Vector boson pair production at NNLO

Massimiliano Grazzini*

University of Zurich

La Thuile 2015, march 5 2015

*On leave of absence from INFN, Sezione di Firenze

Outline

- Introduction
- $pp \to V\gamma + X$ at NNLO
- The q_T-subtraction method
  - Results for $Z\gamma$
  - Results for $W\gamma$
- $pp \to ZZ + X$ at NNLO
- $pp \to WW + X$ at NNLO
  - **NEW:** the fully exclusive calculation
- 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

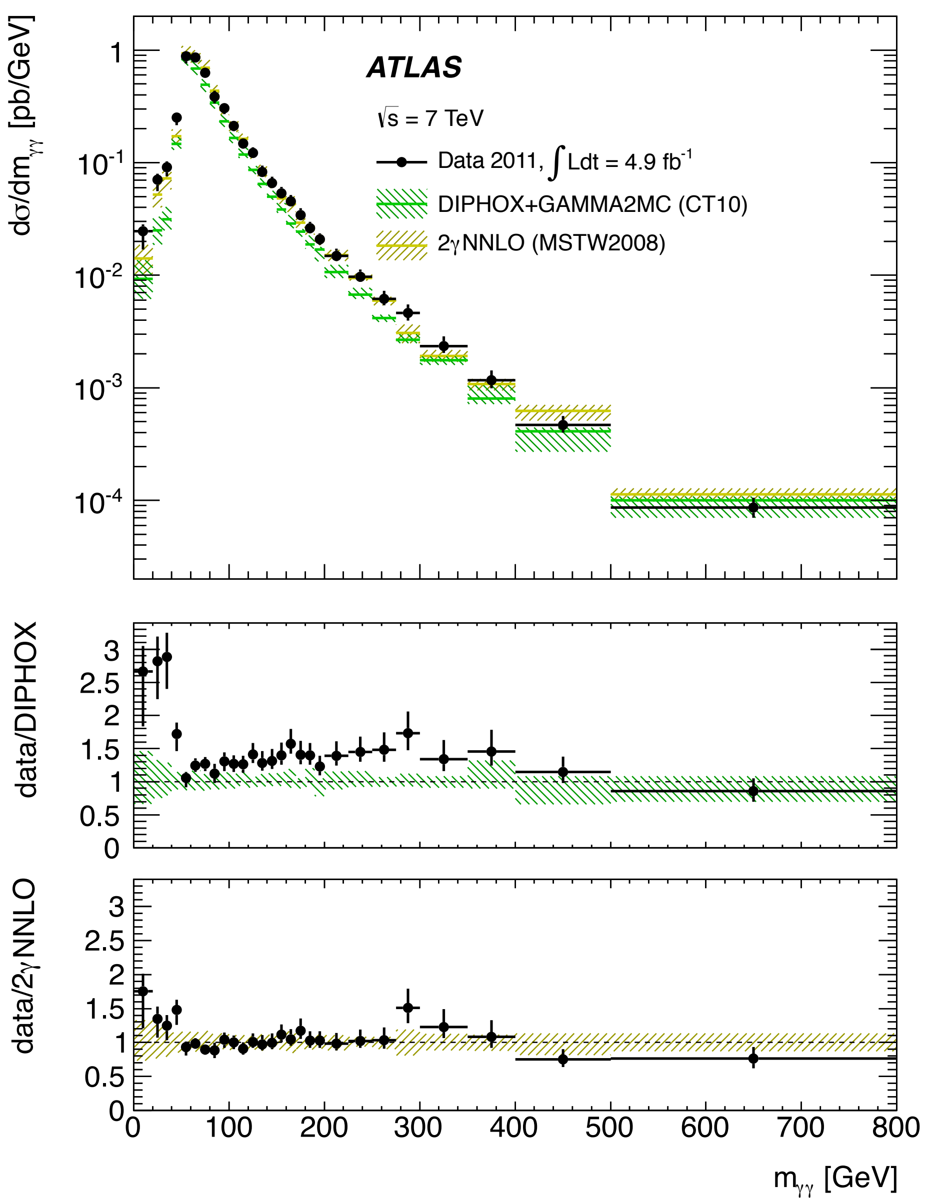
Up to very recently the accuracy was limited to NLO QCD

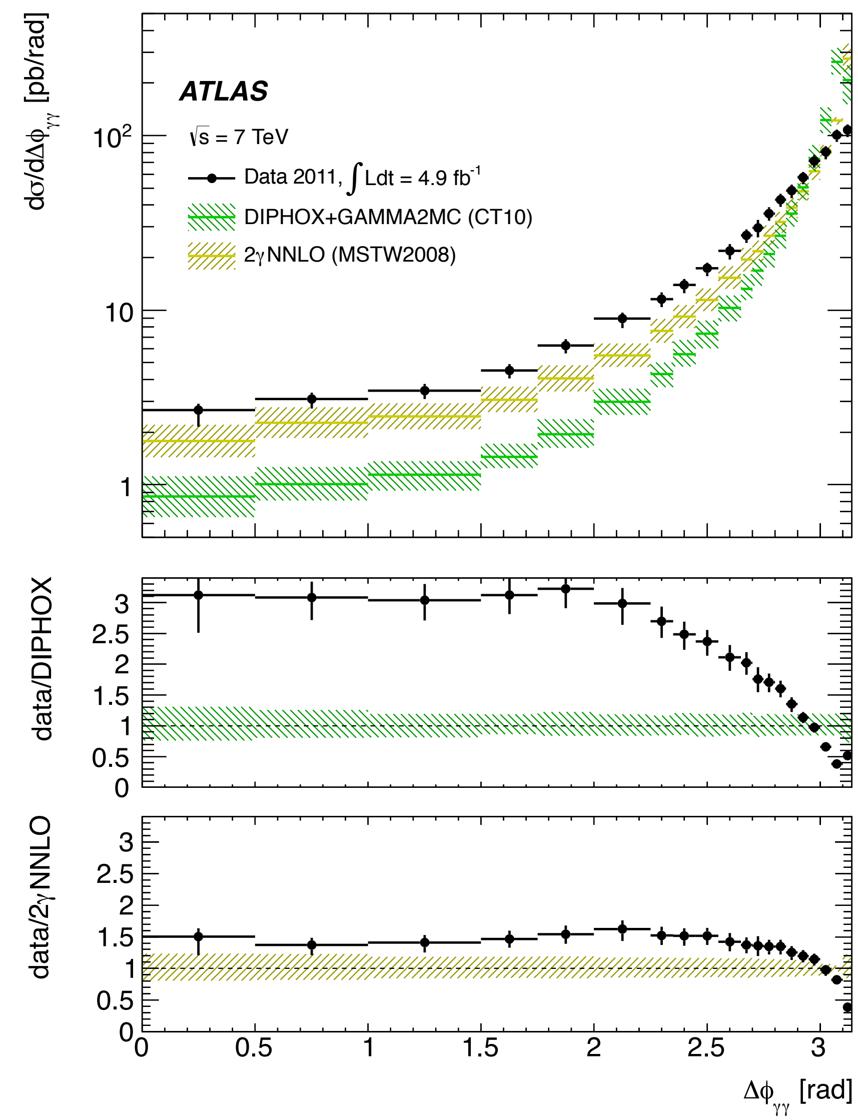
→ Extension to NNLO highly desirable

Introduction

Up to about one year ago, 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→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)

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 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.Amettler 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)
M.Billoni, S.Dittmaier, B.Jager,C.Speckner (2013)
A. Denner, S. Dittmaier, M. Hecht, C. Pasold (2014)

