Supplementary manual for MATRIX version 2

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Abstract

This is the manual extension for version 2 (`v2`) of the computational framework MATRIX [1, 2], which evaluates fully differential cross sections for a wide class of processes at hadron colliders. In version 1 (`v1`) MATRIX included all processes up to next-to-next-to-leading order (NNLO) QCD. In `v2` we have included various improvements of the framework, most importantly NLO QCD corrections to the loop-induced gluon fusion contributions [3,4] as well as NLO EW corrections [5]. This document focusses on the new features and changes of `v2` with respect to `v1` and we refer to the `v1` manual for further information.

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Contents

1 Introduction

This document summarises the new features implemented in Matrix `v2`. The relevant reference of the Matrix code remains the Matrix release paper Ref. [1], which should be cited along with the relevant physics applications (and external tools) when using Matrix. We recall that with every run all relevant references are provided in a file `CITATION.bib` in the `result` folder of the respective Matrix run, which simplifies the identification of the relevant references for the user.

The main updates of the Matrix `v2` release concern the combination of the NNLO QCD cross sections (already available in `v1`) with NLO EW corrections and NLO QCD corrections to the loop-induced gluon fusion contribution for a number of processes. The combination of NNLO QCD and NLO EW predictions with Matrix+OpenLoops has been presented in Ref. [5]. The calculation of NLO QCD corrections to the loop-induced gluon fusion contribution with Matrix has been achieved in Ref. [3] for off-shell ZZ production and in Ref. [4] for off-shell W^+W^- production. The splitting of Higgs signal, background and interference contributions presented in Ref. [6] will be part of a future update of Matrix `v2`, but is available from the authors already upon request.

Moreover, we plan to release the processes $pp \to \gamma\gamma\gamma$ [7], $pp \to HV$, $pp \to t\bar{t}$ [8, 9] in a future update of Matrix `v2`, for which private versions are also available upon request.

In the following, we will also discuss some other, more technical features of the Matrix `v2` release. In particular, we have implemented the possibility to enhance the statistics in the (multi-TeV) tails, where EW corrections become particularly relevant, while retaining the numerical accuracy in the bulk region of the cross section, by combining a normal run with a run that samples more phase-space points in the tails. We have implemented a general syntax to define fiducial cuts (supplementary to the predefined cuts), which provide the possibility to add fiducial cuts directly via the input card, without relying on the predefined cuts or having to modify the C++ code.

Apart from that we have implemented a number of bug fixes, done a substantial clean-up and restructuring of the C++ code to make it more modular, which simplifies interfaces to other codes, and improved various aspects of the automatically generated phase space. Moreover, for clusters with slow shared file systems we now provide the possibility to run locally on the local scratch of the cluster nodes (shared file system still required for copying before and after the jobs).

2 Available processes in Matrix

We are continuously extending the list of the available processes in Matrix, which is provided in Table 1, and processes which have been updated by NLO EW and/or NLO QCD corrections to the loop-induced gluon fusion channel are highlighted in green colour. They include Higgs boson, vector-boson and vector-boson pair production so far, with all the possible leptonic decay channels of the vector bosons. For each process we provide the information (in brackets) whether NLO corrections to the loop-induced gluon fusion contributions (ggNLO) and/or NLO EW corrections are included in addition to the NNLO QCD corrections that are available for every process.

${process_id}	**process**	**description**
pph21	$pp/p\bar{p} \to H$	on-shell Higgs-boson production
ppz01	$pp/p\bar{p} \to Z$	on-shell Z production (EW)
ppw01	$pp/p\bar{p} \to W^-$	on-shell W^- production with CKM
ppwx01	$pp/p\bar{p} \to W^+$	on-shell W^+ production with CKM
ppeex02	$pp/p\bar{p} \to e^-e^+$	Z production with decay (EW)
ppnenex02	$pp/p\bar{p} \to \nu_e\bar{\nu}_e$	Z production with decay (EW)
ppenex02	$pp/p\bar{p} \to e^-\bar{\nu}_e$	W^- production with decay and CKM (EW)
ppexne02	$pp/p\bar{p} \to e^+\nu_e$	W^+ production with decay and CKM (EW)
ppaa02	$pp/p\bar{p} \to \gamma\gamma$	$\gamma\gamma$ production
ppeexa03	$pp/p\bar{p} \to e^-e^+\gamma$	$Z\gamma$ production with decay
ppnenexa03	$pp/p\bar{p} \to \nu_e\bar{\nu}_e\gamma$	$Z\gamma$ production with decay
ppenexa03	$pp/p\bar{p} \to e^-\bar{\nu}_e\gamma$	$W^-\gamma$ with decay
ppexnea03	$pp/p\bar{p} \to e^+\nu_e\gamma$	$W^+\gamma$ with decay
ppzz02	$pp/p\bar{p} \to ZZ$	on-shell ZZ production
ppwxw02	$pp/p\bar{p} \to W^+W^-$	on-shell W^+W^- production
ppemexmx04	$pp/p\bar{p} \to e^-\mu^-e^+\mu^+$	ZZ production with decay (ggNLO, EW)
ppeeexex04	$pp/p\bar{p} \to e^-e^-e^+e^+$	ZZ production with decay (ggNLO, EW)
ppeexnmnmx04	$pp/p\bar{p} \to e^-e^+\nu_\mu\bar{\nu}_\mu$	ZZ production with decay (ggNLO, EW)
ppemxnmnex04	$pp/p\bar{p} \to e^-\mu^+\nu_\mu\bar{\nu}_e$	W^+W^- production with decay (ggNLO, EW)
ppeexnenex04	$pp/p\bar{p} \to e^-e^+\nu_e\bar{\nu}_e$	ZZ / W^+W^- production with decay (ggNLO, EW)
ppemexnmx04	$pp/p\bar{p} \to e^-\mu^-e^+\bar{\nu}_\mu$	W^-Z production with decay (EW)
ppeeexnex04	$pp/p\bar{p} \to e^-e^-e^+\bar{\nu}_e$	W^-Z production with decay (EW)
ppeexmxnm04	$pp/p\bar{p} \to e^-e^+\mu^+\nu_\mu$	W^+Z production with decay (EW)
ppeexexne04	$pp/p\bar{p} \to e^-e^+e^+\nu_e$	W^+Z production with decay (EW)

Table 1: Available processes in MATRIX. All processes feature NNLO QCD predictions. "ggNLO" indicates that NLO corrections to the loop-induced gluon fusion contribution can be computed, while "EW" indicates that MATRIX also evaluates NLO EW corrections for that process.

3 How to use MATRIX

The relevant information how to compile MATRIX is given in the `v1` manual, which we refer the user to. Here, we only gather the most relevant updates in `v2`.

3.1 Compilation with arguments

The MATRIX script also features compilation directly via arguments: Type

```
$ ./matrix --help
```

in order to see the available options.

We summarize the new command line options in v2 below:

1.) To agree with all MATRIX usage terms to properly cite the relevant work and skip the licence-agreement dialog without typing y several times use

```
$ ./matrix ${process_id} --agree_to_all
```

2.) Do the process setup (including download/compilation of all external tools), but without (re-)compiling the C++ Code.

```
$ ./matrix ${process_id} --no_compile
```

3.) Compile with Ginac version 1.6.2 (default)

```
$ ./matrix ${process_id} --old_ginac
```

or with newer Ginac version 1.8.7.

```
$ ./matrix ${process_id} --new_ginac
```

3.2 General structure of a process folder

The most relevant changes in MATRIX v2 concern the results collected in the result folder, which includes now also the results for the newly included NLO EW corrections [5], NLO QCD corrections to the loop-induced gluon fusion contributions [3, 4], and various (additive and multiplicative) combinations, both at the integrated cross section and at the distribution level.

3.3 Configuration file

Some additional global parameters have been added to the MATRIX_configuration file inside the folder config, which controls various global settings for both the compilation and the running of the code. The options controlled by the file MATRIX_configuration are listed in Table 2, and options that were not in the v1 release yet are highlighted in green colour.

4 Settings of a MATRIX run

In this Section we comment on all input parameter that have been added or whose function has been changed/updated in MATRIX v2.

4.1 Process-independent settings

Every run of a process contains three input files in its respective subfolder inside input, which can be modified by the user. The generic inputs in the files parameter.dat, model.dat and distribution.dat of each MATRIX run are described in the following.

variable	description
default_editor	Sets the editor to be used for interactive access to input files. Alternatively, the default editor may be configured directly by exporting the EDITOR environment variable on the system.
mode	Switch to choose local (multicore) run mode or cluster mode.
cluster_name	Name of the cluster; currently supported: Slurm, LSF (e.g. lxplus), Condor, HTCondor (e.g. lxplus), PBS, Torque, SGE.
cluster_queue	Queue/Partition of the cluster to be used for cluster submit; not required in most cases.
cluster_local_run	Switch to run on shared file system or use local scratch on cluster nodes (set cluster_local_scratch_path).
cluster_local_scratch_path	Path to the local scratch directories of the nodes; needed if cluster_local_run = 1.
cluster_runtime	Runtime of jobs in cluster submit; not required in most cases.
cluster_submit_line[1-99]	Lines in cluster submit file to add cluster-specific options.
max_nr_parallel_jobs	Number of cores to be used in multicore mode; maximal number of available cores on cluster.
parallel_job_limit	Upper threshold for number of parallel jobs; if exceeded, user intervention required to continue.
max_jobs_in_cluster_queue	If cluster queue contains more jobs than this value, MATRIX will wait until jobs finish before submitting further jobs.
path_to_executable	This path can be set to the folder that contains the executables of the processes (usually bin in the MATRIX main folder), and provides the possibility to use an executable from a different MATRIX installation; not required in most cases.
max_restarts	If there are still jobs left that failed after all jobs finished, MATRIX will restart all failed jobs n times when this parameter is set to n.
nr_cores	Number of cores to be used for the compilation; determined automatically by the number of available cores on the machine if not set.
path_to_lhapdf	Path to lhapdf-config; not required in most cases.
path_to_openloops	Path to the openloops executable; not required in most cases.
path_to_recola	Path to the recola installation; not required in most cases. (not yet used in current MATRIX v2 release)
path_to_ginac	Path to the ginac installation; not required in most cases.
path_to_cln	Path to the cln installation; not required in most cases.
path_to_libgfortran	Path to the libgfortran library; not required in most cases. This path can also be used if the libquadmath library is not found, to be set to the respective lib folder.
path_to_gsl	Path to gsl-config; not required in most cases.

Table 2: Parameters to be set in the file MATRIX_configuration.

4.1.1 Settings in `parameter.dat`

All main parameters, related to the run itself or the behaviour of the code, are specified in the file `parameter.dat`. Most of them should be completely self-explanatory, but we will provide some additional information here. The settings are organized into certain groups that are discussed in the order they appear in the file `parameter.dat` for the sample case of different-flavour off-shell ZZ production (`ppemexmx04`). Newly introduced or updated inputs in `v2` are highlighted in green and discussed below.

4.1.1.1 General run settings

```
process_class     =  pp-emmumepmup+X  #  process id
E                 =  6500.  #  energy per beam
coll_choice       =  1      #  (1) PP collider; (2) PPbar collider
photon_induced    =  1      #  switch to turn on (1) and off (0) photon-induced contributions
switch_off_shell  =  0      #  switch for effective integration for off-shell Z bosons (eg, Higgs analysis)
enhance_tails     =  0      #  switch to improve statistics in tail of distributions (factor of two slower)
```

`photon_induced` Switch that allows to turn on and off the photon-induced contributions (at all orders). Note that when sets without photon PDFs are used the photon contribution evaluates to zero regardless of this switch. However, it is advisable to simply turn them off with this switch in that case.

`enhance_tails` Switch that allows the user to turn on the new tail-enhancement feature, which improves substantially the statistics in the high-energy tails of distributions, while keeping the accuracy in the bulk region of a usual run. This is achieved by doubling the number of jobs, where half of them correspond to a usual run and the other half to jobs that add statistics to the tails, and combining them appropriately at the end. Note that this feature requires approximately a factor of two more runtime.

