NNLO QCD corrections to vector-boson pair production

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EW precision physics at the LHC
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Outline

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- The q_T-subtraction method
- $pp \to V\gamma + X$ at NNLO

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- $pp \to ZZ + X$ at NNLO
- Summary

Introduction

Vector boson pair production is an important process at hadron colliders

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

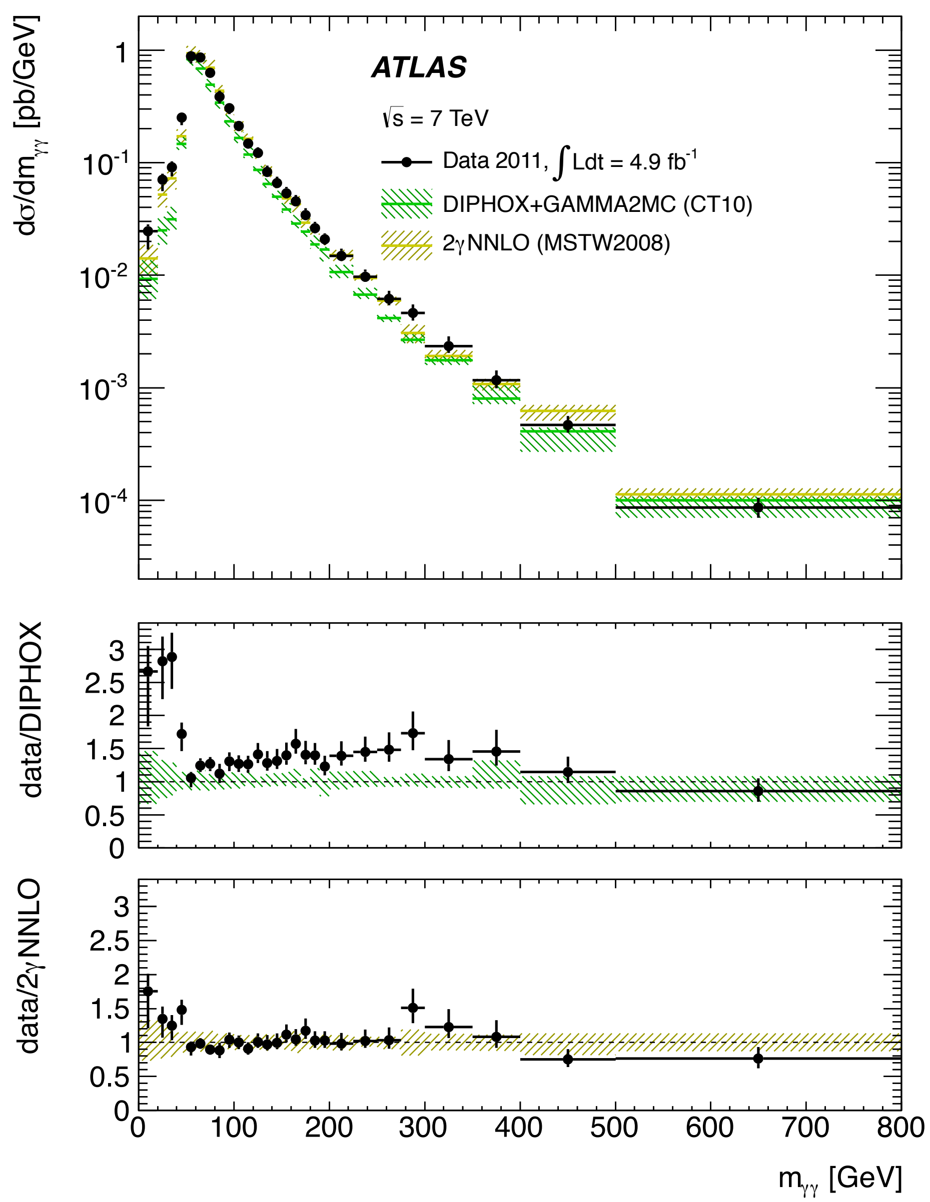
Present accuracy essentially limited to NLO QCD

