Theory status of diboson processes

Massimiliano Grazzini

University of Zurich

Universität Zürich UZH

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FNSNF SWISS NATIONAL SCIENCE FOUNDATION

Outline

- Introduction
- Diboson production at NNLO
- The MATRIX framework
- Results
- EW corrections and anomalous couplings
- Summary

Introduction

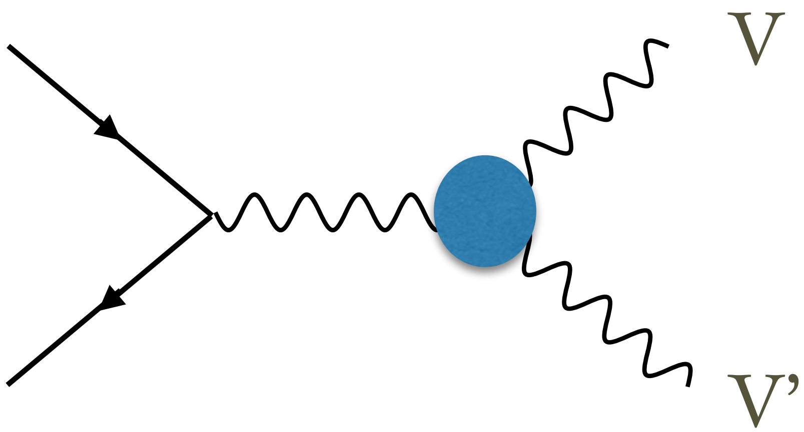
Vector boson pair production is a benchmark process at hadron colliders

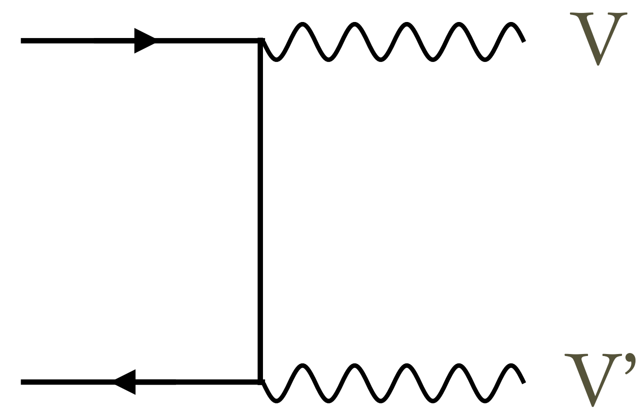
- background to Higgs and new physics searches
- important to set limits on anomalous couplings
- new nice data available from the LHC whose accuracy will soon be comparable with theoretical uncertainties

Up to very recently the accuracy was limited to NLO QCD

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

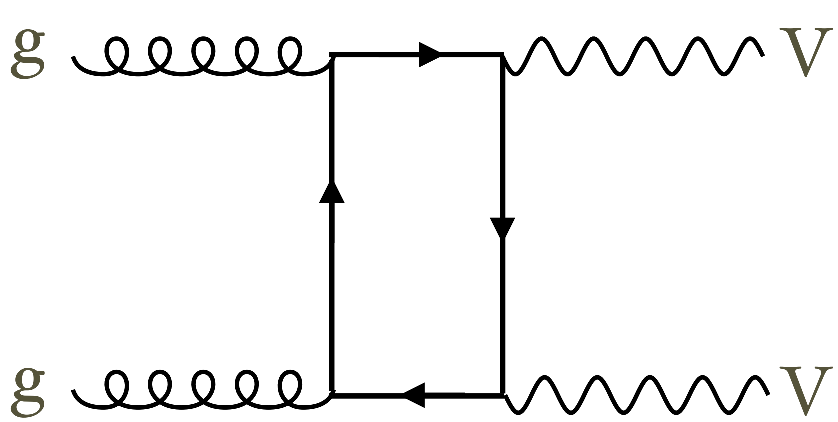
Introduction





Both s and t channel contributions at Born level

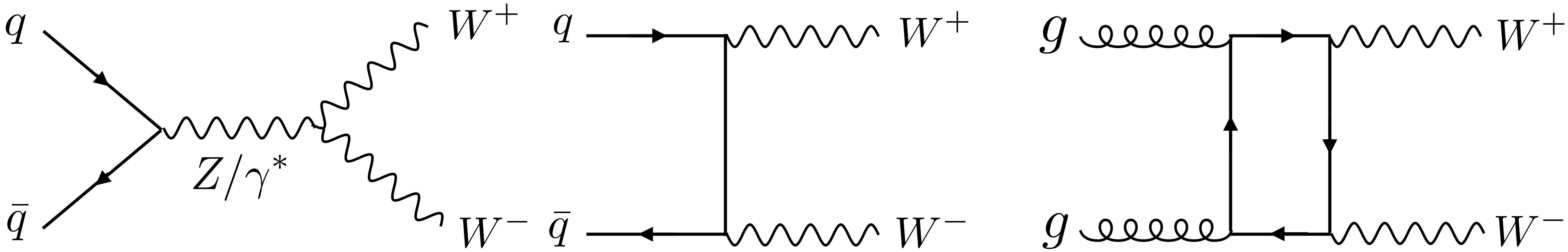
s-channel sensitive to different anomalous trilinear couplings



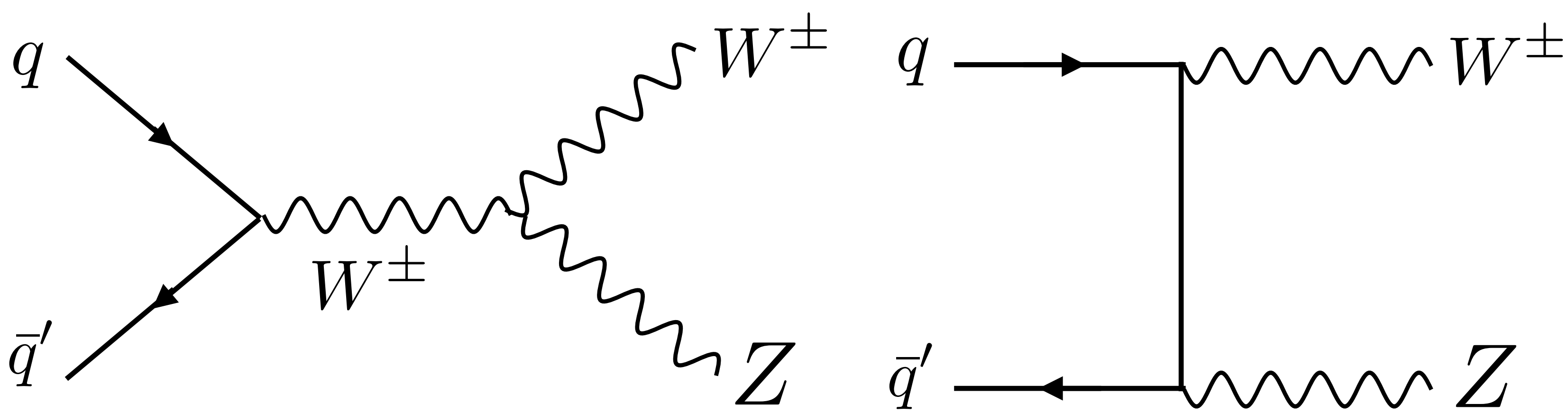
Loop induced gg contribution to processes with neutral final state
Formally NNLO but enhanced by gluon luminosity

