\%}_{-1.2\%}$ nb	+26.3%	+3.14%
$pp \to W^+$ (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	$732.7(3.4)^{+0.43\%}_{-0.79\%}$ 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)	$2972(0)^{+14\%}_{-15\%}$ pb	$3674(1)^{+3.1\%}_{-5.2\%}$ pb	—	$3772(2)^{+0.89\%}_{-0.94\%}$ pb	$3768(3)^{+0.90\%}_{-0.93\%}$ pb	+23.6%	+2.57%
$pp \to e^+\nu_e$ (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)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2.534(1)^{+24\%}_{-17\%}$ pb (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)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1.361(1)^{+25\%}_{-19\%}$ pb (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	$4.091(3)^{+27\%}_{-19\%}$ pb (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	—	$26.17(1)^{+2.2\%}_{-2.1\%}$ fb	$26.17(2)^{+2.2\%}_{-2.1\%}$ 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	—	$26.27(1)^{+2.3\%}_{-2.1\%}$ fb	$26.25(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	$17.33(0)^{+5.3\%}_{-6.3\%}$ fb	$34.14(1)^{+5.3\%}_{-4.3\%}$ fb	—	$37.74(2)^{+2.2\%}_{-2.0\%}$ fb	$37.74(4)^{+2.2\%}_{-2.0\%}$ fb	+97.0%	+10.6%
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	$17.37(0)^{+5.3\%}_{-6.3\%}$ fb	$34.21(2)^{+5.3\%}_{-4.3\%}$ fb	—	$37.85(2)^{+2.3\%}_{-2.0\%}$ fb	$37.84(3)^{+2.3\%}_{-2.0\%}$ fb	+96.9%	+10.6%

Higgs
DY

diphoton

loop-induced gg can be significant fraction of NNLO correction (process dependent)

corrections strongly depend on:

- **process**

MATRIX reference predictions

[Grazzini, Kallweit, MW '17]

process (${process_id})	$\sigma_{\rm LO}$	$\sigma_{\rm NLO}$	$\sigma_{\rm loop}$ ($\sigma_{\rm loop}/\Delta\sigma^{\rm ext}_{\rm NNLO}$)	$\sigma^{r_{\rm cut}}_{\rm NNLO}$	$\sigma^{\rm extrapolated}_{\rm NNLO}$	$K_{\rm NLO}$	$K_{\rm NNLO}$
$pp \to H$ (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	—	$78.36(3)^{+0.98\%}_{-1.2\%}$ nb	$78.33(8)^{+0.98\%}_{-1.2\%}$ nb	+26.3%	+3.14%
$pp \to W^+$ (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	$732.7(3.4)^{+0.43\%}_{-0.79\%}$ 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)	$2972(0)^{+14\%}_{-15\%}$ pb	$3674(1)^{+3.1\%}_{-5.2\%}$ pb	—	$3772(2)^{+0.89\%}_{-0.94\%}$ pb	$3768(3)^{+0.90\%}_{-0.93\%}$ pb	+23.6%	+2.57%
$pp \to e^+\nu_e$ (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)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2.534(1)^{+24\%}_{-17\%}$ pb (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)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1.361(1)^{+25\%}_{-19\%}$ pb (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	$4.091(3)^{+27\%}_{-19\%}$ pb (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	—	$26.17(1)^{+2.2\%}_{-2.1\%}$ fb	$26.17(2)^{+2.2\%}_{-2.1\%}$ 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	—	$26.27(1)^{+2.3\%}_{-2.1\%}$ fb	$26.25(2)^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	$17.33(0)^{+5.3\%}_{-6.3\%}$ fb	$34.14(1)^{+5.3\%}_{-4.3\%}$ fb	—	$37.74(2)^{+2.2\%}_{-2.0\%}$ fb	$37.74(4)^{+2.2\%}_{-2.0\%}$ fb	+97.0%	+10.6%
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	$17.37(0)^{+5.3\%}_{-6.3\%}$ fb	$34.21(2)^{+5.3\%}_{-4.3\%}$ fb	—	$37.85(2)^{+2.3\%}_{-2.0\%}$ fb	$37.84(3)^{+2.3\%}_{-2.0\%}$ fb	+96.9%	+10.6%

Higgs
DY

diphoton

loop-induced gg can be significant fraction of NNLO correction (process dependent)

WW on-shell (inclusive)

WW off-shell (with jet veto)

corrections strongly depend on:

- **process**
- **fiducial cuts**

process (${process_id})	LO runtime (relative uncertainty)	NLO runtime (relative uncertainty)	NNLO runtime (relative uncertainty)
$pp \to H$ (pph21)	0 d 0 h 2 m ($1.5 \cdot 10^{-4}$)	0 d 0 h 12 m ($2.7 \cdot 10^{-4}$)	35 d 23 h 23 m ($7.2 \cdot 10^{-4}$)
$pp \to Z$ (ppz01)	0 d 0 h 10 m ($8.2 \cdot 10^{-5}$)	0 d 0 h 16 m ($2.6 \cdot 10^{-4}$)	53 d 15 h 31 m ($4.6 \cdot 10^{-4}$)
$pp \to W^-$ (ppw01)	0 d 0 h 7 m ($8.1 \cdot 10^{-5}$)	0 d 0 h 22 m ($2.6 \cdot 10^{-4}$)	50 d 17 h 29 m ($4.4 \cdot 10^{-4}$)
$pp \to W^+$ (ppwx01)	0 d 0 h 14 m ($8.1 \cdot 10^{-5}$)	0 d 0 h 24 m ($2.6 \cdot 10^{-4}$)	47 d 7 h 46 m ($4.9 \cdot 10^{-4}$)
$pp \to e^-e^+$ (ppeex02)	0 d 0 h 48 m ($1.0 \cdot 10^{-4}$)	0 d 2 h 24 m ($2.8 \cdot 10^{-4}$)	173 d 20 h 36 m ($3.6 \cdot 10^{-4}$)
$pp \to \nu_e\bar{\nu}_e$ (ppnenex02)	0 d 1 h 31 m ($8.2 \cdot 10^{-5}$)	0 d 1 h 0 m ($2.5 \cdot 10^{-4}$)	89 d 18 h 17 m ($4.5 \cdot 10^{-4}$)
$pp \to e^-\bar{\nu}_e$ (ppenex02)	0 d 1 h 46 m ($8.7 \cdot 10^{-5}$)	0 d 5 h 21 m ($2.2 \cdot 10^{-4}$)	114 d 2 h 18 m ($4.3 \cdot 10^{-4}$)
$pp \to e^+\nu_e$ (ppexne02)	0 d 1 h 56 m ($8.5 \cdot 10^{-5}$)	0 d 3 h 43 m ($2.6 \cdot 10^{-4}$)	114 d 6 h 18 m ($4.6 \cdot 10^{-4}$)
$pp \to \gamma\gamma$ (ppaa02)	0 d 1 h 13 m ($9.8 \cdot 10^{-5}$)	0 d 4 h 11 m ($2.8 \cdot 10^{-4}$)	27 d 17 h 7 m ($4.6 \cdot 10^{-4}$)
$pp \to e^-e^+\gamma$ (ppeexa03)	0 d 17 h 55 m ($9.2 \cdot 10^{-5}$)	1 d 19 h 48 m ($2.8 \cdot 10^{-4}$)	1276 d 12 h 47 m ($3.6 \cdot 10^{-4}$)
$pp \to \nu_e\bar{\nu}_e\gamma$ (ppnenexa03)	0 d 2 h 50 m ($8.7 \cdot 10^{-5}$)	0 d 8 h 59 m ($2.5 \cdot 10^{-4}$)	75 d 9 h 6 m ($4.7 \cdot 10^{-4}$)
$pp \to e^-\bar{\nu}_e\gamma$ (ppenexa03)	0 d 22 h 18 m ($1.0 \cdot 10^{-4}$)	3 d 16 h 59 m ($3.2 \cdot 10^{-4}$)	1484 d 16 h 50 m ($4.0 \cdot 10^{-4}$)
$pp \to e^+\nu_e\gamma$ (ppexnea03)	1 d 7 h 8 m ($9.6 \cdot 10^{-5}$)	6 d 8 h 7 m ($3.0 \cdot 10^{-4}$)	428 d 7 h 1 m ($1.0 \cdot 10^{-3}$)
$pp \to ZZ$ (ppzz02)	0 d 1 h 44 m ($8.2 \cdot 10^{-5}$)	0 d 1 h 6 m ($2.4 \cdot 10^{-4}$)	132 d 19 h 37 m ($4.4 \cdot 10^{-4}$)
$pp \to W^+W^-$ (ppwxw02)	0 d 1 h 23 m ($8.2 \cdot 10^{-5}$)	0 d 0 h 48 m ($2.5 \cdot 10^{-4}$)	69 d 20 h 49 m ($4.3 \cdot 10^{-4}$)
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	0 d 5 h 43 m ($8.2 \cdot 10^{-5}$)	0 d 4 h 32 m ($2.7 \cdot 10^{-4}$)	219 d 16 h 33 m ($4.5 \cdot 10^{-4}$)
$pp \to e^-e^-e^+e^+$ (ppeeexex04)	0 d 11 h 34 m ($9.0 \cdot 10^{-5}$)	0 d 12 h 8 m ($3.4 \cdot 10^{-4}$)	742 d 13 h 37 m ($5.1 \cdot 10^{-4}$)
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	0 d 6 h 33 m ($9.4 \cdot 10^{-5}$)	0 d 6 h 36 m ($2.7 \cdot 10^{-4}$)	158 d 13 h 40 m ($4.4 \cdot 10^{-4}$)
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	0 d 13 h 33 m ($9.2 \cdot 10^{-5}$)	1 d 22 h 9 m ($2.7 \cdot 10^{-4}$)	521 d 2 h 20 m ($4.8 \cdot 10^{-4}$)
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)	0 d 23 h 36 m ($8.2 \cdot 10^{-5}$)	0 d 17 h 46 m ($4.8 \cdot 10^{-4}$)	270 d 6 h 59 m ($4.4 \cdot 10^{-4}$)
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	0 d 5 h 18 m ($1.0 \cdot 10^{-4}$)	0 d 5 h 15 m ($2.9 \cdot 10^{-4}$)	104 d 16 h 46 m ($4.3 \cdot 10^{-4}$)
$pp \to e^-e^-e^+\bar{\nu}_e$ (ppeeexnex04)	0 d 14 h 19 m ($8.3 \cdot 10^{-5}$)	0 d 14 h 56 m ($2.7 \cdot 10^{-4}$)	179 d 14 h 6 m ($4.7 \cdot 10^{-4}$)
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	0 d 10 h 32 m ($8.1 \cdot 10^{-5}$)	0 d 8 h 18 m ($2.6 \cdot 10^{-4}$)	104 d 17 h 58 m ($4.5 \cdot 10^{-4}$)
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	0 d 9 h 19 m ($1.0 \cdot 10^{-4}$)	0 d 13 h 11 m ($4.6 \cdot 10^{-4}$)	167 d 6 h 49 m ($5.1 \cdot 10^{-4}$)