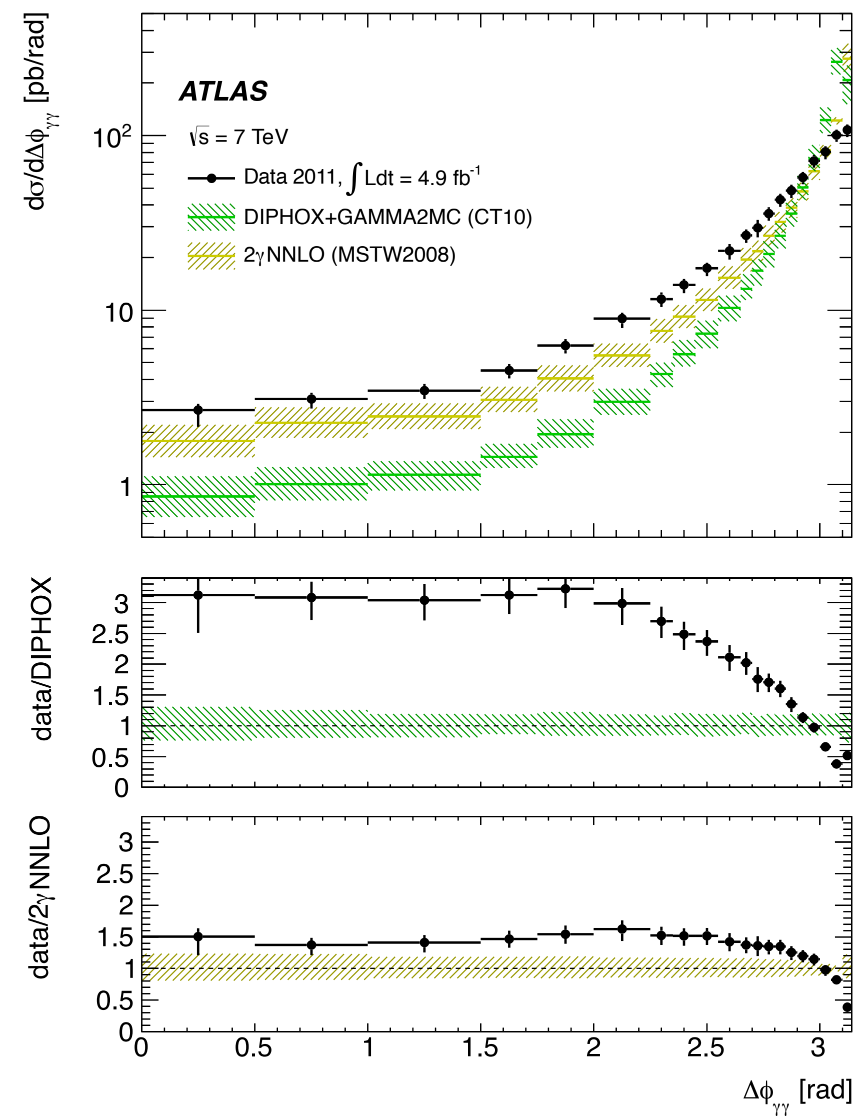
→ Extension to NNLO highly desirable

Introduction

Up to very recently complete NNLO predictions existed only for diphoton production

S.Catani, L.Cieri, D.de Florian,,G.Ferrera, MG (2011)





This calculation allowed to resolve discrepancies in the comparison to data

Status of pp$\rightarrow$VV'+X in QCD

Zγ, Wγ ,WZ, WW, 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)
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)

Also including leptonic decay

The gluon fusion loop contribution (part of NNLO) to Zγ, 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.Ametller et al. (1985)
J. van der Bij, N.Glover (1988)
K. Adamson, D. de Florian, A.Signer (2000)

→ **all this implemented in MCFM**

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)
J.Baglio, L.D.Nihn,M.Weber (2013)
M.Billoni, S.Dittmaier, B.Jager,C.Speckner (2013)

Genuine Vγ two-loop amplitude computed

T.Gehrmann, L.Tancredi (2012)

Two-loop master integrals for WW,WZ and ZZ production recently evaluated

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

pp→Vγ +X at NNLO

S.Kallweit,D.Rathlev, A.Torre, MG (2013,2014)

Having completed pp→γγ+X the next logical step is pp→Vγ+X (V=Z,W)

Ingredients for pp→Vγ+X at NNLO

- One-loop squared and two-loop amplitudes for qqbar→Vγ — W.Van Neerven et al. (1989); T.Gehrmann, L.Tancredi (2012)
- One loop squared gg→Zγ amplitude — L.Amettler et al. (1985); J. van der Bij, N.Glover (1988); K. Adamson, D. de Florian, A.Signer (2000)
- One loop Vγ+1 parton amplitudes — J.Campbell, H.Hartanto, C.Williams (2012)
- Tree-level Vγ+2 parton amplitudes

We obtain the tree-level and one-loop amplitudes with OpenLoops

F.Cascioli, P.Maierhofer, S.Pozzorini (2012)

The OpenLoops generator employs the Denner-Dittmaier algorithm for the numerically stable computation of tensor and scalar integrals and allows a fast evaluation of tree-level and one-loop amplitudes within the SM