Introduction

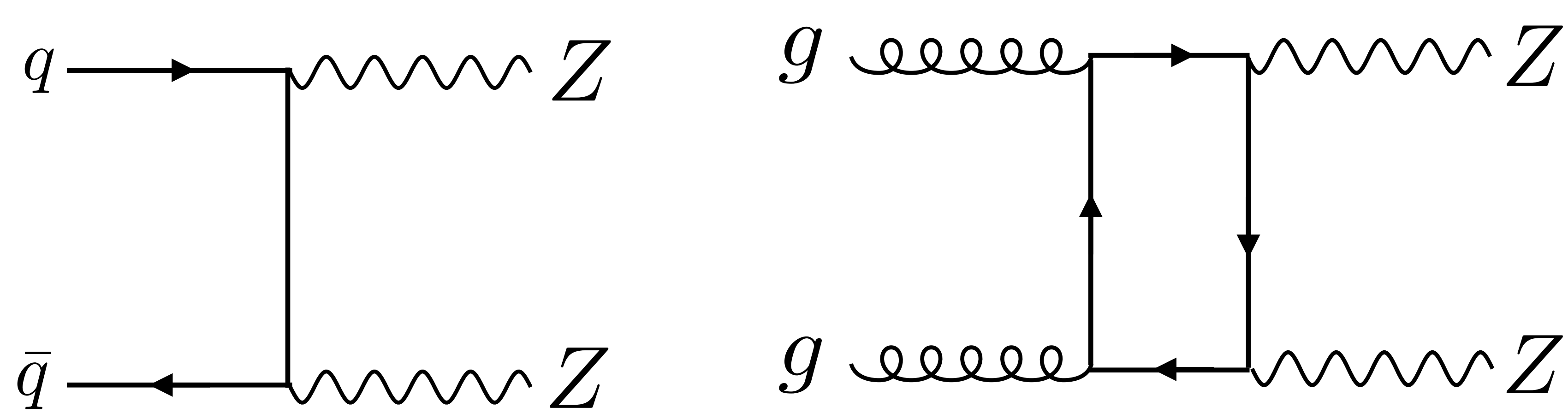
WW production



WZ production

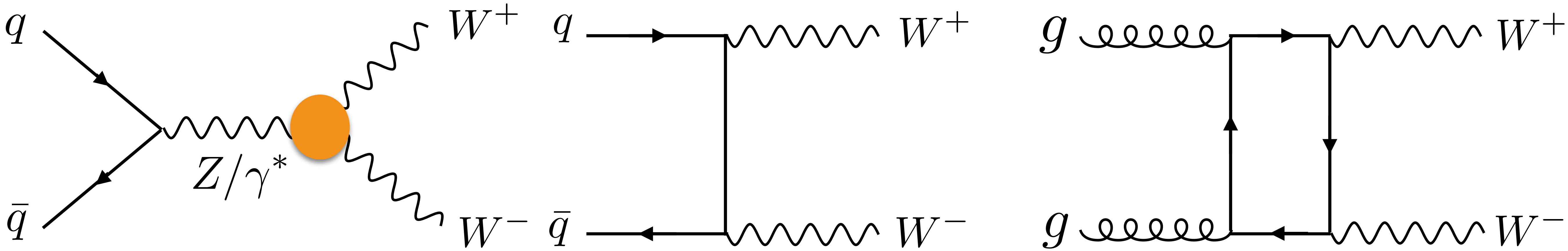


ZZ production

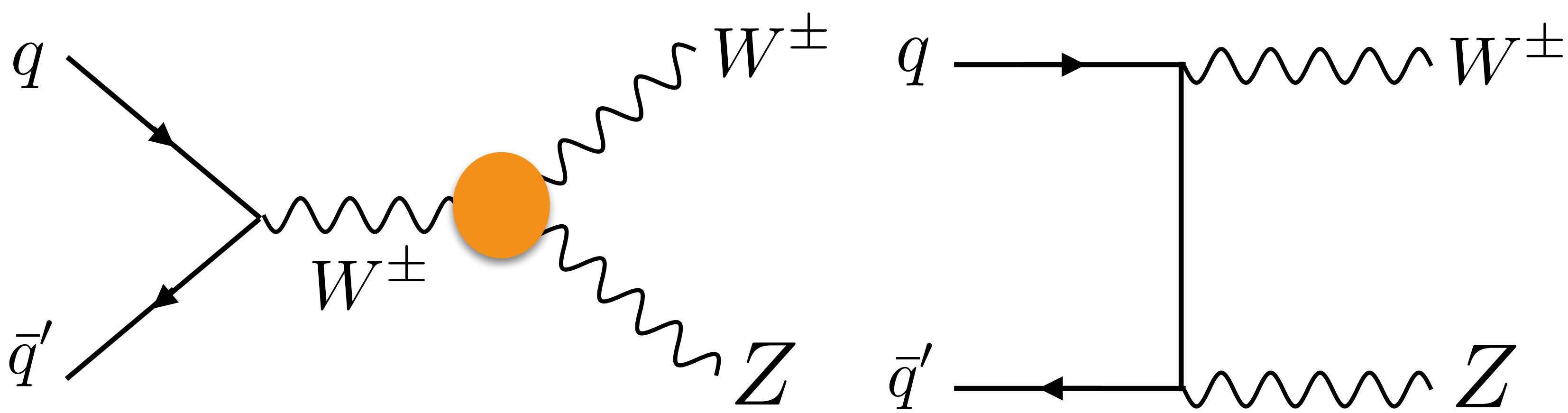


Introduction

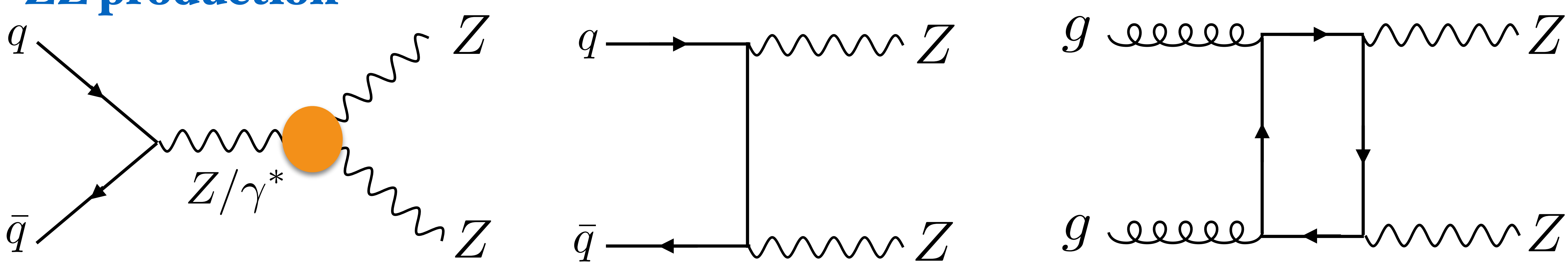
WW production



WZ production



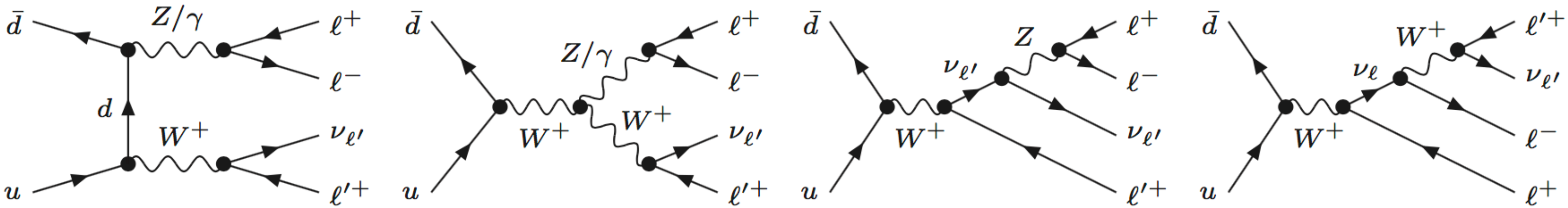
ZZ production



Off-shell and interference effects

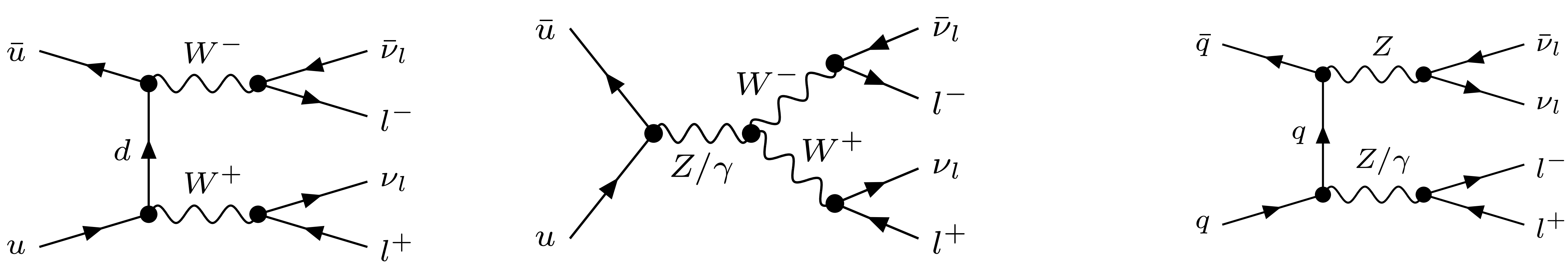
When we talk about VV' production we refer to the full calculation including resonant and non resonant diagrams with off-shell and interference effects

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



In some cases more than one VV' topology may contribute

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



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 known since some time (often assumed to provide the dominant NNLO contribution)

T.Binoth et al. (2005,2008)
M.Duhrssen et al. (2005)
L.Ametller 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

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

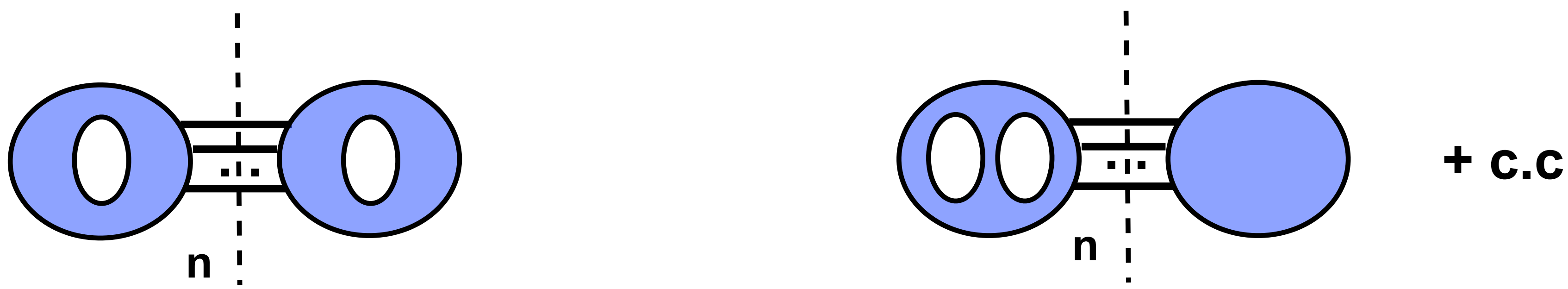
T.Gehrmann, L.Tancredi (2012)
F.Caola, J.Henn, K.Melnikov, A.Smirnov, V.Smirnov (2014)
T.Gehrmann, A. von Manteuffel, L.Tancredi (2014,2015)

➡ **NNLO calculation possible**

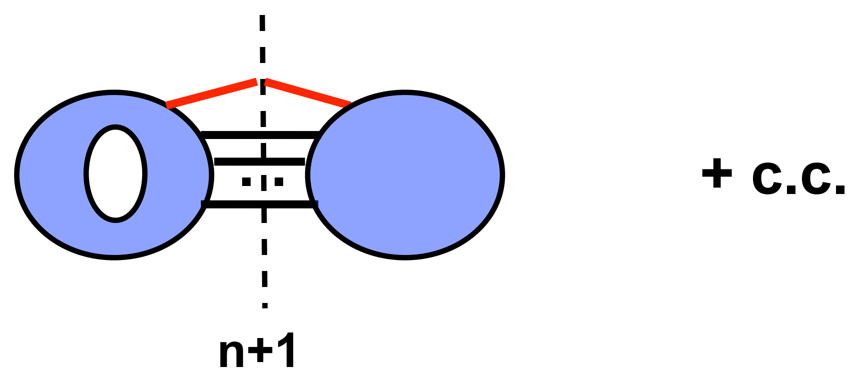
Ingredients of NNLO calculations

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

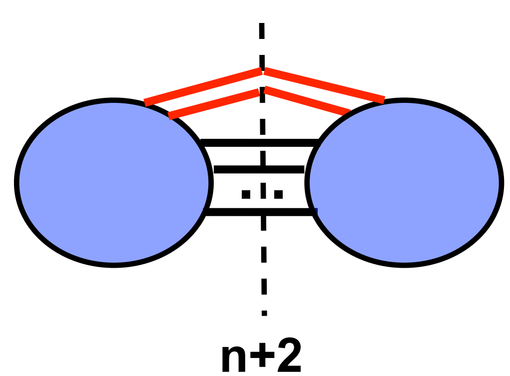
- Double virtual contribution with n resolved partons



- Real-virtual contribution with 1 unresolved parton



- 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)

