Status of QCD corrections for multi-boson processes

Massimiliano Grazzini

University of Zurich

Universität Zürich[UZH]

MBI 2017, Karlsruhe

August 28th 2017

higgstools

Status of QCD corrections for di-boson processes

Massimiliano Grazzini

University of Zurich

MBI 2017, Karlsruhe

August 28th 2017

Outline

- Introduction
- Diboson production at NNLO
- The MATRIX framework
- Results: focus on ZZ, WW, WZ
- Summary & Outlook

Introduction

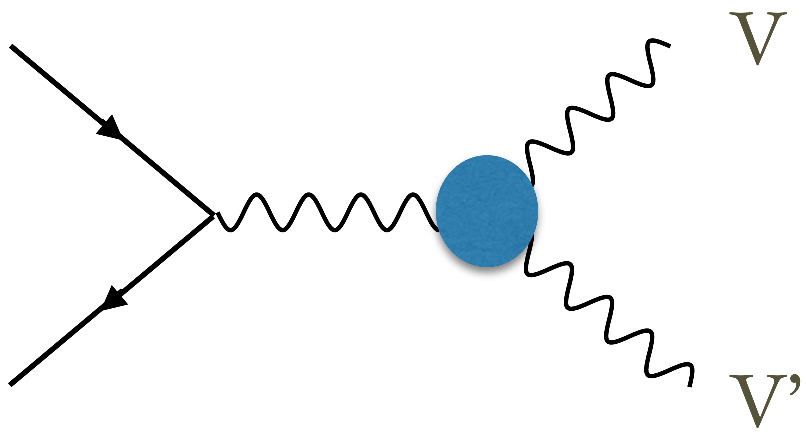
Vector boson pair production is a benchmark process at hadron colliders

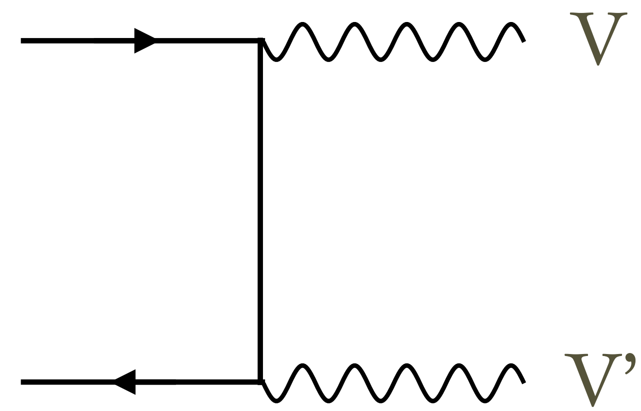
- background to Higgs and new physics searches
- important to set limits on anomalous couplings
- new nice data available from the LHC whose accuracy will soon be comparable with theoretical uncertainties

Up to very recently the accuracy was limited to NLO QCD

→ Extension to NNLO highly desirable to meet the increasing experimental precision

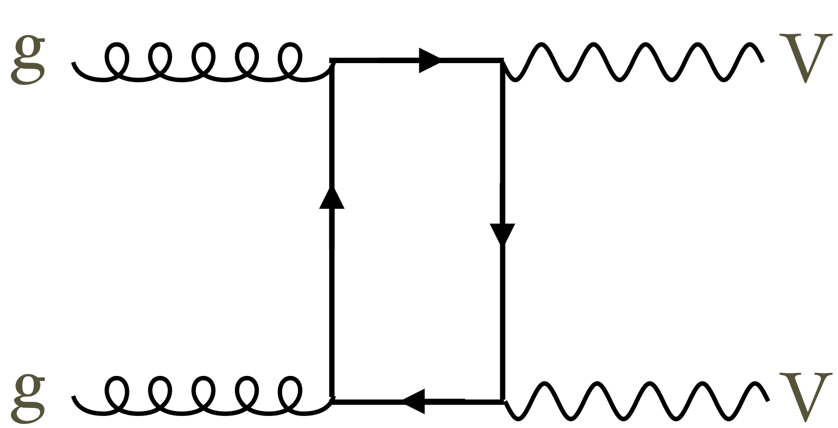
Introduction





Both s and t channel contributions at Born level

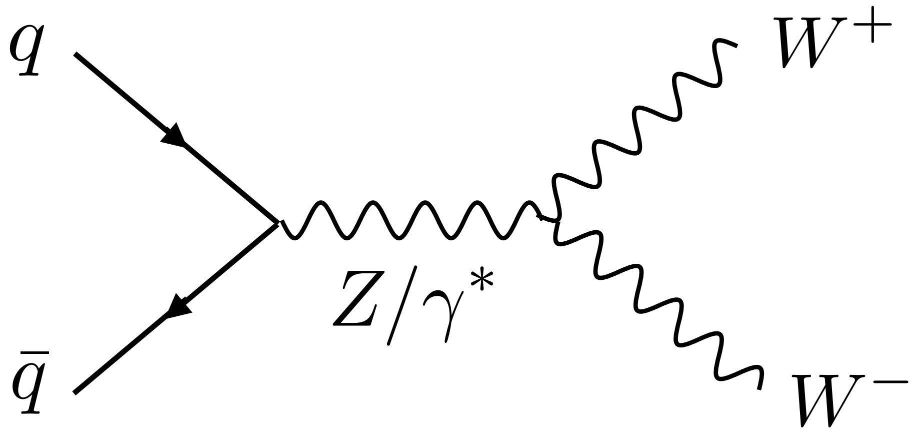
s-channel sensitive to different anomalous trilinear couplings

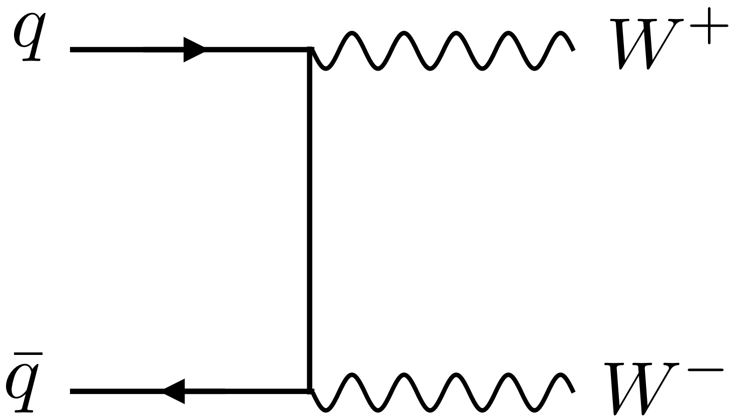


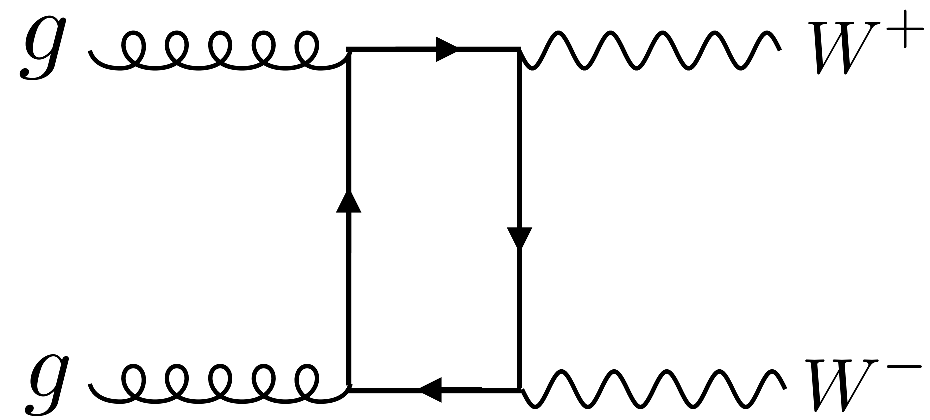
Loop induced gg contribution to processes with neutral final state
Formally NNLO but enhanced by gluon luminosity