The contributing amplitudes are combined with the q_T subtraction method

S. Catani, MG (2007)

The q_T subtraction method

S. Catani, MG (2007)

The amplitudes contributing to the NNLO cross section are separately divergent

- to obtain a finite cross section out of them is still a non trivial task

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

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

process dependent hard-collinear function

NLO F+jets cross section computed with dipole subtraction

universal counterterm

The function $\mathcal{H}^F$ has been 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)

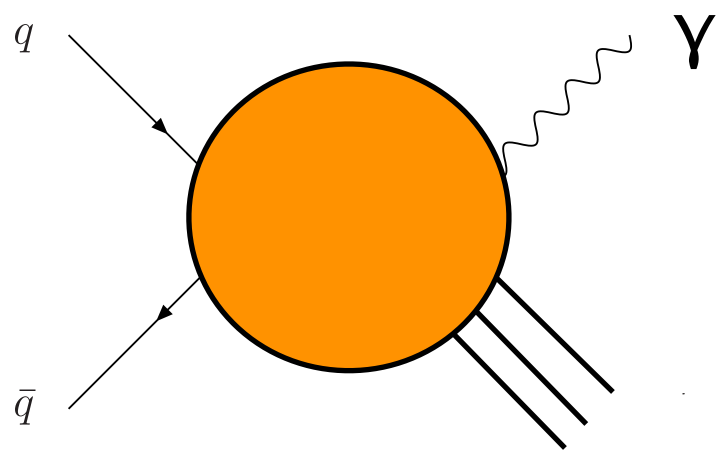
Recently its general form in terms of the relevant virtual amplitudes for an arbitrary colour singlet F has been provided up to NNLO

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

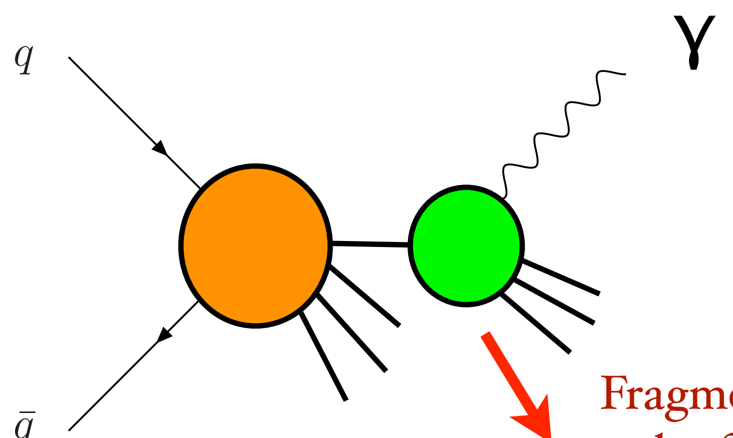
- the method can be applied also to vector boson pair production

Photon isolation

When dealing with photons we have to consider two production mechanisms:



Direct component: photon directly produced through the hard interaction

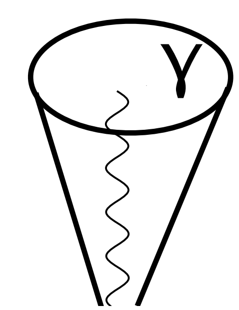


Fragmentation component: photon produced from non-perturbative fragmentation of a hard parton (like a hadron)

Fragmentation function: to be fitted from data

Experimentally photons must be isolated:

Transverse hadronic energy in a cone of fixed radius R smaller than few GeV



We use Frixione smooth cone isolation

$$E_T^{had}(\delta) \leq \chi(\delta)$$

$$\chi(\delta) = \epsilon_\gamma E_T^\gamma \left(\frac{1-\cos(\delta)}{1-\cos(R_0)} \right)^n$$

$$n = 1$$
$$\epsilon_\gamma = 0.5$$
$$R_0 = 0.4$$

➡ kills collinear emissions within the cone

The calculation

S.Kallweit,D.Rathlev, A.Torre, MG (2013,2014)

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 matrix elements are combined into a parton level generator that makes use of multichannel phase space integration and allows us to apply arbitrary kinematical cuts on the final state lepton(s), the photon and the QCD radiation

→ **can compute fiducial cross sections and distributions !**

We consider pp collisions at 7 TeV and we use MSTW2008 PDFs with α_S evaluated at each corresponding order

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

We present a preliminary comparison with ATLAS data based on 4.9 fb^{-1}

Results: $Z\gamma$

- ATLAS setup (arXiv:1302.1283)

$p^{\gamma}_T > 15$ 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

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

jets: anti-kt with D=0.4

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

- CMS setup (arXiv:1308.6832)