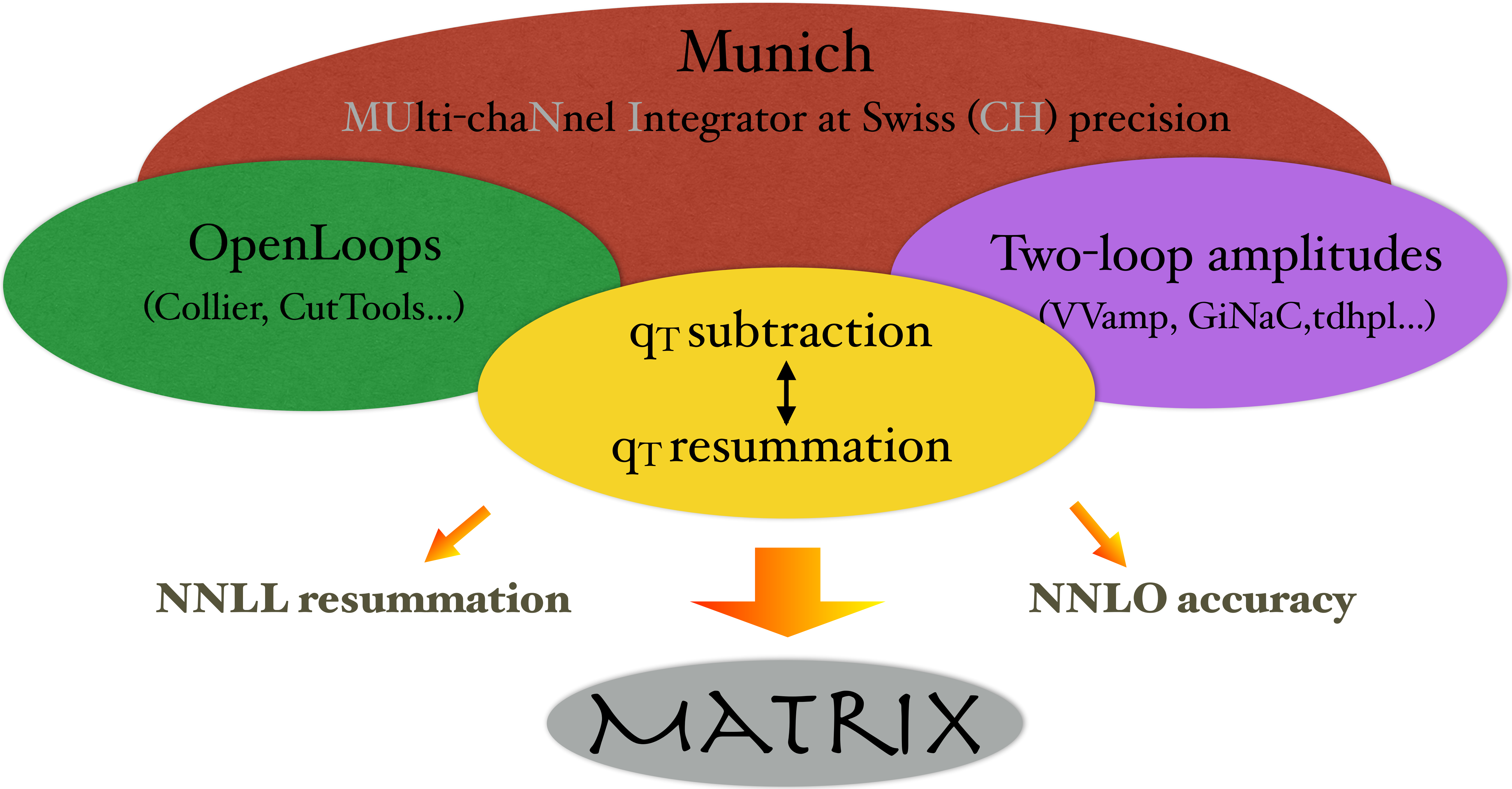
Its general form in terms of the relevant virtual amplitudes for an arbitrary colour singlet F has been provided up to NNLO

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

- $pp \to Z/\gamma^* \ (\to l^+l^-)$ ✅
- $pp \to W(\to l\nu)$ ✅
- $pp \to H$ ✅
- $pp \to \gamma\gamma$ ✅
- $pp \to W\gamma \to l\nu\gamma$ ✅
- $pp \to Z\gamma \to l^+l^- (\nu\nu)\gamma$ ✅ now also in MCFM
- $pp \to ZZ(\to 4l)$ ✅ see also G.Heinrich et al. 2018 for on shell Z bosons
- $pp \to WW \to (l\nu l'\nu')$ ✅
- $pp \to ZZ/WW \to ll\nu\nu$ ✅
- $pp \to WZ \to l\nu ll$ ✅
- $pp \to HH$ (✅) not in public release

First public release out in November 2017

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

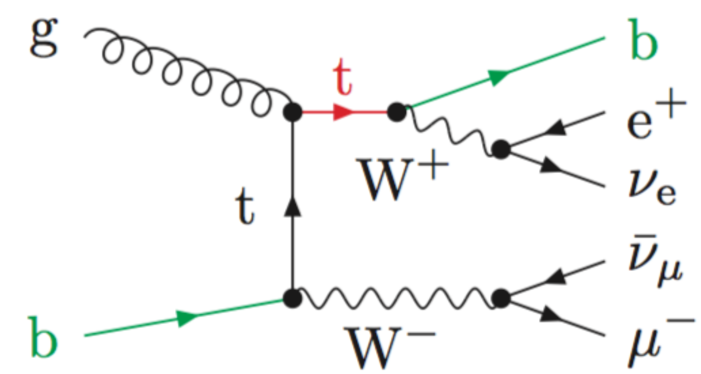
Results

pp→WW+X at NNLO

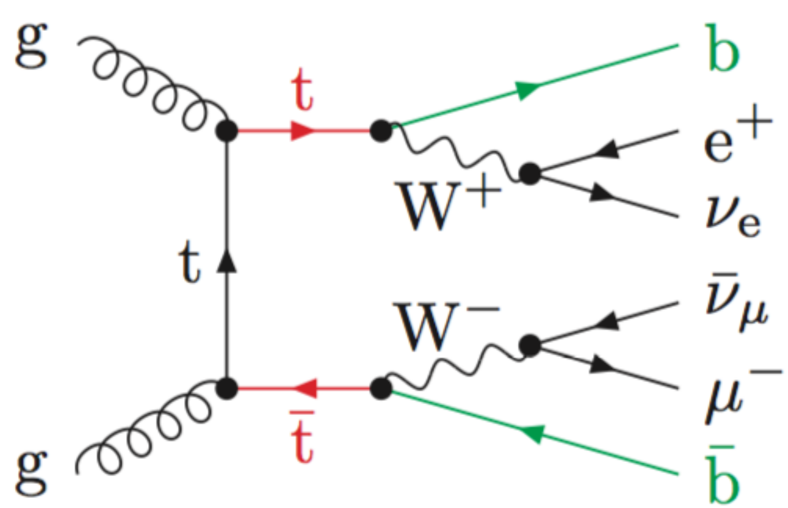
T. Gehrmann, S. Kallweit, P. Maierhofer, A. von Manteuffel,
S. Pozzorini, D. Rathlev, L. Tancredi, MG (2014)

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$\bar{\text{b}}$ 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$\bar{\text{t}}$ diagrams which enhance the cross section at 7(14) TeV by a factor 4(8)

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

WW: fully differential

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

Consider for simplicity only the different flavour channel

Focus in particular on $pp \to W^+W^- + X \to e^-\mu^+\bar{\nu}_e\nu_\mu + X$

WW cuts:

Jets: anti-kt with R=0.4

- $p_{T1} > 25$ GeV $\quad p_{T2} > 20$ GeV
  $\Delta R(l,l) > 0.1 \quad |\eta_\mu| < 2.4 \quad |\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$

- $\begin{cases} p_T^{rel} = p_T^{miss} & \Delta\phi > \pi/2 \\ p_T^{rel} = p_T^{miss} \sin\Delta\phi & \Delta\phi < \pi/2 \end{cases}$

  $\Delta\phi$=azimuthal separation between p_T^{miss} and the closest lepton

- $m_{ll} > 10$ GeV $\quad p_T^{miss} > 20$ GeV $\quad p_T^{rel} > 15$ GeV

- Jet veto: no jets with $p_T > 25$ GeV, $|\eta| < 4.5$

Use NNPDF3.0 with $\mu_F = \mu_R = m_W$ as central scale

Work in the 4FNS but always compare with subtracted 5FNS result

WW: fully differential

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

Corresponding fiducial cross sections and acceptances:

	$\sigma_{\text{fiducial}}(W^+W^-\text{-cuts})$ [fb]		$\sigma/\sigma_{\text{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$147.23\ (2)\,^{+3.4\%}_{-4.4\%}$	$233.04(2)\,^{+6.6\%}_{-7.6\%}$	-3.8%	$-\ 1.3\%$
NLO	$153.07\ (2)\,^{+1.9\%}_{-1.6\%}$	$236.19(2)\,^{+2.8\%}_{-2.4\%}$	0	0
NLO′	$156.71\ (3)\,^{+1.8\%}_{-1.4\%}$	$243.82(4)\,^{+2.6\%}_{-2.2\%}$	$+2.4\%$	$+\ 3.2\%$
NLO′$+gg$	$166.41\ (3)\,^{+1.3\%}_{-1.3\%}$	$267.31(4)\,^{+1.5\%}_{-2.1\%}$	$+8.7\%$	$+13.2\%$
NNLO	$164.16(13)\,^{+1.3\%}_{-0.8\%}$	$261.5(2)\,^{+1.9\%}_{-1.2\%}$	$+7.2\%$	$+10.7\%$

Impact of radiative corrections strongly reduced by the jet veto

	$\epsilon = \sigma_{\text{fiducial}}(W^+W^-\text{-cuts})/\sigma_{\text{inclusive}}$		$\epsilon/\epsilon_{\text{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	$0.29915(6)^{+0.8\%}_{-1.0\%}$	$+41.0\%$	$+52.6\%$
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	$0.19599(4)^{+4.4\%}_{-4.7\%}$	0	0
NLO′$+gg$	$0.25374(7)^{+3.5\%}_{-3.7\%}$	$0.20773(5)^{+3.2\%}_{-3.1\%}$	$+\ 3.3\%$	$+\ 6.0\%$
NNLO	$0.2378(4)\,^{+1.3\%}_{-0.9\%}$	$0.1907(3)\,^{+1.2\%}_{-0.9\%}$	$-\ 3.2\%$	$-\ 2.7\%$

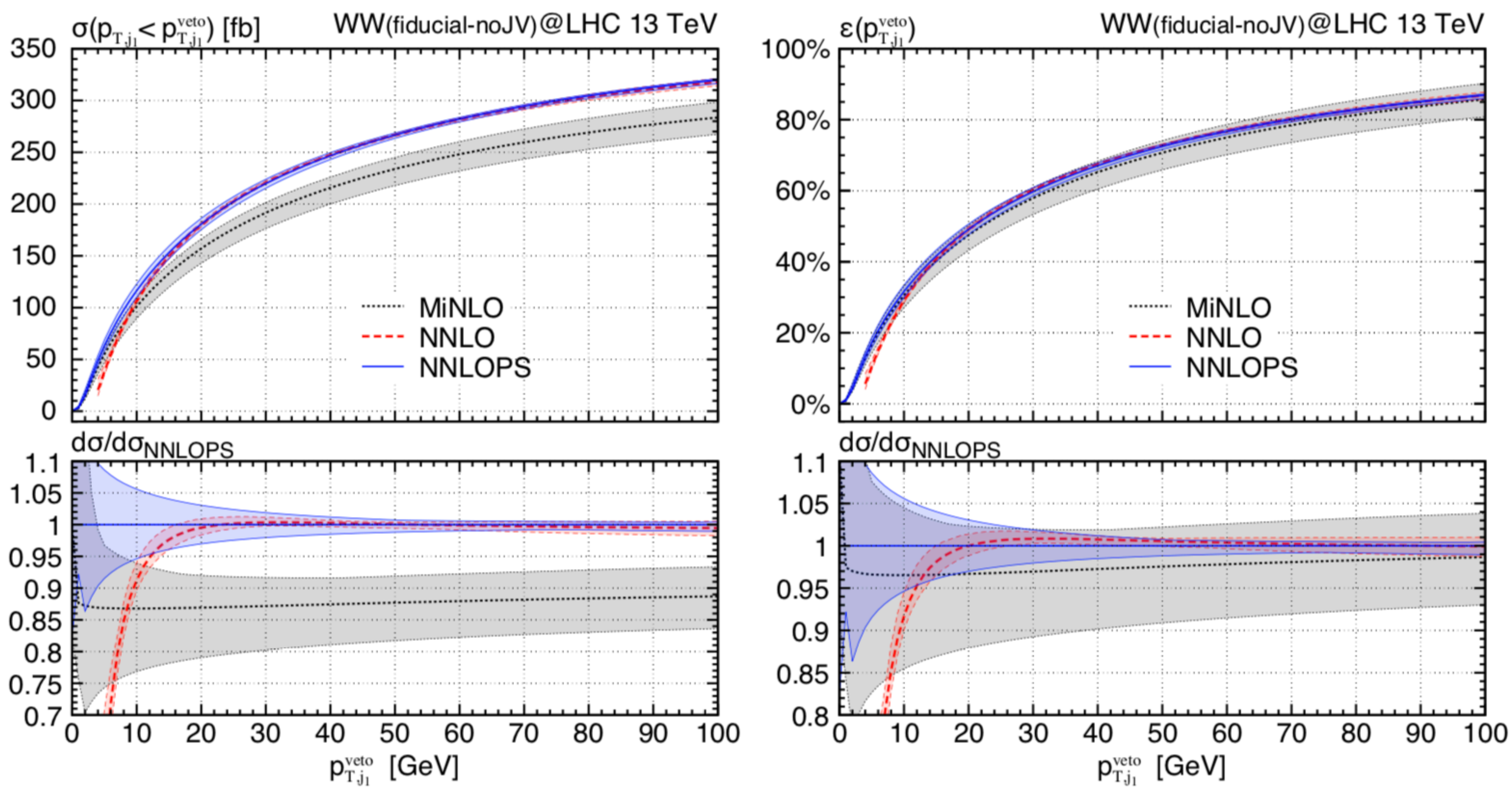
Consequently NLO+gg provides good approximation of the fiducial cross sections (but not of the acceptance)