4.1.1.2 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 colourless final states)
                               #  2: transverse mass (mT^2=Q^2+pT^2) of system (of colourless final states)
                               #  3: geometric average of Z-boson transverse masses:
                               #     sqrt(mT_Z1 * mT_Z2)
                               #  4: sum of Z-boson transverse masses computed with their pole masses:
                               #     sqrt(M_Z^2+pT_ee^2)+sqrt(M_Z^2+pT_mumu^2)
                               #  5: sum of Z-boson transverse masses:
                               #     sqrt(M_Z1^2+pT_Z1^2)+sqrt(M_Z1^2+pT_Z2^2)
factor_central_scale = 1       #  relative factor for central scale (important for dynamic scales)
scale_variation   =  1         #  switch for muR/muF variation (0) off; (1) 7-point (default); (2) 9-point
variation_factor  =  2         #  symmetric variation factor; usually a factor of 2 up and down (default)
```

4.1.1.3 Order-dependent run settings

```
# LO-run
run_LO             =  1        #  switch for LO cross section (1) on; (0) off
```

```
LHAPDF_LO          =  NNPDF31_nlo_as_0118_luxqed  #  LO LHAPDF set
PDFsubset_LO       =  0         #  member of LO PDF set
precision_LO       =  1.e-2     #  precision of LO cross section

# NLO-run
run_NLO_QCD        =  0         #  switch for NLO QCD cross section (1) on; (0) off
run_NLO_EW         =  0         #  switch for NLO EW cross section (1) on; (0) off
LHAPDF_NLO         =  NNPDF31_nlo_as_0118_luxqed  #  NLO LHAPDF set
PDFsubset_NLO      =  0         #  member of NLO PDF set
precision_NLO_QCD  =  1.e-2     #  precision of NLO QCD cross section
precision_NLO_EW   =  1.e-2     #  precision of NLO EW correction
NLO_subtraction_method = 1      #  switch to use (2) qT subtraction (1) Catani-Seymour at NLO

# NNLO-run
run_NNLO_QCD       =  0         #  switch for NNLO QCD cross section (1) on; (0) off
add_NLO_EW         =  0         #  switch to add NLO EW cross section to NNLO run (1) on; (0) off
                                #  note: can be added only if also running NNLO
LHAPDF_NNLO        =  NNPDF31_nnlo_as_0118_luxqed  #  NNLO LHAPDF set
PDFsubset_NNLO     =  0         #  member of NNLO PDF set
precision_NNLO_QCD =  1.e-2     #  precision of NNLO QCD cross section
precision_added_EW =  1.e-2     #  precision of NLO EW correction in NNLO run
loop_induced       =  2         #  switch for loop-induced gg (with NNLO settings): (0) off;
                                #   (1) LO [NNLO contribution];   (2) NLO [N3LO contribution]
                                #  (-1) only loop-induced gg LO; (-2) only loop-induced gg NLO
```

A single run of a process in MATRIX involves up to three different orders, namely LO, NLO and NNLO.

`run_NLO_QCD/EW` In the NLO run we now may choose to run NLO QCD corrections, NLO EW corrections or both. If both are run the code automatically evaluates combinations of QCD and EW corrections in different schemes (additive and various multiplicative combinations).

`precision_NLO_QCD/EW` Desired numerical precision of the cross section (within cuts) for the respective contribution (NLO QCD or NLO EW).

`run_NNLO_QCD` Turn on NNLO QCD corrections in the NNLO run.

`add_NLO_EW` In the NNLO run we may now additionally run NLO EW corrections, but only if `run_NNLO_QCD=1`. In that case the code automatically evaluates combinations of NNLO QCD and NLO EW corrections in different schemes (additive and various multiplicative combinations).

`precision_NNLO_QCD` Desired numerical precision of the cross section (within cuts) for the NNLO QCD corrections.

`precision_added_EW` Desired numerical precision of the cross section (within cuts) for the added NLO EW corrections.

`loop_induced` For certain processes (such as ZZ, W^+W^-, ...) a loop-induced gg contribution enters at the NNLO; this contribution is separately finite and can be calculated either at LO (α_S^2) or at NLO (α_S^3) by choosing `loop_induced=1` or `loop_induced=2`, respectively. The loop-induced gg contribution can be computed alone (choosing negative values) or together with the NNLO QCD cross section (choosing positive values). In the latter case NNLO QCD corrections to the $q\bar{q}$ channel and NLO QCD to the loop-induced gg channel are combined, which is dubbed nNNLO QCD (and, if turned on, also combined with NLO EW corrections). Note that in all cases it has to be `run_NNLO_QCD=1`, when the loop-induced gg contribution should be computed. Moreover, the relative accuracy is controlled by the setting of `precision_NNLO_QCD`.

4.1.1.4 Settings for fiducial cuts

We first note that certain settings, such as photon isolation, naturally only affect dedicated processes. Similarly photon recombination only plays a role when NLO EW corrections are turned on. The default input files are adapted such that they only contain options that are of relevance for the respective process. It is not recommended to add any new blocks to the input files in order to avoid unwanted behaviour, although such additional settings would usually just not have any impact on the run.

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
```

Photon isolation

```
frixione_isolation = 1         #  switch for Frixione isolation (0) off;
                               #  (1) with frixione_epsilon, used by ATLAS;
                               #  (2) with frixione_fixed_ET_max, used by CMS
frixione_n = 1                 #  exponent of delta-term
frixione_delta_0 = 0.4         #  maximal cone size
frixione_epsilon = 0.5         #  photon momentum fraction
#frixione_fixed_ET_max = 5.     #  fixed maximal pT inside cone
```

Photon recombination

When EW corrections are calculated, MATRIX performs a photon recombination for contributions with real final-state photons. Photons that lie within a distance of $\Delta R < R_{\text{recombination}}$ to a charged lepton or a quark are recombined with the respective charged lepton or quark. This means the photon momentum is added to the lepton/quark momentum and the photon removed from the list of photons.

```
photon_recombination = 1       #  switch for photon recombination (1) on; (0) off; must be on for EW runs
photon_R_definition = 0        #  (0) pseudorap; (1) rapidity
photon_R = 0.1                 #  DeltaR: photon combined with charged particle when inside this radius
```

`photon_recombination` Switch for photon recombination to turn it on/off; must be turned on when EW corrections are calculated.

`photon_R_definition` According to the setting of this switch, the distance ΔR is defined either via pseudo-rapidity or rapidity,

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \qquad \text{or} \qquad \Delta R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}\,. \tag{1}$$

`photon_R` Value of $R_{\text{recombination}}$ above.

Particle definition and generic cuts

Some fiducial cuts are defined in a general, i.e. process-independent, way by requiring a minimum and maximum multiplicity of a certain (group of) particle(s) with given requirements (such as

identifier	description
`jet`	parton-level jets, 5 light quarks+gluons, clustered according to jet algorithm
`ljet`	light jets: same as `jet`, but without bottom jets
`bjet`	bottom jets: jets with a bottom charge (see main text)
`photon`	photons, isolated according to chosen smooth-cone isolation
`lep`	charged leptons, i.e. electrons and muons, including particles and anti-particles
`lm`	negatively charged leptons, i.e. electrons and muons
`lp`	positively charged leptons, i.e. positrons and anti-muons
`e`	electrons and positrons
`em`	electrons
`ep`	positrons
`mu`	muons and anti-muons
`mum`	muons
`mup`	anti-muons
`z`	Z bosons
`w`	W^+ and W^- bosons
`wp`	W^+ bosons
`wm`	W^- bosons
`h`	Higgs bosons
`nua`	neutrinos and anti-neutrinos
`nu`	neutrinos
`nux`	anti-neutrinos
`nea`	electron-neutrinos and anti-electron-neutrinos
`ne`	electron-neutrinos
`nex`	anti-electron-neutrinos
`nma`	muon-neutrinos and anti-muon-neutrinos
`nm`	muon-neutrinos
`nmx`	anti-muon-neutrinos
`missing`	sum of all neutrino momenta, containing only one entry (special group)

Table 3: All relevant particle groups predefined in MATRIX. Each group is ordered by the transverse momenta of the respective particles, starting with the hardest one. These groups are most important to recognize by the user in three situations: when using the predefined blocks for fiducial cuts, when using the new syntax to define fiducial cuts by the user and when defining distributions.

minimal transverse momentum or maximal rapidity). For that purpose, the user can define which requirements (clustered) parton-level objects need to fulfil in order to be considered particles that can be accessed in scale definitions, phase-space cuts and distributions. Moreover, in MATRIX v2 we have implemented a new general syntax to define fiducial cuts by the user, which will be introduced below. Table 3 summarizes the content of all relevant predefined particle groups. All objects entering these groups will be ordered by their transverse momenta, starting with the hardest one.

Jet cuts

```
define_pT jet = 30.          #  requirement on jet transverse momentum (lower cut)
define_eta jet = 4.4         #  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)
```

Analogous blocks can be processed by MATRIX for the particle groups `bjet` and `ljet`.

Lepton cuts

```
define_pT lep = 25.          #  requirement on lepton transverse momentum (lower cut)
define_eta lep = 2.47        #  requirement on lepton pseudo-rapidity (upper cut)
define_y lep = 1.e99         #  requirement on lepton rapidity (upper cut)
n_observed_min lep = 2       #  minimal number of observed leptons (with cuts above)
n_observed_max lep = 99      #  maximal number of observed leptons (with cuts above)
```

Analogous blocks are available for other particle groups of charged leptons, namely `lm`, `lp`, `e`, `mu`, `em`, `ep`, `mum` and `mup`.

Photon cuts

```
define_pT photon = 15.       #  requirement on photon transverse momentum (lower cut)
define_eta photon = 2.37     #  requirement on photon pseudo-rapidity (upper cut)
define_y photon = 1.e99      #  requirement on photon rapidity (upper cut)
n_observed_min photon = 1    #  minimal number of observed photons (with cuts above)
n_observed_max photon = 99   #  maximal number of observed photons (with cuts above)
```

Heavy-boson cuts

```
define_pT w = 0.             #  requirement on W-boson transverse momentum (lower cut)
define_eta w = 1.e99         #  requirement on W-boson pseudo-rapidity (upper cut)
define_y w = 1.e99           #  requirement on W-boson rapidity (upper cut)
n_observed_min w = 0         #  minimal number of observed W-bosons (with cuts above)
n_observed_max w = 99        #  maximal number of observed W-bosons (with cuts above)
```

Analogous blocks are available for other particle groups of heavy bosons, namely `w`, `wm`, `wp`, `z` and `h`.

Neutrino cuts

```
define_pT missing = 30.      #  requirement on pT of sum of all neutrinos (lower cut)
```

In particular for technical checks it might be useful to access neutrinos also as individual particles. To do so, MATRIX can process blocks for the particle groups `nua`, `nu`, `nux`, `nea`, `nma`, `ne`, `nex`, `nm` and `nmx`.

User-defined cuts

A number of cuts are defined individually for each process. They enable a realistic definition of fiducial phase spaces as used in experimental measurements. For every process-specific cut there is usually one integer-valued switch (`user_switch`) to either turn on and off a certain cut or to choose between different options. Moreover, each switch typically comes with one or more real-valued parameters (`user_cut`) which are only active if the respective switch is turned on. There are a number of predefined process-specific cuts for each process, all of which are defined directly inside the C++ code in the file `MATRIX_v2.0.0/prc/${process_id}/user/specify.cuts.cxx`. We refer to the manual of the MATRIX `v1` for details. For brevity no user-defined cuts are reported here. Instead we will focus on the new syntax in the next section, which shall eventually supersede the user-defined cuts in MATRIX `v2`.