MATRIX CPU budget (total runtime)

[Grazzini, Kallweit, MW '17]

CPU info:
Intel Haswell 2.6 GHz
(cloud-based computer cluster)

MATRIX CPU budget (total runtime)

[Grazzini, Kallweit, MW '17]

process (${process_id})	LO runtime estimate for 10^{-3} uncertainty	NLO runtime estimate for 10^{-3} uncertainty	NNLO runtime estimate for 10^{-3} uncertainty
$pp \to H$ (pph21)	2 CPU seconds	1 CPU minute	19 CPU days
$pp \to Z$ (ppz01)	4 CPU seconds	1 CPU minute	11 CPU days
$pp \to W^-$ (ppw01)	2 CPU seconds	1 CPU minute	10 CPU days
$pp \to W^+$ (ppwx01)	5 CPU seconds	2 CPU minutes	11 CPU days
$pp \to e^-e^+$ (ppeex02)	28 CPU seconds	12 CPU minutes	22 CPU days
$pp \to \nu_e\bar{\nu}_e$ (ppnenex02)	1 CPU minute	4 CPU minutes	18 CPU days
$pp \to e^-\bar{\nu}_e$ (ppenex02)	1 CPU minute	16 CPU minutes	21 CPU days
$pp \to e^+\nu_e$ (ppexne02)	1 CPU minute	15 CPU minutes	24 CPU days
$pp \to \gamma\gamma$ (ppaa02)	1 CPU minute	19 CPU minutes	6 CPU days
$pp \to e^-e^+\gamma$ (ppeexa03)	9 CPU minutes	4 CPU hours	167 CPU days
$pp \to \nu_e\bar{\nu}_e\gamma$ (ppnenexa03)	1 CPU minute	1 CPU hour	17 CPU days
$pp \to e^-\bar{\nu}_e\gamma$ (ppenexa03)	13 CPU minutes	9 CPU hours	232 CPU days
$pp \to e^+\nu_e\gamma$ (ppexnea03)	17 CPU minutes	1 CPU day	443 CPU days
$pp \to ZZ$ (ppzz02)	1 CPU minute	4 CPU minutes	25 CPU days
$pp \to W^+W^-$ (ppwxw02)	1 CPU minute	3 CPU minutes	13 CPU days
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	2 CPU minutes	20 CPU minutes	45 CPU days
$pp \to e^-e^-e^+e^+$ (ppeeexex04)	6 CPU minutes	1 CPU hour	193 CPU days
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	3 CPU minutes	29 CPU minutes	31 CPU days
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	7 CPU minutes	3 CPU hours	119 CPU days
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)	10 CPU minutes	4 CPU hours	52 CPU days
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	3 CPU minutes	26 CPU minutes	19 CPU days
$pp \to e^-e^-e^+\bar{\nu}_e$ (ppeeexnex04)	6 CPU minutes	1 CPU hour	39 CPU days
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	4 CPU minutes	1 CPU hour	21 CPU days
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	6 CPU minutes	3 CPU hours	44 CPU days

MATRIX CPU budget (total runtime)

[Grazzini, Kallweit, MW '17]

from seconds at LO
to minutes at NLO
to days at NNLO

process (${process_id})	LO runtime estimate for 10^{-3} uncertainty	NLO runtime estimate for 10^{-3} uncertainty	NNLO runtime estimate for 10^{-3} uncertainty
$pp \to H$ (pph21)	2 CPU seconds	1 CPU minute	19 CPU days
$pp \to Z$ (ppz01)	4 CPU seconds	1 CPU minute	11 CPU days
$pp \to W^-$ (ppw01)	2 CPU seconds	1 CPU minute	10 CPU days
$pp \to W^+$ (ppwx01)	5 CPU seconds	2 CPU minutes	11 CPU days
$pp \to e^-e^+$ (ppeex02)	28 CPU seconds	12 CPU minutes	22 CPU days
$pp \to \nu_e\bar{\nu}_e$ (ppnenex02)	1 CPU minute	4 CPU minutes	18 CPU days
$pp \to e^-\bar{\nu}_e$ (ppenex02)	1 CPU minute	16 CPU minutes	21 CPU days
$pp \to e^+\nu_e$ (ppexne02)	1 CPU minute	15 CPU minutes	24 CPU days
$pp \to \gamma\gamma$ (ppaa02)	1 CPU minute	19 CPU minutes	6 CPU days
$pp \to e^-e^+\gamma$ (ppeexa03)	9 CPU minutes	4 CPU hours	167 CPU days
$pp \to \nu_e\bar{\nu}_e\gamma$ (ppnenexa03)	1 CPU minute	1 CPU hour	17 CPU days
$pp \to e^-\bar{\nu}_e\gamma$ (ppenexa03)	13 CPU minutes	9 CPU hours	232 CPU days
$pp \to e^+\nu_e\gamma$ (ppexnea03)	17 CPU minutes	1 CPU day	443 CPU days
$pp \to ZZ$ (ppzz02)	1 CPU minute	4 CPU minutes	25 CPU days
$pp \to W^+W^-$ (ppwxw02)	1 CPU minute	3 CPU minutes	13 CPU days
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	2 CPU minutes	20 CPU minutes	45 CPU days
$pp \to e^-e^-e^+e^+$ (ppeeexex04)	6 CPU minutes	1 CPU hour	193 CPU days
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	3 CPU minutes	29 CPU minutes	31 CPU days
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$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)	10 CPU minutes	4 CPU hours	52 CPU days
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	3 CPU minutes	26 CPU minutes	19 CPU days
$pp \to e^-e^-e^+\bar{\nu}_e$ (ppeeexnex04)	6 CPU minutes	1 CPU hour	39 CPU days
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	4 CPU minutes	1 CPU hour	21 CPU days
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	6 CPU minutes	3 CPU hours	44 CPU days

Higgs
DY

MATRIX CPU budget (total runtime)

[Grazzini, Kallweit, MW '17]

from seconds at LO
to minutes at NLO
to days at NNLO
(MATRIX not optimized for simple processes)

process (`${process_id}`)	LO runtime estimate for 10^{-3} uncertainty	NLO runtime estimate for 10^{-3} uncertainty	NNLO runtime estimate for 10^{-3} uncertainty
$pp \to H$ (`pph21`)	2 CPU seconds	1 CPU minute	19 CPU days
$pp \to Z$ (`ppz01`)	4 CPU seconds	1 CPU minute	11 CPU days
$pp \to W^-$ (`ppw01`)	2 CPU seconds	1 CPU minute	10 CPU days
$pp \to W^+$ (`ppwx01`)	5 CPU seconds	2 CPU minutes	11 CPU days
$pp \to e^-e^+$ (`ppeex02`)	28 CPU seconds	12 CPU minutes	22 CPU days
$pp \to \nu_e\bar{\nu}_e$ (`ppnenex02`)	1 CPU minute	4 CPU minutes	18 CPU days
$pp \to e^-\bar{\nu}_e$ (`ppenex02`)	1 CPU minute	16 CPU minutes	21 CPU days
$pp \to e^+\nu_e$ (`ppexne02`)	1 CPU minute	15 CPU minutes	24 CPU days
$pp \to \gamma\gamma$ (`ppaa02`)	1 CPU minute	19 CPU minutes	6 CPU days
$pp \to e^-e^+\gamma$ (`ppeexa03`)	9 CPU minutes	4 CPU hours	167 CPU days
$pp \to \nu_e\bar{\nu}_e\gamma$ (`ppnenexa03`)	1 CPU minute	1 CPU hour	17 CPU days
$pp \to e^-\bar{\nu}_e\gamma$ (`ppenexa03`)	13 CPU minutes	9 CPU hours	232 CPU days
$pp \to e^+\nu_e\gamma$ (`ppexnea03`)	17 CPU minutes	1 CPU day	443 CPU days
$pp \to ZZ$ (`ppzz02`)	1 CPU minute	4 CPU minutes	25 CPU days
$pp \to W^+W^-$ (`ppwxw02`)	1 CPU minute	3 CPU minutes	13 CPU days
$pp \to e^-\mu^-e^+\mu^+$ (`ppemexmx04`)	2 CPU minutes	20 CPU minutes	45 CPU days
$pp \to e^-e^-e^+e^+$ (`ppeeexex04`)	6 CPU minutes	1 CPU hour	193 CPU days
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (`ppeexnmnmx04`)	3 CPU minutes	29 CPU minutes	31 CPU days
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (`ppemxnmnex04`)	7 CPU minutes	3 CPU hours	119 CPU days
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$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (`ppemexnmx04`)	3 CPU minutes	26 CPU minutes	19 CPU days
$pp \to e^-e^-e^+\bar{\nu}_e$ (`ppeeexnex04`)	6 CPU minutes	1 CPU hour	39 CPU days
$pp \to e^-e^+\mu^+\nu_\mu$ (`ppeexmxnm04`)	4 CPU minutes	1 CPU hour	21 CPU days
$pp \to e^-e^+e^+\nu_e$ (`ppeexexne04`)	6 CPU minutes	3 CPU hours	44 CPU days

Higgs
DY
off-shell WZ

MATRIX CPU budget (total runtime)

[Grazzini, Kallweit, MW '17]

process (${process_id})	LO runtime estimate for 10^{-3} uncertainty	NLO runtime estimate for 10^{-3} uncertainty	NNLO runtime estimate for 10^{-3} uncertainty
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Higgs

DY

diphoton

Wγ

off-shell WZ

from seconds at LO
to minutes at NLO
to days at NNLO

(MATRIX not optimized for simple processes)

diphoton fastest NNLO process

Wγ slowest NNLO process

(dependents on fiducial cuts!)