Introduction

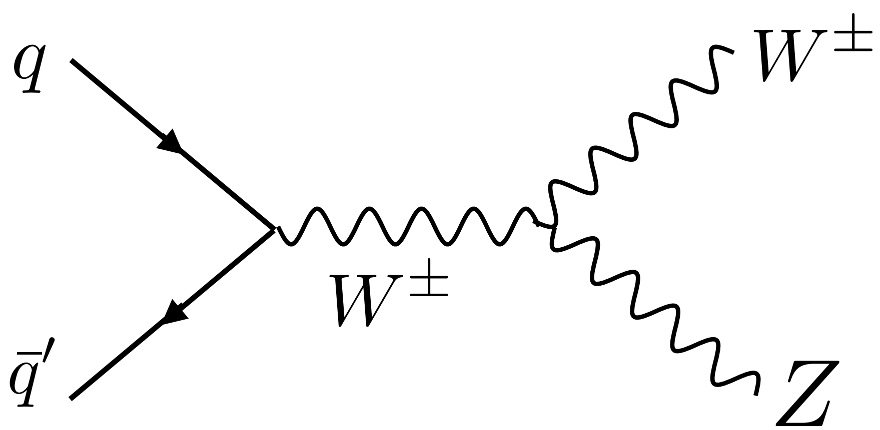
WW production

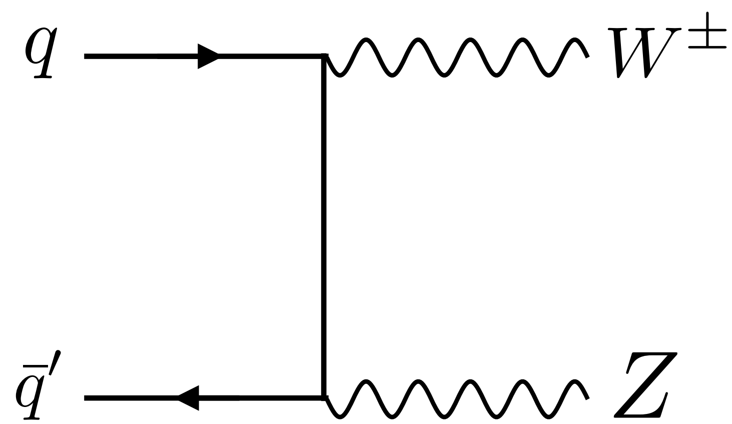




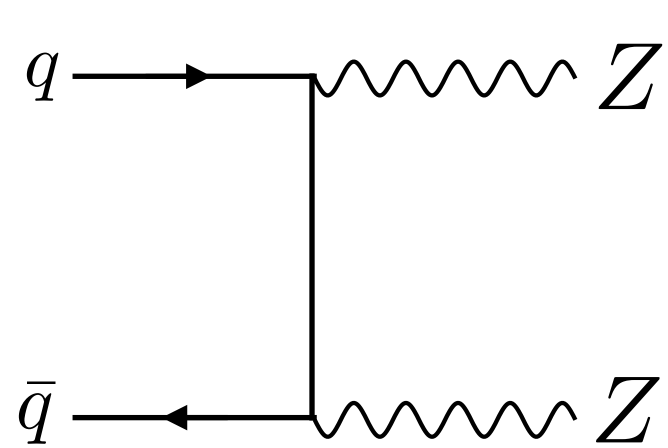


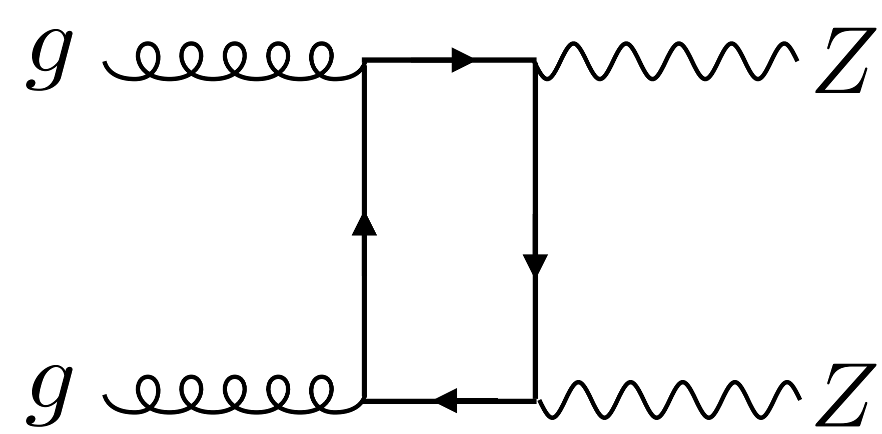
WZ production





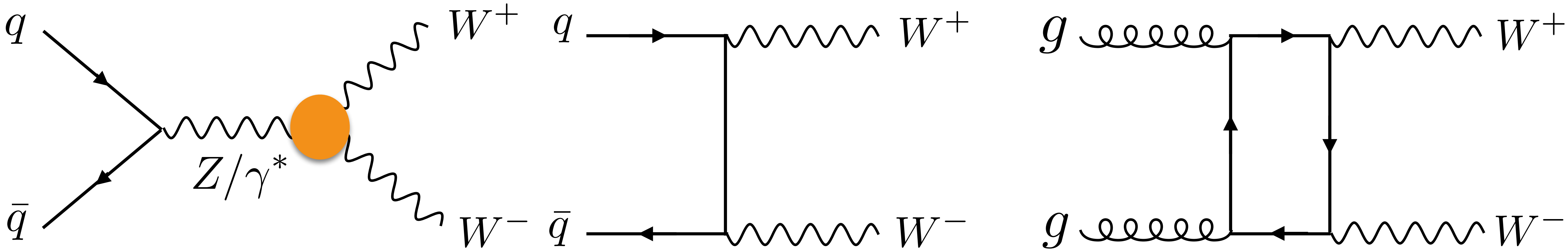
ZZ production



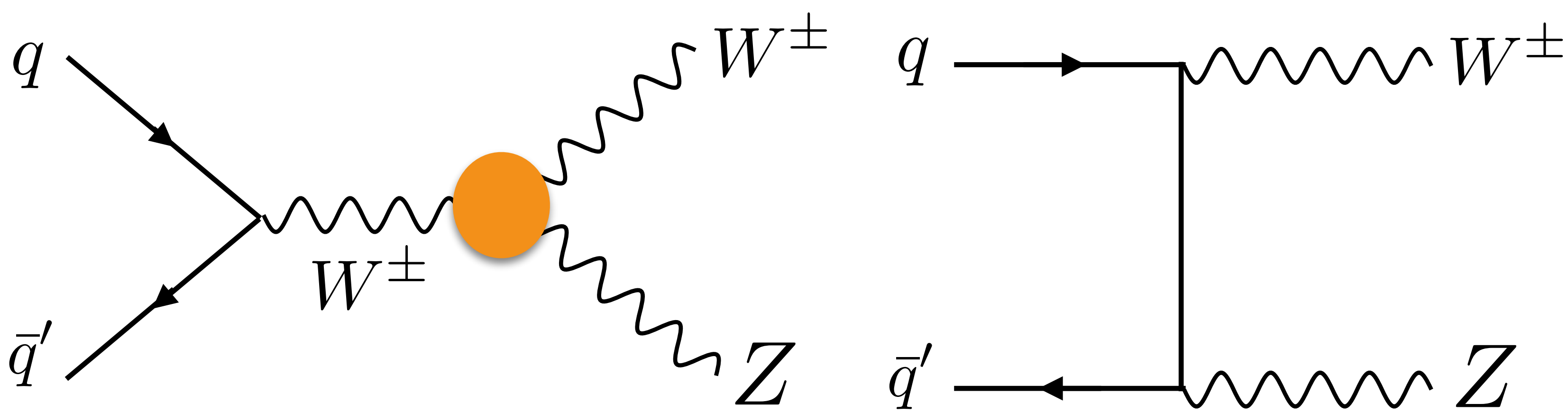


Introduction

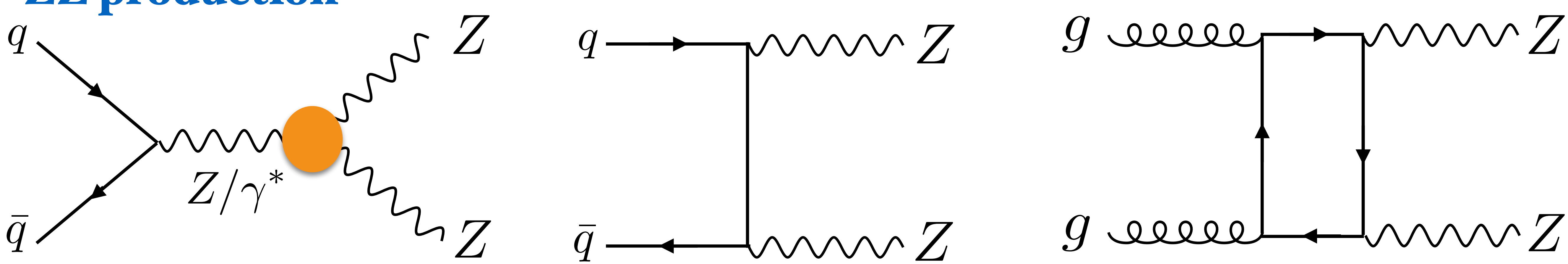
WW production



WZ production



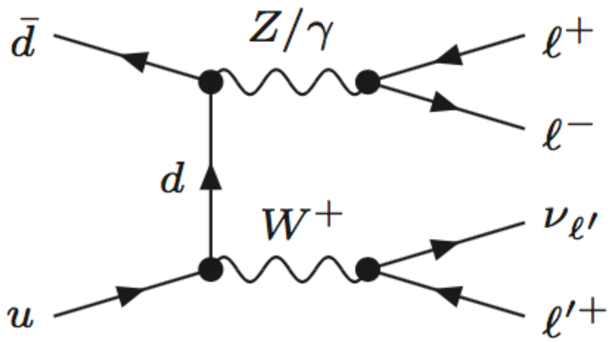
ZZ production

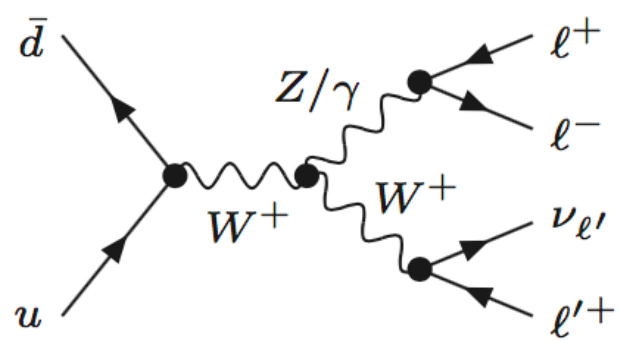


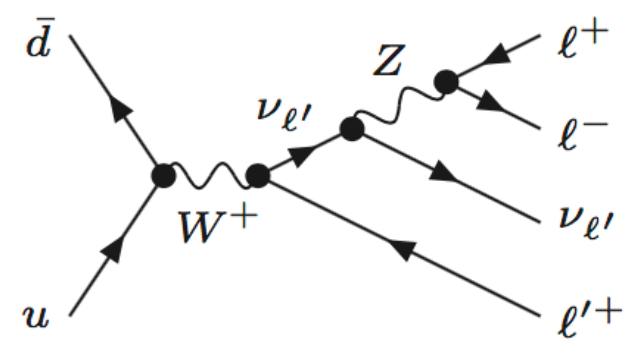
Off-shell and interference effects

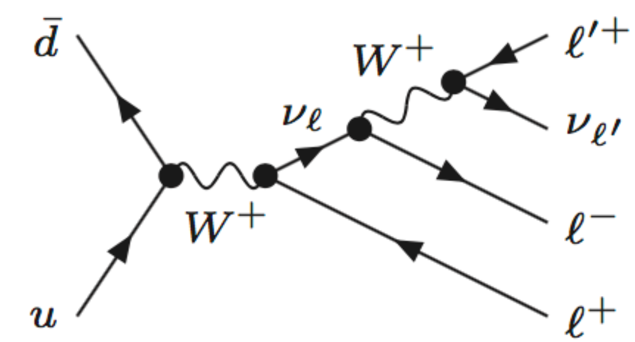
When we talk about VV' production we refer to the full calculation including resonant and non resonant diagrams with off-shell and interference effects

eg: $W^+Z \to l^+l^- l^{+\prime} \nu_{l'}$



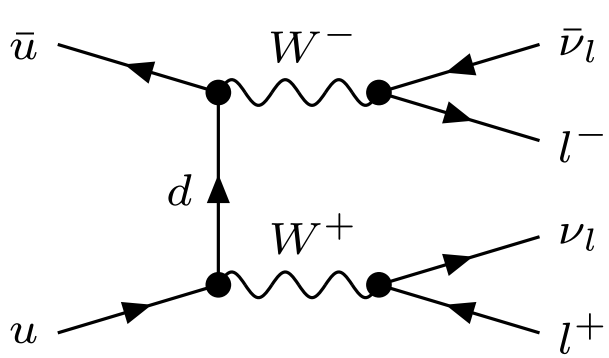


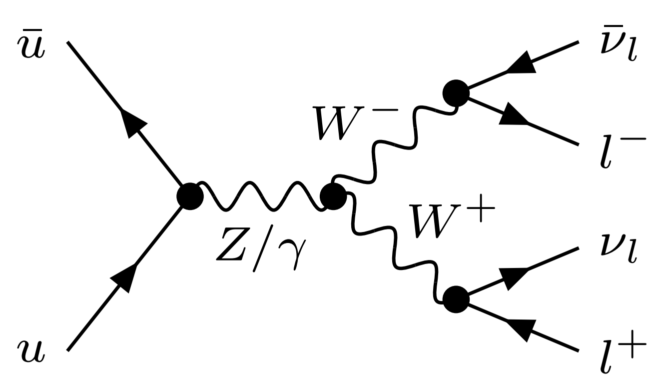


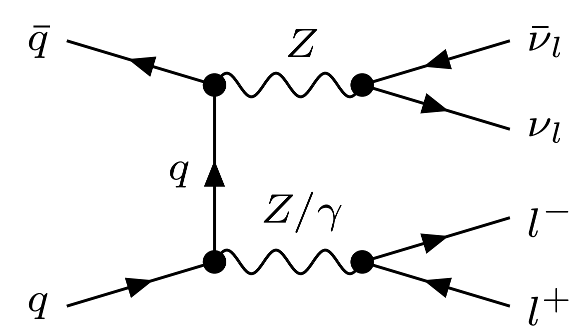


In some cases more than one VV' topology may contribute

eg: $W^+ W^- (ZZ) \to l^+l^- \bar{\nu}_l \nu_l$







Vector boson pair production

$W\gamma$,$Z\gamma$,WW, WZ, ZZ production known in NLO QCD since quite some time

J.Ohnemus (1993); U.Baur, T.Han, J.Ohnemus (1998)
B.Mele, P.Nason,G.Ridolfi (1991)

Also including leptonic decay

S.Frixione, P.Nason,G.Ridolfi (1992); S.Frixione (1993)
L.Dixon,Z.Kunszt,A.Signer (1999); J.Campbell,K.Ellis (1999)
D. de Florian, A.Signer (2000)

The gluon fusion loop contribution (part of NNLO) to $Z\gamma$, ZZ and WW is also known (often assumed to provide the dominant NNLO contribution)

T.Binoth et al. (2005,2008)
M.Duhrssen et al. (2005)
L.Amettler et al. (1985)
J. van der Bij, N.Glover (1988)
K. Adamson, D. de Florian, A.Signer (2000)

NLO EW corrections have also been studied

→ **talk by Pellen**

W.Hollik, C.Meier (2004)
E.Accomando, A.Denner,C.Meier (2005)
A.Bierweiler, T.Kasprzik,J.Kuhn,S.Uccirati(2012)
M.Billoni, S.Dittmaier, B.Jager,C.Speckner (2013)
A.Denner, S. Dittmaier, M. Hecht, C. Pasold (2014)
B. Biedermann et al (2016,2017)
S.Kallweit et al. (2017)

All two-loop helicity amplitudes for $V\gamma$,WW,WZ and ZZ production recently evaluated

T.Gehrmann, L.Tancredi (2012)
F.Caola,J.Henn,K.Melnikov, A.Smirnov, V.Smirnov (2014)
T.Gehrmann, A. von Manteuffel, L.Tancredi (2014,2015)

➡ **NNLO calculation possible**

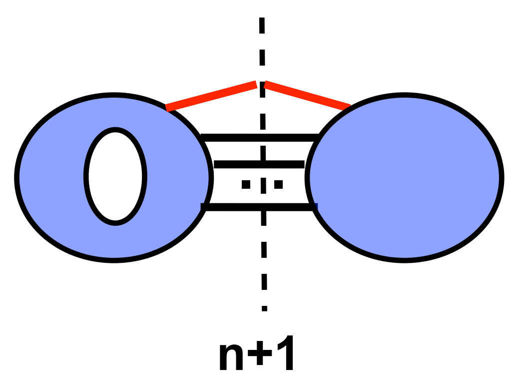
Ingredients of NNLO calculations

Assume that the process involves n partons at LO (n=2 in our case) → we need:

- Double virtual contribution with n resolved partons

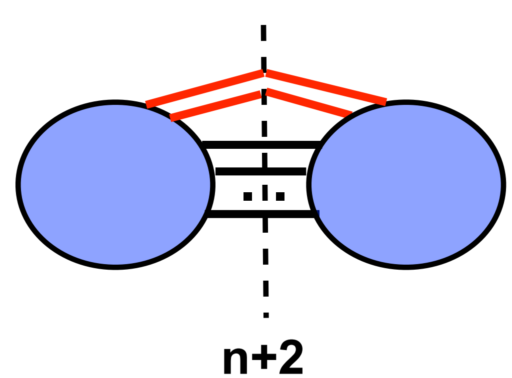
+ c.c.

- Real-virtual contribution with 1 unresolved parton



+ c.c.

- Double-real contribution with 2 unresolved partons



All the three contributions are divergent: how can we handle IR singularities ?