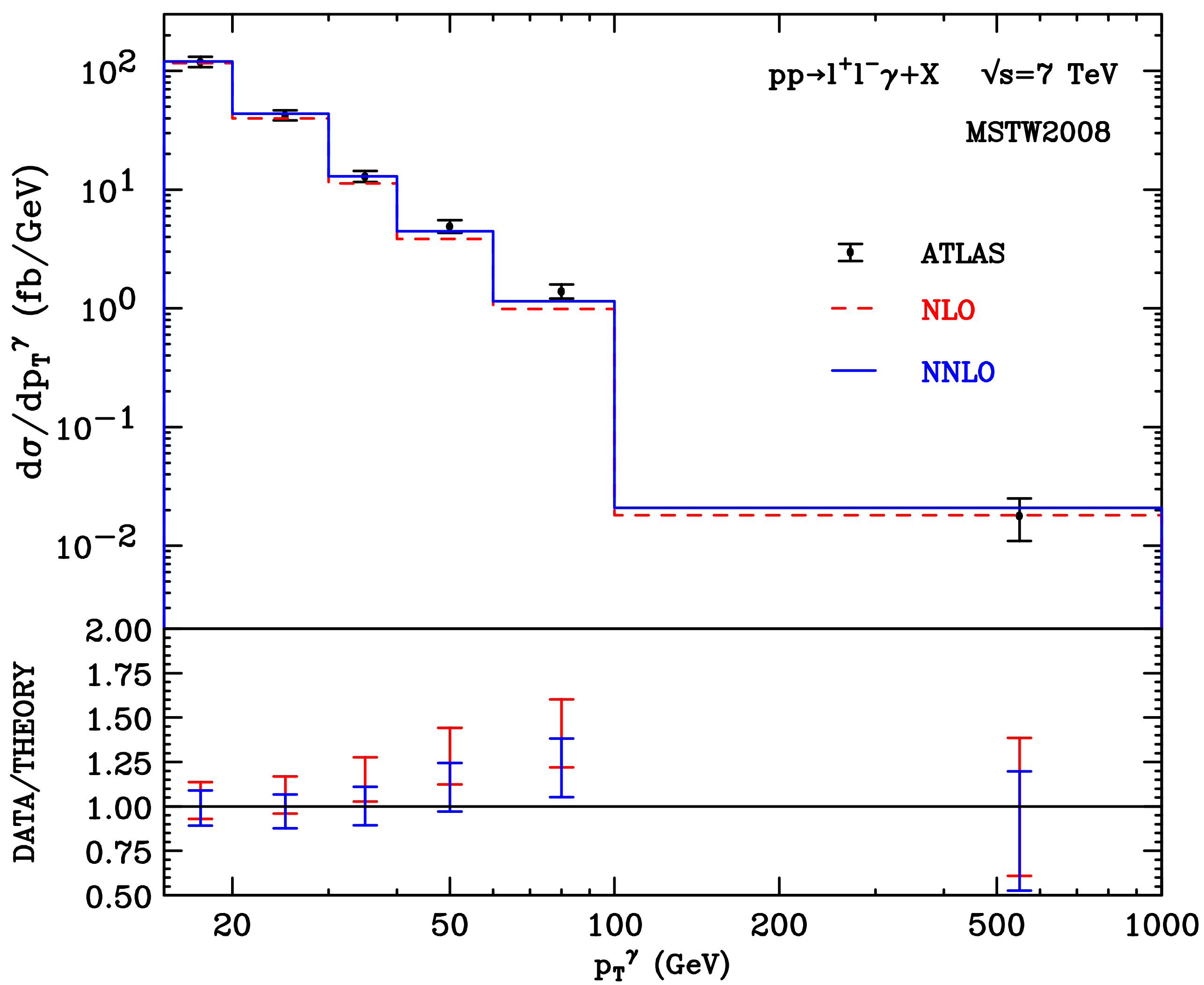
$p^{\gamma}_T > 15$ GeV $p^{l}_T > 20$ GeV $\Delta R(l,\gamma) > 0.7$