Fiducial cuts

In MATRIX `v2` we have created a new general syntax that the user can exploit to implement fiducial cuts directly in the input file. They are introduced by setting `fiducial_cut = ${fiducial_cut}`. The following syntax formats of `${fiducial_cut}` are allowed to define a two-sided fiducial cut:

- `${lower_cut_value} < ${observable} < ${upper_cut_value}`
- `${observable} > ${lower_cut_value} < ${upper_cut_value}`

The conditions on either lower or upper cut may be dropped to define a one-sided cut. If both cuts are set and exclude each other, they shall be understood as an "or" condition, which can be used to define some gap in an observable (e.g. `|eta| lep < 1.37 > 1.52` excludes the pseudo-rapidity gap between barrel and endcap in ATLAS for each lepton). Both `${lower_cut_value}` and `${upper_cut_value}` are real-valued numbers, understood in the usual unit of the respective observable. The argument `${observable}` selects one of the predefined observables listed in Tables 4 and 5, and specifies the particles on which the cut is to be applied. The particle arguments are listed one after the other without a separator. Each particle argument consists of a particle group and (optionally) an ordering number in round, square or curly brackets. If the ordering number is specified, the cut is applied only on a specific particle of that group (e.g. `|pT| lep (1) > 50.` applies a p_T cut of 50 GeV only on the hardest lepton). If not, the cut is applied on each particle of that group (e.g. `|pT| lep > 50.` applies a p_T cut of 50 GeV on each lepton). If the same particle group is set more than once in the argument list, the cut is applied on each combination of representatives of that group (e.g. `|M| lep lep > 4.` applies an invariant-mass cut of 4 GeV on any pair of leptons). Note that overlapping particle groups must be avoided since the cut would in general be applied also on combinations of a particle and itself (e.g. `|M| lep e > 4.` would fail since each electron is a lepton). Moreover, fiducial cuts may be defined in this way only for particles that are required at Born level, explicitly including user-defined particles; jets and photons arising as real emissions cannot be consistently addressed in this format at present.

observable	description
`M`	invariant mass of arbitrary number of particles
`pT`	transverse momentum
`|eta|`	absolute value of pseudo-rapidity
`|y|`	absolute value of rapidity

Table 4: Predefined fiducial-cut observables with arbitrarily many particle arguments. The observable is calculated for the vectorial sum of all argument particles.

observable	description
`deta`	pseudo-rapidity difference
`dy`	rapidity difference
`absdeta`	absolute value of pseudo-rapidity difference
`absdy`	absolute value of rapidity difference
`dReta`	distance in R, defined via pseudo-reapidity
`dRy`	distance in R, defined via pseudo-reapidity
`dphi`	distance in azimuthal angle

Table 5: Predefined fiducial-cut observables that require exactly two particle arguments. In order to apply these cuts on composite particles, user-defined particles need to be used.

This generic cut syntax allows the user to apply cuts for a set of predefined observables on various combinations of particles without having to touch the C++ code. Some cuts are too specific to be implemented on this general ground, so user-defined cuts have to be used in certain cases.

Below we provide a few examples of commented fiducial cuts in the `parameter.dat` file of different-flavour off-shell ZZ production (`ppemexmx04`), which can be uncommented and used alternatively to the hard-coded user-defined cuts. Arbitrarily many cuts constructed following such syntax may be added by the user.

```
#fiducial_cut = 66. < M Zrec < 116.          #  invariant-mass cut on reconstructed Z bosons
#fiducial_cut = dReta lep lep > 0.2          #  lepton-lepton separation in eta-phi-plane
#fiducial_cut = dReta e e > 0.0              #  electron-electron separation in eta-phi-plane
#fiducial_cut = dReta mu mu > 0.0            #  muon-muon separation in eta-phi-plane
#fiducial_cut = dReta e mu > 0.0             #  muon-electron separation in eta-phi-plane
#fiducial_cut = pT lep (1) > 7.              #  transverse-momentum cut on hardest lepton
#fiducial_cut = |eta| lep (1) < 2.7          #  pseudo-rapidity cut on hardest lepton
#fiducial_cut = pT lep (2) > 7.              #  transverse-momentum cut on second-hardest lepton
#fiducial_cut = |eta| lep (2) < 2.7          #  pseudo-rapidity cut on second-hardest lepton
#fiducial_cut = pT lep (3) > 7.              #  transverse-momentum cut on third-hardest lepton
#fiducial_cut = |eta| lep (3) < 2.7          #  pseudo-rapidity cut on third-hardest lepton
#fiducial_cut = pT lep (4) > 7.              #  transverse-momentum cut on fourth-hardest lepton
#fiducial_cut = |eta| lep (4) < 2.7          #  pseudo-rapidity cut on fourth-hardest lepton
#fiducial_cut = pT e (1) > 7.                #  transverse-momentum cut on hardest electron
#fiducial_cut = |eta| e (1) < 2.7            #  pseudo-rapidity cut on hardest electron
#fiducial_cut = pT e (2) > 7.                #  transverse-momentum cut on second-hardest electron
```

```
#fiducial_cut = |eta| e (2) < 2.7              #  pseudo-rapidity cut on second-hardest electron
#fiducial_cut = pT mu (1) > 7.                 #  transverse-momentum cut on hardest muon
#fiducial_cut = |eta| mu (1) < 2.7             #  pseudo-rapidity cut on hardest muon
#fiducial_cut = pT mu (2) > 7.                 #  transverse-momentum cut on second-hardest muon
#fiducial_cut = |eta| mu (2) < 2.7             #  pseudo-rapidity cut on second-hardest muon
#fiducial_cut = 120. < M lep lep lep lep < 130.  #  invariant-mass cut on 4-lepton system
```

For instance the very first line can be used instead of setting the following user-defined cuts:

```
user_switch M_Zrec = 1       #  switch for invariant mass cut on reconstructed Z-bosons (OSSF lepton pairs)
user_cut min_M_Zrec = 66.    #  requirement on reconstructed Z-boson invariant mass (lower cut)
user_cut max_M_Zrec = 116.   #  requirement on reconstructed Z-boson invariant mass (upper cut)
```

4.1.1.5 Matrix behaviour

```
max_time_per_job = 12       #  very rough time(hours) one main run job shall take (default: 24h)
                            #  unreliable when < 1h, use as tuning parameter for degree of parallelization
                            #  note: becomes ineffective when job number > max_nr_parallel_jobs
                            #        which is set in MATRIX_configuration file
switch_distribution = 1     #  switch to turn on (1) and off (0) distributions
save_previous_result = 1    #  switch to save previous result of this run (in result/"run"/saved_result_$i)
save_previous_log = 0       #  switch to save previous log of this run (in log/"run"/saved_result_$i)
#include_pre_in_results = 0  #  switch to (0) only include main run in results; (1) also all pre runs;
                            #  crucial to set to 0 if re-running main with different inputs
                            #  note: if missing (default) pre runs used if important for precision
                            #  (separately for each contribution)
reduce_workload = 0         #  switch to keep full job output (0), reduce (1) or minimize (2) workload
random_seed = 0             #  specify integer value (grid-/pre-run reproducible)
```

4.1.2 Settings in model.dat

All model-related parameters are set in the file `model.dat`. We adopt the SUSY Les Houches accord (SLHA) format [10]. This standard format is used in many codes and thus simplifies the settings of common model parameters. In the SLHA format inputs are organized in blocks which have different entries characterized by a number. For simplicity, we introduce the following short-hand notation: `Block example[i]` corresponds to entry i in `Block example`. For example, entry 25 of `Block mass` (`Block mass[25]`) in the SLHA format corresponds to the Higgs mass in the SM, which is required as an input in the file `model.dat`. Only the format for decay widths is slightly different and not organized in a `Block`, but defined by the keyword `DECAY`, followed by a number which specifies the respective particle. A typical model file is shown below.

```
##########################
# MATRIX model parameter #
##########################

#--------\
# masses |
#--------/
Block MASS
  1 0.000000     # M_d
  2 0.000000     # M_u
  3 0.000000     # M_s
  4 0.000000     # M_c
  5 0.000000     # M_b
  6 1.732000e+02 # M_t
 11 0.000000     # M_e
 12 0.000000     # M_ve
```

```
 13 0.000000     # M_mu
 14 0.000000     # M_vm
 15 1.777000e+00 # M_tau
 16 0.000000     # M_vt
 23 9.118760e+01 # M_Z
 24 8.038500e+01 # M_W
 25 1.250000e+02 # M_H

#-------------------\
# inputs for the SM |
#-------------------/
Block SMINPUTS
  1 1.280000e+02 # 1/alpha_e(MZ)
  2 1.166390e-05 # G_F
111 1.370360e+02 # 1/alpha_e(mu->0)

#------------------\
# Yukawa couplings |
#------------------/
#Block YUKAWA
#  5 4.750000e+00 # M_YB
#  6 1.730000e+02 # M_YT
# 15 1.777000e+00 # M_YTAU

#---------------\
# decays widths |
#---------------/
DECAY  6 1.442620e+00 # WT
DECAY 23 2.495200e+00 # WZ
DECAY 24 2.085400e+00 # WW
DECAY 25 4.070000e-03 # WH

#-----------\
# EW inputs |
#-----------/
Block EWINPUTS
  1 1  # ew_scheme - determines scheme used for EW inputs
       # 0: alpha_e_0 scheme (alpha_e(mu->0) above used to determine inputs)
       # 1: G_mu scheme (G_F above used to determine inputs)
       # 2: alpha_e_MZ scheme (alpha_e(MZ) above used to determine inputs)
  3 1  # use_cms - switch for the complex mass scheme
       # 0: off
       # 1: on
       # 2: on, but alpha_e is determined through real parameters
```

The `Block SMINPUTS` has two new inputs for the EW coupling, and the block `EWINPUTS` has been added in order to deal with different schemes used in the computation of the couplings and matrix elements, which is particularly important in the context of EW corrections. In particular, you may choose between different EW schemes for the EW coupling, following the same settings that are available in OpenLoops, i.e. either through $\alpha_e(m_Z)$ set in `SMINPUTS`, evaluated in the G_μ scheme with G_F from `SMINPUTS` (default), or using $\alpha_e(0)$ from `SMINPUTS`. Note that in all of these schemes $\alpha_e(0)$ is consistently used for the coupling of identified final-state photons, whereas $\alpha_e(G_\mu)$ (`ew_scheme = 0,1`) or $\alpha_e(M_Z)$ (`ew_scheme = 2`) is always used for the coupling of initial-state photons, and the renormalization of the couplings is performed accordingly. Of course at LO (and when only including QCD corrections) this corresponds to an overall rescaling of the coupling factor, and could also be changed a posteriori. Additionally, the user can choose whether the complex-mass scheme should be used in the matrix elements.

4.1.3 Settings in `distribution.dat`

We refer to the manual of the MATRIX `v1` for details, as distributions are still defined with the same general syntax. Moreover, the default file `distribution.dat` contains further examples and information, as well as instructions on how to define distributions in the right format.

4.2 Process-specific settings

The majority of process-specific settings in MATRIX `v2` is still the same as in `v1`. There are a few new predefined cuts and dynamical scales implemented for some of the processes. However, those appear in the input files of the respective processes and are rather self-explanatory. For simplicity, we do not list them here. Moreover, with the newly implemented general syntax for fiducial cuts, introduced above, most of the predefined cuts can be superseded.

5 Phenomenological results

In this Section we present results on integrated cross sections for all processes available in the MATRIX `v2` release. As in `v1` we report a table with LO, NLO, NNLO predictions in QCD perturbation theory, and the loop-induced gluon fusion contribution at LO, if applicable. Additionally, we provide a table reporting NLO EW corrections, NLO QCD predictions for the loop-induced gluon fusion contribution, as well as various individual contributions (splitting $q\bar{q}$, gg, and $\gamma\gamma$ contributions) and various combinations of QCD and EW corrections, as provided in an NNLO run. The results in this Section are obtained with the MATRIX `v2` default setup for each of these processes. Their purpose is both to provide benchmark numbers for all processes that can be evaluated with MATRIX, and to give a reference for the user: These benchmark results can be reproduced (on a statistical level) if no changes are applied to the default input cards (except for turning on the corresponding perturbative orders and the targeted precision the user is interested in). We indicate in green colour everything that has changed in the `v2` compared to the `v1` release.