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)

→ Two-loop on-shell amplitudes for WW and ZZ available

T.Gehrmann et al (to appear)

pp→Vγ +X at NNLO

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

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)
- One loop Vγ+1 parton amplitudes — K. Adamson, D. de Florian, A.Signer (2000); 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 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)

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

The calculation

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 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 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 (to appear)

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

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

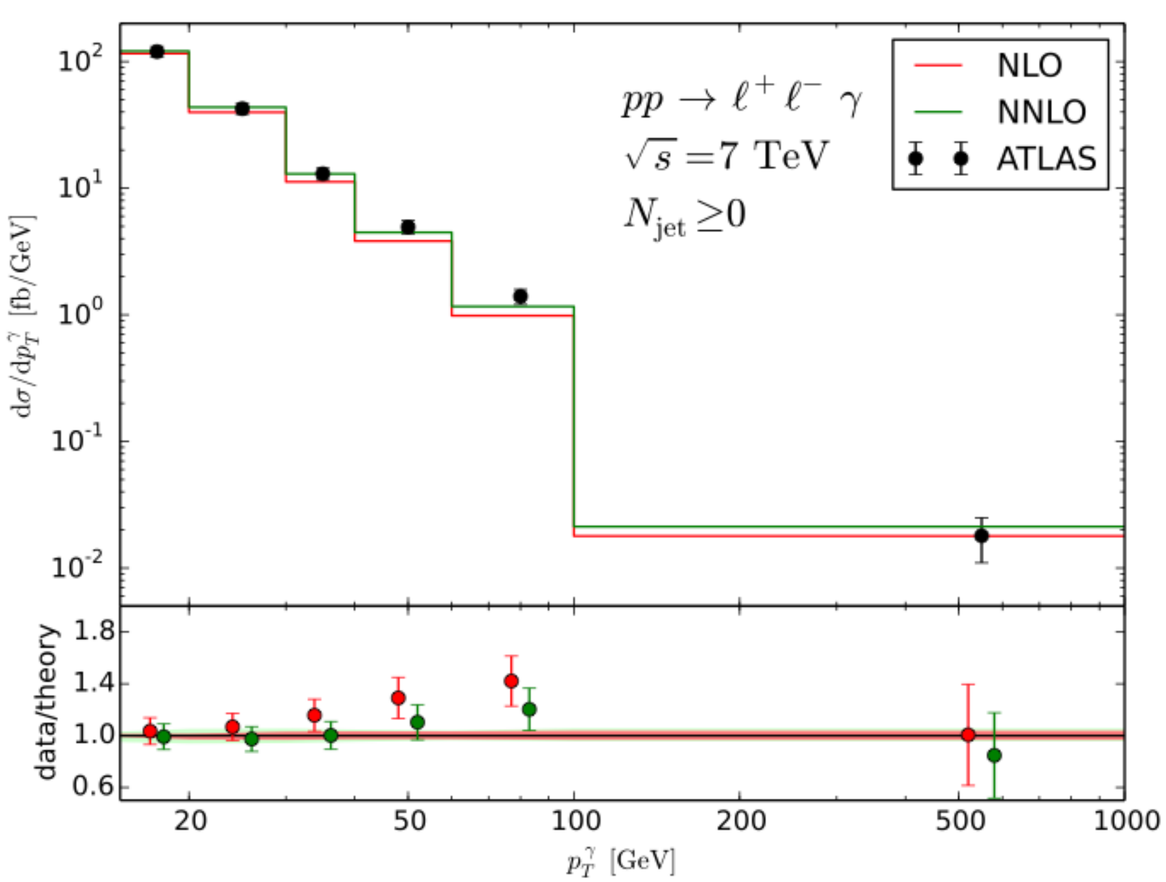
$m_{ll} > 40$ GeV

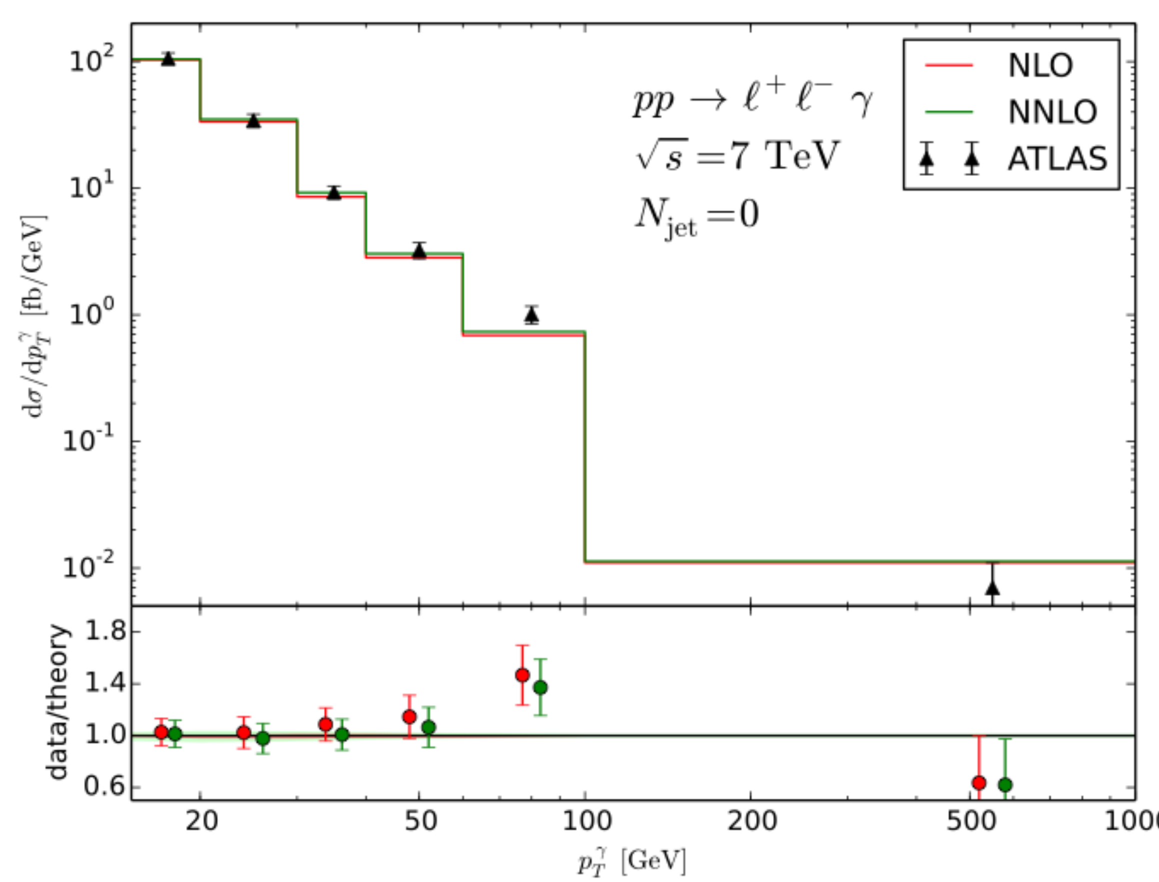
jets: anti-kt with D=0.4

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

+9%

	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]
$N_{\text{jet}} \geq 0$	$1.2222^{+4.2\%}_{-5.3\%}$	$1.327^{+1.3\%}_{-2.3\%}$	1.31 ±0.02 (stat) ±0.11 (syst) ±0.05 (lumi)
$N_{\text{jet}} = 0$	$1.0310^{+2.7\%}_{-4.3\%}$	$1.064^{+0.7\%}_{-1.4\%}$	1.05 ±0.02 (stat) ±0.10 (syst) ±0.04 (lumi)





pp→Wγ +X at NNLO

S.Kallweit,D.Rathlev, MG (to appear)