NNLO methods

Broadly speaking there are two approaches that we can follow:

- Organise the calculation from scratch so as to cancel all the singularities

  - sector decomposition — T. Binoth, G.Heinrich (2000,2004); C.Anastasiou, K.Melnikov, F.Petriello (2004)
  - antenna subtraction — A. & T. Gehrmann, N. Glover (2005)
  - "colourful" subtraction — G, Somogyi, Z. Trocsanyi, V. Del Duca (2005, 2007)
  - joint use of subtraction and sector decomposition — M.Czakon (2010,2011); R.Boughezal, K.Melnikov, F.Petriello (2011)

- Start from an inclusive NNLO calculation (sometimes obtained through resummation) and combine it with an NLO calculation for n+1 parton process

  - q_T subtraction — S.Catani, MG (2007)
  - "N-jettiness" method — R.Boughezal, C.Focke,X.Liu, F.Petriello (2015); F.Tackmann et al. (2015)
  - recently introduced "Born projection" method for VBF — M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)

The q_T subtraction method

S. Catani, MG (2007)

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

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

this difference is computed with a cut r_{cut} on q_T/Q

process dependent hard-collinear function

NLO F+jets cross section computed with dipole subtraction

universal counterterm

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

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

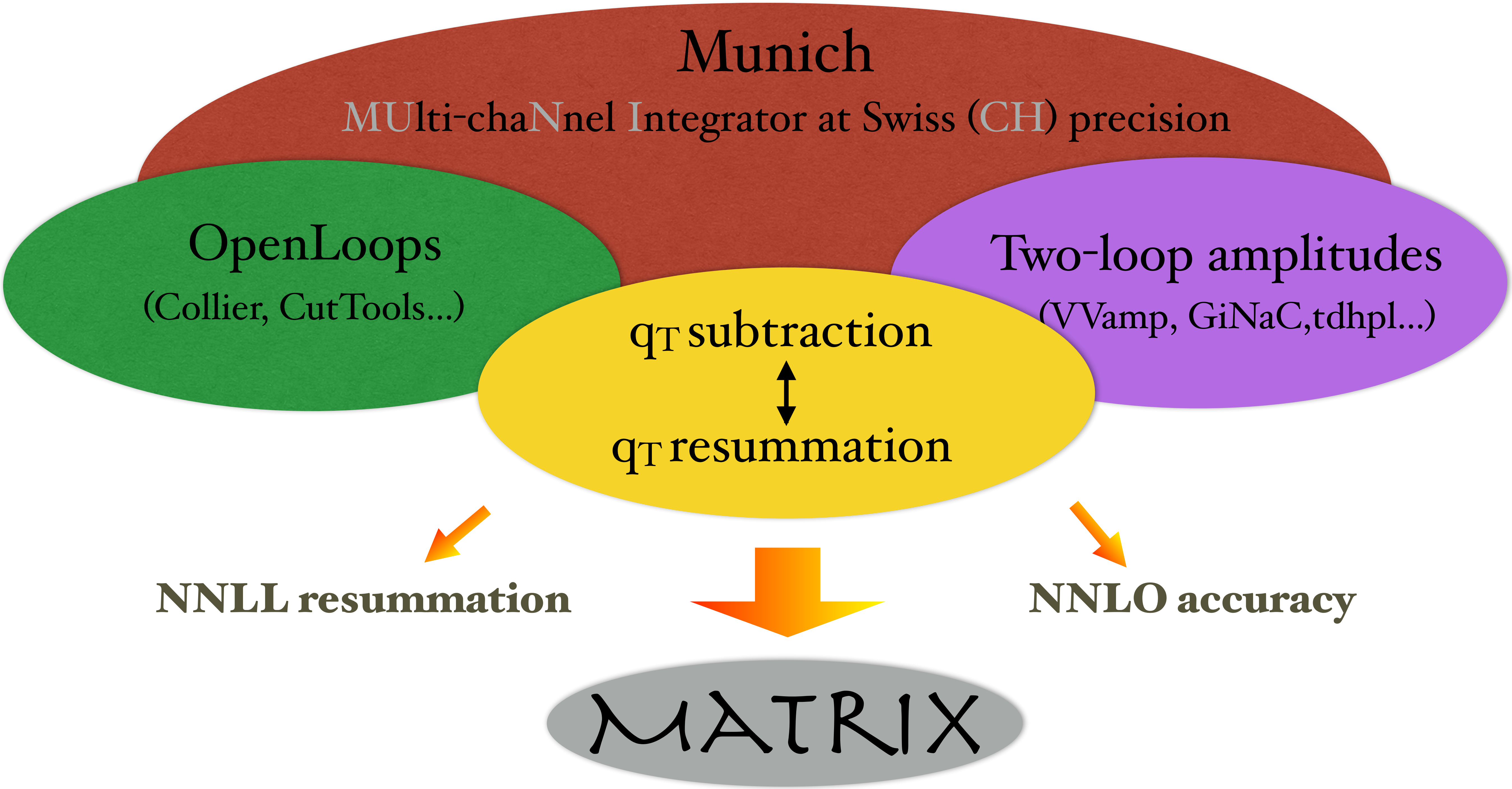
Its general form in terms of the relevant virtual amplitudes for an arbitrary colour singlet F has been provided up to NNLO

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

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

The MATRIX project

S. Kallweit, D. Rathlev, M.Wiesemann, MG



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

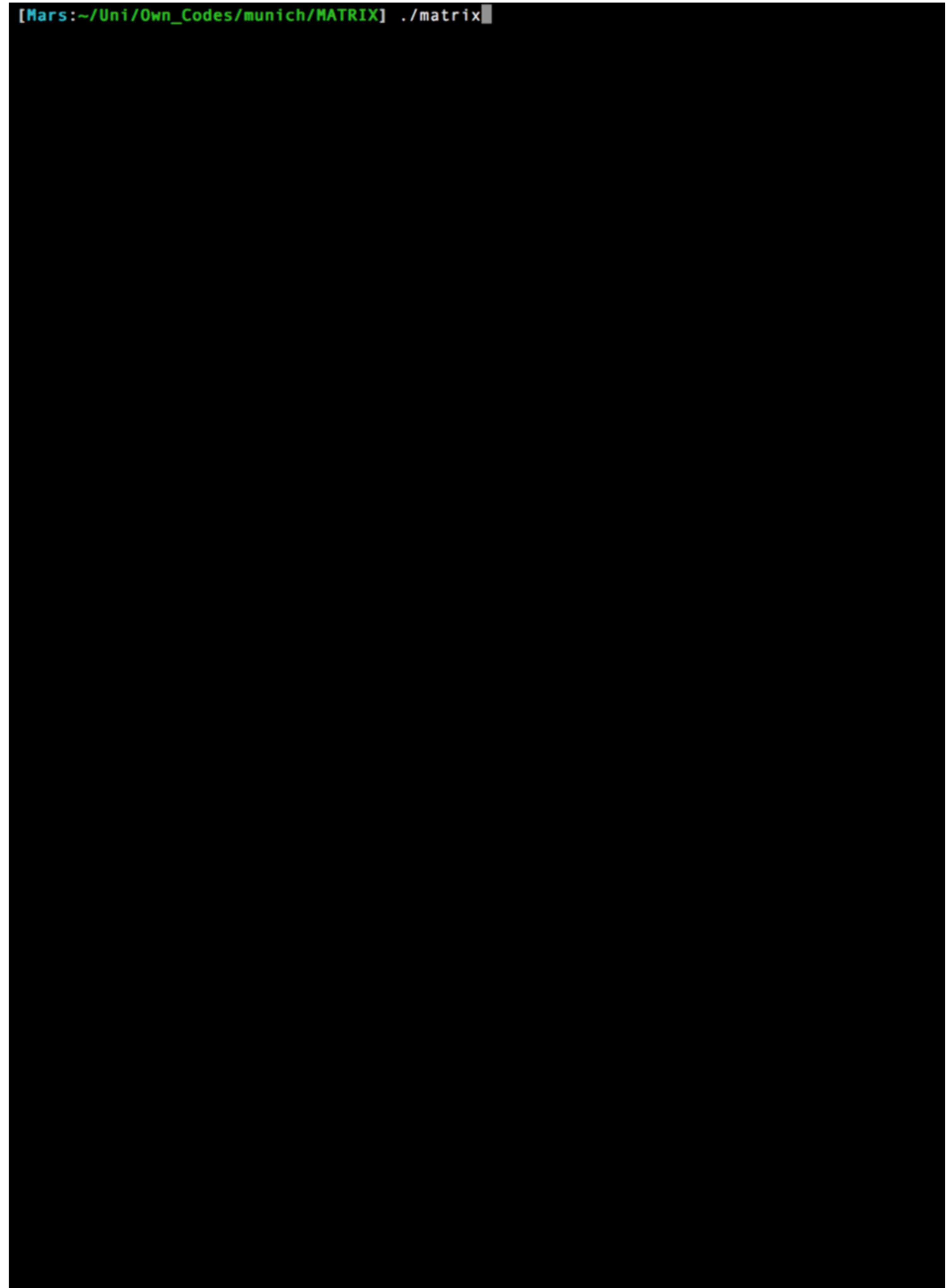
Status

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

MATRIX compilation

- After unpacking MATRIX start the code with

```
$$ ./matrix
```



MATRIX compilation

- After unpacking MATRIX start the code with

$$ ./matrix

- You are now to the MATRIX compilation shell. Type

|===>> list

to list the available processes

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

|===>> ppeeexex04

for pp→ZZ→4l

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

   /-------------------------------------------------------------------\
   | MATRIX: A fully-differential NNLO(+NNLL) process library          |
   |          ___ ___    ____    _____   ____     _    _              |
   |         | _\/_ |   / _  \  |_____| / _  \   ||   \\   //         |
   |         || \/ ||  | |_| |    ||   ||_| ||   ||    \\ //          |
   |         ||    ||  |  ___|    ||   ||\\       ||    // \\          |
   |         ||    || ||    ||    ||   || \\     ||   //   \\         |
   |                                                                   |
   |         Version: 1.0.0.beta4                          Feb 2017    |
   |                                                                   |
   | Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision -- |
   | Automates qT-subtraction and Resummation to Integrate X-sections  |
   |                                                                   |
   | \          \ ____      \          \ ____     \ ____     \         |
   |  \          \          |\          \         |\         |\        |
   |   )====  +   )====  +  | )====  +   )====  + | )====  + |-)====   |
   |  /          /          |/          /____     |/         |/        |
   | /          /           /          /          /          /         |
   |                                                                   |
   | M. Grazzini                              (grazzini@physik.uzh.ch) |
   | S. Kallweit                               (kallweit@uni-mainz.de) |
   | D. Rathlev                                (rathlev@physik.uzh.ch) |
   | M. Wiesemann                              (mariusw@physik.uzh.ch) |
   |-------------------------------------------------------------------|
   | MATRIX is based on a number of different computations and tools   |
   | from various people and groups. Please acknowledge their efforts  |
   | by citing the list of references which is created with every run. |
   \-------------------------------------------------------------------/

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
[|============>> list
------------------------------------------------------------------------------------------
process_id     ||   process                          ||   description
------------------------------------------------------------------------------------------
pph21          >>   p p --> H                        >>   on-shell Higgs production
ppz01          >>   p p --> Z                        >>   on-shell Z production
ppw01          >>   p p --> W^-                      >>   on-shell W+ production
ppwx01         >>   p p --> W^+                      >>   on-shell W- production
ppeex02        >>   p p --> e^- e^+                  >>   Z production with decay
ppnenex02      >>   p p --> v_e^- v_e^+              >>   Z production with decay
ppexne02       >>   p p --> e^+ v_e^-                >>   W+ production with decay
ppenex02       >>   p p --> e^- v_e^+                >>   W- production with decay
pphh22         >>   p p --> H H                      >>   on-shell double Higgs production
ppaa02         >>   p p --> gamma gamma              >>   gamma gamma production
ppeexa03       >>   p p --> e^- e^+ gamma            >>   Z gamma production with decay
ppnenexa03     >>   p p --> v_e^- v_e^+ gamma        >>   Z gamma production with decay
ppexnea03      >>   p p --> e^+ v_e^- gamma          >>   W+ gamma production with decay
ppenexa03      >>   p p --> e^- v_e^+ gamma          >>   W- gamma production with decay
ppzz02         >>   p p --> Z Z                      >>   on-shell ZZ production
ppwxw02        >>   p p --> W^+ W^-                  >>   on-shell WW production
ppeeexex04     >>   p p --> e^- e^- e^+ e^+          >>   ZZ production with decay
ppemexmx04     >>   p p --> e^- mu^- e^+ mu^+        >>   ZZ production with decay
ppeexnmnmx04   >>   p p --> e^- e^+ v_mu^- v_mu^+    >>   ZZ production with decay
ppeexnenex04   >>   p p --> e^- e^+ v_e^- v_e^+      >>   ZZ/WW production with decay
ppemxnmnex04   >>   p p --> e^- mu^+ v_mu^- v_e^+    >>   WW production with decay
ppemexnmx04    >>   p p --> e^- mu^- e^+ v_mu^+      >>   W-Z production with decay
ppeexmxnm04    >>   p p --> e^- e^+ mu^+ v_mu^-      >>   W+Z production with decay
ppeeexnex04    >>   p p --> e^- e^- e^+ v_e^+        >>   W-Z production with decay
ppeexexne04    >>   p p --> e^- e^+ e^+ v_e^-        >>   W+Z production with decay
[|============>> ppeeexex04
```

MATRIX compilation

- After unpacking MATRIX start the code with

$$ ./matrix

- You are now to the MATRIX compilation shell. Type

|===>> list

to list the available processes

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

|===>> ppeeexex04

for pp→ZZ→4l

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