5.1 Settings

We consider proton–proton collisions at the 13 TeV LHC. In terms of the input of the weak parameters, the G_μ scheme is employed: When considering leptonic final states, which are always produced via off-shell EW vector bosons, we use the complex-mass scheme [11] throughout, i.e. we use complex W- and Z-boson masses and define the EW mixing angle as $\cos\theta_W^2 = (m_W^2 - i\Gamma_W\, m_W)/(m_Z^2 - i\Gamma_Z\, m_Z)$ and $\alpha = \sqrt{2}\, G_\mu m_W^2 \sin^2\theta_W/\pi$, using the PDG [12] values $G_F = 1.16639 \times 10^{-5}\,\mathrm{GeV}^{-2}$, $m_W = 80.385\,\mathrm{GeV}$, $\Gamma_W = 2.0854\,\mathrm{GeV}$, $m_Z = 91.1876\,\mathrm{GeV}$ and $\Gamma_Z = 2.4952\,\mathrm{GeV}$. For couplings to identified final-state photons MATRIX `v2` uses $\alpha(0)$ evaluated from the above parameters instead of α in the G_μ scheme (as in MATRIX `v1`) or the $\alpha(M_Z)$ scheme, which is a more appropriate setting for identified final-state photons and also the new default in OPENLOOPS. Furthermore, we set $m_H = 125\,\mathrm{GeV}$ and $\Gamma_H = 0.00407\,\mathrm{GeV}$. When considering on-shell single-boson production or on-shell production of heavy-boson pairs, the masses of the weak vector bosons and the weak mixing angle are consistently kept real by setting $\Gamma_W = \Gamma_Z = 0$, and we also use a real Higgs boson mass, i.e. $\Gamma_H = 0$. The number of heavy-quark flavours depends on the applied flavour scheme. All processes involving W^+W^- contributions use the 4FS as default to consistently remove top-quark contamination by dropping the (separately IR finite) partonic processes with real bottom-quark emissions. In the 4FS we use the on-shell bottom mass $m_b = 4.92\,\text{GeV}$. All other processes apply the 5FS with a vanishing bottom mass $m_b = 0$. The top quark is treated as massive and unstable throughout, and we set $m_t = 173.2\,\text{GeV}$ as well as $\Gamma_t = 1.44262\,\text{GeV}$.[1] Consistently, we use parton distributions (PDFs) with $n_f = 4$ or $n_f = 5$ active quark flavours. For processes where NLO EW corrections are available (see Table 1) we use the NNPDF3.1 [13] sets with with LUX QED [14] photon PDFs, while otherwise we keep the MATRIX `v1` default set NNPDF3.0 [15]. In Table 6, N^{n}LO ($n = 0, 1, 2$) predictions have been obtained by using PDFs at the respective perturbative order and the evolution of α_S at $(n+1)$-loop order, as provided by the corresponding PDF set,[2] while in Table 7a-7c all results originate from an NNLO run, i.e. they have been obtained with NNLO PDFs throughout. The CKM matrix is set to unity except for the production of a single (on- or off-shell) $W^\pm$ boson. In that case we use the PDG SM values as reported in Ref. [12]:

$$V_\text{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.97417 & 0.2248 & 0.00409 \\ 0.22 & 0.995 & 0.0405 \\ 0.0082 & 0.04 & 1.009 \end{pmatrix}. \quad (2)$$

Note that in the EW corrections to off-shell $W^\pm$ production the one-loop diagrams with CKM are not available within OPENLOOPS. Therefore, we approximate only the one-loop EW contribution using a trivial CKM matrix (`approx_ckm_EW = 1`). We also allow for a second option (`approx_ckm_EW = 2`) in the inputs, where the entire NLO EW correction (including also the reals and the counter terms) are computed with a trivial CKM matrix. However, in all use-cases we considered we have found that the differences between those two approximations are numerically subleading, so that it is reasonable to assume that CKM effects in the EW corrections are negligible and our approximation fully justified.

Our reference choice μ_0 for renormalization (μ_R) and factorization (μ_F) scales as well as the set of cuts applied in our default setups depend on the individual process. Both are reported when discussing the results in the upcoming Section. Uncertainties from missing higher-order contributions are estimated in the usual way by independently varying μ_R and μ_F in the range $0.5\mu_0 \le \mu_R, \mu_F \le 2\mu_0$, with the constraint $0.5 \le \mu_R/\mu_F \le 2$. Unless specified otherwise, jets are defined by the anti-k_T clustering algorithm [16], $R = 0.4$, $p_{T,j} > 25\,\text{GeV}$ and $|\eta_j| < 4.5$.

[1] Massive top-quark contributions are neglected in the virtual two-loop corrections, but are kept anywhere else in the computations. Besides the fact that massive quark contributions in the two-loop amplitudes are not available and at the edge of current technology, their numerical effect can be expected to be negligible in most cases.

[2] More precisely, for processes where NLO EW corrections are included we use `NNPDF31_nlo_as_0118_luxqed` at LO and NLO, since the corresponding LO set is not available, and `NNPDF31_nnlo_as_0118_luxqed` at NNLO in the 5FS with $\alpha_\text{S}^{(5F)}(m_Z) = 0.1180$, while in the 4FS we use `NNPDF31_nlo_as_0118_luxqed_nf_4` and `NNPDF31_nnlo_as_0118_luxqed_nf_4` with $\alpha_\text{S}^{(4F)}(m_Z) = 0.1180$, respectively. For the other processes, in the 5FS we use `NNPDF30_lo_as_0118`, `NNPDF30_nlo_as_0118`, and `NNPDF30_nnlo_as_0118` at LO, NLO, and NNLO, corresponding to $\alpha_\text{S}^{(5F)}(m_Z) = 0.1180$ throughout. In the 4FS we use `NNPDF30_lo_as_0118_nf_4`, `NNPDF30_nlo_as_0118_nf_4`, and `NNPDF30_nnlo_as_0118_nf_4` at LO, NLO, and NNLO, corresponding to $\alpha_\text{S}^{(4F)}(m_Z) = 0.1136$, 0.1123, and 0.1123, respectively.

5.2 Cross-section predictions

Reference LO, NLO QCD and NNLO QCD predictions of the integrated cross sections for all processes that are available in Matrix v2 are reported in Table 6. Note that the processes under consideration feature cross sections that may differ by several orders of magnitude, starting from a few fb up to several nb.

Two results are reported at NNLO QCD: $\sigma^{r_{\rm cut}}_{\rm NNLO\ QCD}$ denotes the NNLO QCD cross section at a fixed $r_{\rm cut}$ value; the default $r_{\rm cut} = 0.15\%$ is used throughout for our reference results. Our best prediction is denoted as $\sigma^{\rm extrapolated}_{\rm NNLO\ QCD}$, and it is determined by the $r_{\rm cut} \to 0$ extrapolation of the $r_{\rm cut}$ dependence between $r_{\rm cut} = 0.15\%$ and $r_{\rm cut} = 1\%$ (see Ref. [1] for details). Both NNLO QCD predictions are provided at the end of every Matrix run, and for each process the results in Table 6 are taken from the same Matrix run. The relative uncertainties, automatically computed by the code, refer to customary 7-point $\mu_{\rm R}$ and $\mu_{\rm F}$ variations.[3] The numerical uncertainty is reported in round brackets for all our predictions. For $\sigma^{\rm extrapolated}_{\rm NNLO\ QCD}$ this uncertainty is obtained by combining the statistical uncertainty from Monte Carlo integration with the systematic uncertainty induced by the $r_{\rm cut}$ dependence.

Besides results at LO, NLO QCD and NNLO QCD accuracy, a separate column refers to the absolute (and relative) size of the loop-induced gluon fusion component at LO $\sigma^{gg}_{\rm LO}$ ($\sigma^{gg}_{\rm LO}/\Delta\sigma^{\rm ext}_{\rm NNLO}$) of the NNLO QCD corrections, where applicable. The absolute size of the NNLO QCD contributions for the extrapolated result is defined as $\Delta\sigma^{\rm ext}_{\rm NNLO\ QCD} = \sigma^{\rm extrapolated}_{\rm NNLO\ QCD} - \sigma_{\rm NLO\ QCD}$, where $\sigma_{\rm NLO\ QCD}$ is computed with NLO PDFs. Two additional columns refer to the relative size of the radiative corrections in terms of K factors at NLO QCD and NNLO QCD, defined as

$$K_{\rm NLO\ QCD} = \frac{\sigma_{\rm NLO\ QCD}}{\sigma_{\rm LO}} \quad \text{and} \quad K_{\rm NNLO\ QCD} = \frac{\sigma_{\rm NNLO\ QCD}}{\sigma_{\rm NLO\ QCD}}\,. \tag{3}$$

The latter are computed from our best NNLO QCD predictions, i.e. the extrapolated NNLO QCD results.

Table 6 corresponds essentially to that presented in the Matrix v1 manuscript [1], but with the default inputs of Matrix v2 that have been updated for some of the processes. Those processes are indicated by green colour in Table 6. In particular, we recall that all processes including EW corrections use a different PDF set now and the processes with final-state photons use $\alpha(0)$ for the photon coupling. The latter has the effect of reducing the cross section by a factor of $\alpha/\alpha(0) \approx 1.0363...$ for each photon coupling. Moreover, we have updated the default inputs for all processes involving off-shell ZZ resonances following our study in Ref. [17], as discussed below. All other processes (in black) should be statistically compatible with those quoted in the corresponding table of the Matrix v1 release [1].

On the other hand, Table 7a-7c is an entirely new table for Matrix v2 that provides all relevant information for processes with NLO EW corrections Table 7a-7c and, if applicable, with NLO QCD corrections to the loop-induced gluon fusion contribution. All cross sections reported in this table have been computed from an NNLO Matrix run (with NLO EW and NLO QCD for gg turned on), i.e. NNLO PDFs have been used throughout, so that they can be directly compared to the respective Matrix on-screen/summary output. The superscript $q\bar{q}$ indicates that the cross section has been obtained by computing corrections to the $q\bar{q}$ channel only, without

[3] The automatic evaluation of PDF uncertainties is not yet supported in Matrix, but is planned for a future release.