NNLOPS for WW

E.Re, M.Wiesemann, G.Zanderighi (2018)

NNLO predictions can be matched to parton showers by using the NNLOPS method

K. Hamilton, P. Nason, E. Re and G. Zanderighi (2013)



NNLO works well down to pTveto of about 15 GeV

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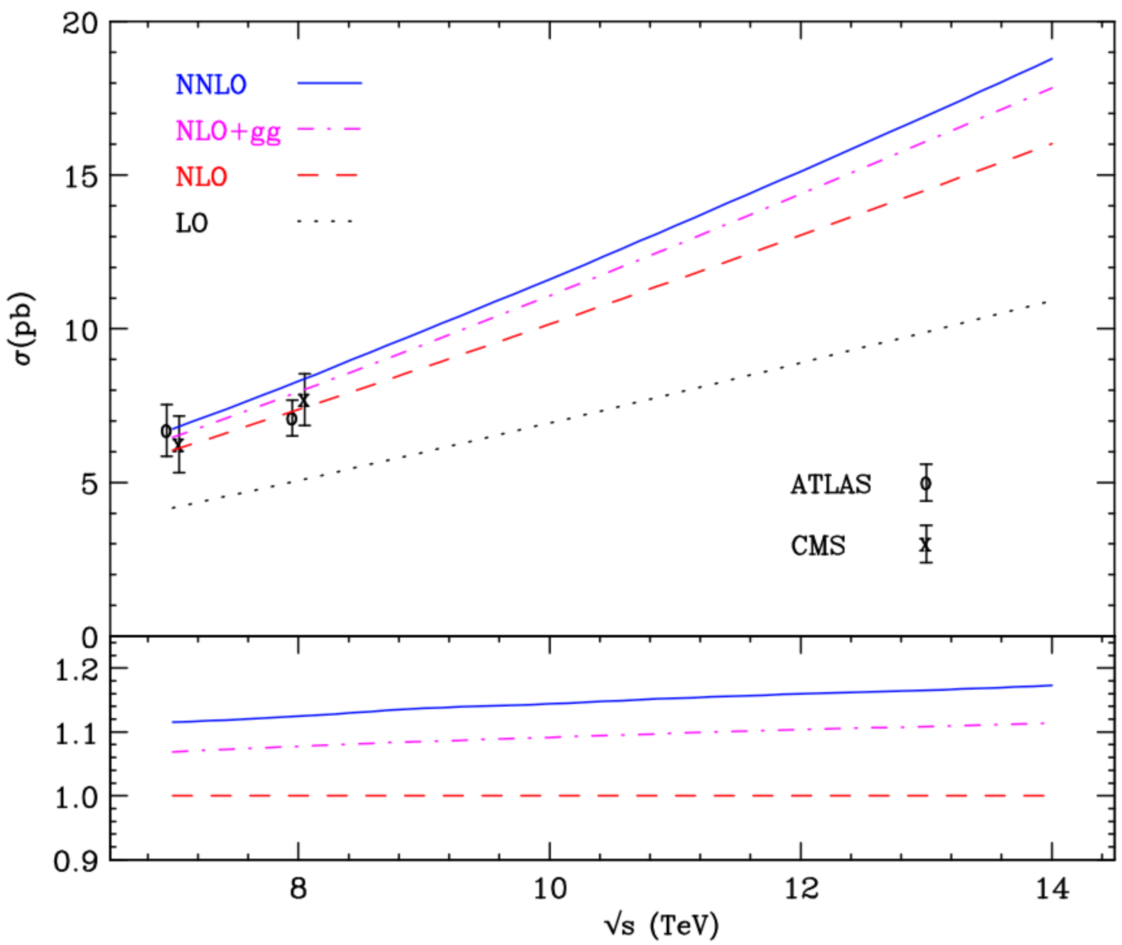
$q\bar{q}$ (no loop^2 gg)	$\sigma_{\text{incl}}(pp \to W^+W^-)$ [pb]	$\sigma_{\text{fid}}(pp \to e^\mp \nu_e\, \mu^\pm \nu_\mu)$ [fb]	$\text{A} = \sigma_{\text{fid}}/\sigma_{\text{incl}}$ [%]
LO	$70.66(1)^{+5.1\%}_{-6.2\%}$	$440.5(0)^{+6.0\%}_{-7.1\%}$	0.623
NLO	$99.96(3)^{+3.5\%}_{-2.8\%}$	$411.8(1)^{+2.7\%}_{-2.3\%}$	0.412
NNLO	$110.0(1)^{+1.6\%}_{-1.6\%}$	$413.1(2)^{+1.0\%}_{-0.7\%}$	0.376
MiNLO	$96.05(1)^{+7.1\%}_{-4.9\%}$	$359.6(1)^{+5.4\%}_{-8.3\%}$	0.374
NNLOPS	$110.2(2)^{+1.7\%}_{-1.6\%}$	$413.0(2)^{+2.2\%}_{-2.3\%}$	0.375
ATLAS$-gg$ [9]	$124.7 \pm 5\,(\text{stat}) \pm 13\,(\text{syst}) \pm 3\,(\text{lumi})$	$473 \pm 20\,(\text{stat}) \pm 50\,(\text{syst}) \pm 11\,(\text{lumi})$	0.379
CMS$-gg$ [10]	$108.5 \pm 5.8\,(\text{stat})\, {}^{\pm 5.7(\text{exp. syst})}_{\pm 6.4(\text{theo. syst})} \pm 3.6\,(\text{lumi})$	—	—

NNLOPS impact more visible in soft-gluon sensitive observables

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

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

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$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\text{stat})^{+0.2}_{-0.2}(\text{syst.})^{+0.2}_{-0.2}(\text{lumi.})$
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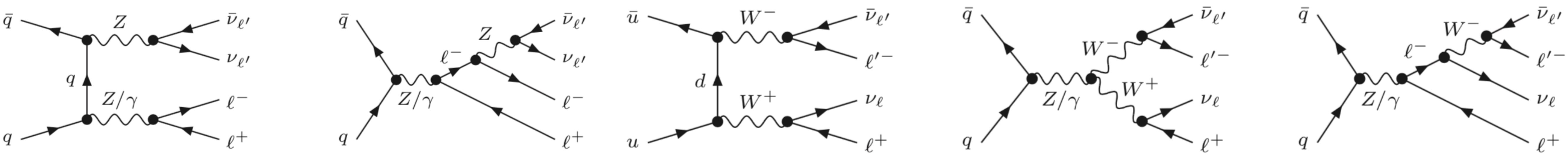
+15% (60% comes from gg fusion)

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)

NEW:

pp→2l2ν+X at NNLO

S. Kallweit, M.Wiesemann (to appear)



$e^+e^-\nu\nu$ and $\mu^+\mu^-\nu\nu$ final states can originate from both ZZ and WW production

First NNLO calculation where two different doubly resonant topologies are accounted for

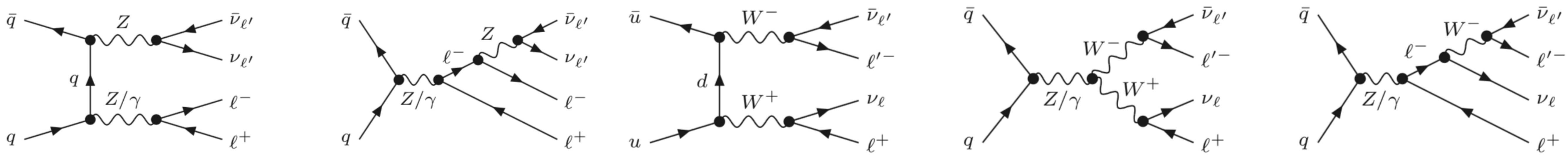
➡ Follow experimental strategy and isolate the ZZ signal by subtracting the different-flavour contribution which includes resonant WW and ttbar production

Their interference with the ZZ signal is instead kept

NEW:

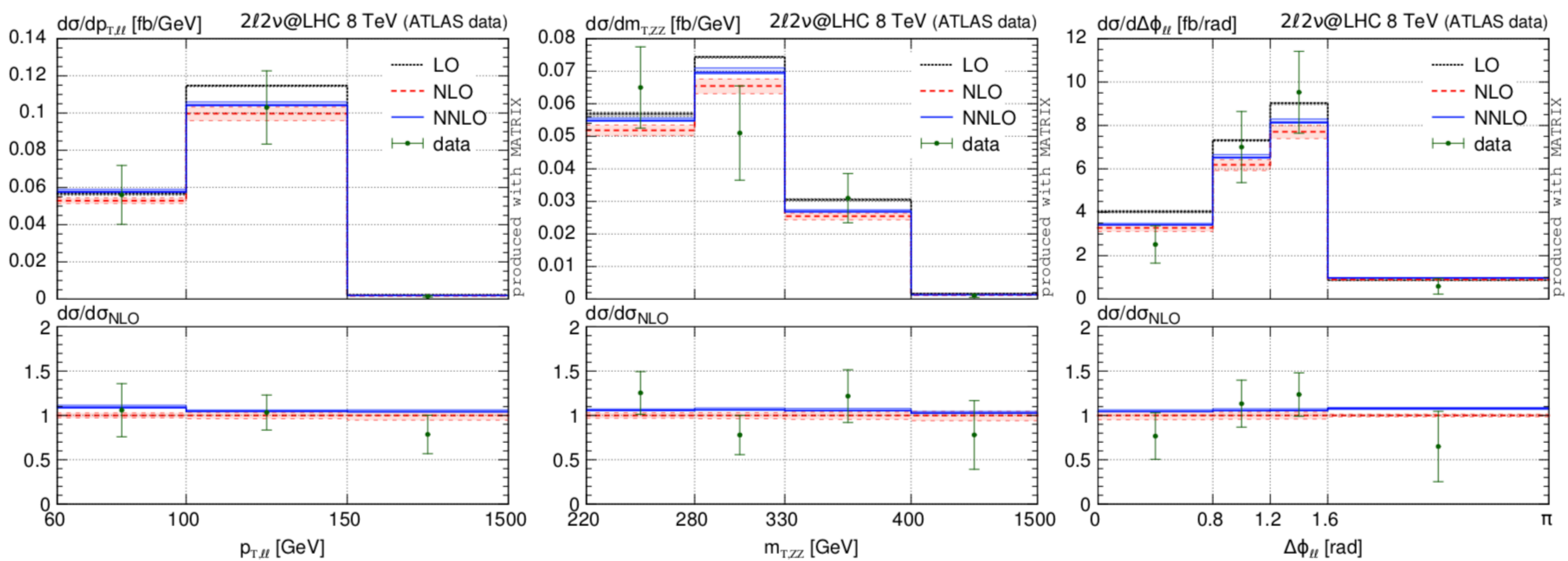
pp→2l2ν+X at NNLO

S. Kallweit, M.Wiesemann (to appear)



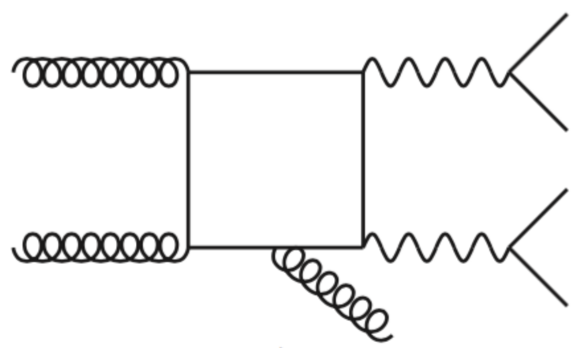
$2l2\nu_l$ final states can originate from both ZZ and WW production