MATRIX CPU budget (total runtime)

[Grazzini, Kallweit, MW '17]

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$pp \to \nu_e\bar{\nu}_e\gamma$ (ppnenexa03)	1 CPU minute	1 CPU hour	17 CPU days
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$pp \to e^+\nu_e\gamma$ (ppexnea03)	17 CPU minutes	1 CPU day	443 CPU days
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$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	2 CPU minutes	20 CPU minutes	45 CPU days
$pp \to e^-e^-e^+e^+$ (ppeeexex04)	6 CPU minutes	1 CPU hour	193 CPU days
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	3 CPU minutes	29 CPU minutes	31 CPU days
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	7 CPU minutes	3 CPU hours	119 CPU days
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)	10 CPU minutes	4 CPU hours	52 CPU days
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	3 CPU minutes	26 CPU minutes	19 CPU days
$pp \to e^-e^-e^+\bar{\nu}_e$ (ppeeexnex04)	6 CPU minutes	1 CPU hour	39 CPU days
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	4 CPU minutes	1 CPU hour	21 CPU days
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	6 CPU minutes	3 CPU hours	44 CPU days

Higgs

DY

diphoton

Wγ

from seconds at LO
to minutes at NLO
to days at NNLO

(MATRIX not optimized for simple processes)

diphoton fastest NNLO process

Wγ slowest NNLO process

(dependents on fiducial cuts!)

off-shell diboson processes

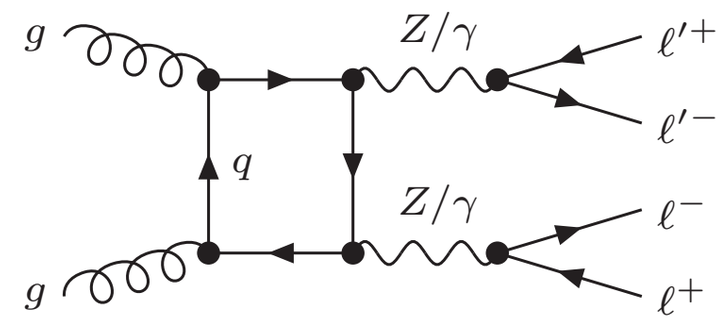
from minutes at LO
to hours at NLO
to days at NNLO

New developments in MATRIX

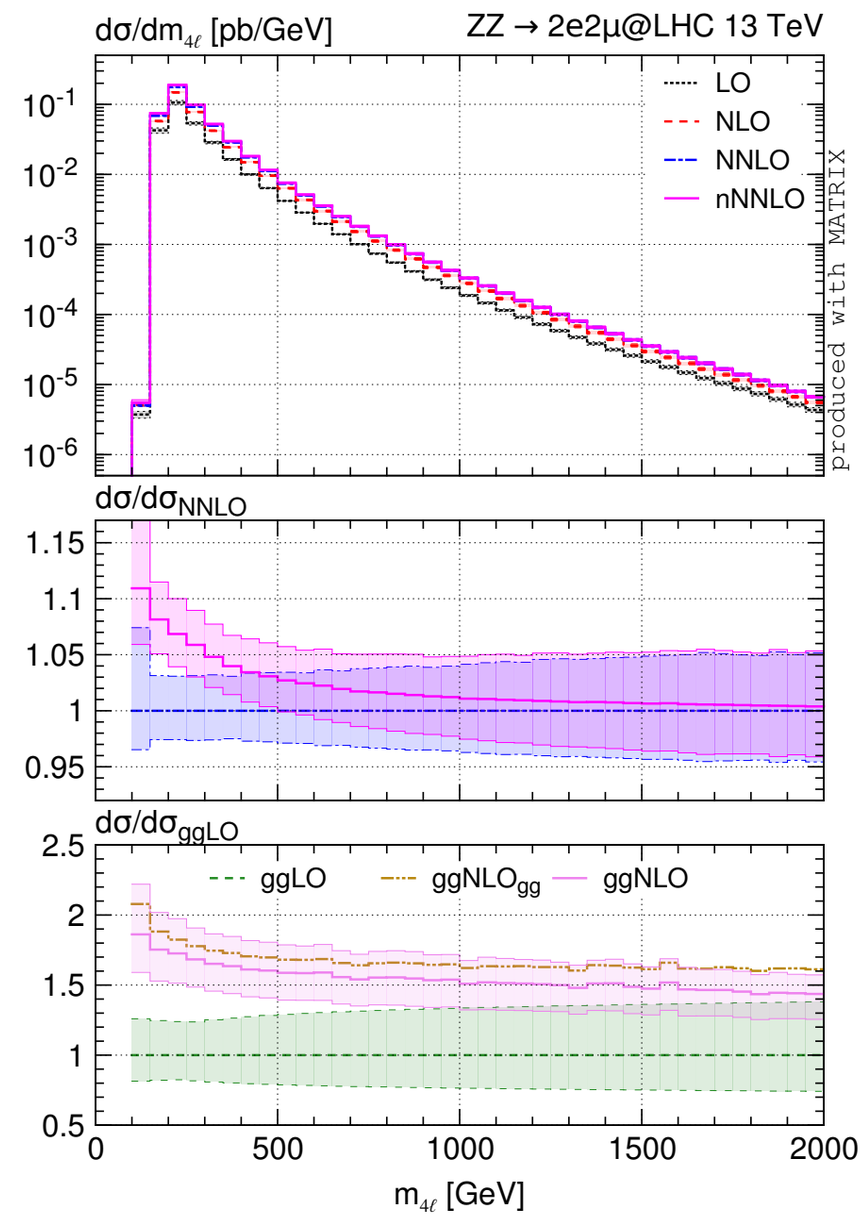
NLO QCD for loop-induced contribution

[Grazzini, Kallweit, MW, Yook '18]

- numerically as intensive as NNLO computation
- first time: qg channels included; combined with NNLO
- partial N3LO result dubbed nNNLO
- significant impact: ~5-6% inclusive; more differentially (often outside NNLO scale uncertainties)



$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\rm NLO} - 1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(7)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
$q\bar{q}$NNLO	$12.08(3)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	$+6.9\%$	$+8.6\%$
	σ [fb]		$\sigma/\sigma_{\rm ggLO} - 1$	
ggLO	$0.79354(8)^{+28.2\%}_{-20.9\%}$	$2.0054(2)^{+23.5\%}_{-17.9\%}$	0%	0%
ggNLO$_{gg}$	$1.4810(9)^{+16.0\%}_{-13.2\%}$	$3.627(3)^{+15.2\%}_{-12.8\%}$	$+86.6\%$	$+80.9\%$
ggNLO	$1.3901(9)^{+15.4\%}_{-13.6\%}$	$3.423(3)^{+13.9\%}_{-12.0\%}$	$+75.2\%$	$+70.7\%$
	σ [fb]		$\sigma/\sigma_{\rm NLO} - 1$	
NNLO	$12.87(3)^{+2.8\%}_{-2.1\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	$+13.9\%$	$+18.7\%$
nNNLO	$13.47(3)^{+2.6\%}_{-2.2\%}$	$24.97(2)^{+2.9\%}_{-2.7\%}$	$+19.2\%$	$+25.8\%$



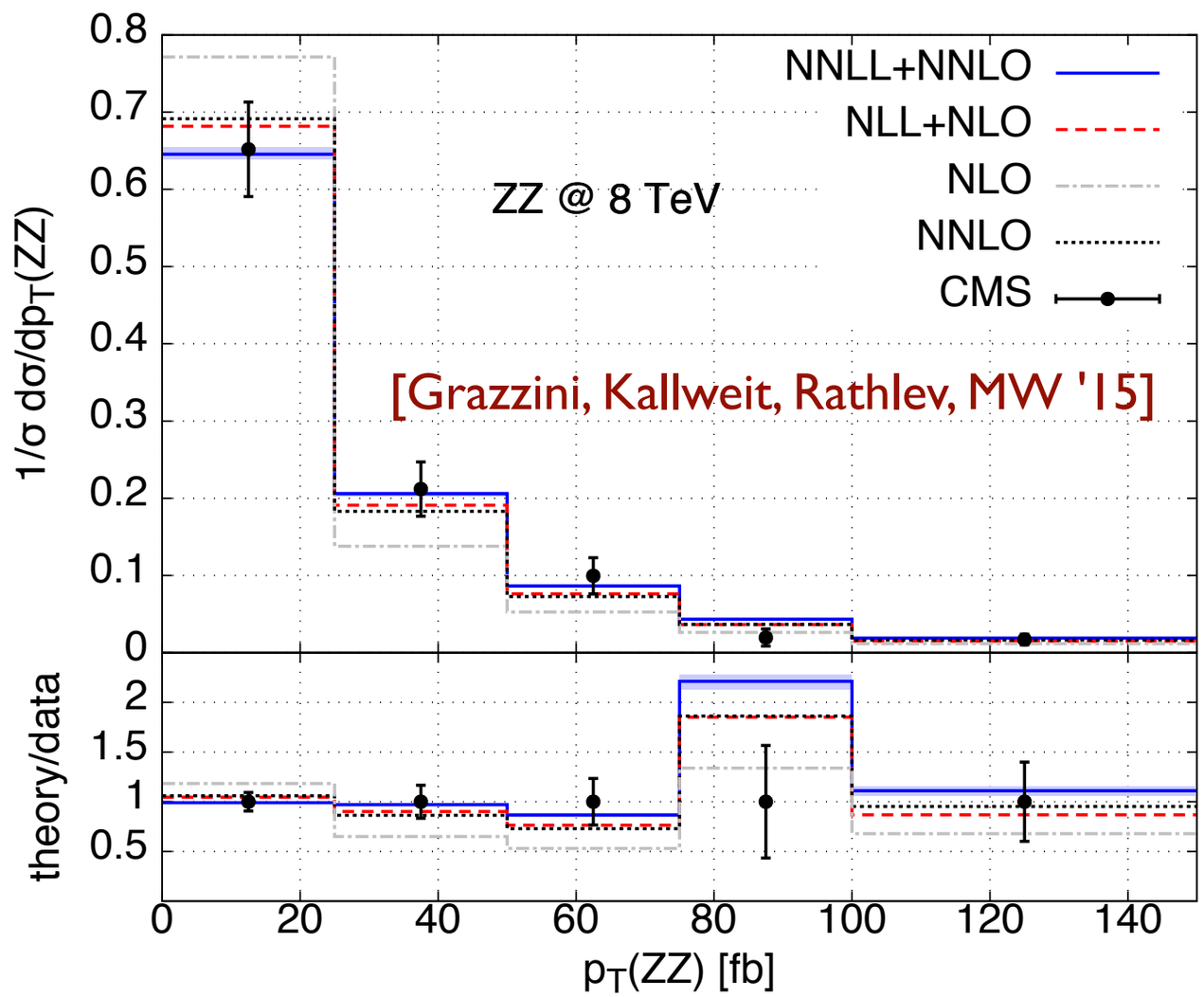
Combination: NNLO QCD and NLO EW

[Grazzini, Kallweit, Lindert, Pozzorini, MW]