ATLAS cuts (arXiv:1302.1283)

photon isolation: ε= 0.5
smooth cone R= 0.4

+21%

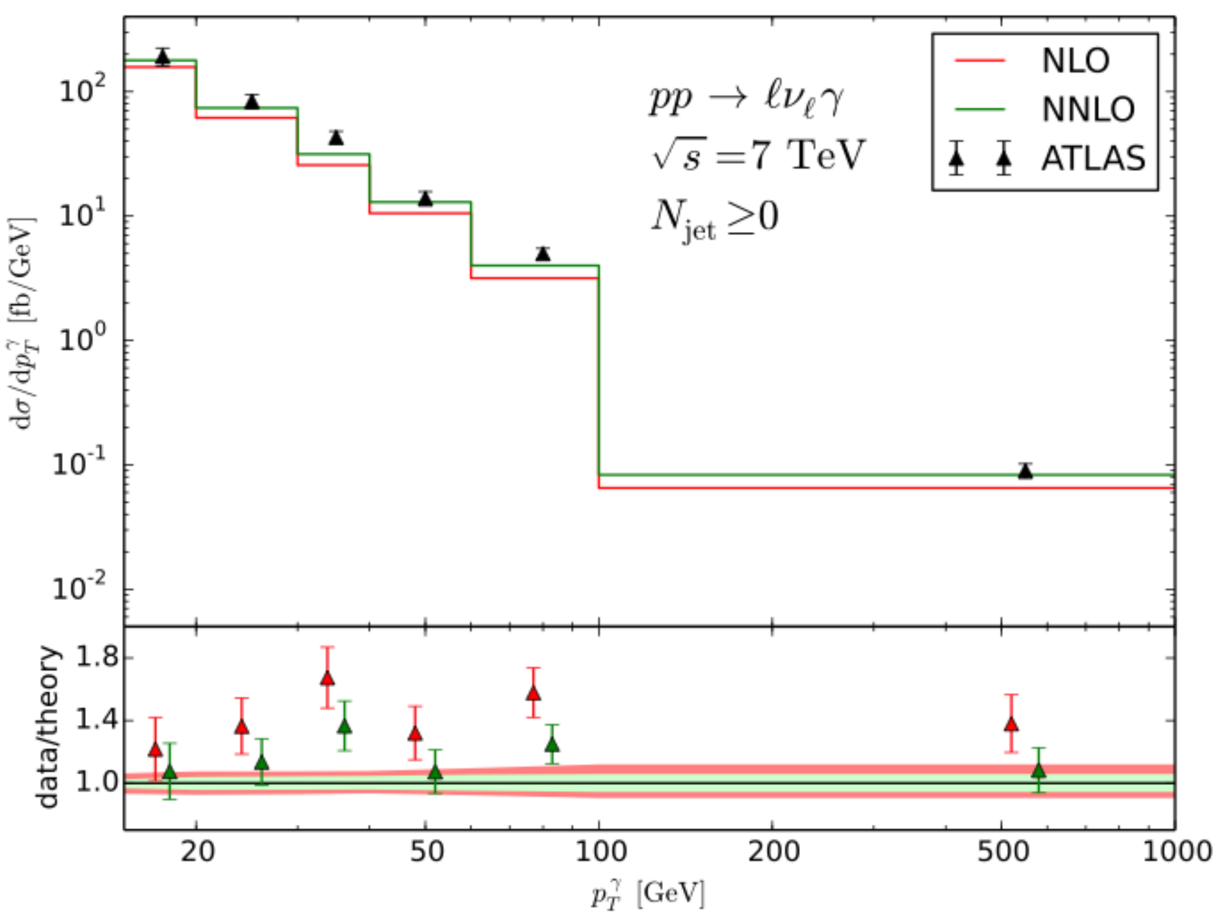
$p^{\gamma}_T > 15$ GeV $p^{l}_T > 25$ GeV $\Delta R(l/\gamma,\text{jet}) > 0.3$

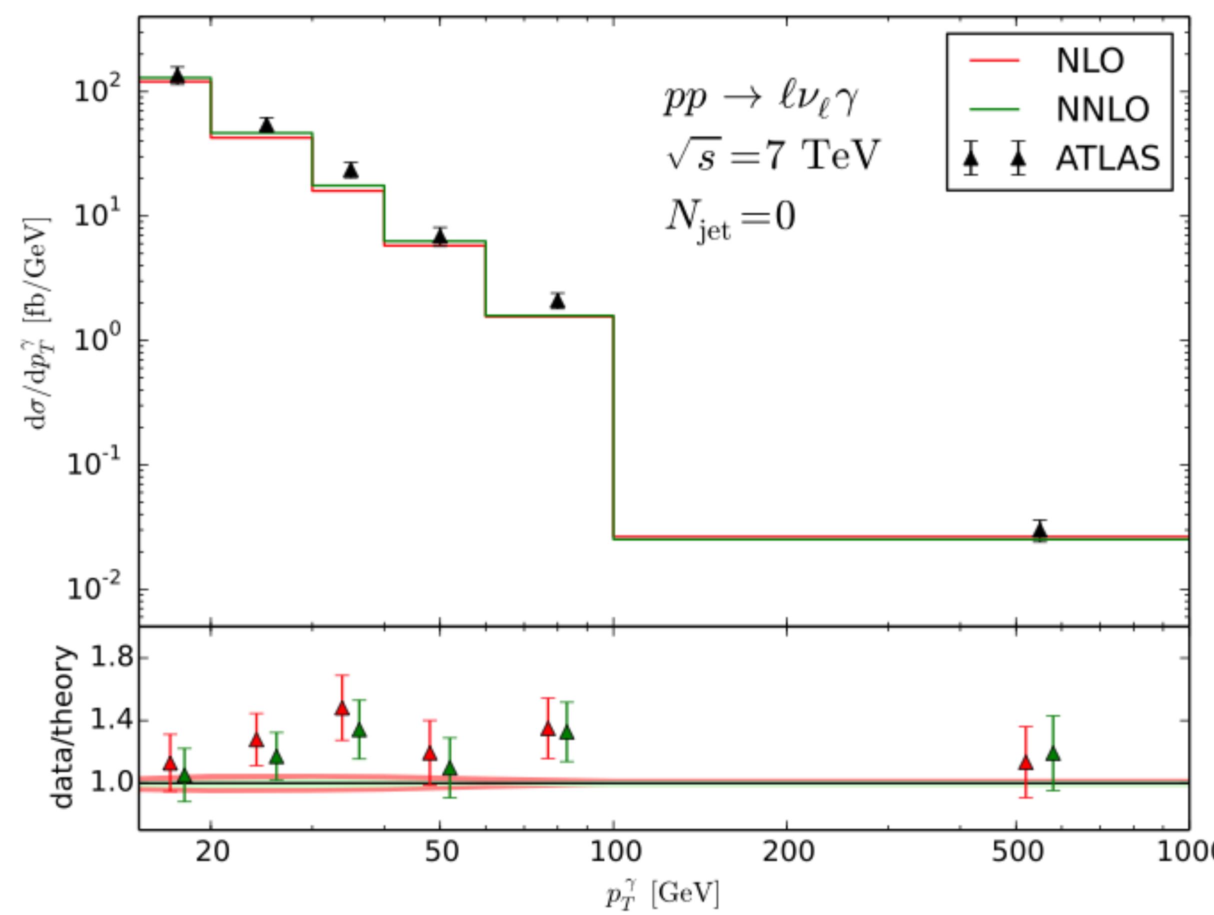
$|\eta^{\gamma}| < 2.37$ $|\eta^{l}| < 2.47$ $\Delta R(l,\gamma) > 0.7$