process (${process_id})	σ_{LO}	$\sigma_{\mathrm{NLO\ QCD}}$	$\sigma^{gg}_{\mathrm{LO}}$ ($\sigma^{gg}_{\mathrm{LO}}/\Delta\sigma^{\mathrm{ext}}_{\mathrm{NNLO}}$)	$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO\ QCD}}$	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO\ QCD}}$	K_{NLO}	K_{NNLO}
$pp \to H$ (pph21)	$15.42(0)^{+22\%}_{-17\%}$ pb	$30.26(1)^{+20\%}_{-15\%}$ pb	—	$39.98(2)^{+11\%}_{-10\%}$ pb	$39.98(3)^{+11\%}_{-10\%}$ pb	+96.2%	+32.1%
$pp \to Z$ (ppz01)	$49.29(0)^{+11\%}_{-12\%}$ nb	$56.26(1)^{+3.0\%}_{-4.7\%}$ nb	—	$57.56(3)^{+0.80\%}_{-1.1\%}$ nb	$57.55(3)^{+0.80\%}_{-1.1\%}$ nb	+14.1%	+2.30%
$pp \to W^-$ (ppw01)	$60.15(0)^{+13\%}_{-14\%}$ nb	$75.98(2)^{+3.3\%}_{-5.3\%}$ nb	—	$78.42(3)^{+0.98\%}_{-1.3\%}$ nb	$78.41(7)^{+0.98\%}_{-1.2\%}$ nb	+26.3%	+3.19%
$pp \to W^+$ (ppwx01)	$81.27(1)^{+13\%}_{-14\%}$ nb	$102.2(0)^{+3.4\%}_{-5.3\%}$ nb	—	$105.8(0)^{+0.94\%}_{-1.3\%}$ nb	$105.9(1)^{+0.93\%}_{-1.3\%}$ nb	+25.8%	+3.60%
$pp \to e^-e^+$ (ppeex02)	$703.8(1)^{+13\%}_{-14\%}$ pb	$738.4(2)^{+2.8\%}_{-4.3\%}$ pb	—	$758.1(3)^{+0.47\%}_{-0.71\%}$ pb	$763.6(43)^{+0.38\%}_{-0.77\%}$ pb	+4.92%	+3.42%
$pp \to \nu_e\bar{\nu}_e$ (ppnenex02)	$3276(0)^{+12\%}_{-13\%}$ pb	$3726(1)^{+2.9\%}_{-4.7\%}$ pb	—	$3803(2)^{+0.82\%}_{-1.1\%}$ pb	$3802(3)^{+0.82\%}_{-1.1\%}$ pb	+13.7%	+2.05%
$pp \to e^-\bar{\nu}_e$ (ppenex02)	$3477(0)^{+13\%}_{-14\%}$ pb	$3828(1)^{+2.9\%}_{-5.1\%}$ pb	—	$3883(2)^{+0.86\%}_{-0.93\%}$ pb	$3883(4)^{+0.85\%}_{-0.93\%}$ pb	+10.1%	+1.45%
$pp \to e^+\nu_e$ (ppexne02)	$4605(0)^{+13\%}_{-14\%}$ pb	$5048(1)^{+2.9\%}_{-5.0\%}$ pb	—	$5109(3)^{+0.90\%}_{-0.96\%}$ pb	$5104(6)^{+0.92\%}_{-0.97\%}$ pb	+9.62%	+1.10%
$pp \to \gamma\gamma$ (ppaa02)	$5.209(0)^{+10\%}_{-11\%}$ pb	$23.98(1)^{+8.8\%}_{-7.5\%}$ pb	$2.360(1)^{+24\%}_{-18\%}$ pb (17.5%)	$38.04(2)^{+8.7\%}_{-7.2\%}$ pb	$37.50(27)^{+8.5\%}_{-7.0\%}$ pb	+360%	+56.4%
$pp \to e^-e^+\gamma$ (ppeexa03)	$1419(0)^{+12\%}_{-12\%}$ fb	$2045(1)^{+2.9\%}_{-4.6\%}$ fb	$15.49(1)^{+24\%}_{-18\%}$ fb (7.67%)	$2247(1)^{+1.2\%}_{-1.3\%}$ fb	$2247(7)^{+1.2\%}_{-1.3\%}$ fb	+44.1%	+9.88%
$pp \to \nu_e\bar{\nu}_e\gamma$ (ppnenexa03)	$61.44(1)^{+2.7\%}_{-3.5\%}$ fb	$95.39(3)^{+3.3\%}_{-2.7\%}$ fb	$2.473(1)^{+26\%}_{-19\%}$ fb (17.7%)	$110.7(1)^{+3.2\%}_{-2.6\%}$ fb	$109.3(7)^{+2.9\%}_{-2.4\%}$ fb	+55.3%	+14.6%
$pp \to e^-\bar{\nu}_e\gamma$ (ppenexa03)	$701.3(1)^{+11\%}_{-12\%}$ fb	$1786(0)^{+6.6\%}_{-5.3\%}$ fb	—	$2208(1)^{+4.0\%}_{-3.7\%}$ fb	$2177(16)^{+3.6\%}_{-3.5\%}$ fb	+155%	+21.9%
$pp \to e^+\nu_e\gamma$ (ppexnea03)	$832.2(1)^{+10\%}_{-11\%}$ fb	$2113(1)^{+6.6\%}_{-5.3\%}$ fb	—	$2616(1)^{+4.1\%}_{-3.8\%}$ fb	$2592(12)^{+3.8\%}_{-3.6\%}$ fb	+154%	+22.7%
$pp \to ZZ$ (ppzz02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1.361(0)^{+25\%}_{-19\%}$ pb (52.4%)	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	$16.69(2)^{+3.2\%}_{-2.7\%}$ pb	+43.2%	+18.4%
$pp \to W^+W^-$ (ppwxw02)	$66.66(1)^{+5.7\%}_{-6.7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4.097(2)^{+27\%}_{-19\%}$ pb (29.4%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.2(1)^{+2.5\%}_{-2.3\%}$ pb	+54.9%	+13.5%
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$15.74(0)^{+5.3\%}_{-6.5\%}$ fb	$21.09(0)^{+3.0\%}_{-2.4\%}$ fb	$2.214(0)^{+25\%}_{-19\%}$ fb (57.5%)	$24.95(1)^{+3.4\%}_{-2.8\%}$ fb	$24.93(1)^{+3.5\%}_{-2.8\%}$ fb	+34.0%	+18.2%
$pp \to e^-e^-e^+e^+$ (ppeeexex04)	$9.006(1)^{+5.2\%}_{-6.3\%}$ fb	$12.06(0)^{+3.0\%}_{-2.4\%}$ fb	$1.219(0)^{+25\%}_{-19\%}$ fb (56.8%)	$14.22(1)^{+3.4\%}_{-2.7\%}$ fb	$14.21(1)^{+3.4\%}_{-2.7\%}$ fb	+33.9%	+17.8%
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	$3.893(0)^{+2.2\%}_{-3.2\%}$ fb	$2.811(1)^{+5.3\%}_{-5.3\%}$ fb	$0.5783(0)^{+29\%}_{-21\%}$ fb (94.6%)	$3.422(1)^{+5.3\%}_{-3.0\%}$ fb	$3.423(1)^{+5.3\%}_{-3.0\%}$ fb	−27.8%	+21.8%
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$271.1(0)^{+6.0\%}_{-7.1\%}$ fb	$253.5(1)^{+2.8\%}_{-2.4\%}$ fb	$26.85(0)^{+27\%}_{-19\%}$ fb (102%)	$279.9(1)^{+2.1\%}_{-1.3\%}$ fb	$279.8(1)^{+2.1\%}_{-1.3\%}$ fb	−6.46%	+10.4%
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)	$4.514(0)^{+2.4\%}_{-3.3\%}$ fb	$3.476(1)^{+4.5\%}_{-4.5\%}$ fb	$0.7391(2)^{+28\%}_{-21\%}$ fb (101%)	$4.204(4)^{+4.8\%}_{-2.8\%}$ fb	$4.207(11)^{+4.8\%}_{-2.8\%}$ fb	−23.0%	+21.0%
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$13.03(0)^{+5.1\%}_{-6.3\%}$ fb	$24.22(0)^{+5.5\%}_{-4.4\%}$ fb	—	$26.75(1)^{+2.3\%}_{-2.1\%}$ fb	$26.74(2)^{+2.3\%}_{-2.1\%}$ fb	+86.0%	+10.4%
$pp \to e^-e^-e^+\bar{\nu}_e$ (ppeeexnex04)	$13.06(0)^{+5.1\%}_{-6.3\%}$ fb	$24.29(1)^{+5.5\%}_{-4.4\%}$ fb	—	$26.83(1)^{+2.3\%}_{-2.1\%}$ fb	$26.84(1)^{+2.3\%}_{-2.1\%}$ fb	+86.0%	+10.5%
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	$19.60(0)^{+4.8\%}_{-6.0\%}$ fb	$35.16(1)^{+5.2\%}_{-4.2\%}$ fb	—	$38.81(2)^{+2.2\%}_{-2.0\%}$ fb	$38.79(3)^{+2.3\%}_{-2.0\%}$ fb	+79.4%	+10.3%
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	$19.64(0)^{+4.8\%}_{-6.0\%}$ fb	$35.25(1)^{+5.2\%}_{-4.2\%}$ fb	—	$38.91(2)^{+2.2\%}_{-2.0\%}$ fb	$38.91(2)^{+2.2\%}_{-2.0\%}$ fb	+79.5%	+10.4%

Table 6: Integrated cross sections for all available processes in MATRIX using the default setups. Process with updated inputs in MATRIX `v2` with respect to `v1` are marked in green.

photon-induced or loop-induced gg contributions (the $q\bar{q}$ channel naturally includes qg and $\bar{q}g$ channels at NLO QCD as well as further gg and $q(\bar{q})q'$ channels at NNLO QCD). The superscript gg refers to the loop-induced gluon fusion contribution, and the cross sections with superscript $\gamma\gamma$ state the photon-induced contributions. Note that the $\gamma q \equiv \{\gamma q, \gamma\bar{q}, q\gamma, \bar{q}\gamma\}$ channel appearing at NLO EW mixes NLO EW corrections to the $q\bar{q}$ and $\gamma\gamma$ channels, which are both included in $\sigma_{\mathrm{NLO}}^{\gamma\gamma/\gamma q}$. Besides individual QCD and EW corrections Table 7a-7c also reports combined results. "nNNLO" refers to adding NNLO QCD predictions in the $q\bar{q}$ channel and NLO QCD predictions in the loop-induced gg channel. The additive combination of QCD and EW corrections is indicated by "+", while the fully factorized combination (including photon-induced and NLO gg contributions) is indicated by a simple "×". There are two more factorized combinations that exclude certain parts from being factorized: "NNLO QCD×EW+ggNLO" adds the loop-induced gg contributions (both LO and NLO) separately, while "nNNLO QCD×EW$_{\mathrm{qq}}$" separately adds both the loop-induced gg contributions and the photon-induced contributions up to NLO, while only keeping the $q\bar{q}$ QCD and EW corrections factorized. We refer to Ref. [5] for a rigorous definition of those combinations.

We now comment on the (default) cuts and scales that have been used to produce the numbers in Tables 6 and 7a-7c. For all production processes involving massive on-shell bosons (H, Z, $W^\pm$, W^+W^- and ZZ production), Tables 6 and 7a-7c report fully inclusive cross sections, i. e. no phase-space cuts are applied. For all remaining processes, phase-space cuts are applied on the final-state leptons, neutrinos and photons in order to simulate a realistic selection in a fiducial volume. The respective sets of cuts for each of these processes are discussed below. For studies of phenomenological results we refer to dedicated publications on the respective processes.

Higgs boson production

The corresponding cross sections in Table 6 have been computed with fixed renormalization and factorization scales set to $\mu_0 = m_H$.

Drell–Yan production

The results reported in Table 6 are obtained with renormalization and factorization scales set to $\mu_0 = m_Z$ and $\mu_0 = m_W$ for $pp \to Z$ and $pp \to W^\pm$, respectively. The same fixed scales are applied to the corresponding off-shell processes. The sets of cuts applied to the off-shell processes are summarized in Table 8.

Diphoton and vector-boson plus photon production

For diphoton production we choose the invariant mass of the photon pair as the central scale, i.e. $\mu_0 = m_{\gamma\gamma}$, and the fiducial cuts are summarized in Table 8. For the associated production of an off-shell vector boson with a photon, i.e. the leptonic final states $e^-e^+\gamma/\nu_e\bar{\nu}_e\gamma$ (summarized as $Z\gamma$ production) and $e^+\nu_e\gamma/e^-\bar{\nu}_e\gamma$ (summarized as $W\gamma$ production),[4] the cuts are summarized in Table 9, which has been adopted from Ref. [18]. The dynamical scale $\mu_0 = \sqrt{m_V^2 + p_{T,\gamma}^2}$ is chosen as central value for both renormalization and factorization scales, where $m_V = m_Z$ for $Z\gamma$ and $m_V = m_W$ for $W\gamma$ production.

[4]We note again that $Z\gamma$ and $W\gamma$ are only used as shorthand notations here. The full amplitudes for the leptonic final states are used throughout without any approximation, including off-shell effects and spin correlations.