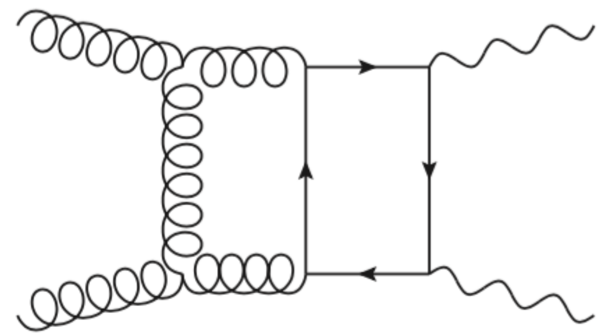
PRELIMINARY



Improved agreement between data and theoretical predictions

gg→WW/ZZ+X at NLO





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

Two-loop amplitude available

F. Caola, J. M. Henn, K. Melnikov, A. V. Smirnov and V. A. Smirnov (2015)
A. von Manteuffel and L. Tancredi (2015)

Computation completed (no fermionic channels)

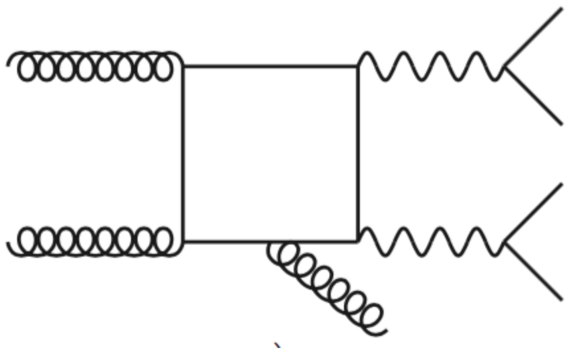
F.Caola, K.Melnikov, R.Röntsch, L.Tancredi (2015)

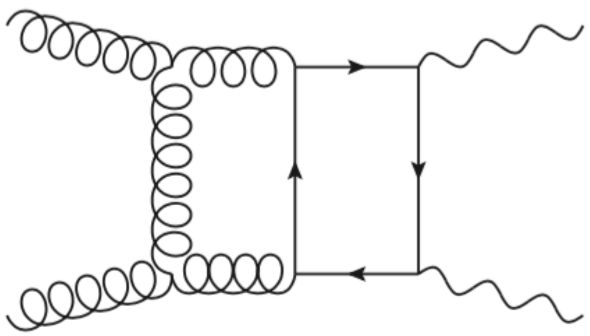
Impact particularly relevant for ZZ

Recently matched to parton shower in the POWHEG framework

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

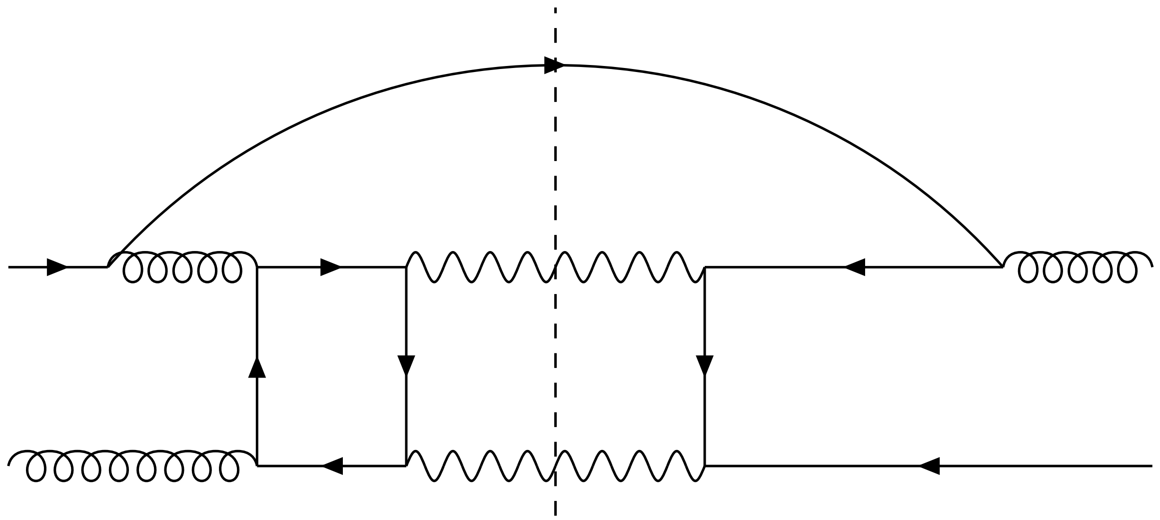
gg→WW/ZZ+X at NLO





Experimental analyses combine NNLO in qqbar and NLO in gg as if they were independent processes

But this is only an approximation !



Already at NNLO the two production channels mix

It would be useful to include the two calculations in a single generator

NEW:

$gg \to ZZ+X$ at NLO

JY Yook, S. Kallweit, M.Wiesemann, MG (in progress)

We have included the NLO calculation within the MATRIX framework

Use ATLAS cuts at 13 TeV and consider $gg \to ZZ \to 2e2\mu$

$$p_{T,\ell} > 7\,\text{GeV}, \quad \text{one electron with } |\eta_e| < 4.9, \quad \text{the others } |\eta_e| < 2.5, \quad |\eta_\mu| < 2.7$$

$$\Delta R_{\ell\ell} > 0.2, \quad \Delta R_{\ell\ell'} > 0.2, \quad 66\,\text{GeV} \leq m_{Z^{\text{rec}}_{a/b}} \leq 116\,\text{GeV},$$

$$\text{anti-}k_T \text{ jets with } R = 0.4,\ p_{T,j} > 25\,\text{GeV},\ |\eta_j| < 4.5$$

$$\mu_F = \mu_R = m_{ZZ}/2$$

PRELIMINARY:

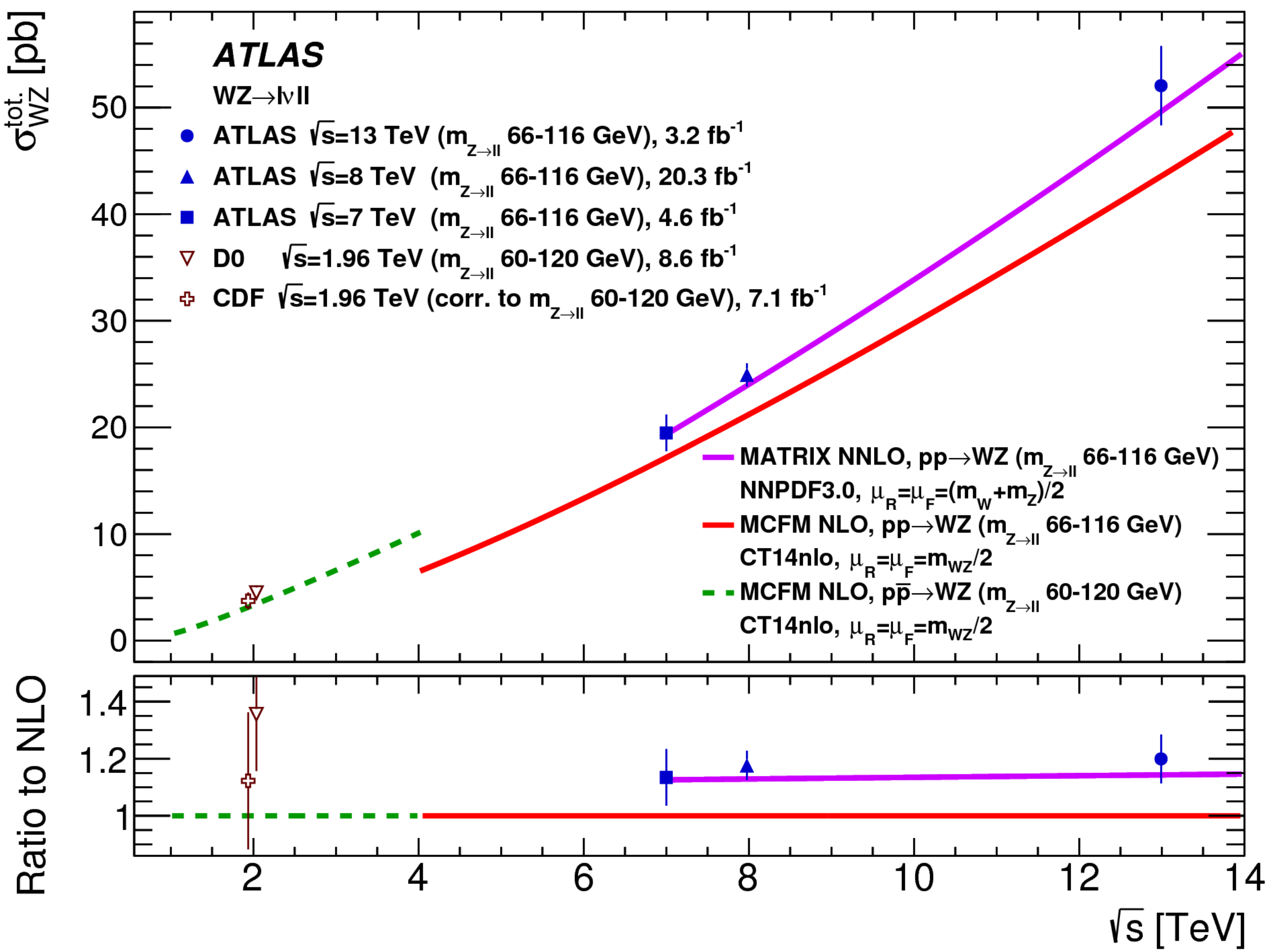
	NLO	NNLO	LO_{gg}	NLO_{gg} (gg only)	NLO_{gg}	N^3LO approx
$\sigma(\text{fb})$	$19.82(6)^{+2.5\%}_{-2.0\%}$	$23.57(2)^{+3.2\%}_{-2.6\%}$	$2.002(4)^{+23.5\%}_{-17.9\%}$	$3.62(2)^{+15.2\%}_{-12.7\%}$	$3.41(2)^{+13.8\%}_{-12.0\%}$	$24.98(4)^{+3.0\%}_{-2.7\%}$