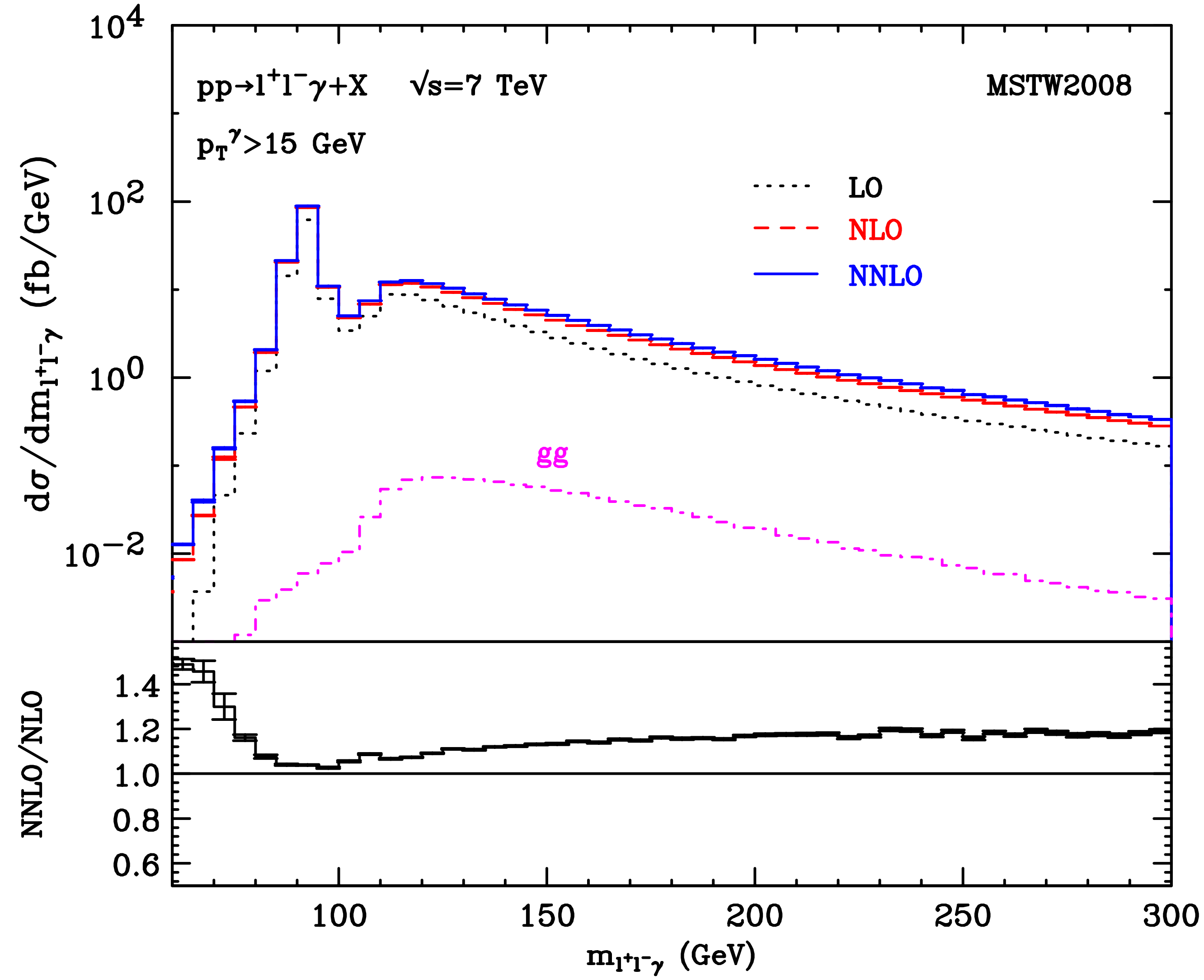
$|\eta^{\gamma}| < 2.5$ $|\eta^{l}| < 2.5$ $m_{ll} > 50$ GeV

photon isolation:
$\varepsilon = 0.05$ $R = 0.3$

σ (fb)	LO	NLO	NNLO	data
$p^{\gamma}_T > 15$ GeV	850.7±0.2	1226.2±0.4 44%	1305±3 6%	1310±20(stat)±110(syst)±50(lumi)
$p^{\gamma}_T > 40$ GeV	77.48 ± 0.06	132.89±0.07 71%	152.5 ±0.5 15%	
CMS setup	1333.6 ± 0.2	1843.8 ± 0.7 38%	1917± 8 4%	

Results: Zγ





gg fusion contribution provides only *8%* of the NNLO correction

NNLO effect not uniform in $m_{ll\gamma}$: the effect is larger where the cross section is smaller (constant K factor does not work here !)