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

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

	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]
$N_{\text{jet}} \geq 0$	$2.057^{+6.8\%}_{-6.8\%}$	$2.484^{+4.1\%}_{-4.1\%}$	2.77 ±0.03 (stat) ±0.33 (syst) ±0.14 (lumi)
$N_{\text{jet}} = 0$	$1.389^{+5.2\%}_{-5.8\%}$	$1.495^{+1.7\%}_{-2.7\%}$	1.76 ±0.03 (stat) ±0.21 (syst) ±0.08 (lumi)



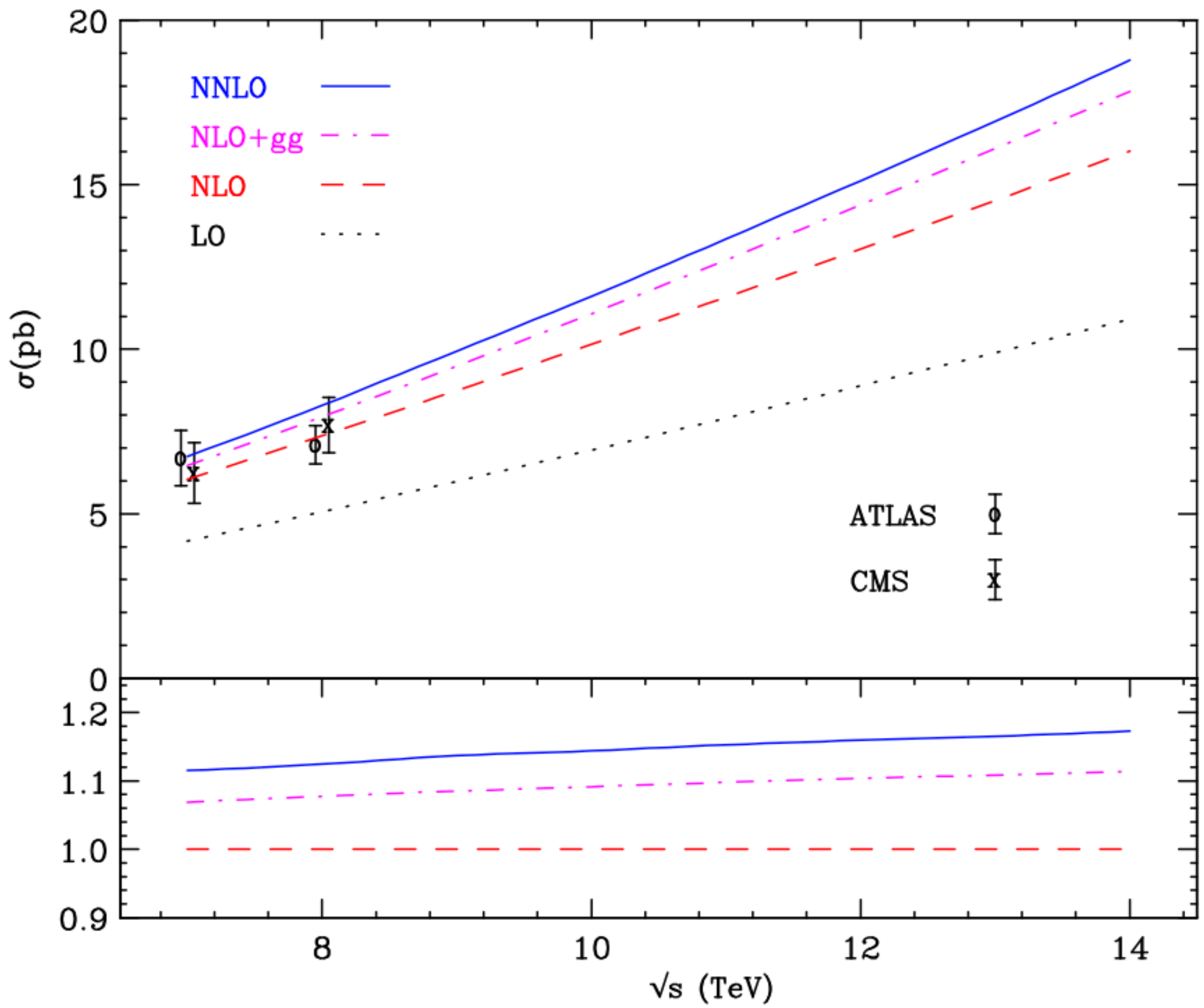


$pp \to ZZ+X$ at NNLO

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 $pp \to VV$ 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 12 to 17 % when √s varies from 7 to 14 TeV

gg contribution 58-62% of the full NNLO effect

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

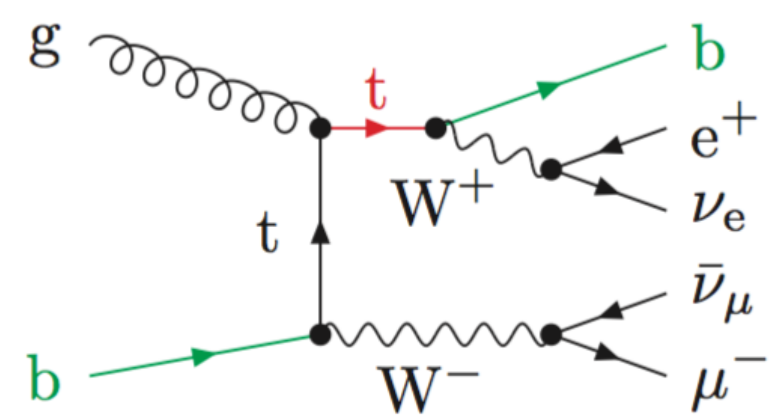
The WW cross section at NNLO

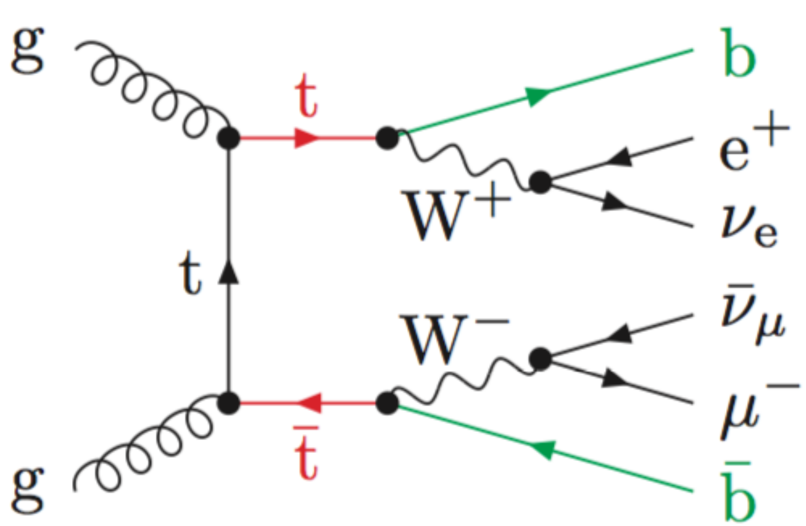
T. Gehrmann, S. Kallweit, P. Maierhofer, A. von Manteuffel,
S. Pozzorini, D. Rathlev, L. Tancredi, MG (2014)