+19% wrt NLO

+6% wrt NNLO

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)

EW corrections

When precision is concerned EW corrections should also be considered: automatic NLO (QCD+)EW generators now exist that can complement the progress on the NNLO side

Recola2 → **talk by Jean-Nicolas Lang**

Setup	LO [fb]	NLO QCD [fb]	NLO EW [fb]
W^-Z ATLAS	$12.6455(9)^{+5.5\%}_{-6.8\%}$	$23.780(4)^{+5.5\%}_{-4.6\%}$	$11.891(4)^{+5.6\%}_{-6.9\%}$
W^-Z CMS	$9.3251(8)^{+5.3\%}_{-6.7\%}$	$17.215(4)^{+5.4\%}_{-4.3\%}$	$8.870(2)^{+5.5\%}_{-6.7\%}$
W^+Z ATLAS	$18.875(1)^{+5.2\%}_{-6.4\%}$	$34.253(6)^{+5.3\%}_{-4.3\%}$	$17.748(8)^{+5.3\%}_{-6.5\%}$
W^+Z CMS	$14.307(1)^{+5.0\%}_{-6.2\%}$	$26.357(6)^{+5.4\%}_{-4.3\%}$	$13.600(4)^{+5.1\%}_{-6.3\%}$

M.Chiesa, A.Denner, J.Lang (2018)

EW corrections

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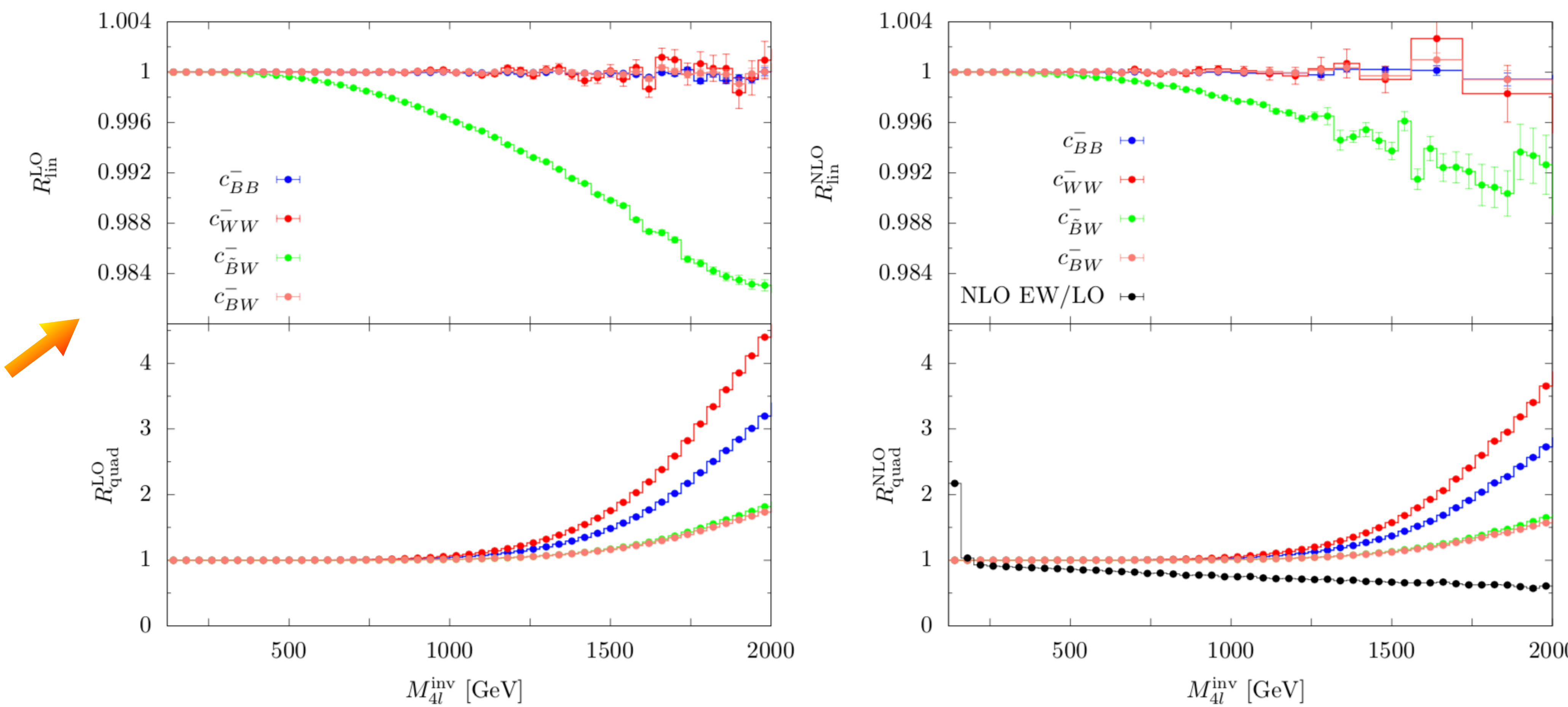
Recola2 → **talk by Jean-Nicolas Lang**

Inclusion of Dimension 6 and Dimension 8 operators !

$$\mathrm{pp} \to \mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$$

Relative impact of anomalous coupling in the linear and quadratic approximation



M.Chiesa, A.Denner, J.Lang (2018)

EW corrections

When precision is concerned EW corrections should also be considered: automatic NLO (QCD+)EW generators now exist that can complement the progress on the NNLO side

See also:

- Munich/Sherpa+Openloops — S. Kallweit, J.M. Lindert, S. Pozzorini, M. Schönherr (2017)
- MadGraph5 aMC@NLO — R. Frederix, S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro (2018)
- Gosam — M.Chiesa, N.Greiner, F.Tramontano (2015)

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
- The NNLO parton level generator MATRIX implements all these calculations in a unique framework and includes all the vector-boson pair production processes
- The program combines the MUNICH Monte Carlo framework with amplitudes from Openloops and q_T subtraction and is able to compute inclusive and differential cross sections for vector boson pair production including off-shell and interference effects

Summary & Outlook

- The impact of NNLO corrections is significant and generally depends on the applied cuts

- Other groups are working on diboson production at NNLO and produced results in the last period

- In the case of WW production the NNLO calculation has been matched to the Parton Shower with the NNLOPS method

- I have presented preliminary results for ZZ production with the inclusion of a class of N3LO contributions originating from the NLO corrections to the loop-induced gg contribution

- When precision is concerned EW corrections should also be considered: automatic NLO QCD+EW generators now exist including also anomalous couplings

→ It would be great to have a single generator with all these features

Backup

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 $r = q_T/Q$

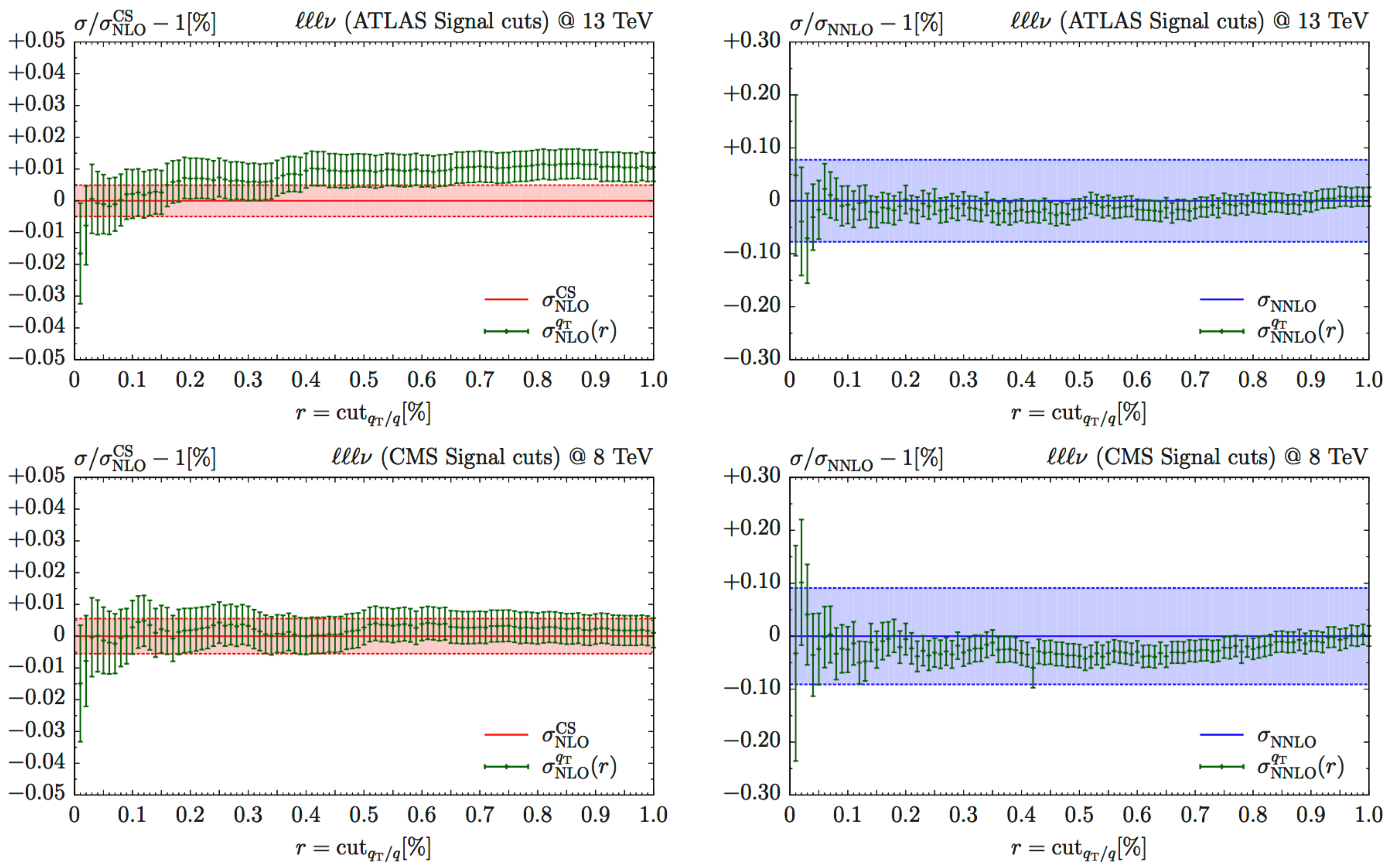
In our implementation q_T subtraction indeed works as a slicing method