```
pph21        >>  p p --> H                     >>  on-shell Higgs production
ppz01        >>  p p --> Z                     >>  on-shell Z production
ppw01        >>  p p --> W^-                   >>  on-shell W+ production
ppwx01       >>  p p --> W^+                   >>  on-shell W- production
ppeex02      >>  p p --> e^- e^+               >>  Z production with decay
ppnenex02    >>  p p --> v_e^- v_e^+           >>  Z production with decay
ppexne02     >>  p p --> e^+ v_e^-             >>  W+ production with decay
ppenex02     >>  p p --> e^- v_e^+             >>  W- production with decay
pphh22       >>  p p --> H H                   >>  on-shell double Higgs production
ppaa02       >>  p p --> gamma gamma           >>  gamma gamma production
ppeexa03     >>  p p --> e^- e^+ gamma         >>  Z gamma production with decay
ppnenexa03   >>  p p --> v_e^- v_e^+ gamma     >>  Z gamma production with decay
ppexnea03    >>  p p --> e^+ v_e^- gamma       >>  W+ gamma production with decay
ppenexa03    >>  p p --> e^- v_e^+ gamma       >>  W- gamma production with decay
ppzz02       >>  p p --> Z Z                   >>  on-shell ZZ production
ppwxw02      >>  p p --> W^+ W^-               >>  on-shell WW production
ppeeexex04   >>  p p --> e^- e^- e^+ e^+       >>  ZZ production with decay
ppemexmx04   >>  p p --> e^- mu^- e^+ mu^+     >>  ZZ production with decay
ppeexnmnmx04 >>  p p --> e^- e^+ v_mu^- v_mu^+ >>  ZZ production with decay
ppeexnenex04 >>  p p --> e^- e^+ v_e^- v_e^+   >>  ZZ/WW production with decay
ppemxnmnex04 >>  p p --> e^- mu^+ v_mu^- v_e^+ >>  WW production with decay
ppemexnmx04  >>  p p --> e^- mu^- e^+ v_mu^+   >>  W-Z production with decay
ppeexmxnm04  >>  p p --> e^- e^+ mu^+ v_mu^-   >>  W+Z production with decay
ppeeexnex04  >>  p p --> e^- e^- e^+ v_e^+     >>  W-Z production with decay
ppeexexne04  >>  p p --> e^- e^+ e^+ v_e^-     >>  W+Z production with decay
|============>> ppeeexex04
<<MATRIX-MAKE>> Starting compilation...
<<MATRIX-MAKE>> Using compiled LHAPDF installation under
                (config/MATRIX_configuration) path_to_lhapdf=/usr/local/bin
                /lhapdf-config
<<MATRIX-MAKE>> Download and Compilation of OpenLoops via svn checkout from
                http://openloops.hepforge.org/svn/OpenLoops/branches/public into
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-external/OpenLoops-
                install...
<<MATRIX-MAKE>> Downloading OpenLoops...
<<MATRIX-MAKE>> Compiling OpenLoops...
<<MATRIX-MAKE>> MoRe already compiled. Remove folder
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-MoRe/MoRe-v1.0.0 if
                you want to re-compile...
<<MATRIX-MAKE>> Extracting and Compiling Cln from
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-
                external/cln-1.3.4.tar into
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-external/cln-
                install...
<<MATRIX-MAKE>> Extracting and Compiling Ginac from
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-
                external/ginac-1.6.2.tar into
                /Users/Mars/Uni/Own_Codes/munich/MATRIX/src-external/ginac-
                install...
<<MATRIX-MAKE>> Compiling process <ppeeexex04>, this may take a while...
                (see make.log file to monitor the progress)
<<MATRIX-MAKE>> Downloading and compiling ppllll amplitude with OpenLoops...
<<MATRIX-MAKE>> Downloading and compiling pplllj amplitude with OpenLoops...
<<MATRIX-MAKE>> Downloading and compiling ppllll2 amplitude with OpenLoops...
<<MATRIX-INFO>> Running on Mac. Trying to make relative paths of linked
                OpenLoops dylibs absolute. Please consider using
export DYLD_LIBRARY_PATH=DYLD_LIBRARY_PATH:/Users/Mars/Uni/Own_Codes/munich/MATRIX/src-ext
<<MATRIX-INFO>> in your terminal and possibly adding it to your
                .bashrc/.bash_profile, in case you still experience linking
                errors when running the code.
<<MATRIX-MAKE>> Creating process folder in "run"-directory: "/Users/Mars/Uni/Own
                _Codes/munich/MATRIX/run/ppeeexex04_MATRIX"...
<<MATRIX-INFO>> Process folder successfully created.
<<MATRIX-INFO>> Process generation finished, to go to the run directory type:
                cd /Users/Mars/Uni/Own_Codes/munich/MATRIX/run/ppeeexex04_MATRIX
<<MATRIX-INFO>> and start run by typing:
                ./bin/run_process
```

MATRIX use

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

  $$ ./bin/run_process

- First choose the name of the run

  |===>> run_my_first_ZZ

- Adjust the input cards

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

- Then start the run

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

MATRIX use

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

$$ ./bin/run_process

- First choose the name of the run

|===>> run_my_first_ZZ

- Adjust the input cards

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

- Then start the run

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

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

      /---------------------------------------------------------------------\
```

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

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


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

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

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

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


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

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

```
|============>> model
|============>> distribution
|============>> run
```

MATRIX use

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

$$ ./bin/run_process

- First choose the name of the run

|===>> run_my_first_ZZ

- Adjust the input cards

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

- Then start the run
- With default input cards the code runs LO with 1% accuracy
- Automatic evaluation of 7-point or 9-point scale variations

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

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

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

MATRIX use

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

  $$ ./bin/run_process

- First choose the name of the run

  |===>> run_my_first_ZZ

- Adjust the input cards

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

- Then start the run
- With default input cards the code runs LO with 1% accuracy
- Automatic evaluation of 7-point or 9-point scale variations

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

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


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

<MATRIX-RESULT> 1 separate run was made

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

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

Stability of the subtraction procedure

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

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

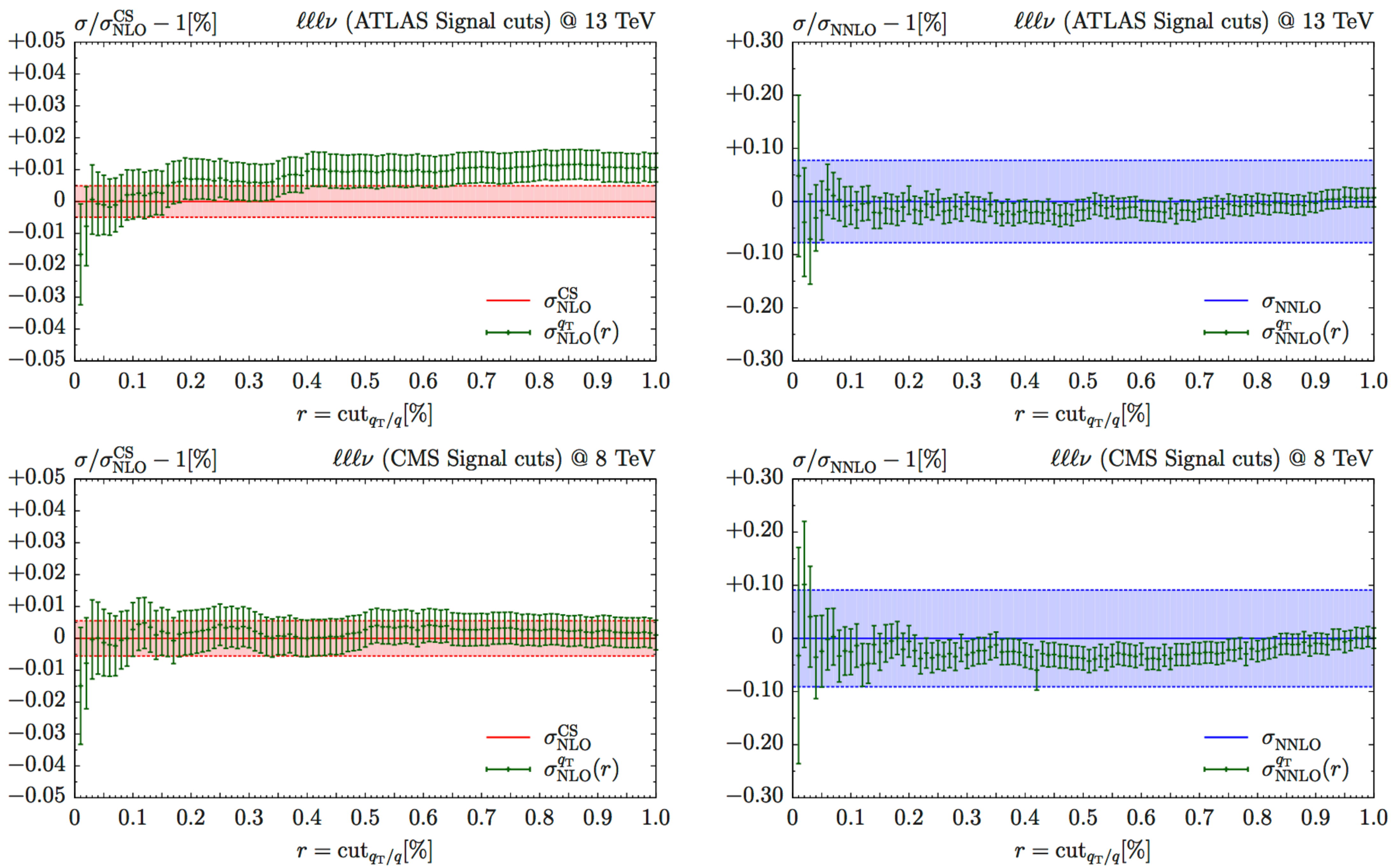
In our implementation q_T subtraction indeed works as a slicing method

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

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

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

Stability of the subtraction procedure

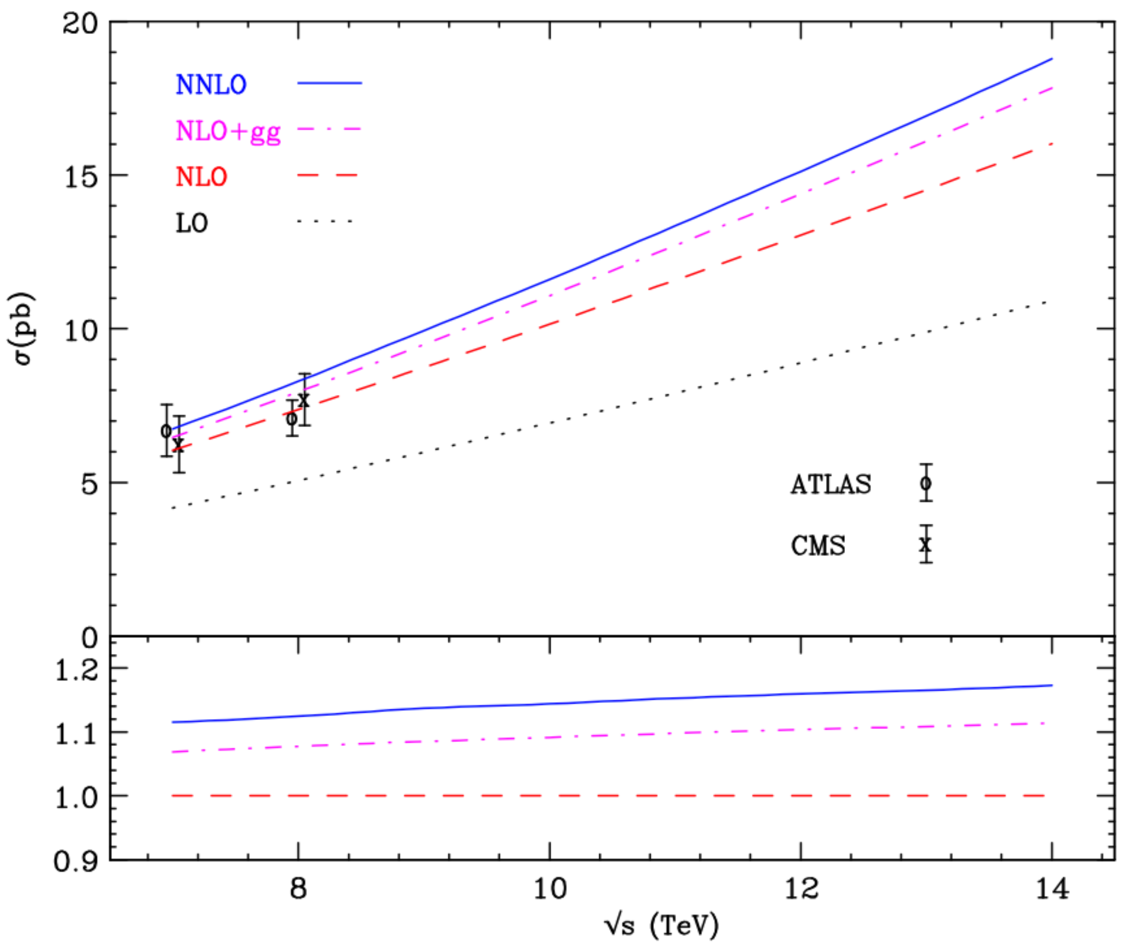


For all processes we consider (except those involving photons)
the NNLO uncertainties are typically at the 0.1% level or smaller