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 $g \to b\bar{b}$ 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)

The WW cross section at NNLO

A first possible solution: use the 4-flavor scheme

In this scheme the bottom quarks are massive: we can omit diagrams with b-quark emissions and obtain a consistent WW cross section at NNLO

As for the $V\gamma$ and ZZ calculations, we obtain the tree-level and one-loop amplitudes with OpenLoops

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

The last missing ingredient, the two loop $q\bar{q} \to WW$ amplitude has been obtained recently

T. Gehrmann, A. von Manteuffel, L.Tancredi (to appear)

The contributing amplitudes are combined with the q_T subtraction method

S. Catani, MG (2007)

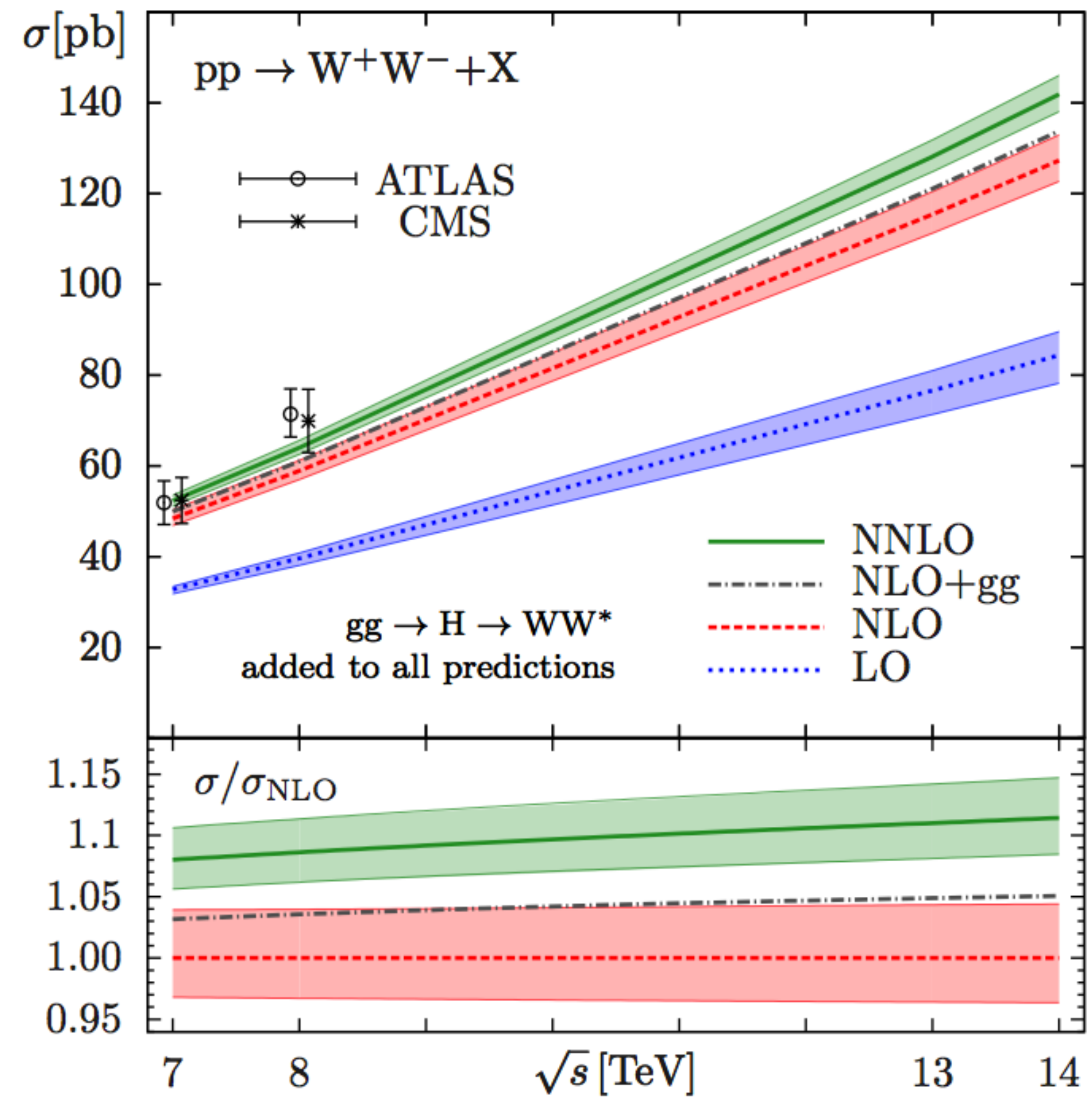
The WW cross section at NNLO

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

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

gg contribution 35% of the full NNLO effect

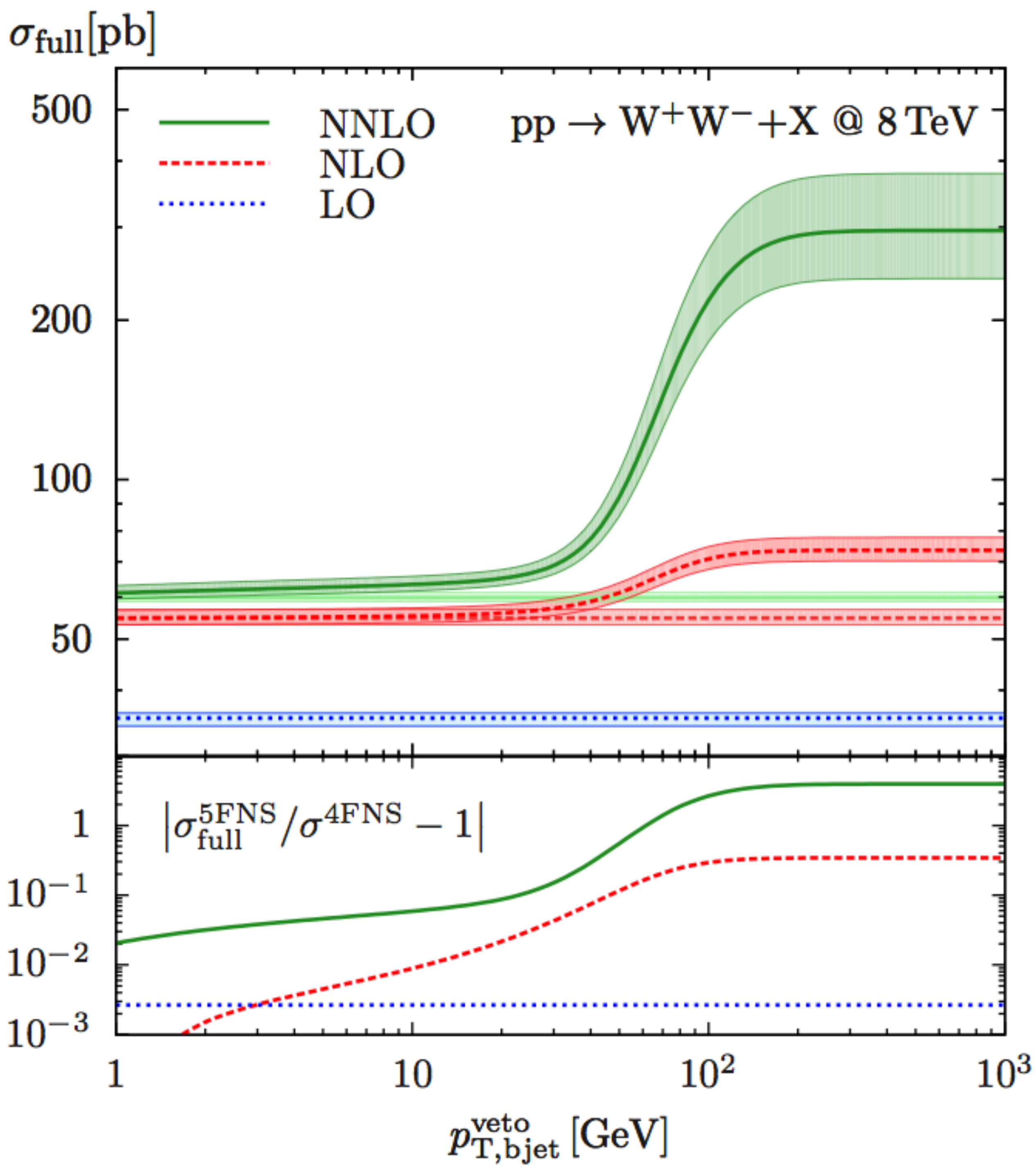
$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$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