process (${process_id})	$pp \to Z$ (ppz01)	$pp \to e^- e^+$ (ppeex02)	$pp \to \nu_e \bar{\nu}_e$ (ppnenex02)	$pp \to e^- \bar{\nu}_e$ (ppenex02)	$pp \to e^+ \nu_e$ (ppexne02)
$\sigma^{q\bar{q}}_{\text{LO}}$	$50.53(0)^{+11\%}_{-12\%}$ nb	$723.1(0)^{+12\%}_{-13\%}$ pb	$3358(0)^{+11\%}_{-12\%}$ pb	$3581(0)^{+13\%}_{-14\%}$ pb	$4733(0)^{+13\%}_{-14\%}$ pb
$\sigma^{q\bar{q}}_{\text{NLO QCD}}$	$57.87(1)^{+2.9\%}_{-4.6\%}$ nb	$761.7(1)^{+2.6\%}_{-4.1\%}$ pb	$3831(0)^{+2.8\%}_{-4.6\%}$ pb	$3956(0)^{+2.8\%}_{-4.9\%}$ pb	$5206(0)^{+2.8\%}_{-4.9\%}$ pb
$\sigma^{q\bar{q}}_{\text{NLO EW}}$	$50.35(0)^{+11\%}_{-12\%}$ nb	$703.7(0)^{+12\%}_{-13\%}$ pb	$3378(0)^{+11\%}_{-12\%}$ pb	$3525(0)^{+13\%}_{-14\%}$ pb	$4652(0)^{+13\%}_{-14\%}$ pb
$\sigma^{q\bar{q},\, r_{\text{cut}}}_{\text{NNLO QCD}}$	$57.56(3)^{+0.80\%}_{-1.1\%}$ nb	$757.5(3)^{+0.45\%}_{-0.69\%}$ pb	$3803(2)^{+0.82\%}_{-1.1\%}$ pb	$3883(2)^{+0.86\%}_{-0.93\%}$ pb	$5109(3)^{+0.90\%}_{-0.96\%}$ pb
$\sigma^{q\bar{q},\,\text{extrapolated}}_{\text{NNLO QCD}}$	$57.55(3)^{+0.80\%}_{-1.1\%}$ nb	$762.9(43)^{+0.36\%}_{-0.76\%}$ pb	$3802(3)^{+0.82\%}_{-1.1\%}$ pb	$3883(4)^{+0.85\%}_{-0.93\%}$ pb	$5104(6)^{+0.92\%}_{-0.97\%}$ pb
σ^{gg}_{LO}	—	—	—	—	—
$\sigma^{gg}_{\text{NLO QCD}}$	—	—	—	—	—
$\sigma^{\gamma\gamma}_{\text{LO}}$	—	$0.6501(0)^{+23\%}_{-20\%}$ pb	—	—	—
$\sigma^{\gamma\gamma/q\gamma}_{\text{NLO EW}}$	$-0.003485(6)^{+120\%}_{-159\%}$ nb	$0.3067(1)^{+32\%}_{-45\%}$ pb	$-0.2392(4)^{+117\%}_{-155\%}$ pb	$2.558(2)^{+3.0\%}_{-8.5\%}$ pb	$3.186(2)^{+0.68\%}_{-5.1\%}$ pb
σ_{LO}	$50.53(0)^{+11\%}_{-12\%}$ nb	$723.7(0)^{+12\%}_{-13\%}$ pb	$3358(0)^{+11\%}_{-12\%}$ pb	$3581(0)^{+13\%}_{-14\%}$ pb	$4733(0)^{+13\%}_{-14\%}$ pb
$\sigma_{\text{NLO QCD}}$	$57.87(1)^{+2.9\%}_{-4.6\%}$ nb	$762.4(1)^{+2.7\%}_{-4.2\%}$ pb	$3831(0)^{+2.8\%}_{-4.6\%}$ pb	$3956(0)^{+2.8\%}_{-4.9\%}$ pb	$5206(0)^{+2.8\%}_{-4.9\%}$ pb
$\sigma_{\text{NLO EW}}$	$50.35(0)^{+11\%}_{-12\%}$ nb	$704.0(0)^{+12\%}_{-13\%}$ pb	$3377(0)^{+11\%}_{-12\%}$ pb	$3528(0)^{+13\%}_{-14\%}$ pb	$4655(0)^{+13\%}_{-14\%}$ pb
$\sigma_{\text{NLO QCD+EW}}$	$57.69(1)^{+2.9\%}_{-4.6\%}$ nb	$742.6(1)^{+2.4\%}_{-3.9\%}$ pb	$3850(0)^{+2.9\%}_{-4.7\%}$ pb	$3903(0)^{+2.8\%}_{-4.9\%}$ pb	$5128(0)^{+2.7\%}_{-4.8\%}$ pb
$\sigma_{\text{NLO QCD}\times\text{EW}}$	$57.67(1)^{+2.9\%}_{-4.6\%}$ nb	$741.6(1)^{+2.7\%}_{-4.2\%}$ pb	$3853(0)^{+2.9\%}_{-4.6\%}$ pb	$3897(0)^{+2.9\%}_{-5.0\%}$ pb	$5120(0)^{+2.9\%}_{-4.9\%}$ pb
$\sigma_{\text{NLO QCD}\times\text{EW}_{\text{qq}}}$	—	$741.6(1)^{+2.7\%}_{-4.2\%}$ pb	—	—	—
$\sigma^{r_{\text{cut}}}_{\text{NNLO QCD}}$	$57.56(3)^{+0.80\%}_{-1.1\%}$ nb	$758.1(3)^{+0.47\%}_{-0.71\%}$ pb	$3803(2)^{+0.82\%}_{-1.1\%}$ pb	$3883(2)^{+0.86\%}_{-0.93\%}$ pb	$5109(3)^{+0.90\%}_{-0.96\%}$ pb
$\sigma^{\text{extrapolated}}_{\text{NNLO QCD}}$	$57.55(3)^{+0.80\%}_{-1.1\%}$ nb	$763.6(43)^{+0.38\%}_{-0.77\%}$ pb	$3802(3)^{+0.82\%}_{-1.1\%}$ pb	$3883(4)^{+0.85\%}_{-0.93\%}$ pb	$5104(6)^{+0.92\%}_{-0.97\%}$ pb
$\sigma^{r_{\text{cut}}}_{\text{nNNLO QCD}}$	—	—	—	—	—
$\sigma^{\text{extrapolated}}_{\text{nNNLO QCD}}$	—	—	—	—	—
$\sigma^{r_{\text{cut}}}_{\text{(n)NNLO QCD+EW}}$	$57.38(3)^{+0.83\%}_{-1.1\%}$ nb	$738.4(3)^{+0.24\%}_{-0.44\%}$ pb	$3823(2)^{+0.93\%}_{-1.2\%}$ pb	$3830(2)^{+0.77\%}_{-0.81\%}$ pb	$5031(3)^{+0.78\%}_{-0.80\%}$ pb
$\sigma^{\text{extrapolated}}_{\text{(n)NNLO QCD+EW}}$	$57.38(3)^{+0.83\%}_{-1.1\%}$ nb	$743.9(43)^{+0.34\%}_{-0.45\%}$ pb	$3821(3)^{+0.93\%}_{-1.2\%}$ pb	$3830(4)^{+0.77\%}_{-0.80\%}$ pb	$5026(6)^{+0.80\%}_{-0.82\%}$ pb
$\sigma^{r_{\text{cut}}}_{\text{(n)NNLO QCD}\times\text{EW}}$	$57.35(3)^{+0.86\%}_{-1.1\%}$ nb	$737.5(3)^{+0.49\%}_{-0.72\%}$ pb	$3825(2)^{+0.88\%}_{-1.1\%}$ pb	$3825(2)^{+0.94\%}_{-1.0\%}$ pb	$5025(3)^{+0.96\%}_{-1.0\%}$ pb
$\sigma^{\text{extrapolated}}_{\text{(n)NNLO QCD}\times\text{EW}}$	$57.35(3)^{+0.86\%}_{-1.1\%}$ nb	$742.8(42)^{+0.40\%}_{-0.79\%}$ pb	$3824(3)^{+0.88\%}_{-1.1\%}$ pb	$3826(4)^{+0.93\%}_{-1.0\%}$ pb	$5020(6)^{+0.98\%}_{-1.0\%}$ pb
$\sigma^{r_{\text{cut}}}_{\text{NNLO QCD}\times\text{EW}+gg\text{NLO}}$	—	—	—	—	—
$\sigma^{\text{extrapolated}}_{\text{NNLO QCD}\times\text{EW}+gg\text{NLO}}$	—	—	—	—	—
$\sigma^{r_{\text{cut}}}_{\text{nNNLO QCD}\times\text{EW}_{\text{qq}}}$	—	—	—	—	—
$\sigma^{\text{extrapolated}}_{\text{nNNLO QCD}\times\text{EW}_{\text{qq}}}$	—	—	—	—	—

Table 7a: Integrated cross sections for all available processes with EW corrections in MATRIX using the default setups for a NNLO run (i.e. using NNLO PDFs throughout).