Results

pp→ZZ+X at NNLO

F.Cascioli, T.Gehrmann, S.Kallweit, P.Maierhoefer, A. von Manteuffel, S.Pozzorini, D.Rathlev, L.Tancredi, E.Weihs, MG (2014)



We choose $\mu_F = \mu_R = m_Z$ as central scale

Scale uncertainties of order ± 3% at NLO and at NNLO

Inclusive cross sections for on shell ZZ pairs

NNLO effect ranges from 12 to 17 % when √s varies from 7 to 14 TeV

Loop induced gg contribution 58-62% of the full NNLO effect

$\sqrt{s}$ (TeV)	σ_{LO} (pb)	σ_{NLO} (pb)	σ_{NNLO} (pb)
7	$4.167^{+0.7\%}_{-1.6\%}$	$6.044^{+2.8\%}_{-2.2\%}$	$6.735^{+2.9\%}_{-2.3\%}$
8	$5.060^{+1.6\%}_{-2.7\%}$	$7.369^{+2.8\%}_{-2.3\%}$	$8.284^{+3.0\%}_{-2.3\%}$
9	$5.981^{+2.4\%}_{-3.5\%}$	$8.735^{+2.9\%}_{-2.3\%}$	$9.931^{+3.1\%}_{-2.4\%}$
10	$6.927^{+3.1\%}_{-4.3\%}$	$10.14^{+2.9\%}_{-2.3\%}$	$11.60^{+3.2\%}_{-2.4\%}$
11	$7.895^{+3.8\%}_{-5.0\%}$	$11.57^{+3.0\%}_{-2.4\%}$	$13.34^{+3.2\%}_{-2.4\%}$
12	$8.882^{+4.3\%}_{-5.6\%}$	$13.03^{+3.0\%}_{-2.4\%}$	$15.10^{+3.2\%}_{-2.4\%}$
13	$9.887^{+4.9\%}_{-6.1\%}$	$14.51^{+3.0\%}_{-2.4\%}$	$16.91^{+3.2\%}_{-2.4\%}$
14	$10.91^{+5.4\%}_{-6.7\%}$	$16.01^{+3.0\%}_{-2.4\%}$	$18.77^{+3.2\%}_{-2.4\%}$

pp→ZZ+X at NNLO: lepton decays and off-shell effects

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

Consider pp→ZZ→4 leptons at 8 TeV

Use ATLAS cuts to define fiducial region:

$p_{Tl} > 7$ GeV $|\eta_l| < 2.7$ $\Delta R(l,l) > 0.2$
66 GeV < m_{Z1}, m_{Z2} < 116 GeV ↘ crucial for IR safety !

In the identical flavour case there is an ambiguity in choosing the Z candidates:
solved by choosing the pairs for which the sum of the distances from m_Z is minimum

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	σ_{exp} (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\text{stat})^{+0.4}_{-0.4}(\text{syst.})^{+0.1}_{-0.1}(\text{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\text{stat})^{+0.2}_{-0.2}(\text{syst.})^{+0.2}_{-0.2}(\text{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\text{stat})^{+0.5}_{-0.5}(\text{syst.})^{+0.3}_{-0.3}(\text{lumi.})$

NNLO corrections improve agreement with ATLAS data in the 2e2μ channel but make the agreement worse in the other channels (but experimental uncertainties still large)

pp→ZZ+X at NNLO: lepton decays and off-shell effects

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

Consider pp→ZZ→4 leptons at 8 TeV

Use ATLAS cuts to define fiducial region:

$p_{Tl} > 7$ GeV $|\eta_l| < 2.7$ $\Delta R(l,l) > 0.2$
66 GeV < m_{Z1}, m_{Z2} < 116 GeV

crucial for IR safety !

In the identical flavour case there is an ambiguity in choosing the Z candidates: solved by choosing the pairs for which the sum of the distances from m_Z is minimum

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	σ_{exp} (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\text{stat})^{+0.4}_{-0.4}(\text{syst.})^{+0.1}_{-0.1}(\text{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\text{stat})^{+0.2}_{-0.2}(\text{syst.})^{+0.2}_{-0.2}(\text{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\text{stat})^{+0.5}_{-0.5}(\text{syst.})^{+0.3}_{-0.3}(\text{lumi.})$

+15% (60% comes from gg fusion)

NNLO corrections improve agreement with ATLAS data in the 2e2μ channel but make the agreement worse in the other channels (but experimental uncertainties still large)

pp→ZZ+X at NNLO: the Higgs background region

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

YR4 ZZ cuts:

- $p_{T1} > 20$ GeV $p_{T2} > 10$ GeV
  $p_{Te} > 7$ GeV $|\eta_e| < 2.5$ $p_{T\mu} > 5$ GeV $|\eta_\mu| < 2.5$
  $\Delta R(l,l) > 0.1$
- lepton isolation: Σ (p_{Ti} of all particles i with $\Delta R(l,i) < 0.4$) $< 0.4\, p_{Tl}$
  Jets: anti-kt with R=0.4
- Leading pair: same flavour pair with smallest $|m-m_Z|$ → m_1
  Subleading pair: remaining same flavour pair with smallest $|m-m_Z|$ → m_2
  40 GeV $< m_1 <$ 120 GeV 12 GeV $< m_2 <$ 120 GeV
- 120 GeV $< m_{4l} <$ 130 GeV
- Use PDF4LHC15 at NLO and NNLO with $\mu_F = \mu_R = m_{4l}$ as central scale

pp→ZZ+X at NNLO: the Higgs background region

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

Since the cuts are not very aggressive we would expect the impact of radiative corrections not to change

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NLO+gg} (fb)	σ_{NNLO} (fb)
$e^+e^-e^+e^-$	$0.1347(1)^{+10\%}_{-11\%}$	$0.1485(2)^{+2.4\%}_{-3.6\%}$	$0.1584(2)^{+2.4\%}_{-3.6\%}$	$0.159(1)^{+0.7\%}_{-0.9\%}$
$\mu^+\mu^-\mu^+\mu^-$	$0.1946(2)^{+10\%}_{-11\%}$	$0.2150(2)^{+2.4\%}_{-3.6\%}$	$0.2291(2)^{+2.4\%}_{-3.6\%}$	$0.230(1)^{+0.9\%}_{-0.8\%}$
$e^+e^-\mu^+\mu^-$	$0.3165(3)^{+10\%}_{-11\%}$	$0.3457(3)^{+2.4\%}_{-3.6\%}$	$0.3677(2)^{+2.3\%}_{-3.5\%}$	$0.3690(6)^{+0.5\%}_{-0.8\%}$

+9-10%

+6-7%

0-1%

With this choice of parameters NLO corrections for on shell inclusive ZZ production amount to +23%

The combination of the cuts acts to reduce the impact of radiative corrections !

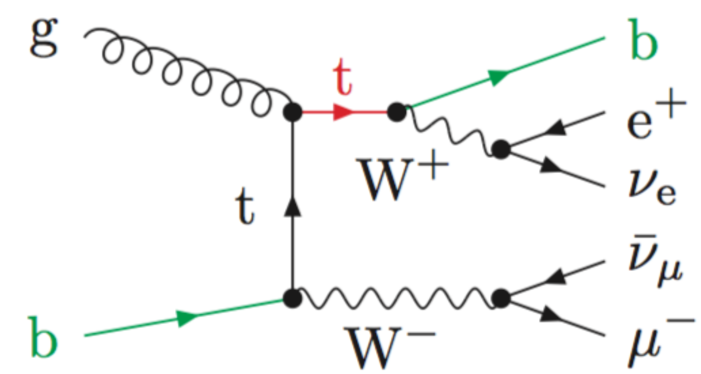
gg contribution provides almost the entire NNLO corrections

pp→WW+X at NNLO

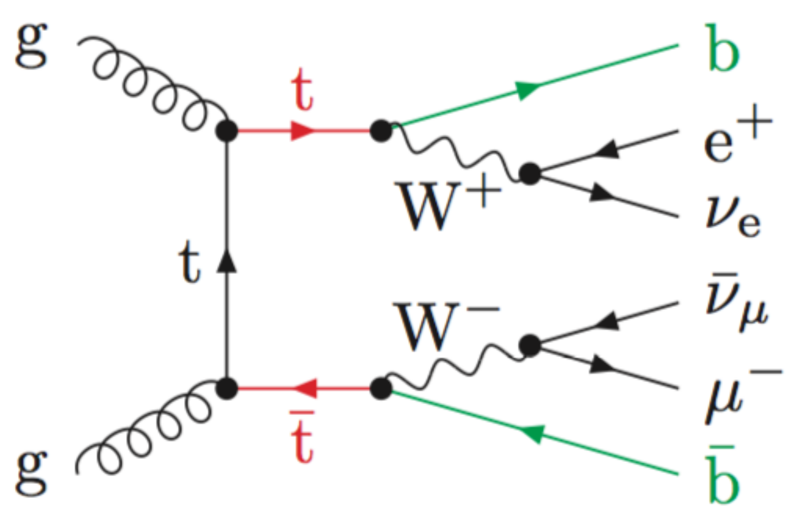
T. Gehrmann, S. Kallweit, P. Maierhofer, A. von Manteuffel,
S. Pozzorini, D. Rathlev, L. Tancredi, MG (2014)

The WW cross section cannot be naively defined in QCD perturbation theory

In the 5-flavor scheme diagrams with real b-quarks are crucial to cancel collinear singularities from g →b$\bar{b}$ splitting



Already at NLO there are contributions with final state b-quarks coming from Wt production (+30-60%)



At NNLO it is even worse with doubly resonant t$\bar{t}$ diagrams which enhance the cross section at 7(14) TeV by a factor 4(8)

A first possible solution: use the 4-flavor scheme: the bottom quarks are massive: we can omit diagrams with b-quark emissions and obtain a consistent WW cross section at NNLO

pp→WW+X at NNLO

T. Gehrmann, S. Kallweit, P. Maierhofer, A. von Manteuffel,
S. Pozzorini, D. Rathlev, L. Tancredi, MG (2014)

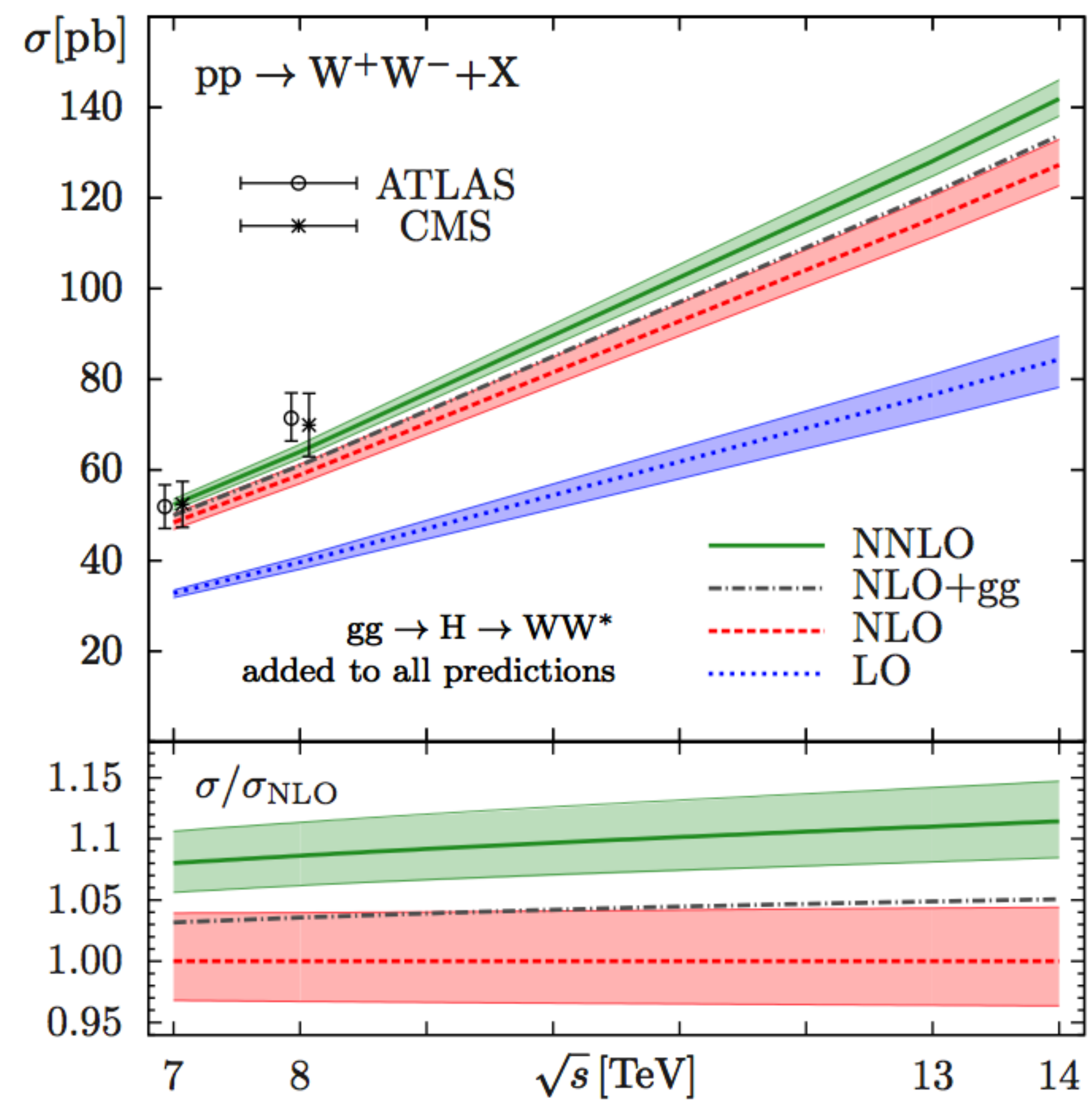
The NNLO effect in the 4FS ranges from 9 to 12 % when √s varies from 7 to 14 TeV