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 $1/2 < \mu_F/\mu_R < 2$

The 4FNS-5FNS ambiguities



Cross section in the 5FNS with a b-jet veto compared to the 4FNS result

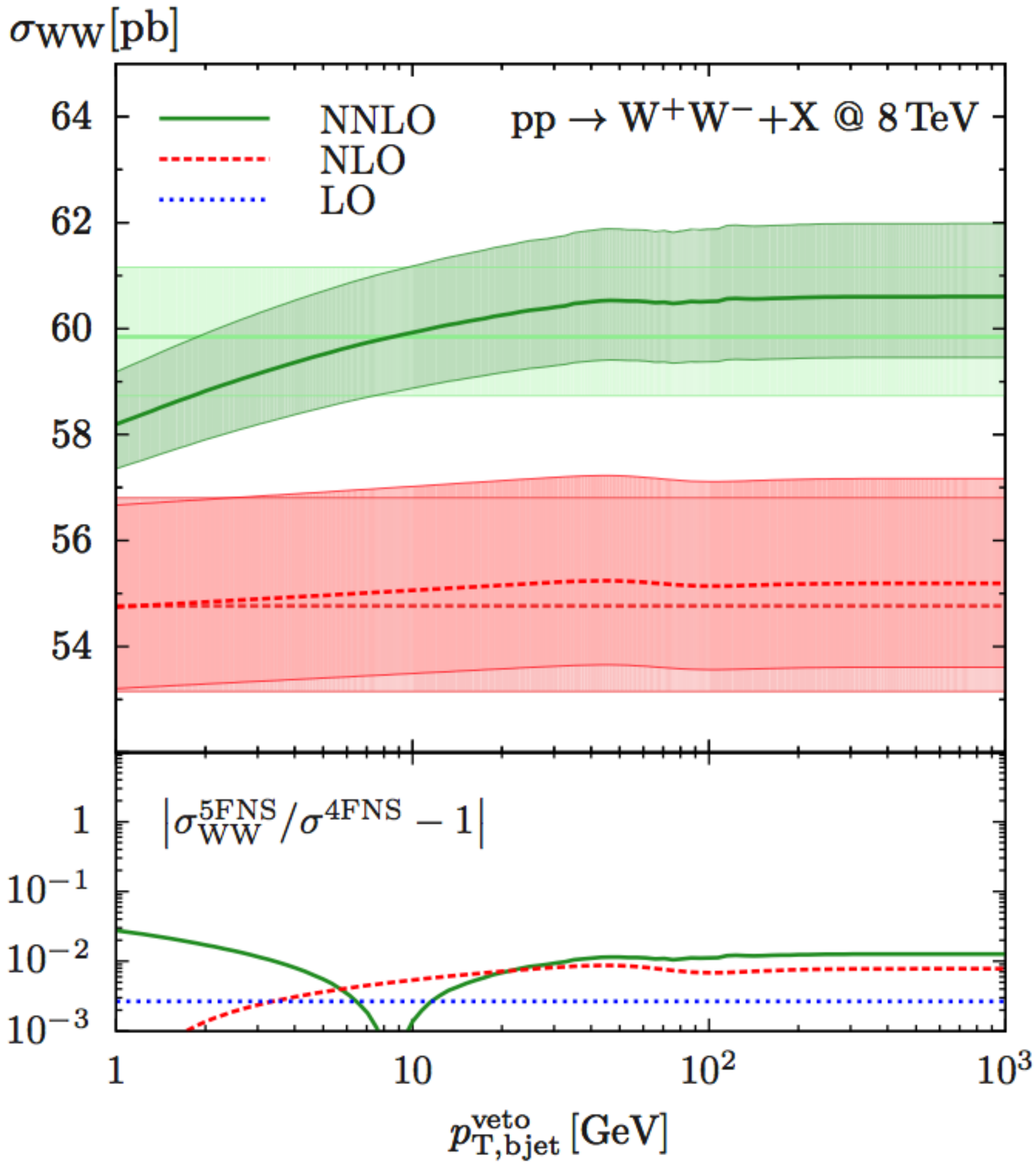
At large values of $p_{T,bjet}^{veto}$ the 5FNS result suffers from a huge contamination from top resonances

This contamination is suppressed with a b-jet veto but for $p_{T,bjet}^{veto} \sim 30$ GeV it remains as large as 10% at NNLO

As $p_{T,bjet}^{veto} \to 0$ the 5FNS cross section displays a logarithmic singularity associated to the g →bb splitting

➡ This sensitivity to $p_{T,bjet}^{veto}$ represents a theoretical ambiguity of the 5FNS

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

NEW: Beyond the inclusive cross section

S. Kallweit, N.Moretti, S. Pozzorini, D. Rathlev, MG (in progress)

To carry out the fully exclusive calculation including the leptonic decay the two-loop helicity amplitudes are needed

However we can try to approximate their effect

We have extended the calculation to the fully exclusive level by including the W boson leptonic decays and off-shell effects

All the NNLO contributions are accounted for exactly except the finite part of the two-loop matrix element → computed by using an on-shell projection

1) Given a four lepton llνν event compute the W boson 3-momenta

2) Define the W energies by setting the Ws on shell

3) Use the on-shell WW matrix element to compute the hard-collinear coefficient

Checked at NLO: the inclusive and fiducial WW cross sections are reproduced at the 0.2 % level ! (at NNLO further reduction by a factor O(10))

NEW: Beyond the inclusive cross section

S. Kallweit, N.Moretti, S. Pozzorini, D. Rathlev, MG (in progress)

Consider for simplicity only the $e^+ \mu^- + e^- \mu^+$ channel

Use cuts from ATLAS-CONF-2014-033

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

  Jets: anti-kt with R=0.4

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

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

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

- Jet veto: no jets with $p_T > 25$ GeV, $|\eta| < 4.5$ and $\Delta R(e,j) > 0.3$

Use the 4-flavour scheme (4FNS) and MSTW2008 PDFs

For the central renormalisation and factorisation scale we choose the sum of the transverse masses of the W bosons $\mu_0 = m_{T1} + m_{T2}$

Scale variations: $\mu_0/2 < \mu_F, \mu_R < 2\mu_0$ $0.5 < \mu_F/\mu_R < 2$

NEW: Beyond the inclusive cross section

S. Kallweit, N.Moretti, S. Pozzorini, D. Rathlev, MG (in progress)

We compare our fixed-order results with those obtained from an NLO merged and an NLO matched simulation with Sherpa+Openloops

F.Cascioli, S.Hoche, F.Krauss,P.Maierhofer, S.Pozzorini, F.Siegert (2013)

- NLO matching (S-MC@NLO) includes WW+1 parton and WW virtual ME
- NLO merging (MEPS@NLO) also WW+2 partons and WW+1 parton virtual ME

A preliminary estimate of scale uncertainties is obtained by varying factorisation (μ_F), renormalisation (μ_R) and resummation (μ_Q) scales in the following way:

- $\mu_0/2 < \mu_F=\mu_R=\mu_Q < 2\mu_0$
- $\mu_0/2 < \mu_F=\mu_Q < 2\mu_0$ $\quad \mu_R = \mu_0$
- $\mu_0/2 < \mu_R < 2\mu_0$ $\quad \mu_F=\mu_Q= \mu_0$

NLO merging (MEPS@NLO): the merging scale is taken to be $Q_{cut} = 20 \pm 10$ GeV

Fiducial cross section (preliminary !)