Results: $W\gamma$

- ATLAS setup (arXiv:1302.1283)

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

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

$p_T^{miss} > 35$ GeV

photon isolation:

$\varepsilon = 0.5$ $R = 0.4$

jets: anti-kt with D=0.4

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

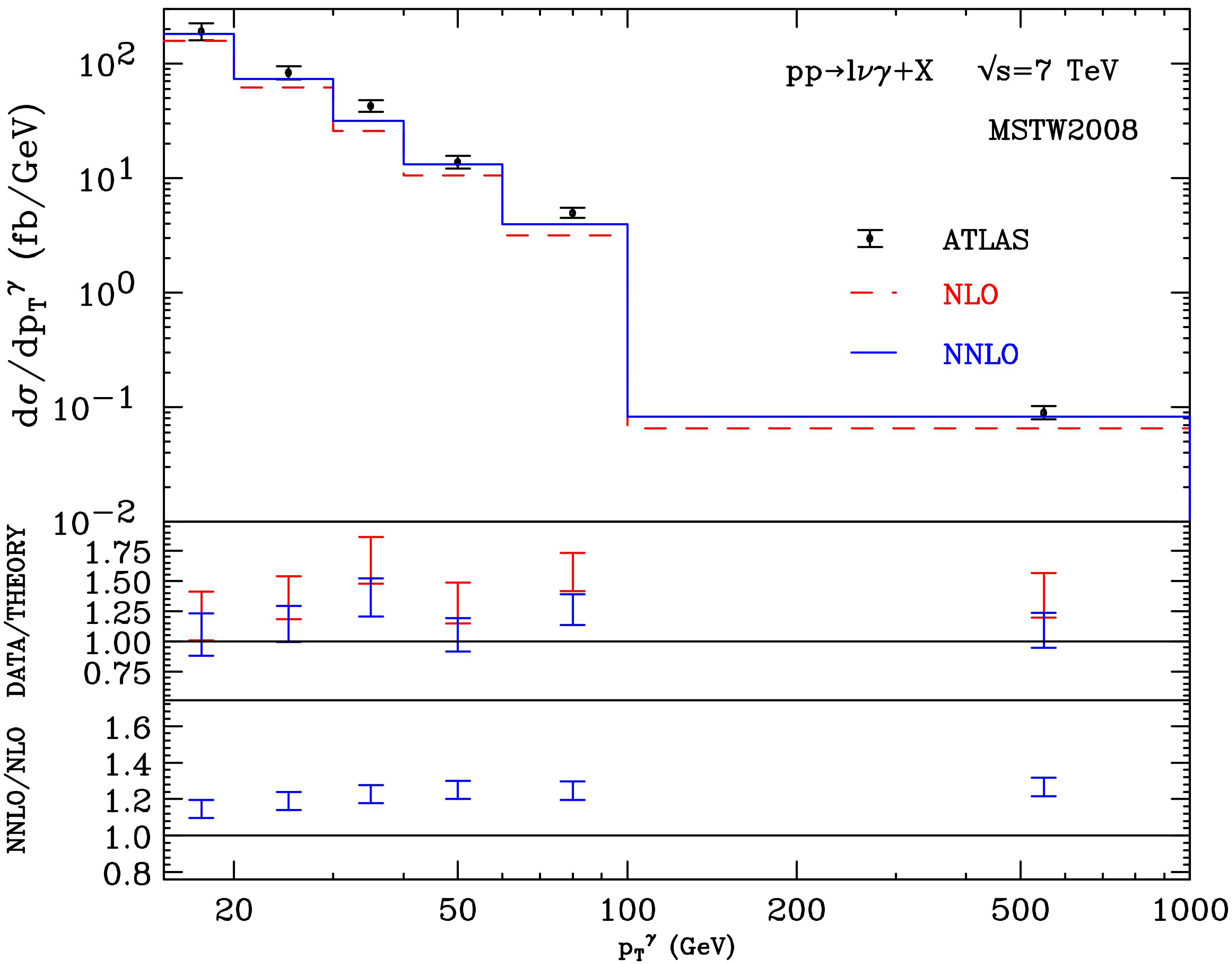
σ (fb)	LO	NLO	NNLO	data
$W^+\gamma$	511.0±0.2	1155.3±0.8 126%	1371 ±5 19%	
$W^-\gamma$	395.3 ± 0.2	909.9±0.4 130%	1085 ±4 19%	
total	906.3 ± 0.3	2065.2 ± 0.9 128%	2456± 6 19%	2770±30(stat)±330(syst)±140(lumi)