- work in progress...
- vector-boson pair production processes
- find optimal approach to combine NNLO QCD and NLO EW (multiplicative, additive, K-factor, bin-wise, split by order, ...)
- NLO EW is numerically only slightly slower NLO QCD (in particular at 1-loop) for the same number of phase space points in an inclusive run

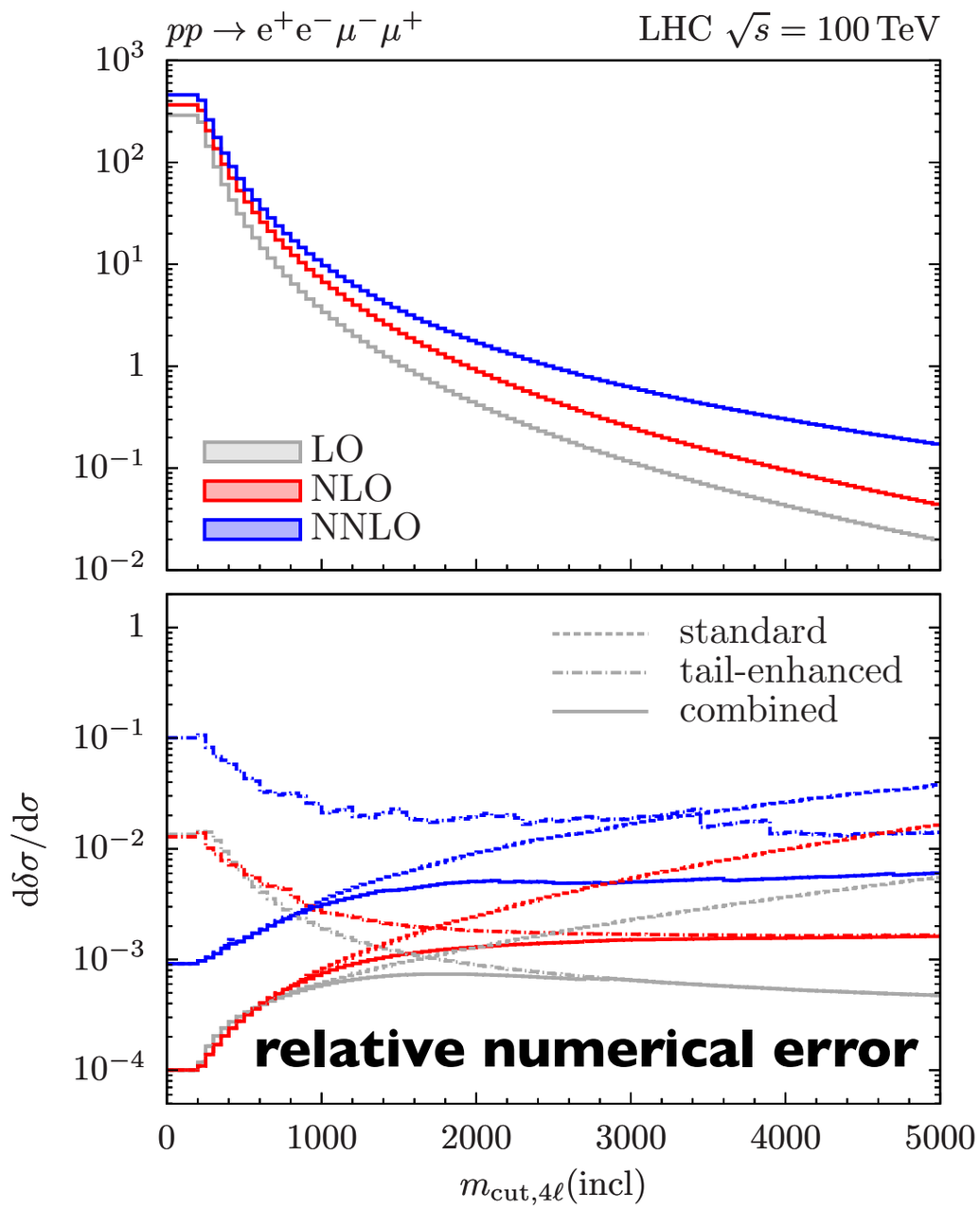
Combination with resummation

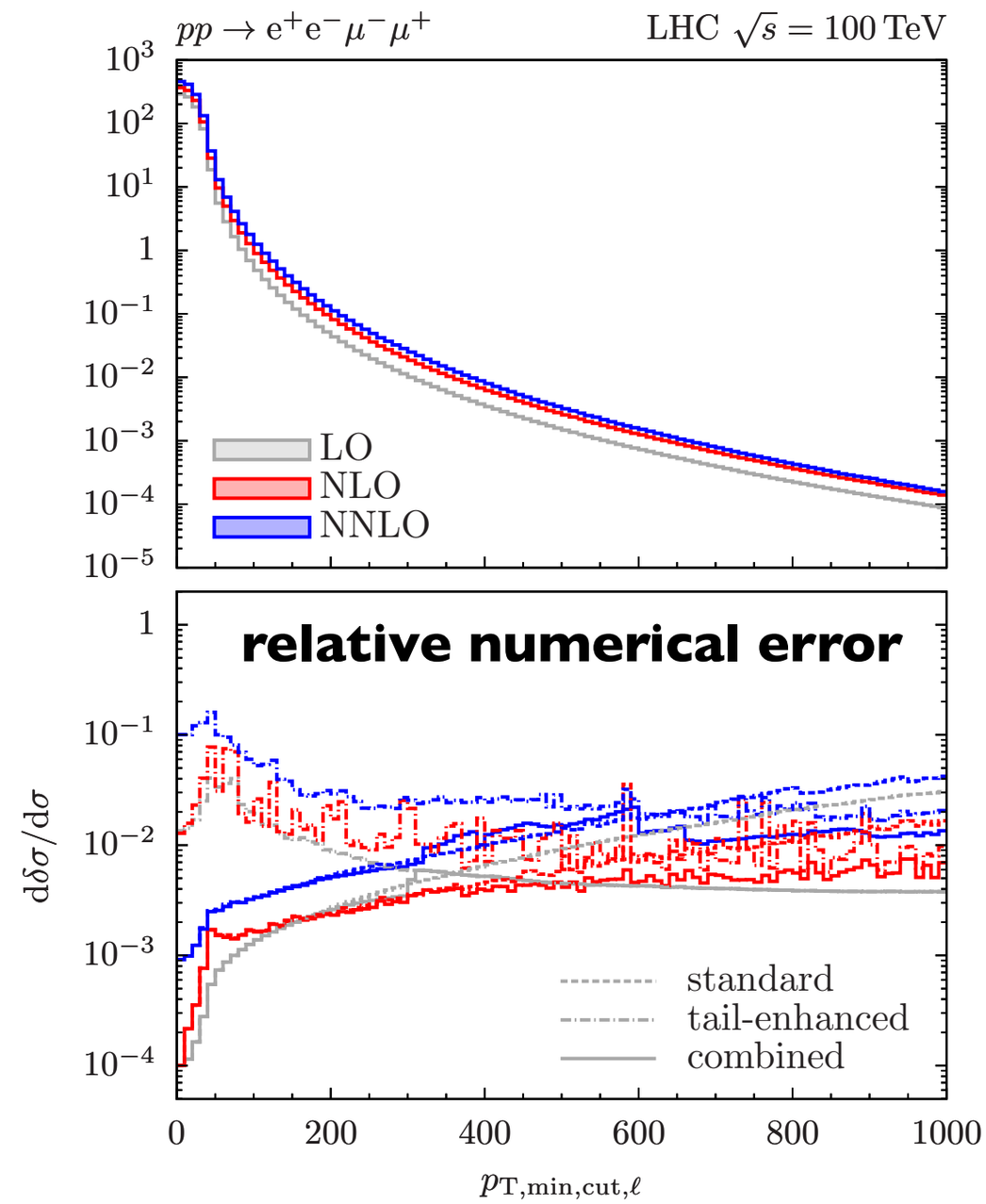
- Matching of NNLO QCD with various resummation approaches:
  - NNLL in b-space (for p_T of Born system) [Grazzini, Kallweit, MW]
  - (N)NNLL in direct-space (p_T, φ^*, jet-veto) [Monni, Kallweit, Re, Rottoli, MW]
- included for all MATRIX processes
- Requires generation of Born-level phase space plus resummation variable
- Two-loop amplitude remains numerical bottleneck for complicated processes, since they are input to the resummation
- work in progress...



Improvements of tails for HL/HE-LHC

- two separate runs: standard & with weight-function
- combined through weighted average → tail improvement reaches order of magnitude
  → roughly flat numerical errors in tails





CPU budget for HL/HE-LHC/FCC

- real-virtual and double virtual more unstable in tails; otherwise time per point similar
- runtimes/accuracy for tail-improved runs very observable dependent
- double real hardly improved; double virtual most significant improvement
  → runtime comparison for tail-improved runs not quite meaningful (at the moment)
- massive diboson processes: similar budget for inclusive HL/HE-LHC/FCC cross section
- runtimes increase with collider energy: 100 TeV about 2-3 times slower than 14 TeV

process	**collider**	LO runtime estimate for 10^{-3} uncertainty	NLO runtime estimate for 10^{-3} uncertainty	NNLO runtime estimate for 10^{-3} uncertainty
$pp \to e^-\mu^-e^+\mu^+ \quad (ZZ)$	LHC 14 TeV	6 CPU minutes	1 CPU day	203 CPU days
	HE-LHC 27 TeV	6 CPU minutes	2 CPU days	275 CPU days
	FCC 100 TeV	6 CPU minutes	2 CPU days	548 CPU days
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e \quad (W^+W^-)$	LHC 14 TeV	13 CPU minutes	3 CPU days	204 CPU days
	HE-LHC 27 TeV	14 CPU minutes	3 CPU days	375 CPU days
	FCC 100 TeV	12 CPU minutes	5 CPU days	523 CPU days
$pp \to \mu^-\bar{\nu}_\mu e^+e^- \quad (W^-Z)$	LHC 14 TeV	10 CPU minutes	2 CPU days	137 CPU days
	HE-LHC 27 TeV	10 CPU minutes	2 CPU days	168 CPU days
	FCC 100 TeV	9 CPU minutes	2 CPU days	462 CPU days
$pp \to \mu^+\nu_\mu e^+e^- \quad (W^+Z)$	LHC 14 TeV	10 CPU minutes	2 CPU days	134 CPU days
	HE-LHC 27 TeV	9 CPU minutes	2 CPU days	159 CPU days
	FCC 100 TeV	9 CPU minutes	2 CPU days	248 CPU days

Summary

MATRIX: **(publicly available under https://matrix.hepforge.org/)**

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

  → realistic computation of cross section in the fiducial phase space
- fully-automated extrapolation and uncertainty estimate for p_T subtraction cut-off

  → control of systematics at the few permille level (or better)
- CPU runtimes strongly dependent on process and order (~100-1000 times longer at NNLO)
- All processes well manageable with a middle-sized cluster (~100 cores) many even locally

many things in progress...