S. Kallweit, N.Moretti, S. Pozzorini, D. Rathlev, MG (in progress)

The Higgs contribution is computed with HNNLO ($\mu_F=\mu_R=m_H=125$ GeV as central scale)

Higgs: $9.72^{+5.5\%}_{-6.8\%}$ fb

gg: $13.66^{+26\%}_{-20\%}$ fb

NNLO (no gg)	S-MC@NLO	MEPS@NLO
$317.12^{+0.9\%}_{-0.7\%}$	$305.24^{+3.2\%}_{-1.6\%}$	$307.26^{+5.9\%}_{-1.7\%}$

Scale uncertainties combined linearly in the total

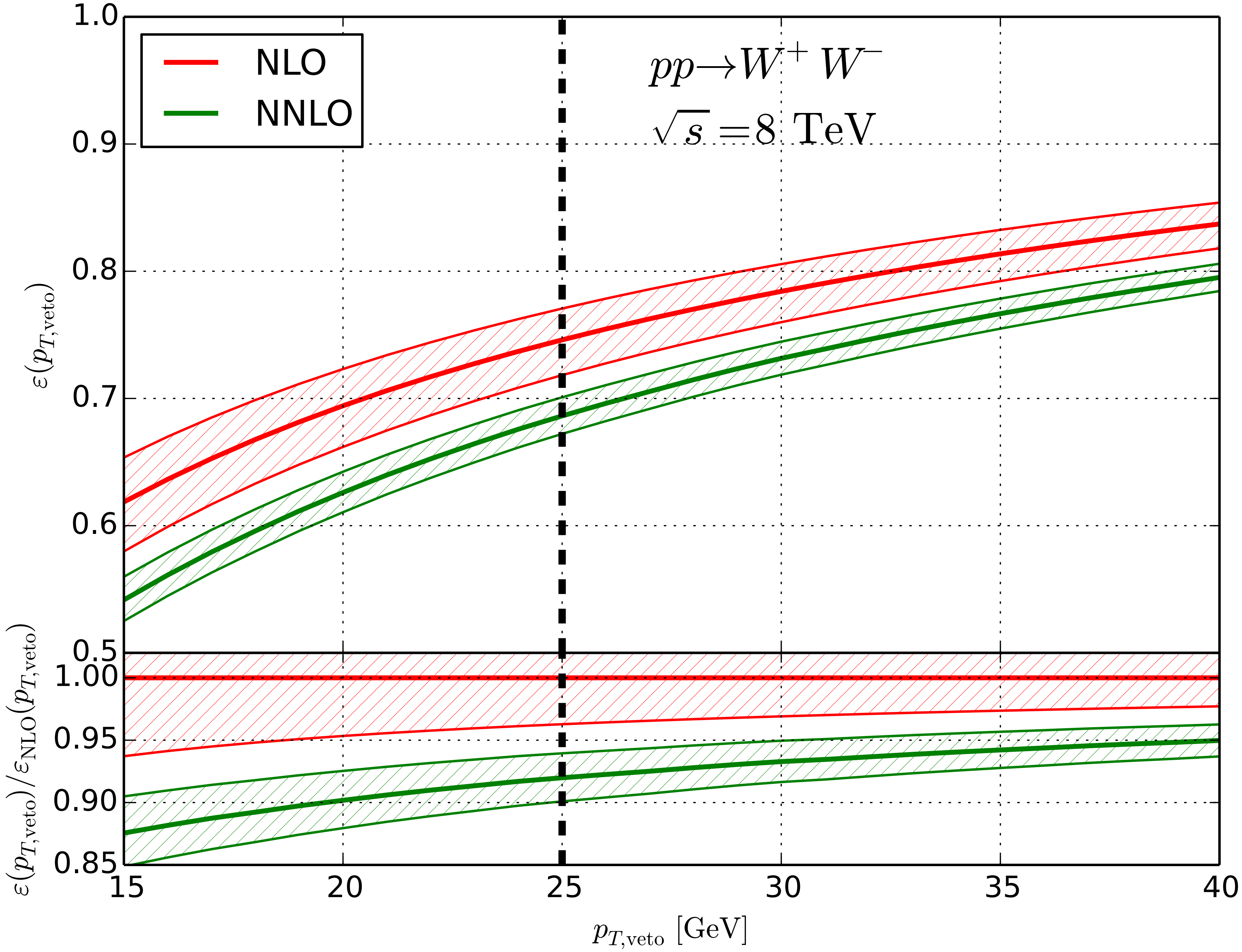
Total:	$340.5^{+2.0\%}_{-1.6\%}$	$328.6^{+4.2\%}_{-2.5\%}$	$330.6^{+6.7\%}_{-2.6\%}$