Some tension between data and NLO result

QCD corrections are much larger than for $Z\gamma$

→ NNLO significantly improves Data/Theory agreement

Results: Wγ



NNLO effect ranges from 15 to 25% as a function of $p^{\gamma}{}_{T}$

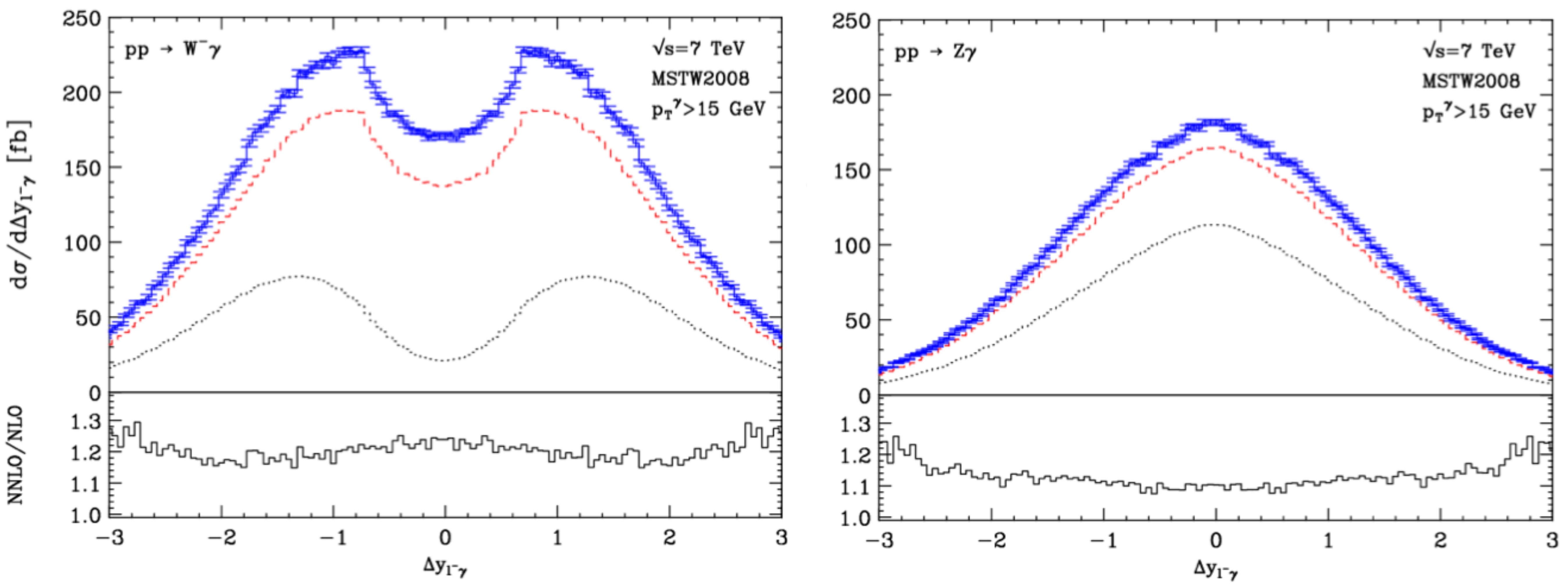
Results: Wγ

The W couplings are larger than the Z couplings: we would expect the Wγ cross section to be larger than for Zγ

Radiation zero at $\cos\theta^*$ for Wγ suppresses the LO cross section

K.Mikaelian et al. (1979)
J.Ohnemus (1993)

Radiation zero is filled at NLO ➡ large corrections



Scale Uncertainties

When studying scale variations around $\mu_0 = \sqrt{m_V^2 + (p_T^\gamma)^2}$

we find that *symmetric* scale variations $\mu_F=\mu_R=a\mu_0$ with $0.5 < a < 2$

give tiny effects, especially for $Z\gamma$

- we follow the suggestion of MCFM authors and use *asymmetric* scale variations $\mu_F=a\mu_0$, $\mu_R=\mu_0/a$ with $0.5 < a < 2$

J.Campbell,K.Ellis, C.Williams (2011)

σ (fb)	NLO	NNLO
$Z\gamma$	1226.2 $^{-5\%}_{+4\%}$	1305 ± 2%
$W^+\gamma$	1155.3 ± 7%	1371 $^{+5}_{-4}\%$
$W^-\gamma$	909.9 ±7%	1085 ±4%