- NLO QCD for loop-induced gluon fusion contribution for all (color-neutral) diboson processes
- Combination of NNLO QCD and NLO EW
- Inclusion of various resummation approaches in MATRIX
- Improvement of tails for predictions of the HE/HL-LHC

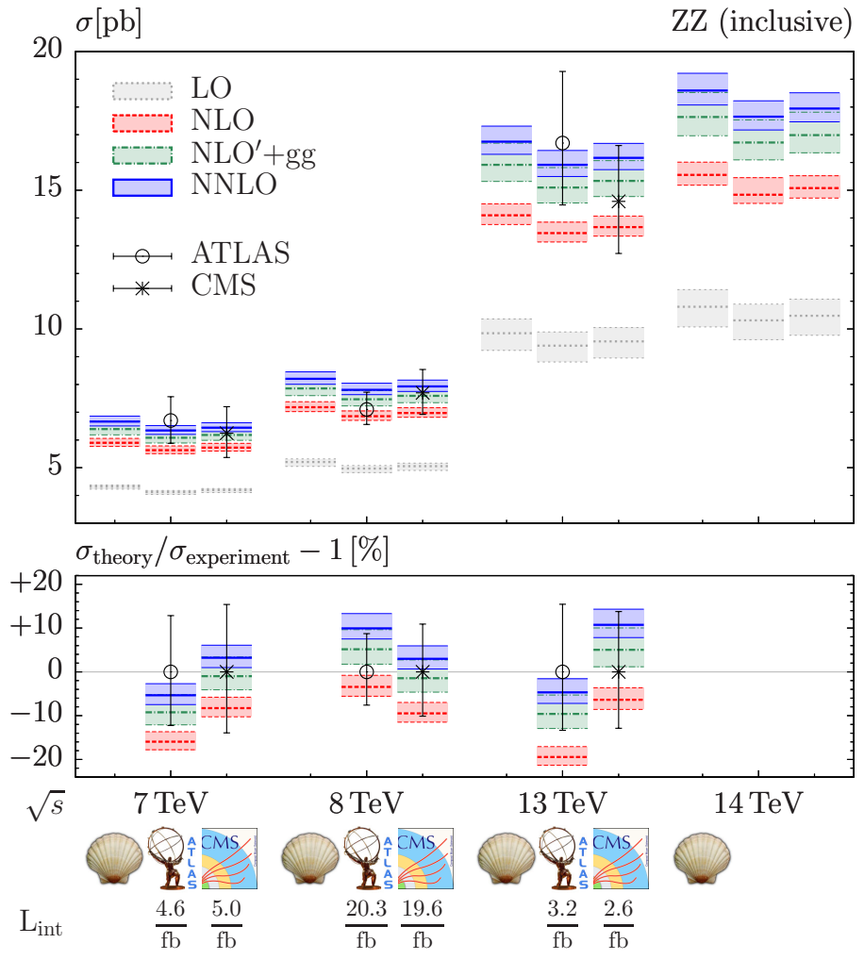
FREE YOUR MIND.

THE MATRIX

Thank You !

Back Up

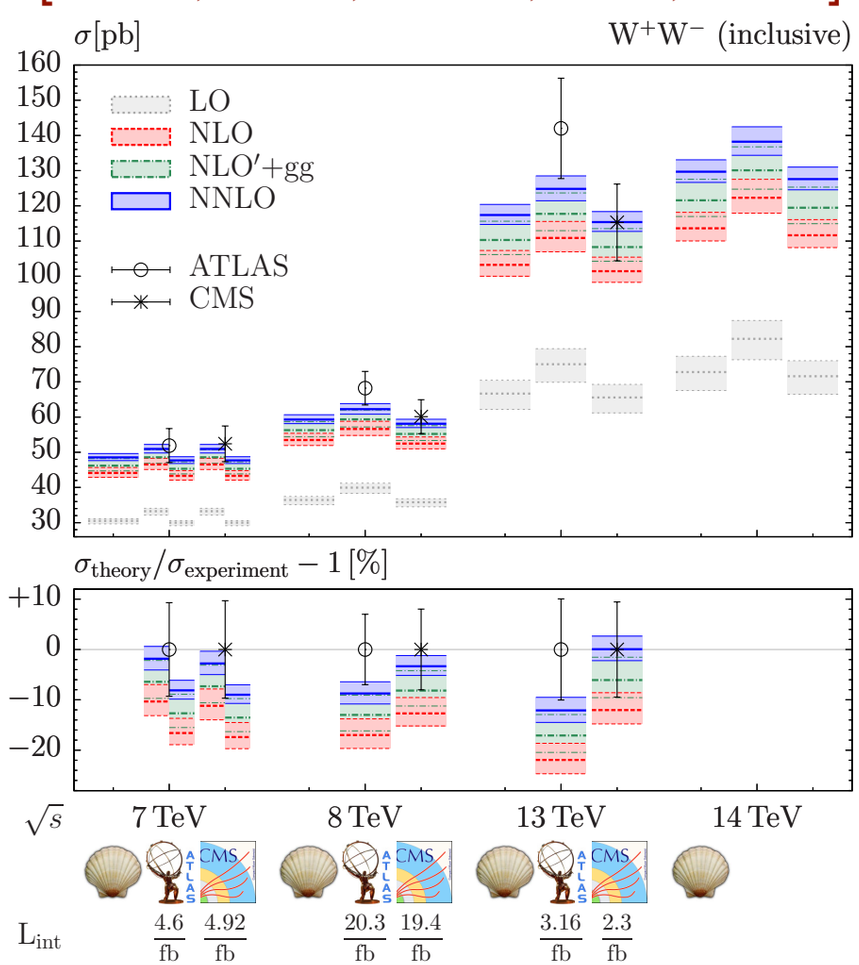
Inclusive diboson results: NNLO vs data

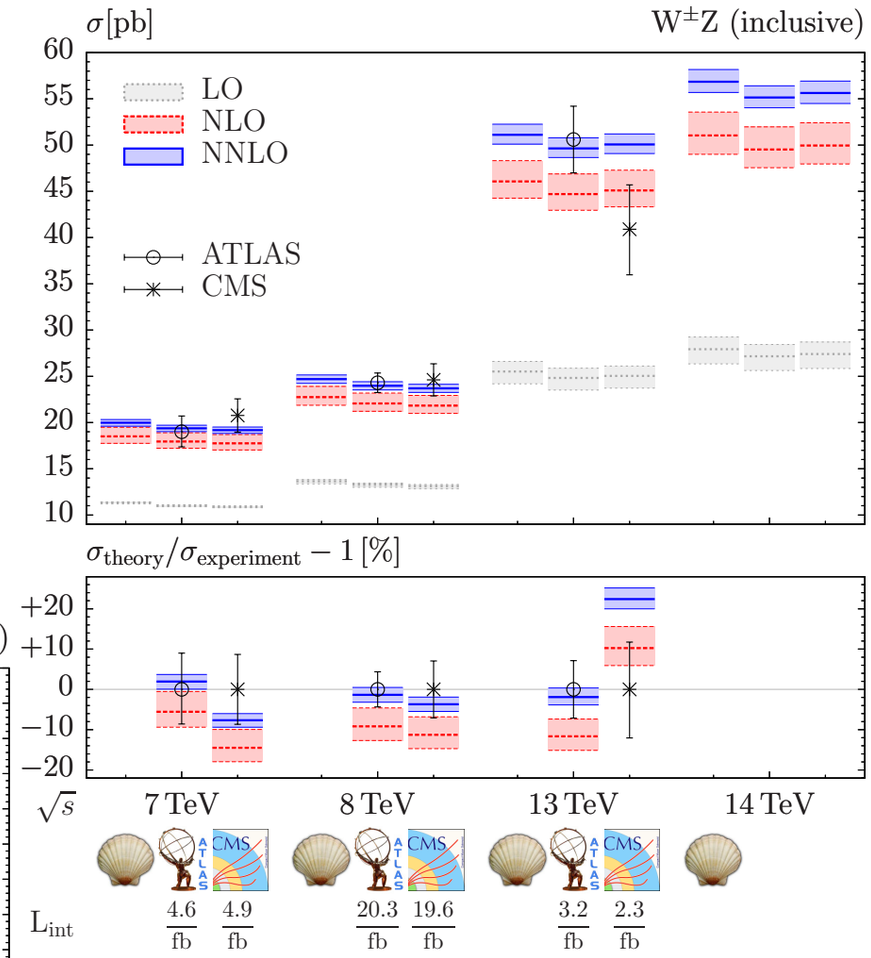


[Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]