process (${process_id})	$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$pp \to e^-e^-e^+e^+$ (ppeeexex04)	$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)
$\sigma^{q\bar{q}}_{\mathrm{LO}}$	$16.04(0)^{+5.0\%}_{-6.1\%}$ fb	$9.164(0)^{+4.9\%}_{-6.0\%}$ fb	$3.948(0)^{+2.0\%}_{-2.9\%}$ fb	$272.8(0)^{+5.6\%}_{-6.7\%}$ fb	$4.551(0)^{+2.1\%}_{-3.0\%}$ fb
$\sigma^{q\bar{q}}_{\mathrm{NLO\ QCD}}$	$21.46(0)^{+3.0\%}_{-2.4\%}$ fb	$12.27(0)^{+3.0\%}_{-2.4\%}$ fb	$2.866(0)^{+5.2\%}_{-5.2\%}$ fb	$255.9(0)^{+2.4\%}_{-2.1\%}$ fb	$3.512(1)^{+4.3\%}_{-4.3\%}$ fb
$\sigma^{q\bar{q}}_{\mathrm{NLO\ EW}}$	$14.85(0)^{+5.1\%}_{-6.2\%}$ fb	$8.506(0)^{+5.0\%}_{-6.1\%}$ fb	$3.495(0)^{+2.2\%}_{-3.1\%}$ fb	$264.4(0)^{+5.7\%}_{-6.8\%}$ fb	$4.057(0)^{+2.3\%}_{-3.1\%}$ fb
$\sigma^{q\bar{q},\ r_{\mathrm{cut}}}_{\mathrm{NNLO\ QCD}}$	$22.72(1)^{+1.4\%}_{-1.3\%}$ fb	$12.98(1)^{+1.4\%}_{-1.3\%}$ fb	$2.843(1)^{+0.69\%}_{-0.27\%}$ fb	$249.8(1)^{+0.88\%}_{-0.60\%}$ fb	$3.442(4)^{+0.93\%}_{-0.32\%}$ fb
$\sigma^{q\bar{q},\ \mathrm{extrapolated}}_{\mathrm{NNLO\ QCD}}$	$22.71(1)^{+1.4\%}_{-1.3\%}$ fb	$12.97(1)^{+1.4\%}_{-1.3\%}$ fb	$2.844(1)^{+0.68\%}_{-0.28\%}$ fb	$249.8(1)^{+0.90\%}_{-0.58\%}$ fb	$3.446(11)^{+0.92\%}_{-0.30\%}$ fb
$\sigma^{gg}_{\mathrm{LO}}$	$2.214(0)^{+25\%}_{-19\%}$ fb	$1.219(0)^{+25\%}_{-19\%}$ fb	$0.5783(0)^{+29\%}_{-21\%}$ fb	$26.85(0)^{+27\%}_{-19\%}$ fb	$0.7391(2)^{+28\%}_{-21\%}$ fb
$\sigma^{gg}_{\mathrm{NLO\ QCD}}$	$3.598(2)^{+13\%}_{-12\%}$ fb	$1.935(1)^{+13\%}_{-12\%}$ fb	$0.3124(1)^{+21\%}_{-53\%}$ fb	$31.23(11)^{+4.0\%}_{-7.0\%}$ fb	$0.4366(29)^{+17\%}_{-43\%}$ fb
$\sigma^{\gamma\gamma}_{\mathrm{LO}}$	$0.01037(0)^{+18\%}_{-16\%}$ fb	$0.01554(0)^{+18\%}_{-17\%}$ fb	$0.00009607(1)^{+17\%}_{-16\%}$ fb	$3.178(0)^{+18\%}_{-16\%}$ fb	$0.02213(1)^{+18\%}_{-16\%}$ fb
$\sigma^{\gamma\gamma/q\gamma}_{\mathrm{NLO\ EW}}$	$0.01148(1)^{+7.7\%}_{-11\%}$ fb	$0.01365(1)^{+5.0\%}_{-7.2\%}$ fb	$-0.0002370(1)^{+112\%}_{-130\%}$ fb	$2.648(0)^{+1.7\%}_{-2.7\%}$ fb	$0.01768(4)^{+2.6\%}_{-3.8\%}$ fb
σ_{LO}	$16.05(0)^{+5.0\%}_{-6.1\%}$ fb	$9.179(0)^{+4.9\%}_{-6.0\%}$ fb	$3.949(0)^{+2.0\%}_{-2.9\%}$ fb	$276.0(0)^{+5.7\%}_{-6.8\%}$ fb	$4.573(0)^{+2.2\%}_{-3.0\%}$ fb
$\sigma_{\mathrm{NLO\ QCD}}$	$21.48(0)^{+3.0\%}_{-2.4\%}$ fb	$12.28(0)^{+3.0\%}_{-2.4\%}$ fb	$2.866(0)^{+5.2\%}_{-5.2\%}$ fb	$259.1(0)^{+2.6\%}_{-2.2\%}$ fb	$3.534(1)^{+4.3\%}_{-4.4\%}$ fb
$\sigma_{\mathrm{NLO\ EW}}$	$14.87(0)^{+5.1\%}_{-6.2\%}$ fb	$8.519(0)^{+5.0\%}_{-6.1\%}$ fb	$3.495(0)^{+2.2\%}_{-3.1\%}$ fb	$267.1(0)^{+5.6\%}_{-6.8\%}$ fb	$4.075(0)^{+2.2\%}_{-3.1\%}$ fb
$\sigma_{\mathrm{NLO\ QCD+EW}}$	$20.29(0)^{+3.1\%}_{-2.5\%}$ fb	$11.62(0)^{+3.1\%}_{-2.5\%}$ fb	$2.412(0)^{+6.0\%}_{-5.9\%}$ fb	$250.2(0)^{+2.4\%}_{-2.0\%}$ fb	$3.036(1)^{+4.8\%}_{-4.8\%}$ fb
$\sigma_{\mathrm{NLO\ QCD\times EW}}$	$19.89(0)^{+3.0\%}_{-2.4\%}$ fb	$11.40(0)^{+3.0\%}_{-2.4\%}$ fb	$2.536(0)^{+5.4\%}_{-5.4\%}$ fb	$250.8(0)^{+2.5\%}_{-2.2\%}$ fb	$3.149(1)^{+4.4\%}_{-4.5\%}$ fb
$\sigma_{\mathrm{NLO\ QCD\times EW_{qq}}}$	$19.89(0)^{+3.0\%}_{-2.4\%}$ fb	$11.40(0)^{+3.0\%}_{-2.4\%}$ fb	$2.536(0)^{+5.4\%}_{-5.4\%}$ fb	$250.7(0)^{+2.5\%}_{-2.2\%}$ fb	$3.149(1)^{+4.4\%}_{-4.5\%}$ fb
$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO\ QCD}}$	$24.95(1)^{+3.4\%}_{-2.8\%}$ fb	$14.22(1)^{+3.4\%}_{-2.7\%}$ fb	$3.422(1)^{+5.3\%}_{-3.0\%}$ fb	$279.9(1)^{+2.1\%}_{-1.3\%}$ fb	$4.204(4)^{+4.8\%}_{-2.8\%}$ fb
$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO\ QCD}}$	$24.93(1)^{+3.5\%}_{-2.8\%}$ fb	$14.21(1)^{+3.4\%}_{-2.7\%}$ fb	$3.423(1)^{+5.3\%}_{-3.0\%}$ fb	$279.8(1)^{+2.1\%}_{-1.3\%}$ fb	$4.207(11)^{+4.8\%}_{-2.8\%}$ fb
$\sigma^{r_{\mathrm{cut}}}_{\mathrm{nNNLO\ QCD}}$	$26.33(1)^{+3.0\%}_{-2.7\%}$ fb	$14.93(1)^{+2.9\%}_{-2.6\%}$ fb	$3.156(1)^{+2.7\%}_{-4.8\%}$ fb	$284.3(2)^{+0.63\%}_{-0.91\%}$ fb	$3.901(5)^{+2.8\%}_{-5.0\%}$ fb
$\sigma^{\mathrm{extrapolated}}_{\mathrm{nNNLO\ QCD}}$	$26.32(1)^{+3.0\%}_{-2.7\%}$ fb	$14.92(1)^{+2.9\%}_{-2.6\%}$ fb	$3.157(1)^{+2.7\%}_{-4.8\%}$ fb	$284.2(2)^{+0.64\%}_{-0.91\%}$ fb	$3.904(12)^{+2.8\%}_{-5.0\%}$ fb
$\sigma^{r_{\mathrm{cut}}}_{\mathrm{(n)NNLO\ QCD+EW}}$	$25.15(1)^{+3.4\%}_{-2.9\%}$ fb	$14.27(1)^{+3.2\%}_{-2.8\%}$ fb	$2.702(1)^{+3.0\%}_{-5.4\%}$ fb	$275.4(2)^{+0.39\%}_{-0.66\%}$ fb	$3.403(5)^{+3.0\%}_{-5.4\%}$ fb
$\sigma^{\mathrm{extrapolated}}_{\mathrm{(n)NNLO\ QCD+EW}}$	$25.14(1)^{+3.4\%}_{-2.9\%}$ fb	$14.26(1)^{+3.2\%}_{-2.7\%}$ fb	$2.703(1)^{+3.0\%}_{-5.3\%}$ fb	$275.3(2)^{+0.40\%}_{-0.65\%}$ fb	$3.406(12)^{+3.0\%}_{-5.4\%}$ fb
$\sigma^{r_{\mathrm{cut}}}_{\mathrm{(n)NNLO\ QCD\times EW}}$	$24.39(1)^{+2.9\%}_{-2.7\%}$ fb	$13.86(1)^{+2.8\%}_{-2.6\%}$ fb	$2.793(1)^{+2.9\%}_{-5.0\%}$ fb	$275.1(2)^{+0.55\%}_{-0.84\%}$ fb	$3.476(5)^{+2.9\%}_{-5.1\%}$ fb
$\sigma^{\mathrm{extrapolated}}_{\mathrm{(n)NNLO\ QCD\times EW}}$	$24.38(1)^{+2.9\%}_{-2.7\%}$ fb	$13.85(1)^{+2.8\%}_{-2.6\%}$ fb	$2.794(1)^{+2.9\%}_{-5.0\%}$ fb	$275.1(2)^{+0.57\%}_{-0.84\%}$ fb	$3.479(10)^{+2.9\%}_{-5.1\%}$ fb
$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO\ QCD\times EW+}gg\mathrm{NLO}}$	$24.66(1)^{+3.0\%}_{-2.8\%}$ fb	$14.00(1)^{+2.9\%}_{-2.7\%}$ fb	$2.829(1)^{+3.1\%}_{-5.6\%}$ fb	$276.1(2)^{+0.57\%}_{-0.86\%}$ fb	$3.523(5)^{+3.1\%}_{-5.6\%}$ fb
$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO\ QCD\times EW+}gg\mathrm{NLO}}$	$24.65(1)^{+3.0\%}_{-2.8\%}$ fb	$13.99(1)^{+2.9\%}_{-2.7\%}$ fb	$2.830(1)^{+3.1\%}_{-5.6\%}$ fb	$276.1(2)^{+0.59\%}_{-0.86\%}$ fb	$3.526(10)^{+3.0\%}_{-5.6\%}$ fb
$\sigma^{r_{\mathrm{cut}}}_{\mathrm{nNNLO\ QCD\times EW_{qq}}}$	$24.66(1)^{+3.0\%}_{-2.8\%}$ fb	$14.00(1)^{+2.9\%}_{-2.7\%}$ fb	$2.829(1)^{+3.1\%}_{-5.6\%}$ fb	$275.6(2)^{+0.35\%}_{-0.66\%}$ fb	$3.520(5)^{+2.9\%}_{-5.5\%}$ fb
$\sigma^{\mathrm{extrapolated}}_{\mathrm{nNNLO\ QCD\times EW_{qq}}}$	$24.65(1)^{+3.0\%}_{-2.8\%}$ fb	$13.99(1)^{+2.9\%}_{-2.7\%}$ fb	$2.830(1)^{+3.1\%}_{-5.6\%}$ fb	$275.5(2)^{+0.36\%}_{-0.66\%}$ fb	$3.523(10)^{+2.9\%}_{-5.5\%}$ fb

Table 7b: Integrated cross sections for all available processes with EW corrections in MATRIX using the default setups for a NNLO run (i.e. using NNLO PDFs throughout).

process (`${process_id}`)	$pp \to e^- \mu^- e^+ \bar{\nu}_\mu$ (`ppemexnmx04`)	$pp \to e^- e^- e^+ \bar{\nu}_e$ (`ppeeexnex04`)	$pp \to e^- e^+ \mu^+ \nu_\mu$ (`ppeexmxnm04`)	$pp \to e^- e^+ e^+ \nu_e$ (`ppeexexne04`)
$\sigma^{q\bar{q}}_{\text{LO}}$	$13.24(0)^{+4.8\%}_{-6.0\%}$ fb	$13.28(0)^{+4.8\%}_{-6.0\%}$ fb	$19.97(0)^{+4.6\%}_{-5.7\%}$ fb	$20.01(0)^{+4.6\%}_{-5.7\%}$ fb
$\sigma^{q\bar{q}}_{\text{NLO QCD}}$	$24.50(0)^{+5.5\%}_{-4.4\%}$ fb	$24.57(0)^{+5.5\%}_{-4.4\%}$ fb	$35.65(0)^{+5.2\%}_{-4.2\%}$ fb	$35.74(0)^{+5.2\%}_{-4.2\%}$ fb
$\sigma^{q\bar{q}}_{\text{NLO EW}}$	$12.45(0)^{+4.9\%}_{-6.2\%}$ fb	$12.50(0)^{+4.9\%}_{-6.2\%}$ fb	$18.77(0)^{+4.7\%}_{-5.8\%}$ fb	$18.82(0)^{+4.7\%}_{-5.8\%}$ fb
$\sigma^{q\bar{q},\, r_{\text{cut}}}_{\text{NNLO QCD}}$	$26.75(1)^{+2.3\%}_{-2.1\%}$ fb	$26.83(1)^{+2.3\%}_{-2.1\%}$ fb	$38.81(2)^{+2.2\%}_{-2.0\%}$ fb	$38.91(2)^{+2.2\%}_{-2.0\%}$ fb
$\sigma^{q\bar{q},\, \text{extrapolated}}_{\text{NNLO QCD}}$	$26.74(2)^{+2.3\%}_{-2.1\%}$ fb	$26.84(1)^{+2.3\%}_{-2.1\%}$ fb	$38.79(3)^{+2.3\%}_{-2.0\%}$ fb	$38.91(2)^{+2.2\%}_{-2.0\%}$ fb
σ^{gg}_{LO}	—	—	—	—
$\sigma^{gg}_{\text{NLO QCD}}$	—	—	—	—
$\sigma^{\gamma\gamma}_{\text{LO}}$	—	—	—	—
$\sigma^{\gamma\gamma/q\gamma}_{\text{NLO EW}}$	$0.2305(0)^{+4.8\%}_{-5.3\%}$ fb	$0.2317(0)^{+4.8\%}_{-5.3\%}$ fb	$0.3268(0)^{+4.4\%}_{-4.8\%}$ fb	$0.3283(0)^{+4.4\%}_{-4.9\%}$ fb
σ_{LO}	$13.24(0)^{+4.8\%}_{-6.0\%}$ fb	$13.28(0)^{+4.8\%}_{-6.0\%}$ fb	$19.97(0)^{+4.6\%}_{-5.7\%}$ fb	$20.01(0)^{+4.6\%}_{-5.7\%}$ fb
$\sigma_{\text{NLO QCD}}$	$24.50(0)^{+5.5\%}_{-4.4\%}$ fb	$24.57(0)^{+5.5\%}_{-4.4\%}$ fb	$35.65(0)^{+5.2\%}_{-4.2\%}$ fb	$35.74(0)^{+5.2\%}_{-4.2\%}$ fb
$\sigma_{\text{NLO EW}}$	$12.69(0)^{+4.9\%}_{-6.1\%}$ fb	$12.73(0)^{+4.9\%}_{-6.1\%}$ fb	$19.09(0)^{+4.7\%}_{-5.8\%}$ fb	$19.15(0)^{+4.7\%}_{-5.8\%}$ fb
$\sigma_{\text{NLO QCD+EW}}$	$23.94(0)^{+5.6\%}_{-4.5\%}$ fb	$24.02(0)^{+5.6\%}_{-4.5\%}$ fb	$34.78(0)^{+5.4\%}_{-4.3\%}$ fb	$34.88(0)^{+5.4\%}_{-4.3\%}$ fb
$\sigma_{\text{NLO QCD}\times\text{EW}}$	$23.47(0)^{+5.5\%}_{-4.4\%}$ fb	$23.56(0)^{+5.5\%}_{-4.4\%}$ fb	$34.09(0)^{+5.2\%}_{-4.2\%}$ fb	$34.20(0)^{+5.2\%}_{-4.2\%}$ fb
$\sigma_{\text{NLO QCD}\times\text{EW}_{\text{qq}}}$	—	—	—	—
$\sigma^{r_{\text{cut}}}_{\text{NNLO QCD}}$	$26.75(1)^{+2.3\%}_{-2.1\%}$ fb	$26.83(1)^{+2.3\%}_{-2.1\%}$ fb	$38.81(2)^{+2.2\%}_{-2.0\%}$ fb	$38.91(2)^{+2.2\%}_{-2.0\%}$ fb
$\sigma^{\text{extrapolated}}_{\text{NNLO QCD}}$	$26.74(2)^{+2.3\%}_{-2.1\%}$ fb	$26.84(1)^{+2.3\%}_{-2.1\%}$ fb	$38.79(3)^{+2.3\%}_{-2.0\%}$ fb	$38.91(2)^{+2.2\%}_{-2.0\%}$ fb
$\sigma^{r_{\text{cut}}}_{\text{nNNLO QCD}}$	—	—	—	—
$\sigma^{\text{extrapolated}}_{\text{nNNLO QCD}}$	—	—	—	—
$\sigma^{r_{\text{cut}}}_{\text{(n)NNLO QCD+EW}}$	$26.19(1)^{+2.4\%}_{-2.1\%}$ fb	$26.28(1)^{+2.4\%}_{-2.1\%}$ fb	$37.94(2)^{+2.4\%}_{-2.1\%}$ fb	$38.05(2)^{+2.4\%}_{-2.1\%}$ fb
$\sigma^{\text{extrapolated}}_{\text{(n)NNLO QCD+EW}}$	$26.18(2)^{+2.4\%}_{-2.1\%}$ fb	$26.29(1)^{+2.4\%}_{-2.1\%}$ fb	$37.92(3)^{+2.4\%}_{-2.0\%}$ fb	$38.05(2)^{+2.4\%}_{-2.1\%}$ fb
$\sigma^{r_{\text{cut}}}_{\text{(n)NNLO QCD}\times\text{EW}}$	$25.62(1)^{+2.2\%}_{-2.1\%}$ fb	$25.72(1)^{+2.2\%}_{-2.1\%}$ fb	$37.11(2)^{+2.2\%}_{-2.0\%}$ fb	$37.24(2)^{+2.2\%}_{-2.0\%}$ fb
$\sigma^{\text{extrapolated}}_{\text{(n)NNLO QCD}\times\text{EW}}$	$25.62(2)^{+2.2\%}_{-2.1\%}$ fb	$25.73(1)^{+2.2\%}_{-2.1\%}$ fb	$37.09(3)^{+2.2\%}_{-2.0\%}$ fb	$37.23(2)^{+2.2\%}_{-2.0\%}$ fb
$\sigma^{r_{\text{cut}}}_{\text{NNLO QCD}\times\text{EW}+gg\text{NLO}}$	—	—	—	—
$\sigma^{\text{extrapolated}}_{\text{NNLO QCD}\times\text{EW}+gg\text{NLO}}$	—	—	—	—
$\sigma^{r_{\text{cut}}}_{\text{nNNLO QCD}\times\text{EW}_{\text{qq}}}$	—	—	—	—
$\sigma^{\text{extrapolated}}_{\text{nNNLO QCD}\times\text{EW}_{\text{qq}}}$	—	—	—	—