gg contribution 35% of the full NNLO effect

$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$

We choose $\mu_F=\mu_R=m_W$ as central scale

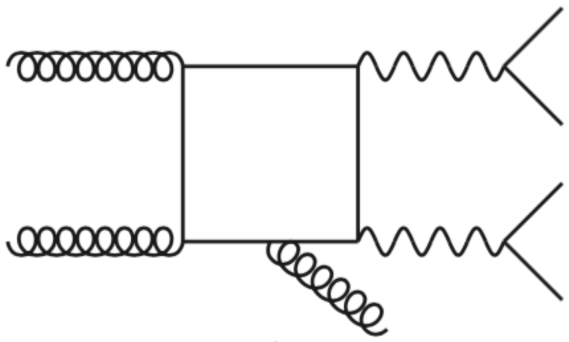
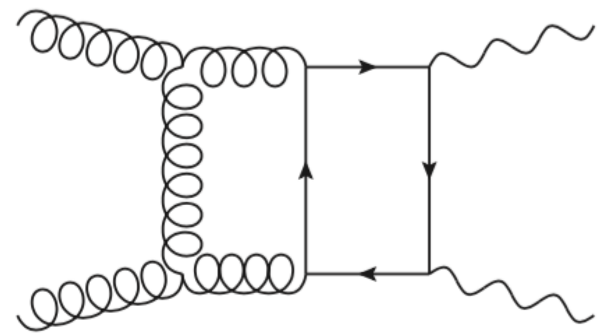
Comparing with 5FS with subtraction of tt and Wt contribution we find agreement at the 1(2)% level



Scale uncertainties computed by varying μ_F and μ_R simultaneously and independently with $1/2\, m_W < \mu_F, \mu_R < 2m_W$ and $1/2 < \mu_F/\mu_R < 2$

gg→WW/ZZ+X at NLO

F.Caola, K.Melnikov, R.Röntsch, L.Tancredi (2015)

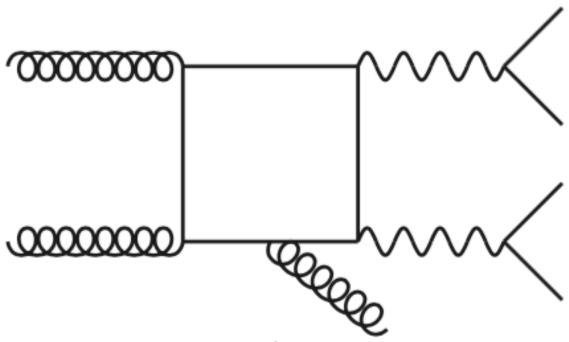
NLO corrections to gg→WW/ZZ are formally N^3LO but important given the large gluon luminosity

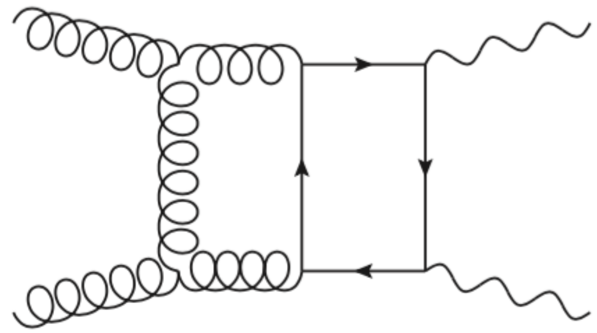
qqb and gg channels are often considered as independent processes and people think one can study them independently

→ but QCD evolution mixes the two channels and the only consistent approach would be to carry out a complete calculation at each order

gg→WW/ZZ+X at NLO

F.Caola, K.Melnikov, R.Röntsch, L.Tancredi (2015)





NLO corrections to gg→WW/ZZ recently completed (no fermionic channels)

- NLO corrections to gg→WW increase the inclusive WW cross section by *+2%*

  → moderate effect within NNLO scale uncertainties

- As for ZZ, by using our NNLO setup they get an additional *+6%* shift at 8 TeV (*+7%* at 13 TeV): exceeds the O(3%) scale uncertainty at NNLO

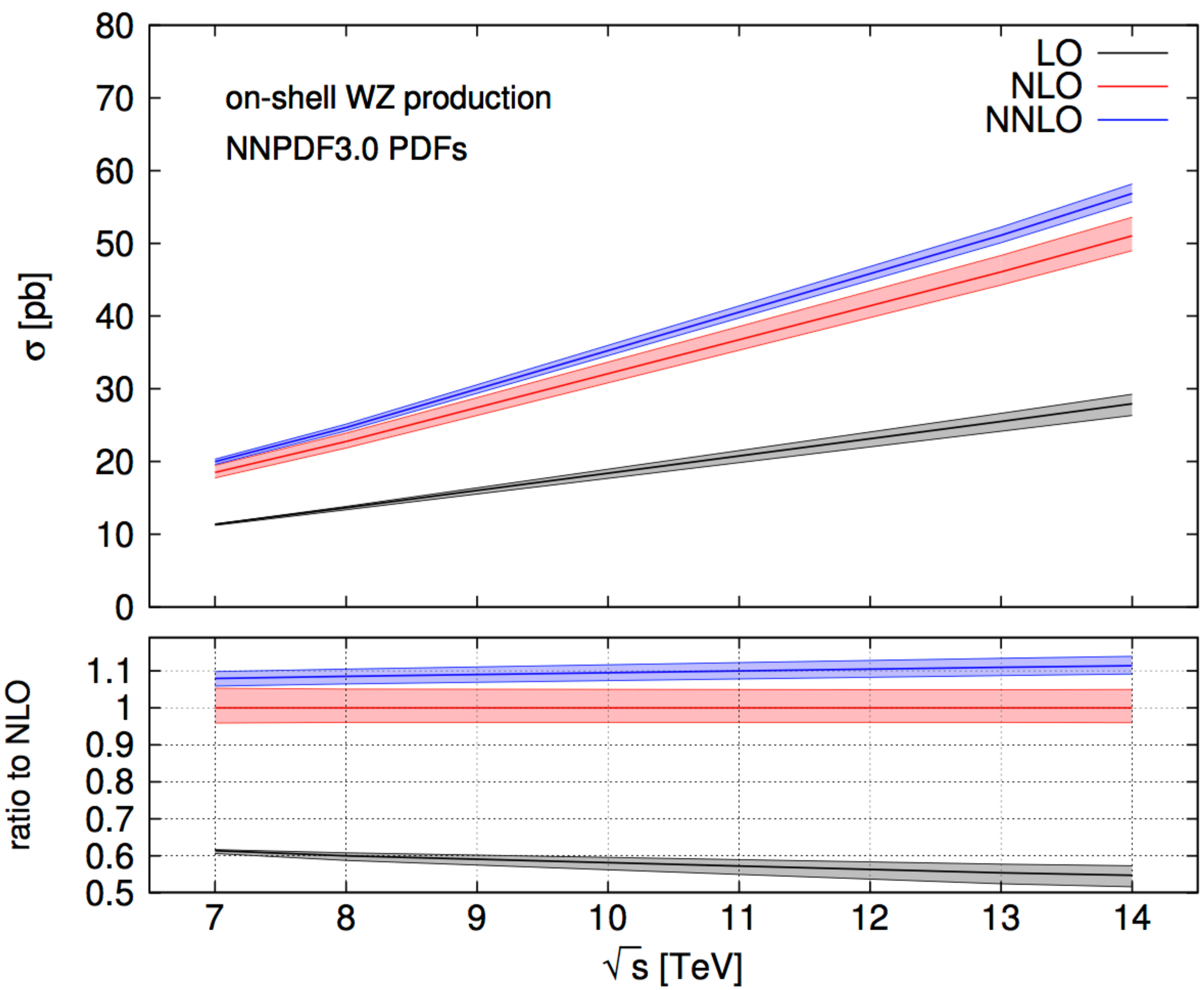
  → Not unexpected, given the larger size of gg contribution

Recently matched to parton shower in the POWHEG framework

S.Alioli, F.Caola, G.Luisoni, R.Röntsch (2016)

WZ: inclusive cross section

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



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

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

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

From 7 to 14 TeV:

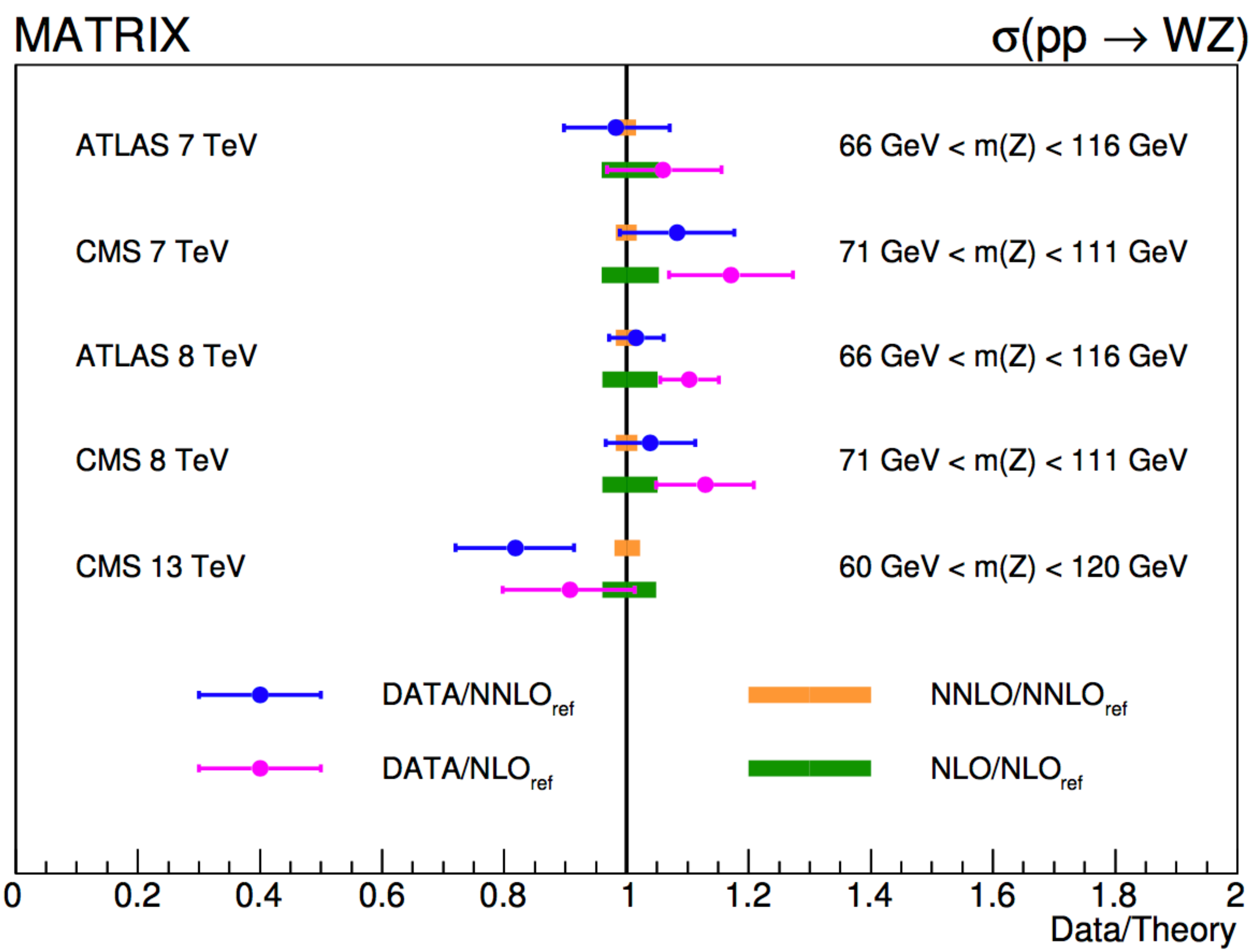
NLO effects range from 62 to 82%

NNLO effects range from 8 to 11%

Scale uncertainties reduced down to the 2% level

WZ: inclusive cross section

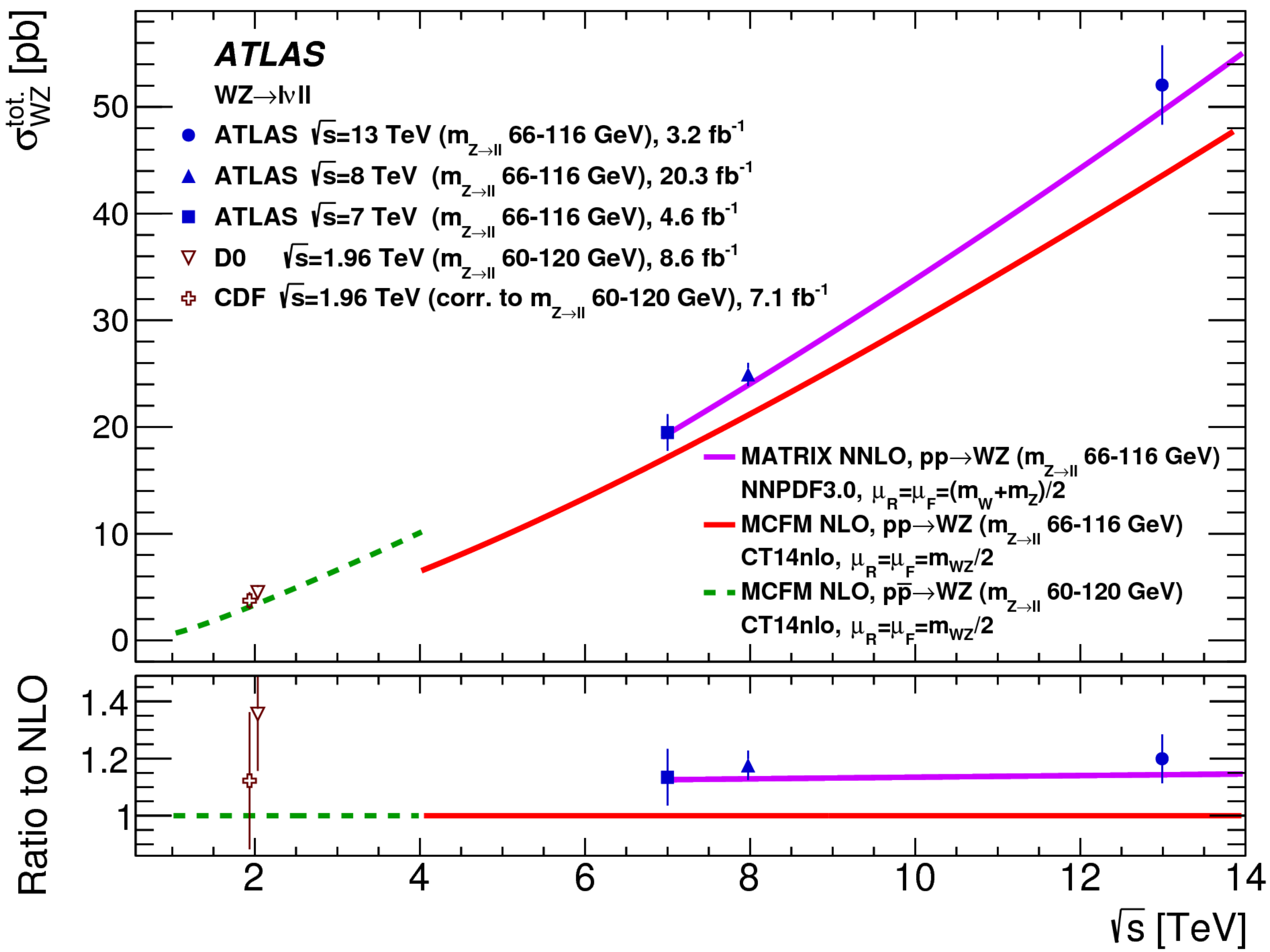
S. Kallweit, D. Rathlev, M.Wiesemann, MG (2016)



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

WZ: inclusive cross section

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



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

WZ: fully differential

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

Setup: NNPDF3.0

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

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

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

Pair with highest P is assigned to the Z boson

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

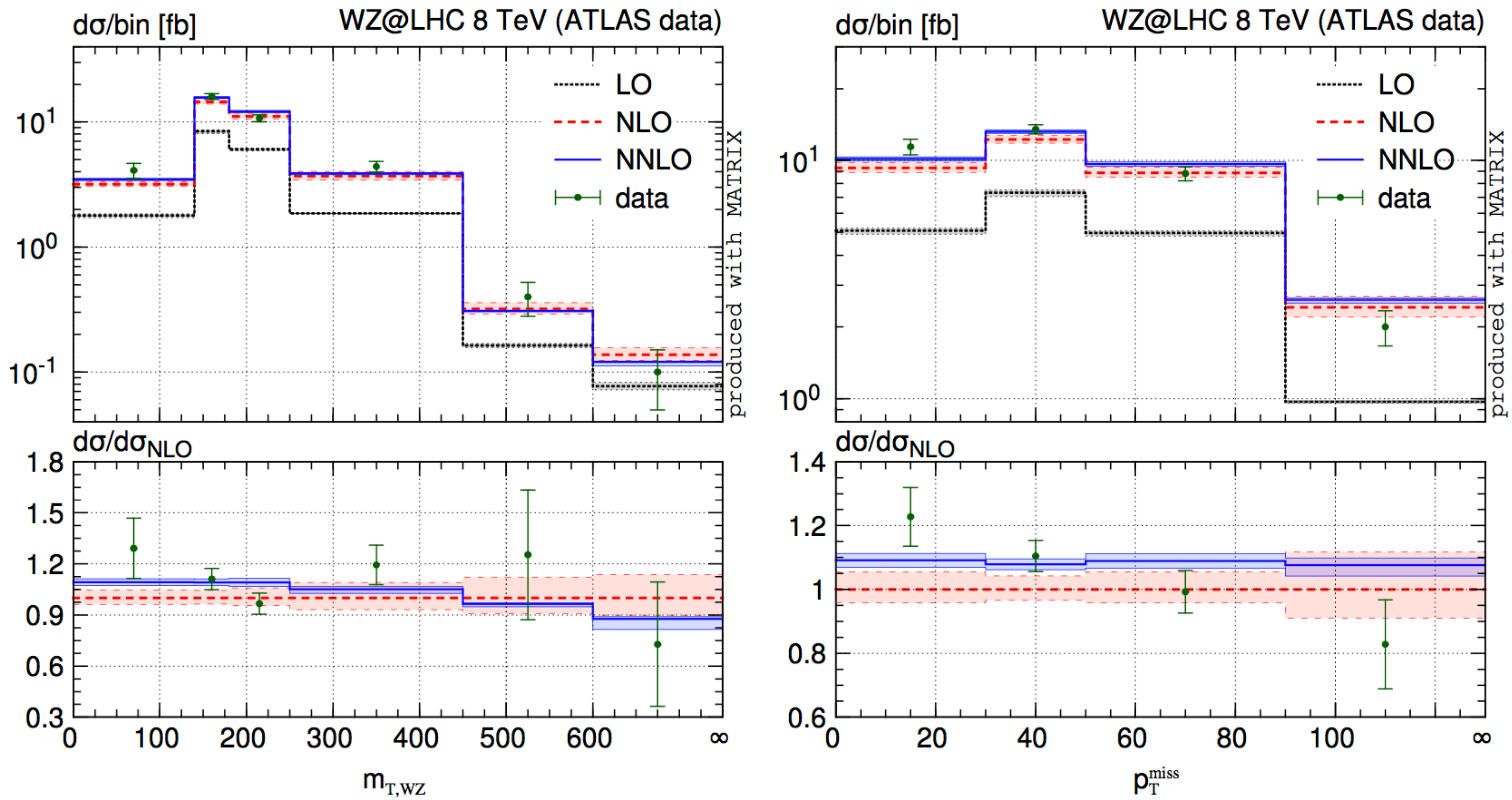
Fiducial cuts:

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

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

WZ: fully differential

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



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

WZ: fully differential: NP searches

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

Three lepton+MET signature relevant for many NP searches

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

Selection cuts:

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

Four categories are considered:

Category I: no additional cut

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

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

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

Dynamic scale more appropriate here

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

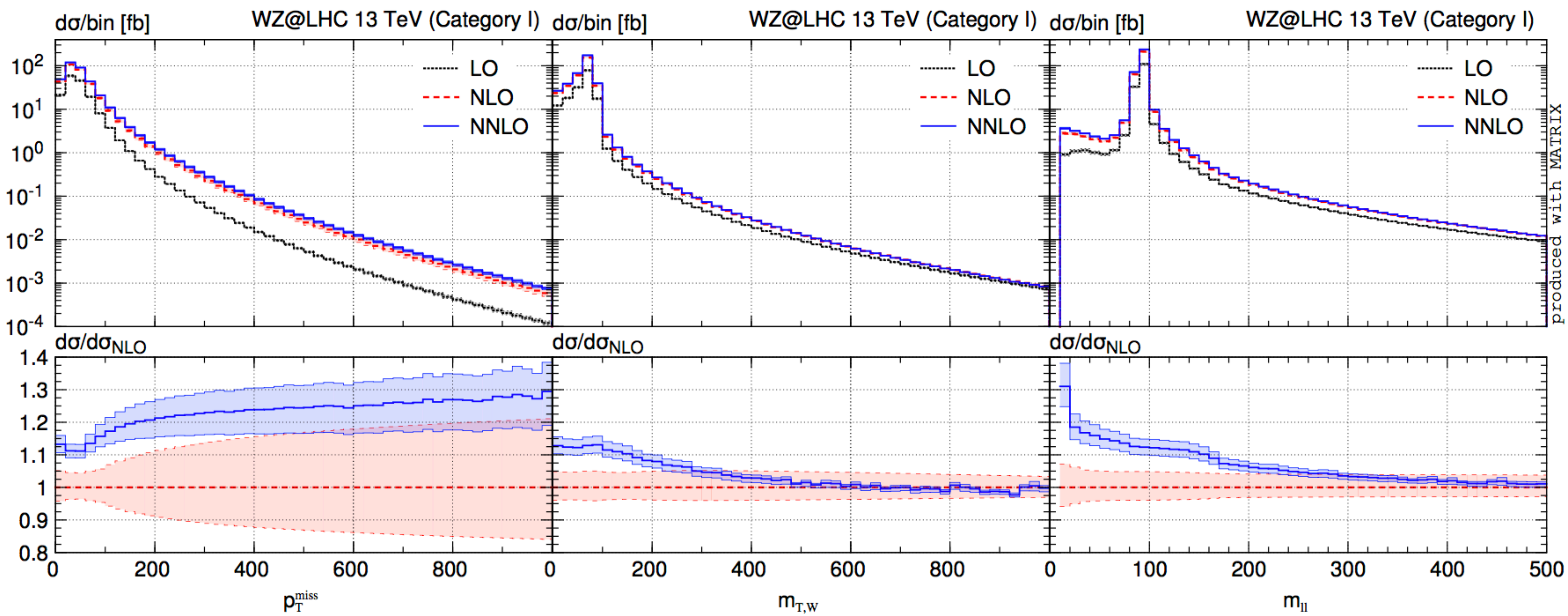
WZ: fully differential: NP searches

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

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

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

WZ: fully differential: NP searches



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

Summary & Outlook

- Vector boson pair production is an essential process at hadron colliders: it is a background for Higgs and new physics searches and it may provide first evidence of new physics signatures

- The computation of the two-loop helicity amplitudes made possible the exact fully exclusive NNLO calculations of ZZ, WW and WZ including leptonic decays