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

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

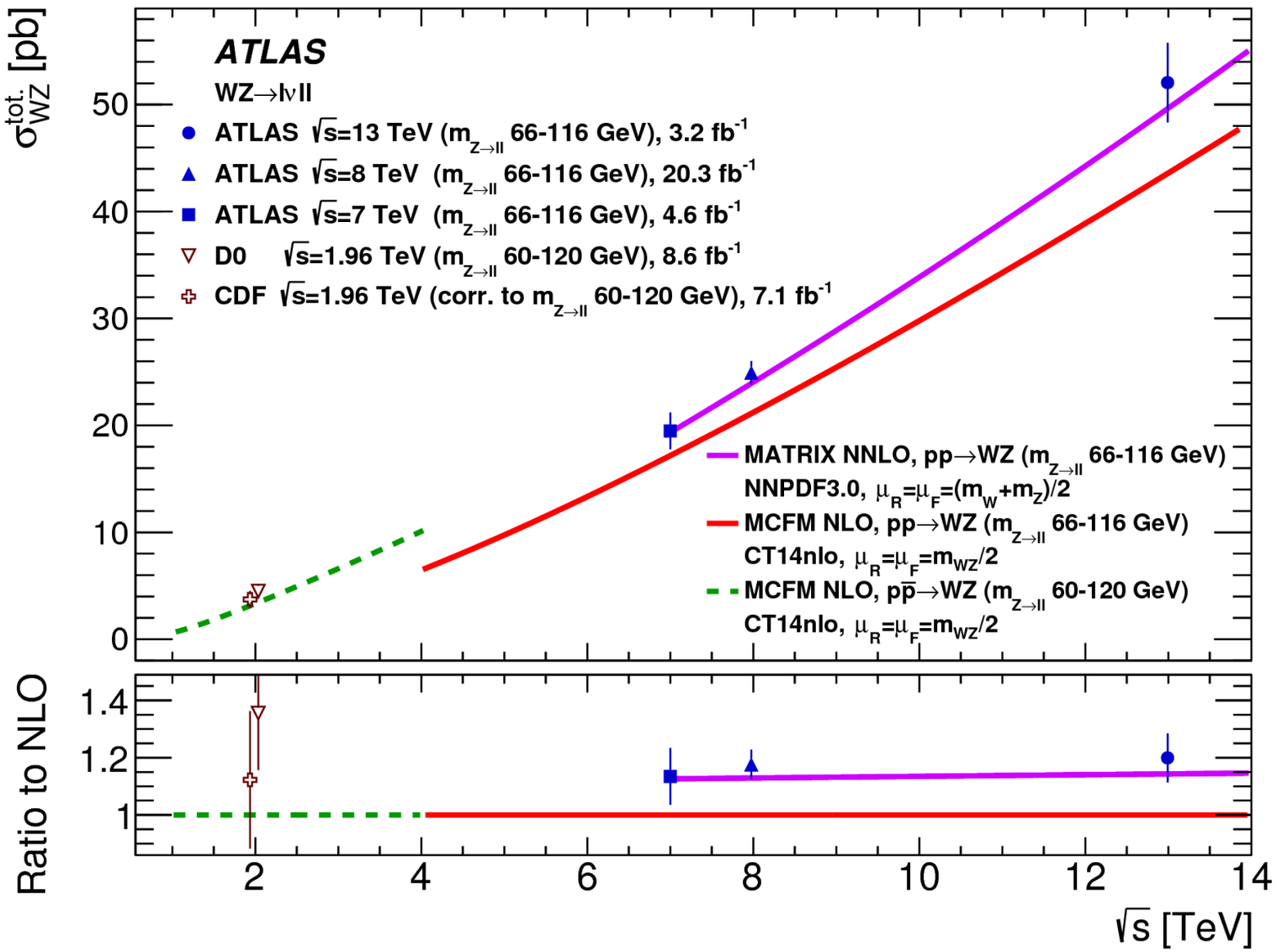




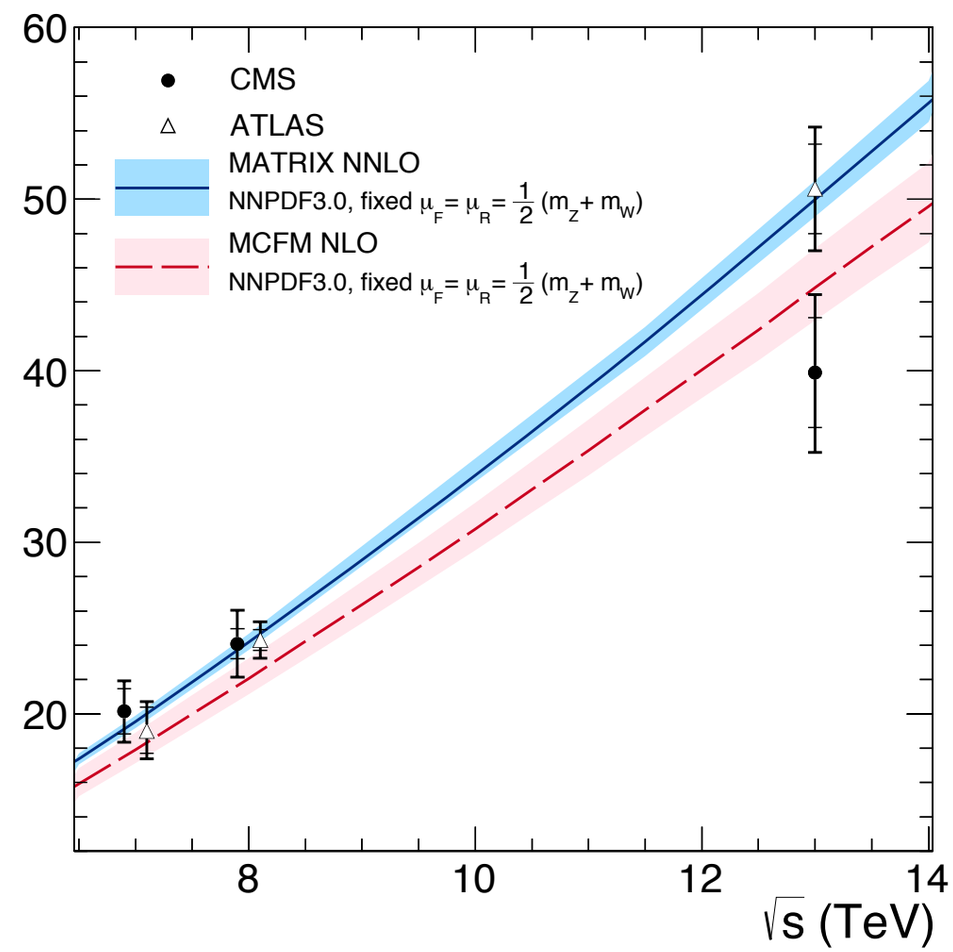
[Grazzini, Kallweit, Rathlev, MW '16]

Inclusive diboson results: NNLO vs data

[ATLAS '16]



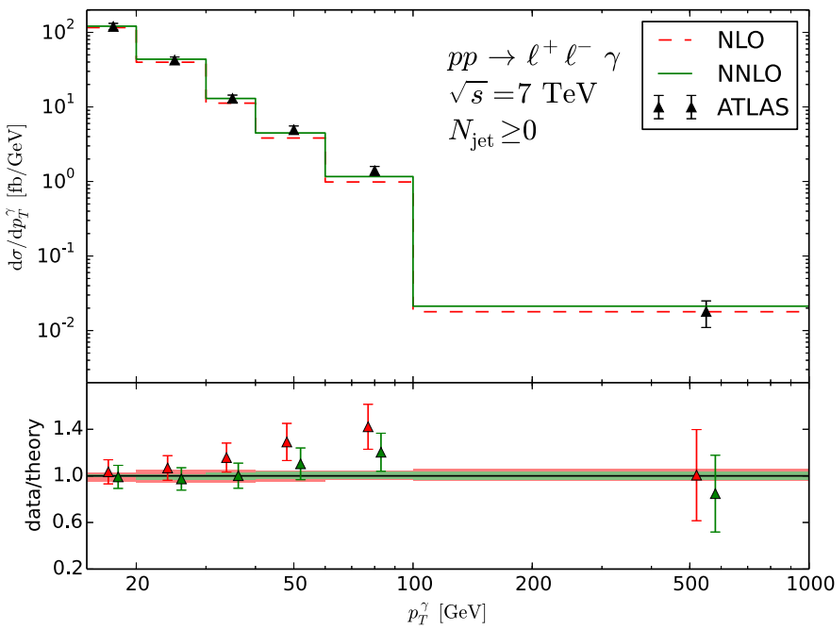
[CMS '16]



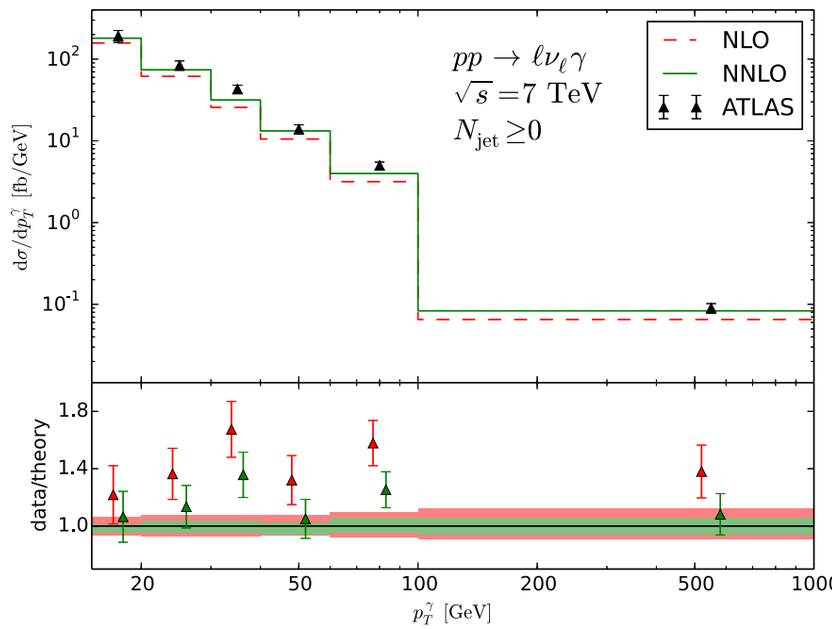
Differential diboson results: NNLO vs data

[Grazzini, Kallweit, Rathlev '15]

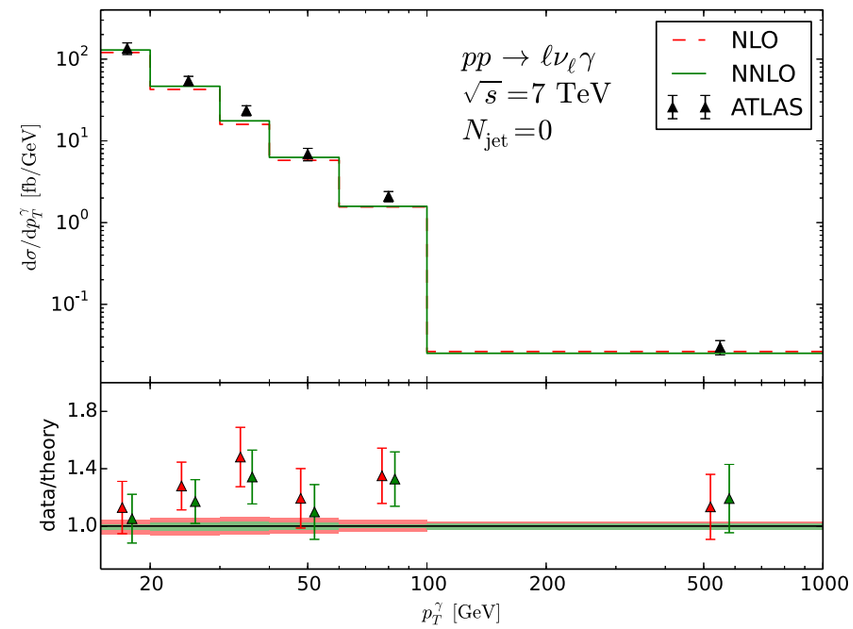
Zγ:



Wγ:

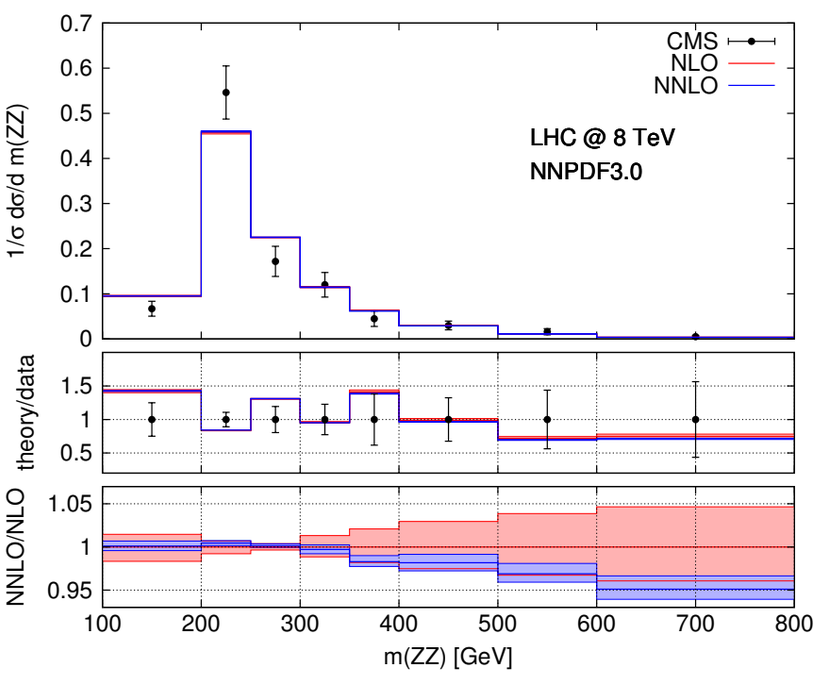


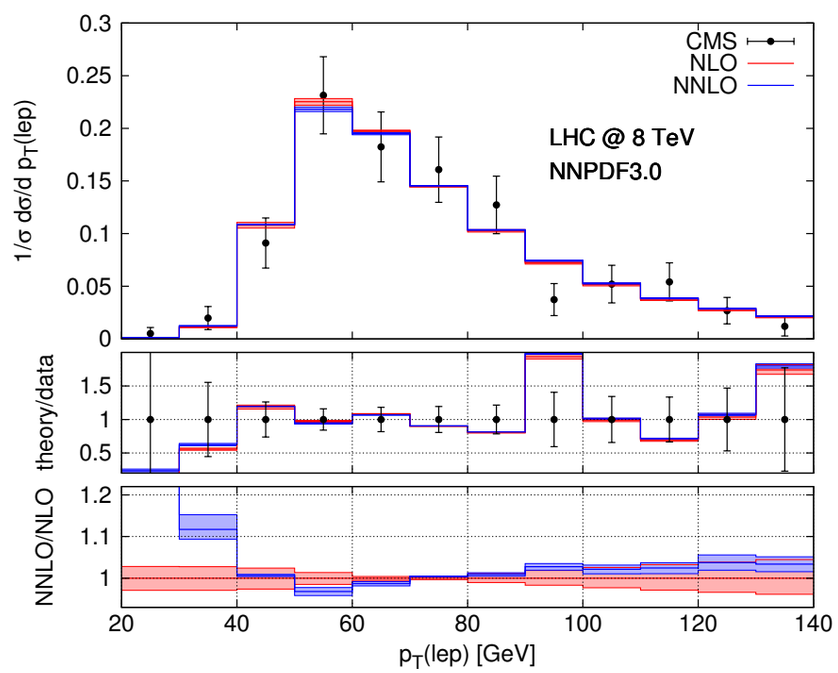
Wγ:

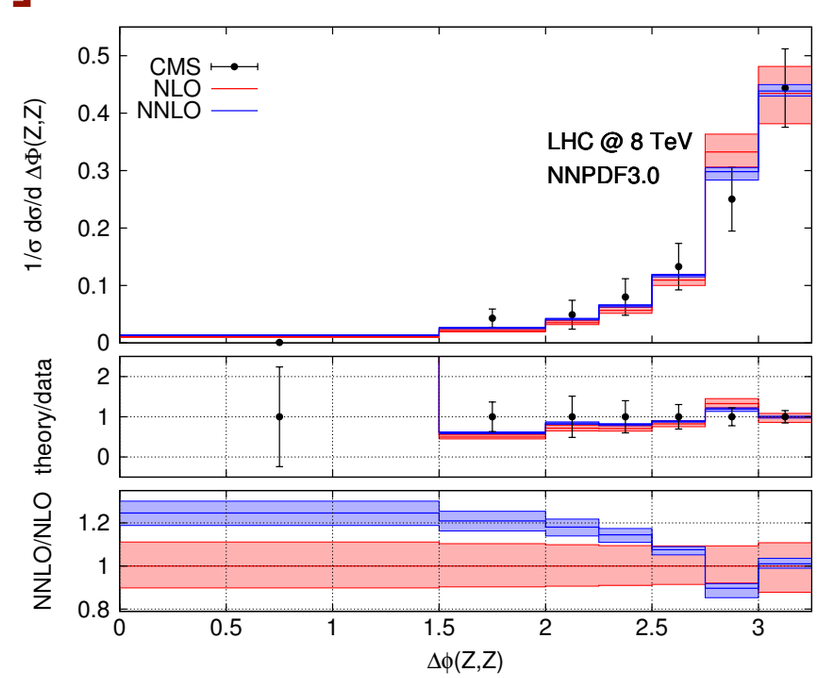


ZZ:

[Grazzini, Kallweit, Rathlev '15]

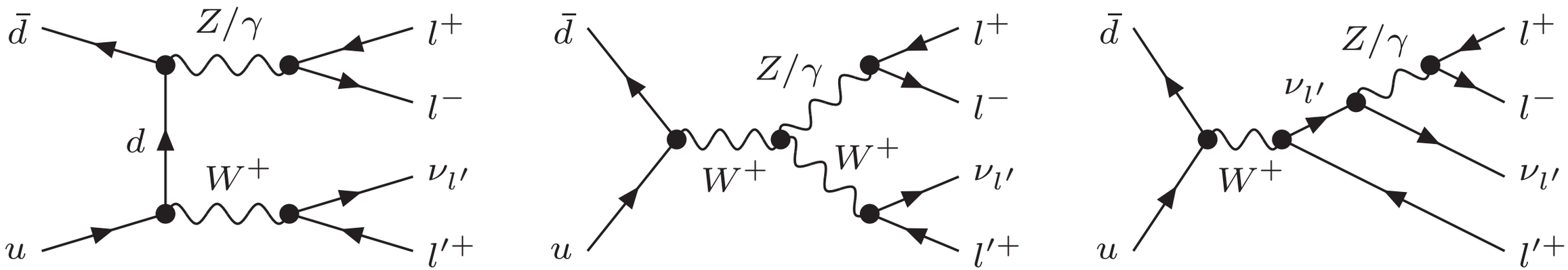






WZ fully differential at NNLO

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

WZ fully differential at NNLO

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

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$e^\pm \mu^+ \mu^-$				$75.2 \pm 9.5\%(\text{stat}) \pm 5.3\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^\pm e^+ e^-$	$28.90(0)^{+5.4\%}_{-6.5\%}$	$57.84(1)^{+5.4\%}_{-4.3\%}$	$64.09(3)^{+2.2\%}_{-2.1\%}$	$50.5 \pm 14.2\%(\text{stat}) \pm 10.6\%(\text{syst}) \pm 2.4\%(\text{lumi})$
$\mu^\pm \mu^+ \mu^-$				$63.6 \pm 8.9\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.3\%(\text{lumi})$
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	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm CMS}$ [fb]
combined	$148.4(0)^{+5.4\%}_{-6.4\%}$	$301.4(1)^{+5.5\%}_{-4.5\%}$	$334.3(2)^{+2.3\%}_{-2.1\%}$	$258 \pm 8.1\%(\text{stat})^{+7.4\%}_{-7.7\%}(\text{syst}) \pm 3.1(\text{lumi})$

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

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perfect agreement at NNLO

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ATLAS (13 TeV):

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm ATLAS}$ [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	$28.86(0)^{+5.4\%}_{-6.5\%}$	$57.76(1)^{+5.4\%}_{-4.3\%}$	$64.01(3)^{+2.3\%}_{-2.1\%}$	$63.2 \pm 5.2\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.4\%(\text{lumi})$

perfect agreement at NNLO

CMS (13 TeV):