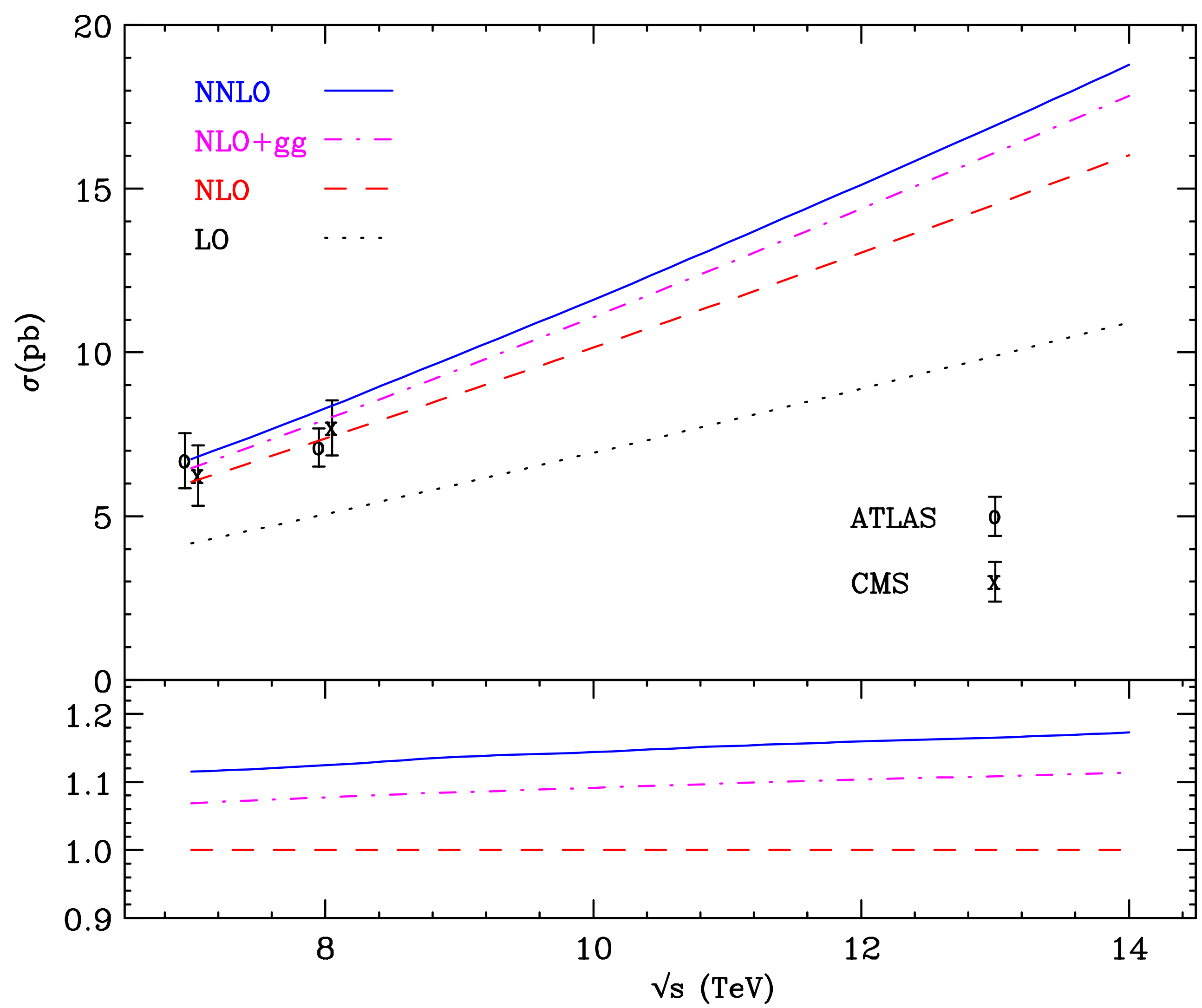
In the case of $W\gamma$ the NLO uncertainty does not cover the large NNLO effect which is due to the qg channel

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)

The recent computation of the two-loop master integrals relevant for pp→VV makes now the full NNLO calculation possible

Inclusive cross sections for on shell ZZ pairs at NNLO



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

NNLO effect ranges from 11 to 17 % when √s varies from 7 to 14 TeV

gg contribution 58-62% of the full NNLO effect

data still have relatively large uncertainties

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)

The recent computation of the two-loop master integrals relevant for pp→VV makes now the full NNLO calculation possible

Inclusive cross sections for on shell ZZ pairs at NNLO

$\sqrt{s}$ (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	$10.91^{+5.4\%}_{-6.7\%}$	$16.01^{+3.0\%}_{-2.4\%}$	$18.77^{+3.2\%}_{-2.4\%}$

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

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

Scale uncertainties at NNLO remain at the ±3% level

Summary

- Vector boson pair production is an essential process at hadron colliders: it is a background for Higgs and new physics searches and it allows studies of anomalous couplings
- I have presented an NNLO QCD calculation of $Z\gamma$ and $W\gamma$ production at the LHC and a preliminary comparison to experimental data
- In the case of $Z\gamma$ production the impact of NNLO corrections is moderate, with a slight improvement of the agreement with ATLAS data
- In the case of $W\gamma$ production the impact of NNLO corrections is sizable, and the agreement with ATLAS data significantly improves
- The computation of the two-loop master integrals relevant for WW, ZZ, and WZ production makes the corresponding NNLO calculations possible
- First step completed: NNLO corrections to inclusive ZZ production
- More to come → **Stay tuned !**