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}

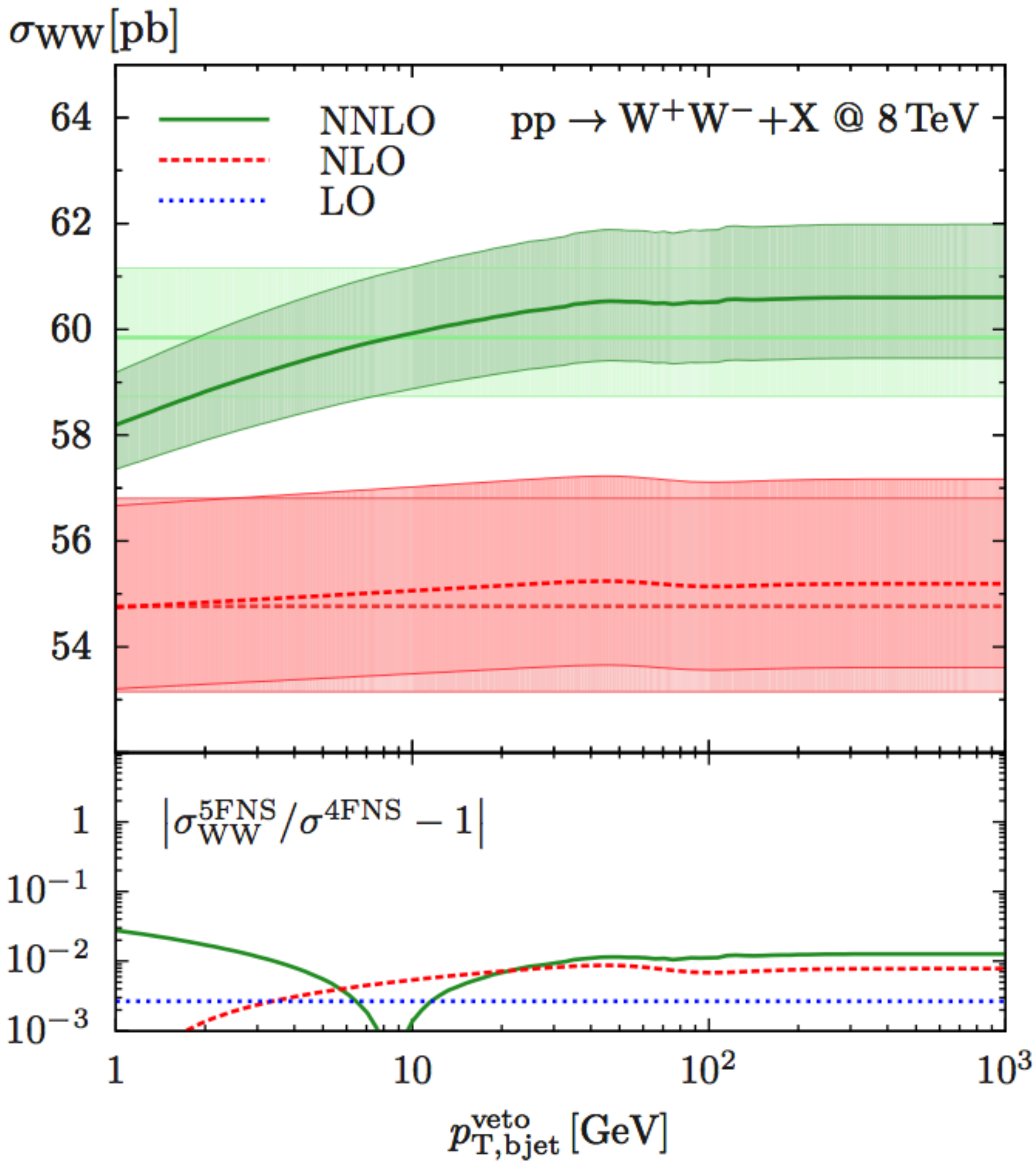
The dependence on r_{cut} is used by the code to provide an estimate of the systematic uncertainty in any NNLO run

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

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 $p_{T,bjet}^{veto} \to 0$ the logarithmic singularity is still present but for $p_{T,bjet}^{veto} \gtrsim 10$ 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→Zγ +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: ε= 0.5
smooth cone R= 0.4

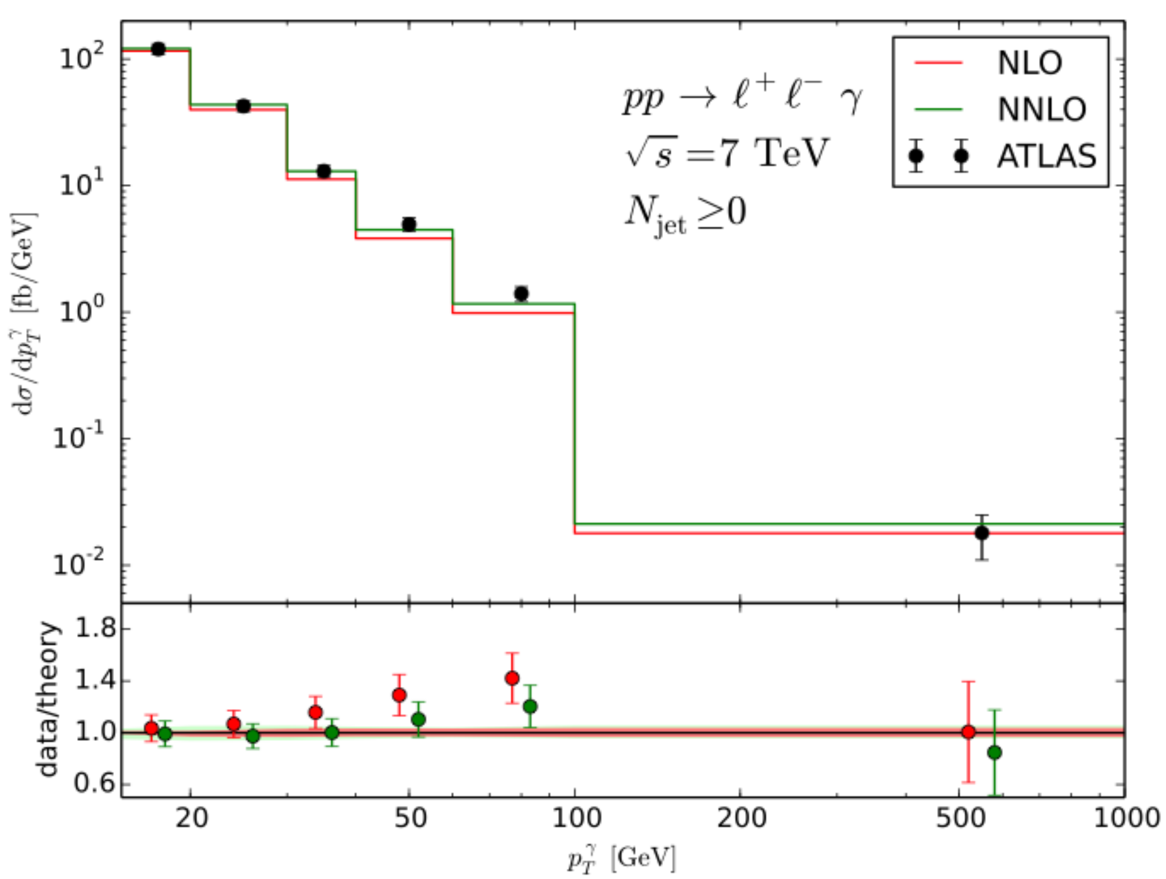
$p^{\gamma}_T > 15$ GeV $p^{l}_T > 25$ GeV $\Delta R(l/\gamma,\mathrm{jet}) > 0.3$

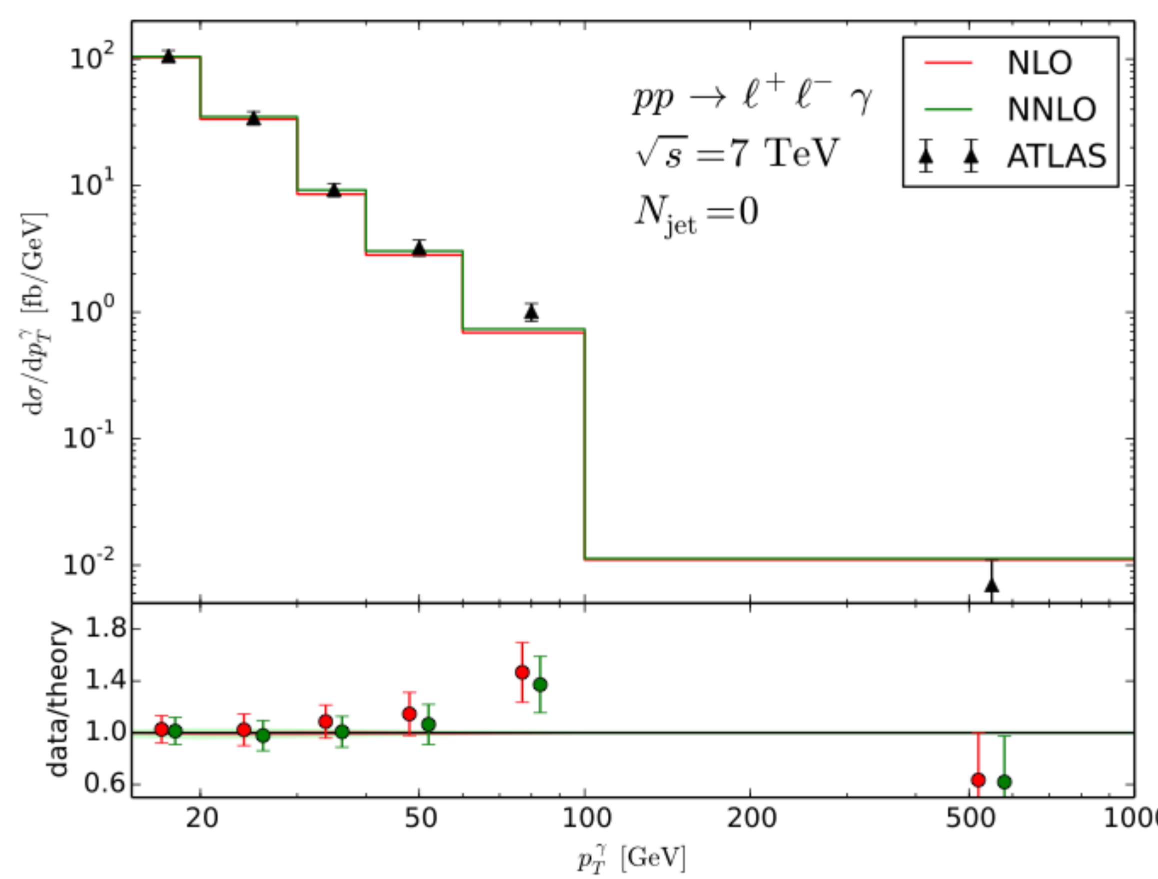
$|\eta^{\gamma}| < 2.37$ $|\eta^{l}| < 2.47$ $\Delta R(l,\gamma) > 0.7$

$m_{ll} > 40$ GeV   jets: anti-kt with D=0.4
$p_T^{jet} > 15$ GeV $|\eta^{jet}| < 2.47$

+8%

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





$pp \to W\gamma$ at NNLO

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

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 $\Delta R(l/\gamma,\text{jet}) > 0.3$