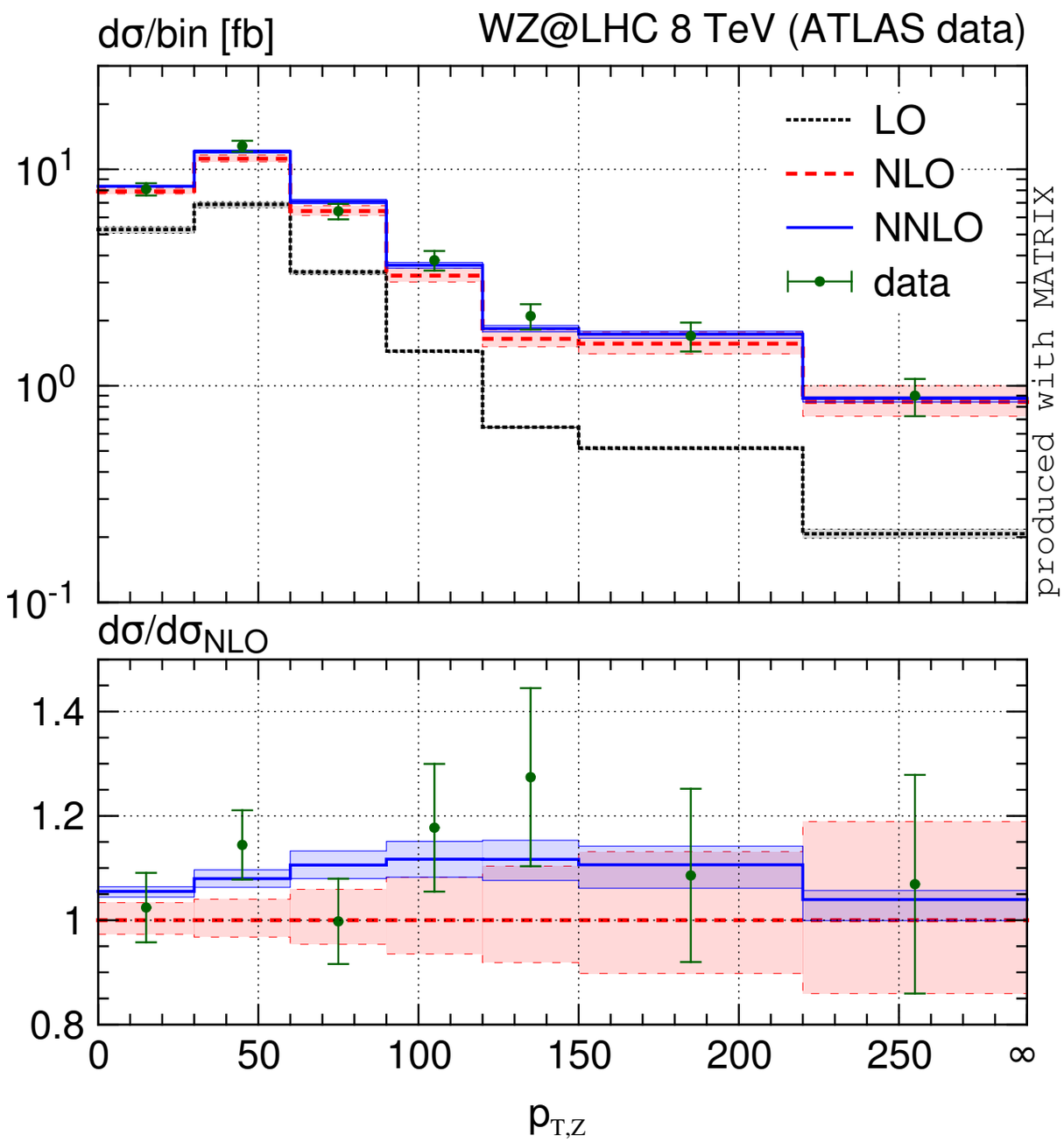
2.6σ, BUT low statistics

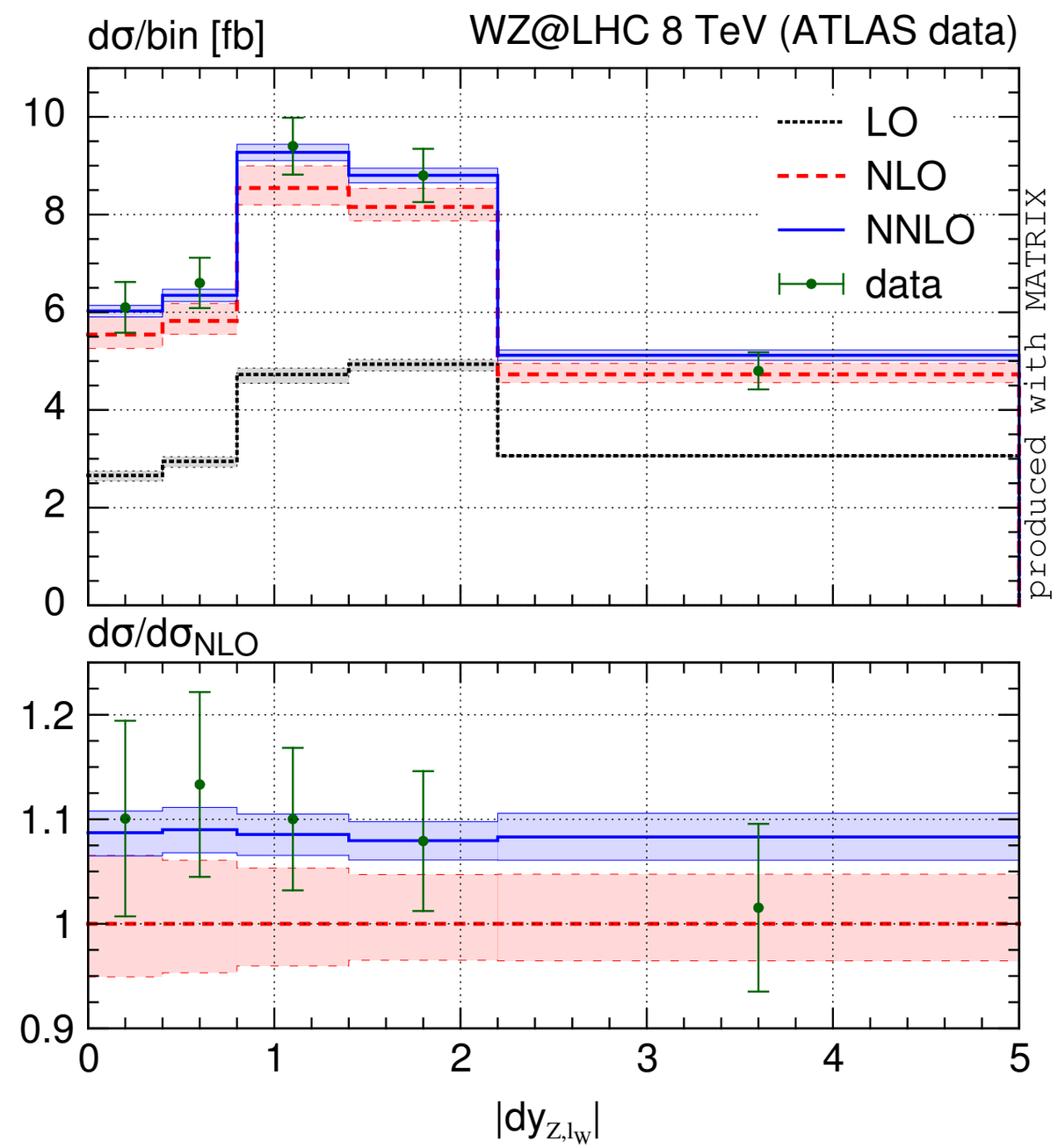
channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm CMS}$ [fb]
combined	$148.4(0)^{+5.4\%}_{-6.4\%}$	$301.4(1)^{+5.5\%}_{-4.5\%}$	$334.3(2)^{+2.3\%}_{-2.1\%}$	$258 \pm 8.1\%(\text{stat})^{+7.4\%}_{-7.7\%}(\text{syst}) \pm 3.1(\text{lumi})$

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW '17]

SM measurements





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

Category I: no additional cut

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

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

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

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channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm NLO}/\sigma_{\rm LO}$	$\sigma_{\rm NNLO}/\sigma_{\rm NLO}$ [fb]
			Category I		
$\ell'^+\ell^+\ell^-$	$49.45(0)^{+4.9\%}_{-5.8\%}$	$94.12(2)^{+4.8\%}_{-3.9\%}$	$105.9(1)^{+2.3\%}_{-2.2\%}$	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%

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QCD corrections VERY different for various Categories (cuts)

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm NLO}/\sigma_{\rm LO}$	$\sigma_{\rm NNLO}/\sigma_{\rm NLO}$ [fb]
			Category I		
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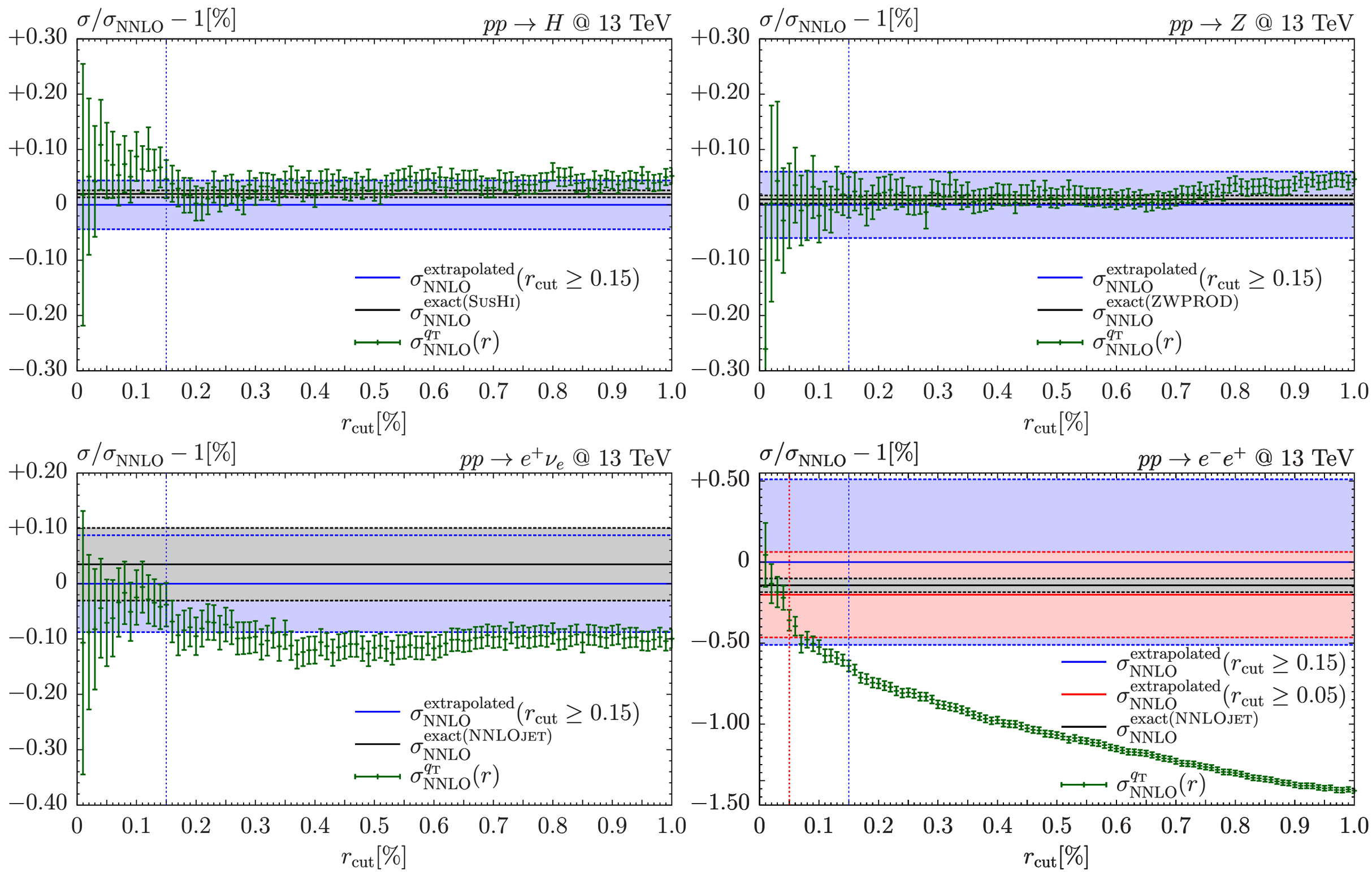
$r_{cut} \to 0$ extrapolation in MATRIX



Status of p_T resummation

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

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

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

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

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

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

[Grazzini, Kallweit, Rathlev, MW '15]