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

→ MATRIX

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

Summary & Outlook

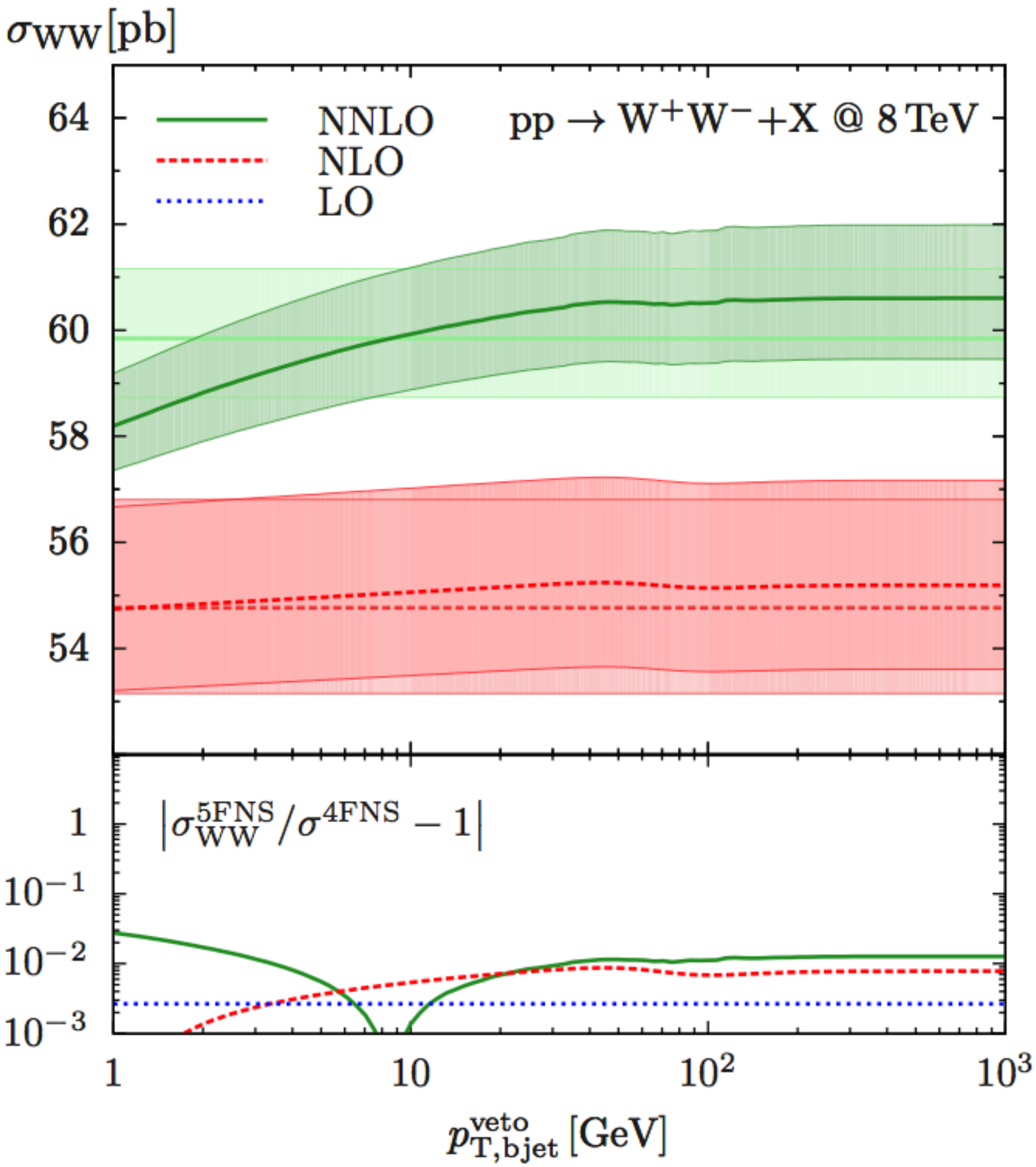
- I have presented results for inclusive and differential cross sections for WW, ZZ, WZ including non-resonant contributions, off-shell and interference effects
- The impact of NNLO corrections is significant and generally depends on the applied cuts
- In the WW and in particular in the ZZ channels the loop-induced gg contributions is important and further increases the cross section
- Some items on our to do list:

  - NLO gg in WW and ZZ
  - Include EW corrections
  - Include anomalous couplings/BSM effects

Thank you !

Backup

The WW cross section in the 5FNS



A better definition of the 5FNS cross section can be obtained by exploiting the different scaling behaviour with $1/\Gamma_t$

Doubly (singly) resonant diagrams scale quadratically (linearly) with $1/\Gamma_t$

A.Denner, S.Dittmaier, S.Kallweit,S.Pozzorini (2012)
F.Cascioli, P.Maierhofer, S.Kallweit, S.Pozzorini (2013)

$t\bar{t}$ and Wt component subtracted by exploiting this different behaviour

As $p^{veto}_{T,bjet} \to 0$ the logarithmic singularity is still present but for $p^{veto}_{T,bjet} \gtrsim 10$ GeV the 5FNS result is approximately independent on the veto

➡ The agreement with the 4FNS result is at the 1(2)% level for 8(14) TeV

$pp \to V\gamma + X$ at NNLO

S.Kallweit,D.Rathlev, A.Torre, MG (2013)
S.Kallweit,D.Rathlev, MG (2015)

We present results of a complete calculation of $pp \to V\gamma + X$ up to NNLO

We compute NNLO corrections to $pp \to l^+l^- \gamma + X$ and $pp \to l\nu\gamma + X$ by consistently including the final state photon radiation from the leptons and the non resonant diagrams

The calculation allows us to apply arbitrary kinematical cuts on the final state lepton(s), the photon and the QCD radiation

➡ **We can compute fiducial cross sections and distributions !**

We consider pp collisions at 7 TeV and we use MMHT2014 PDFs with α_S evaluated at each corresponding order

We set the central values of the scales to $\mu_0 = \sqrt{m_V^2 + (p_T^\gamma)^2}$

Scale uncertainties computed by varying μ_F and μ_R simultaneously and independently with $1/2\,\mu_0 < \mu_F, \mu_R < 2\,\mu_0$ with no constraint on their ratio

$pp \to Z\gamma + X$ at NNLO

S.Kallweit, D.Rathlev, MG (2015)
see also J.Campbell, T.Neumann, C.Williams (2017)

ATLAS cuts (arXiv:1302.1283)

photon isolation: $\varepsilon = 0.5$
smooth cone $R = 0.4$

$p^{\gamma}_T > 15$ GeV $p^{l}_T > 25$ GeV $\Delta R(l/\gamma,\text{jet}) > 0.3$

$|\eta^{\gamma}| < 2.37$ $|\eta^{ll}| < 2.47$ $\Delta R(l,\gamma) > 0.7$

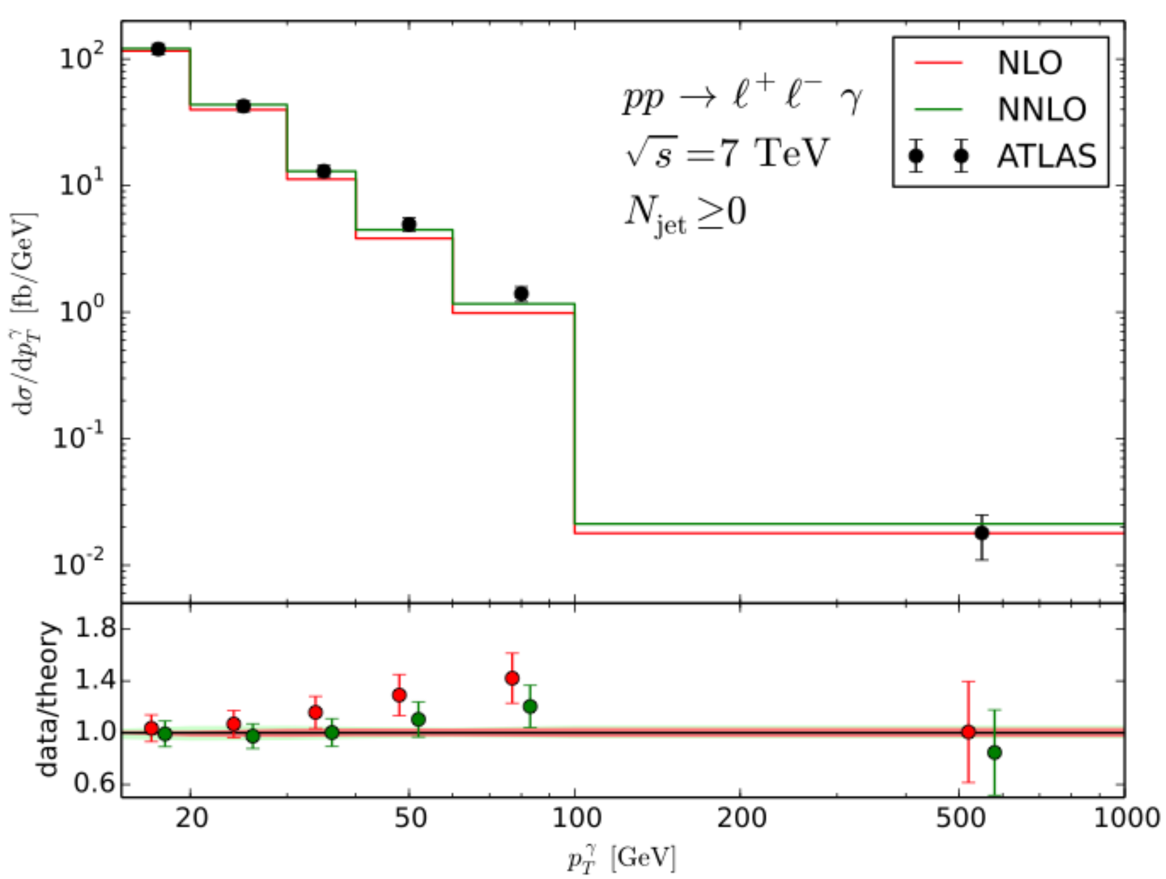
$m_{ll} > 40$ GeV

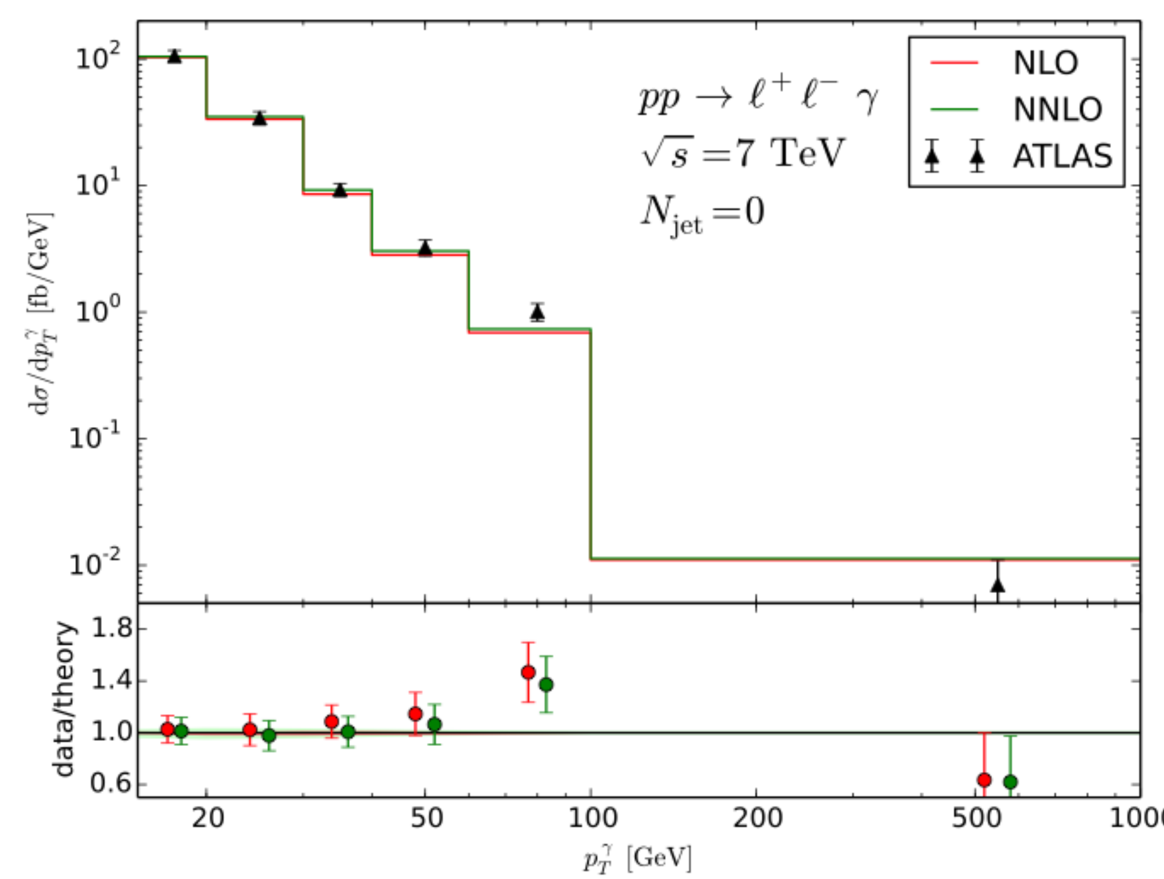
jets: anti-kt with D=0.4

$p_T^{\text{jet}} > 15$ GeV $|\eta^{\text{jet}}| < 2.47$

+8%

	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]
$N_{\text{jet}} \geq 0$	$1.222^{+4.2\%}_{-5.3\%}$	$1.320^{+1.3\%}_{-2.3\%}$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)
$N_{\text{jet}} = 0$	$1.031^{+2.7\%}_{-4.3\%}$	$1.059^{+0.7\%}_{-1.4\%}$	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi)





pp→Wγ at NNLO

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

ATLAS cuts (arXiv:1302.1283)

photon isolation: ε= 0.5
smooth cone R= 0.4

$p^{\gamma}_T > 15$ GeV $p^{l}_T > 25$ GeV $\Delta R(l/\gamma,\mathrm{jet}) > 0.3$

$|\eta^{\gamma}| < 2.37$ $|\eta^{l}| < 2.47$ $\Delta R(l,\gamma) > 0.7$

$p_T^{miss} > 35$ GeV jets: anti-kt with D=0.4

$p_T^{jet} > 15$ GeV $|\eta^{jet}| < 2.47$

+19%

	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]
$N_{\mathrm{jet}} \geq 0$	$2.058^{+6.8\%}_{-6.8\%}$	$2.453^{+4.1\%}_{-4.1\%}$	2.77 ±0.03 (stat) ±0.33 (syst) ±0.14 (lumi)
$N_{\mathrm{jet}} = 0$	$1.395^{+5.2\%}_{-5.8\%}$	$1.493^{+1.7\%}_{-2.7\%}$	1.76 ±0.03 (stat) ±0.21 (syst) ±0.08 (lumi)