Table 7c: Integrated cross sections for all available processes with EW corrections in Matrix using the default setups for a NNLO run (i.e. using NNLO PDFs throughout).

	$pp \to e^-e^+$	$pp \to e^-\bar{\nu}_e / pp \to e^+\nu_e$	$pp \to \gamma\gamma$
lepton cuts	$p_{T,\ell} > 25\,\text{GeV}$, $\lvert\eta_\ell\rvert < 2.47$ $66\,\text{GeV} < m_{\ell^-\ell^+} < 116\,\text{GeV}$	$p_{T,\ell} > 25\,\text{GeV}$, $\lvert\eta_\ell\rvert < 2.47$	——
photon cuts	——	——	$p_{T,\gamma_1} > 40\,\text{GeV}$, $p_{T,\gamma_2} > 25\,\text{GeV}$ $\lvert\eta_\gamma\rvert < 2.5$
neutrino cuts	——	$p_T^{\text{miss}} > 20\,\text{GeV}$	——
photon isolation	——	——	Frixione isolation with $n = 1$, $\varepsilon = 0.5$ and $\delta_0 = 0.4$
jet definition	anti-k_T algorithm with $R = 0.4$; $p_{T,j} > 25\,\text{GeV}$, $\lvert\eta_j\rvert < 4.5$		

Table 8: Default setup of fiducial cuts for Z, $W^\pm$ and $\gamma\gamma$ production processes.

Vector-boson pair production

The on-shell ZZ and W^+W^- results in Table 6 correspond to the inclusive cross sections of Ref. [19] and Ref. [20], respectively, with an updated set of input parameters. We have explicitly checked that MATRIX reproduces the results of Refs. [19, 20] when adjusting the setup accordingly. Consistent with these studies, we have used fixed renormalization and factorization scales of $\mu_0 = m_Z$ and $\mu_0 = m_W$ for ZZ and W^+W^- production, respectively.

Several leptonic channels originate from off-shell ZZ production. They involve the SF and DF four-lepton channels, 4ℓ and $2\ell 2\ell'$, respectively, which have been studied at NNLO QCD in Refs. [17, 21]. On the other hand, one of the Z bosons may decay to two neutrinos instead, for which NNLO QCD corrections have been studied also in Ref. [17]. In that case the SF channel is defined as the one where the neutrino flavour matches the lepton flavour ($2\ell 2\nu$), while the DF flavour channel is defined as the one where the lepton and neutrino flavours are different ($2\ell 2\nu'$).[5] The SF $2\ell 2\nu$ final state is special since it receives contributions from both resonant ZZ and W^+W^- sub-topologies, which mix the two processes.

For the off-shell ZZ processes the renormalization and factorization scales are fixed to $\mu_0 = m_Z$. The fiducial cuts are those of Ref. [17] and summarized in Table 10. Z_{rec} is the reconstructed Z boson. In the $2\ell 2\ell'$ channel, the reconstruction is unambiguously defined. In the 4ℓ channel, there are two possible combinations of OSSF lepton pairs that can be associated with the reconstructed Z bosons. We choose the combination that minimizes $|m_{\ell^-\ell^+} - m_Z| + |m_{\ell^{-\prime}\ell^{+\prime}} - m_Z|$ using `user_switch lepton_identification = 1` in the `parameter.dat` input file. The fiducial cuts for the $2\ell 2\nu$ processes use the following definitions in Table 10: Axial-$p_T^{\text{miss}} = -p_T^{\text{miss}} \cdot \cos(\Delta\phi_{\ell\ell,\nu\nu})$, where $p_T^{\text{miss}} \equiv p_{T,\nu\nu}$ and $\Delta\phi_{\ell\ell,\nu\nu}$ is the azimuthal angle between the dilepton and the neutrino pair. Furthermore, the two Z-boson momenta are balanced by putting an upper cut on p_T-balance $= |p_T^{\text{miss}} - p_{T,\ell\ell}|/p_{T,\ell\ell}$.

[5] We note that both final states contain an OSSF lepton pair and (possibly) missing transverse momentum from the two neutrinos that cannot be detected. Our distinction into SF and DF final states is motivated more by the underlying technical calculations than by their phenomenology in this case.

	$pp \to e^- e^+ \gamma$	$pp \to \nu_e \bar{\nu}_e \gamma$	$pp \to e^- \bar{\nu}_e \gamma / pp \to e^+ \nu_e \gamma$
lepton cuts	$p_{T,\ell} > 25\,\text{GeV}$, $\lvert\eta_\ell\rvert < 2.47$ $m_{\ell^-\ell^+} > 40\,\text{GeV}$	——	$p_{T,\ell} > 25\,\text{GeV}$, $\lvert\eta_\ell\rvert < 2.47$
photon cuts	$p_{T,\gamma} > 15\,\text{GeV}$, $\lvert\eta_\gamma\rvert < 2.37$	$p_{T,\gamma} > 100\,\text{GeV}$, $\lvert\eta_\gamma\rvert < 2.37$	$p_{T,\gamma} > 15\,\text{GeV}$, $\lvert\eta_\gamma\rvert < 2.37$
neutrino cuts	——	$p_T^{\text{miss}} > 90\,\text{GeV}$	$p_T^{\text{miss}} > 35\,\text{GeV}$
separation cuts	$\Delta R_{\ell j} > 0.3$, $\Delta R_{\gamma j} > 0.3$, $\Delta R_{\ell\gamma} > 0.7$	$\Delta R_{\gamma j} > 0.3$	$\Delta R_{\ell j} > 0.3$, $\Delta R_{\gamma j} > 0.3$, $\Delta R_{\ell\gamma} > 0.7$
photon isolation	Frixione isolation with $n = 1$, $\varepsilon = 0.5$ and $\delta_0 = 0.4$		
jet definition	anti-k_T algorithm with $R = 0.4$; $p_{T,j} > 30\,\text{GeV}$, $\lvert\eta_j\rvert < 4.4$		

Table 9: Default setup of fiducial cuts for $Z\gamma$ and $W^\pm\gamma$ production processes.

	$pp \to e^- \mu^- e^+ \mu^+ / pp \to e^- e^- e^+ e^+$	$pp \to e^- e^+ \nu_e \bar{\nu}_e / pp \to e^- e^+ \nu_\mu \bar{\nu}_\mu$
lepton cuts	$p_{T,\ell} > 7\,\text{GeV}$, one electron with $\lvert\eta_e\rvert < 4.9$, $\lvert\eta_e\rvert < 2.5$ otherwise, $\lvert\eta_\mu\rvert < 2.7$ $66\,\text{GeV} < m_{Z_{\text{rec}}} < 116\,\text{GeV}$	$p_{T,\ell} > 25\,\text{GeV}$, $\lvert\eta_\ell\rvert < 2.5$ $76\,\text{GeV} < m_{\ell^-\ell^+} < 106\,\text{GeV}$
neutrino cuts	——	Axial-$p_T^{\text{miss}} > 90\,\text{GeV}$, p_T-balance < 0.4
separation cuts	$\Delta R_{\ell\ell} > 0.2$, $\Delta R_{\ell\ell'} > 0.2$	$\Delta R_{\ell\ell} > 0.3$
jet cuts	——	$N_{\text{jets}} = 0$
jet definition	anti-k_T algorithm with $R = 0.4$; $p_{T,j} > 25\,\text{GeV}$, $\lvert\eta_j\rvert < 4.5$, $\Delta R_{ej} > 0.3$	

Table 10: Default setup of fiducial cuts for ZZ and ZZ/W^+W^- production processes.

	$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$	$pp \to \ell'^\pm\nu_{\ell'}\ell^+\ell^-, \quad \ell,\ell' \in \{e,\mu\}$
lepton cuts	$p_{T,\ell_1} > 25\,\text{GeV},\ p_{T,\ell_2} > 20\,\text{GeV}$ $\lvert\eta_e\rvert < 2.47,\ \lvert\eta_e\rvert \notin [1.37; 1.52]$ $\lvert\eta_\mu\rvert < 2.4,\ m_{\ell^-\ell^+} > 10\,\text{GeV}$	$p_{T,\ell_z} > 15\,\text{GeV},\ p_{T,\ell_w} > 20\,\text{GeV}$ $\lvert\eta_\ell\rvert < 2.5$ $\lvert m_{\ell_z\ell_z} - m_Z\rvert < 10\,\text{GeV}$
neutrino cuts	$p_T^{\text{miss}} > 20\,\text{GeV},\ p_T^{\text{miss,rel}} > 15\,\text{GeV}$	$m_{T,W} > 30\,\text{GeV}$
separation cuts	$\Delta R_{\ell\ell} > 0.1$	$\Delta R_{\ell_z\ell_z} > 0.2,\ \Delta R_{\ell_z\ell_w} > 0.3$
jet cuts	$N_{\text{jets}} = 0$	——
jet definition	anti-k_T algorithm with $R = 0.4$; $p_{T,j} > 25\,\text{GeV}$, $\lvert\eta_j\rvert < 4.5$	

Table 11: Default setup of fiducial cuts for W^+W^- and $W^\pm Z$ production processes.

The off-shell W^+W^- process with DF leptons ($\ell\nu\ell'\nu'$), namely $pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$, has been studied at NNLO in Ref. [22]. We adopt the fixed scale choice of $\mu_0 = m_W$ and the fiducial cuts used in that study. The latter are summarized in Table 11.

We considered NNLO QCD corrections to $W^\pm Z$ production in Ref. [23, 24]. Four different processes with three leptons and one neutrino are associated with $W^\pm Z$ production: W^-Z and W^+Z production can each be split into a SF and a DF channel. Since these processes have charged final states, no loop-induced gg component contributes at NNLO. Following Ref. [24] we set $\mu_0 = (m_Z + m_W)/2$ for the central value of renormalization and factorization scales and use the fiducial cuts summarized in Table 11. In the SF channel there is an ambiguity how to assign the leptons to the Z- and W-boson decays, and we follow the resonant-shape identification procedure of Ref. [25].

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