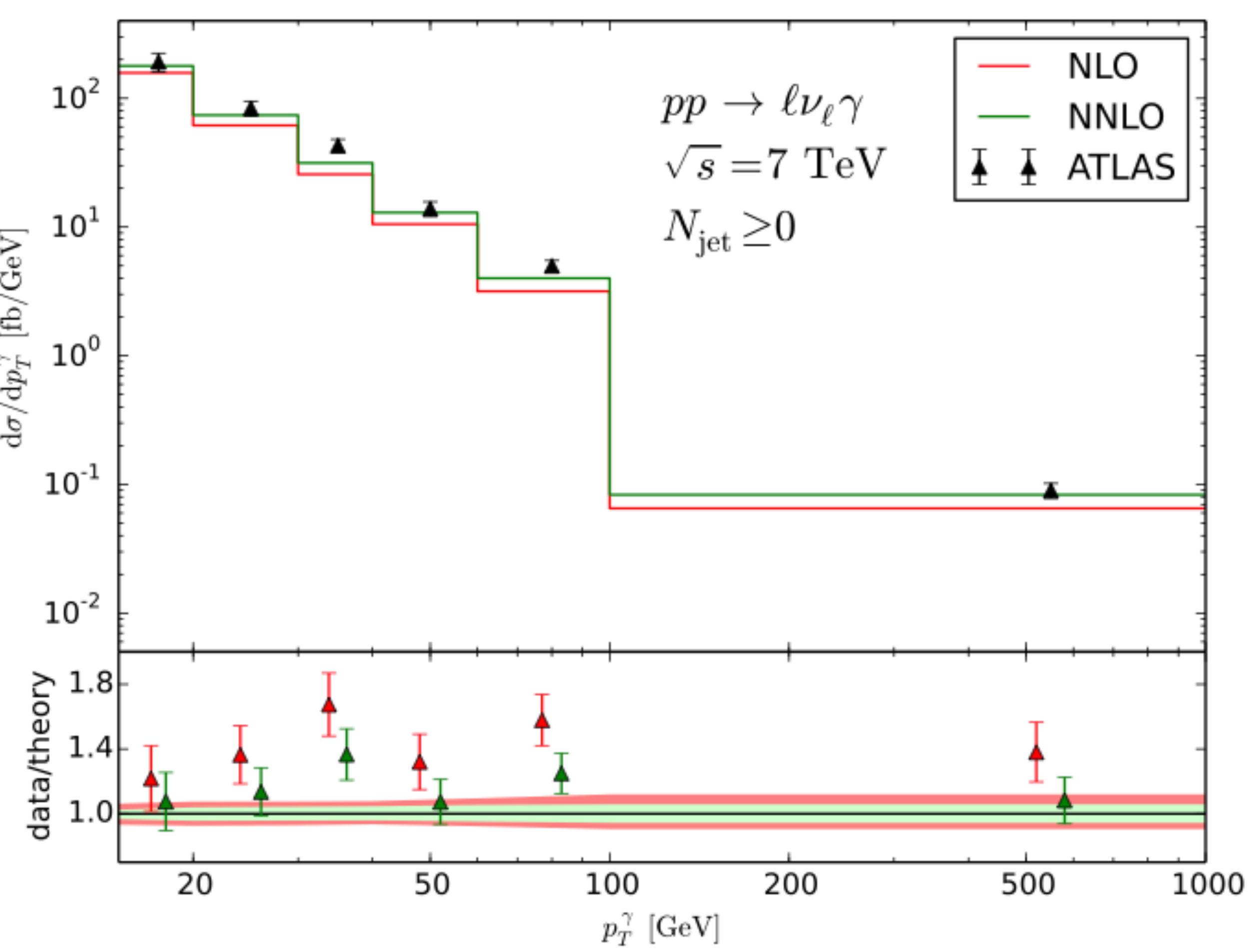
$|\eta^{\gamma}| < 2.37$ $|\eta^{l}| < 2.47$ $\Delta R(l,\gamma) > 0.7$

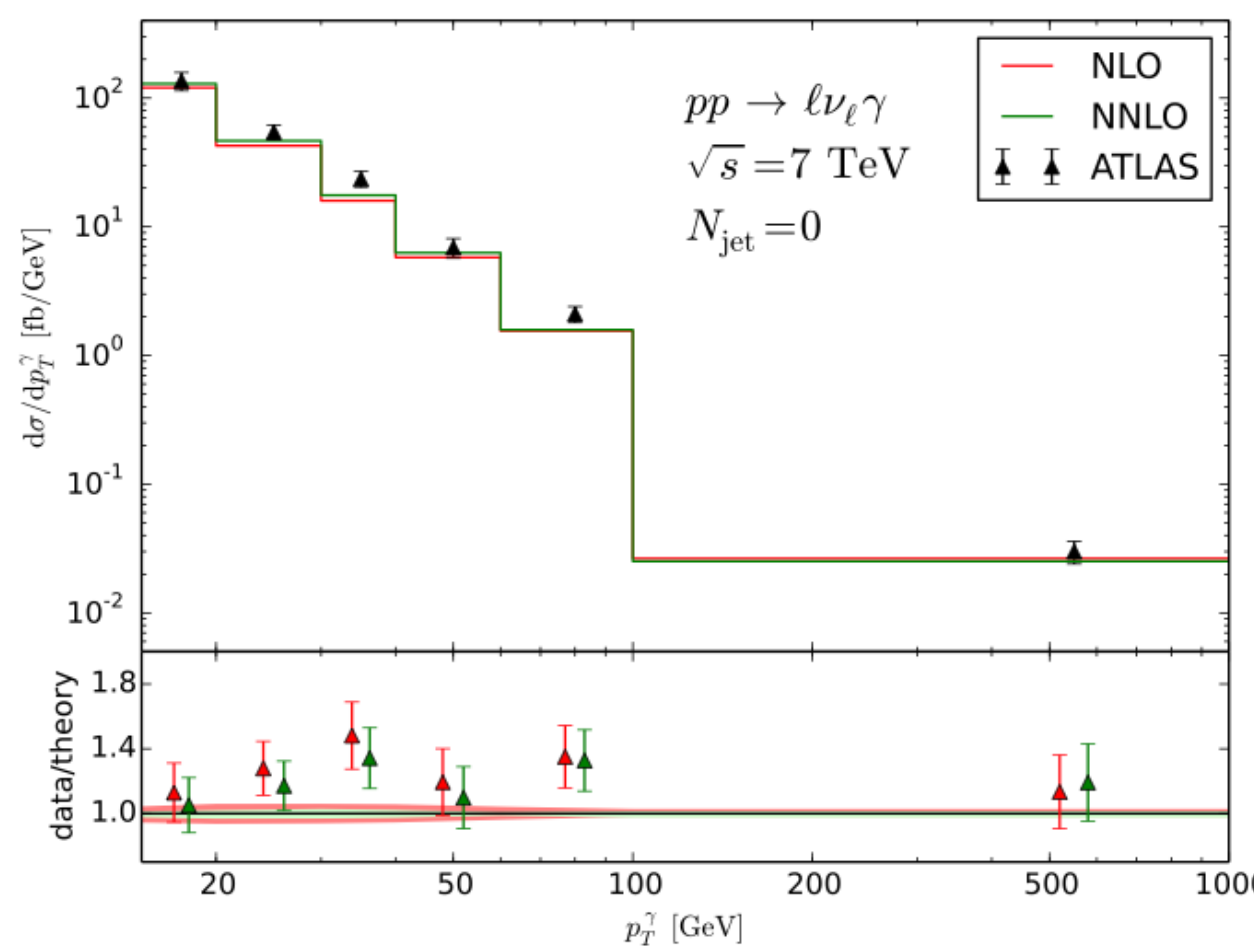
$p_T^{miss} > 35$ GeV   jets: anti-kt with D=0.4

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

+19%

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





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

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

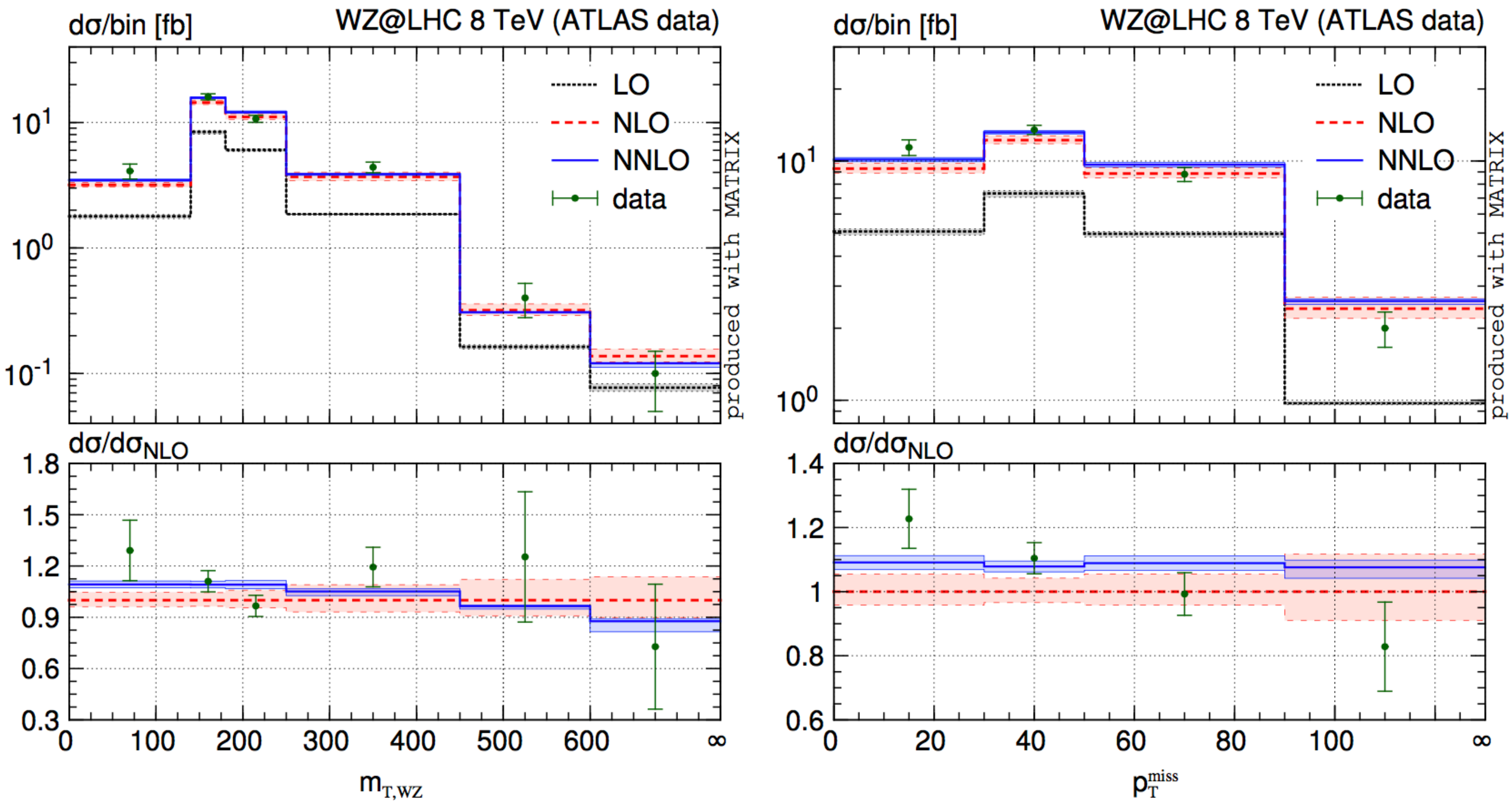
Fiducial cuts:

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

Four categories are considered:

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