Nice consistency of the NNLO result with S-MC@NLO and MEPS@NLO

ATLAS finds: $377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$ fb

Jet veto efficiency: NNLO

S. Kallweit, N.Moretti, S. Pozzorini, D. Rathlev, MG (in progress)



Only jet veto is applied here and gg channel is not included

NNLO corrections lead to a suppression of the efficiency by 7-10 %

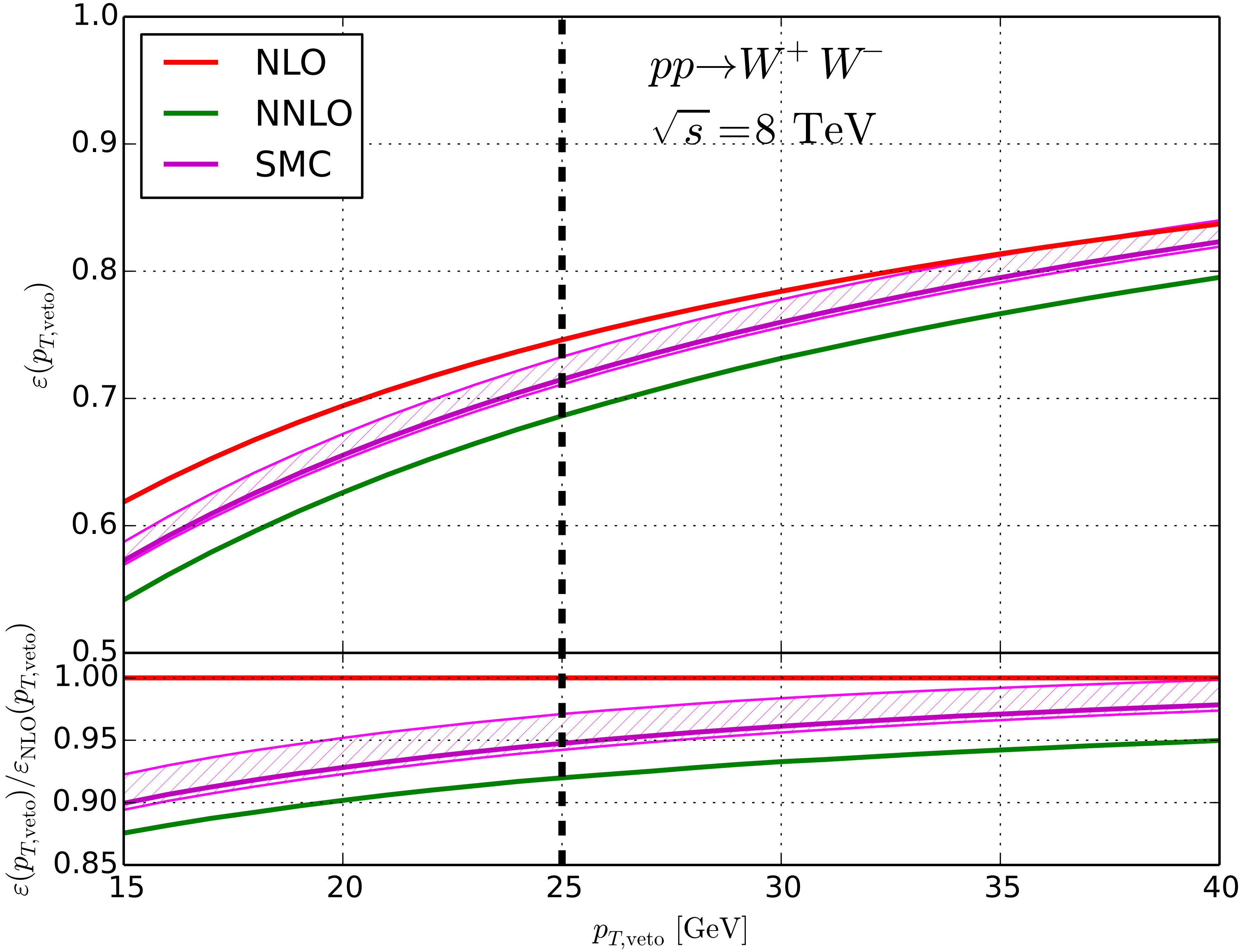
Suppression is driven by the suppression of QCD corrections in the jet vetoed cross section

Suppression wrt NLO seems consistent with POWHEG

c.f. P.Monni, G.Zanderighi (2014)

Jet veto efficiency: S-MC@NLO

S. Kallweit, N.Moretti, S. Pozzorini, D. Rathlev, MG (in progress)



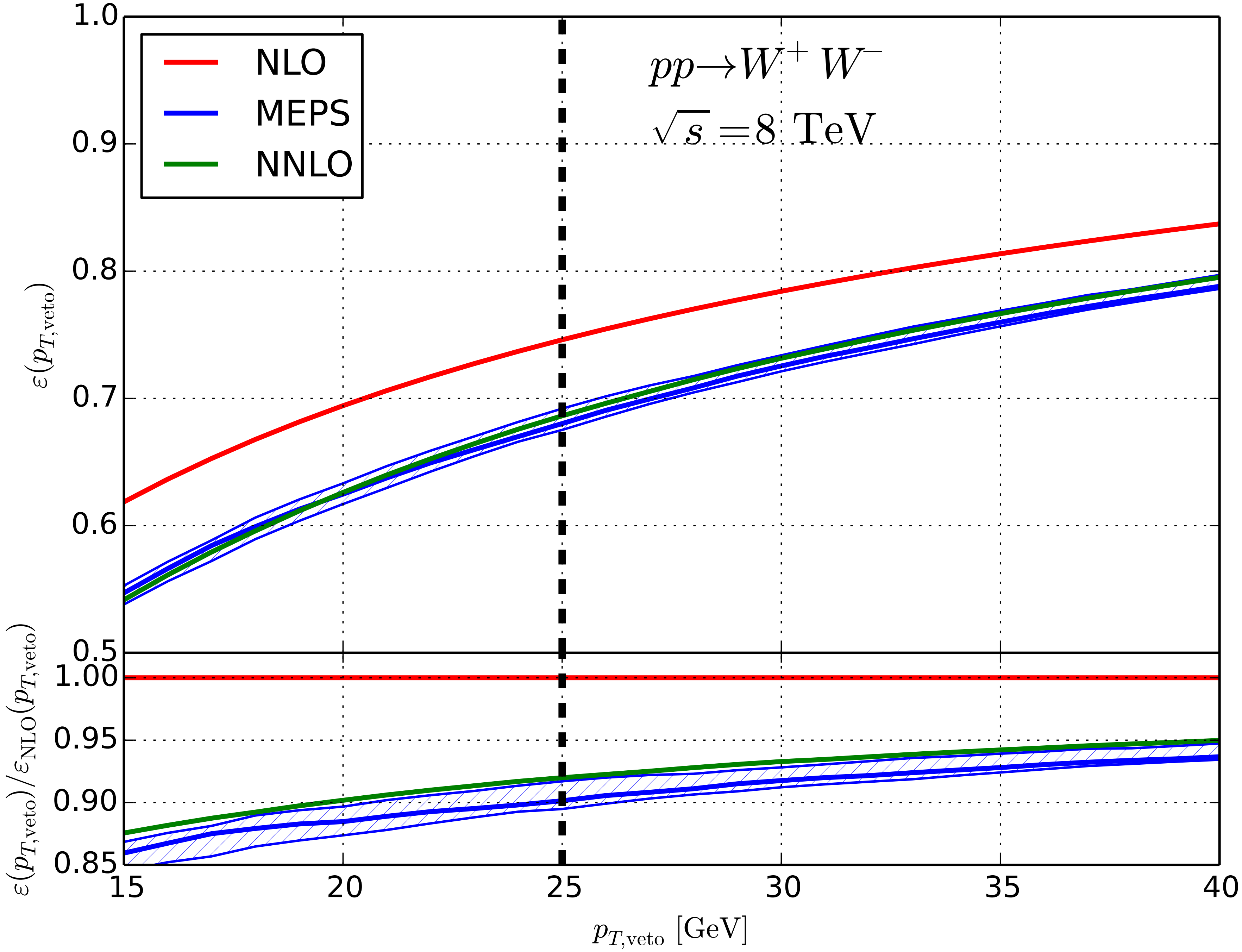
Only jet veto is applied here and gg channel is not included

S-MC@NLO leads to a larger efficiency wrt NNLO

S-MC@NLO marginally consistent with NNLO within scale uncertainties

Jet veto efficiency: MEPS@NLO

S. Kallweit, N.Moretti, S. Pozzorini, D. Rathlev, MG (in progress)



Only jet veto is applied here and gg channel is not included

MEPS@NLO leads to a further suppression of the efficiency vs NNLO

NNLO and MEPS@NLO results consistent within uncertainties

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
- I have presented results for the fully exclusive NNLO calculation to $Z\gamma$ and $W\gamma$ production

  - For $Z\gamma$ the NNLO corrections are generally moderate, and of O(10%) for typical selection cuts

  - For $W\gamma$ the NNLO corrections are larger, and of O(20%)

- For WW and ZZ production the helicity amplitudes are still not available

  ➡ Exact fully exclusive NNLO calculation with leptonic decay still not possible: we have focused on the total cross section

  - In the case of ZZ production the NNLO effect ranges from 12 to 17%
  - In the case of WW production the NNLO effect ranges from 9 to 12%

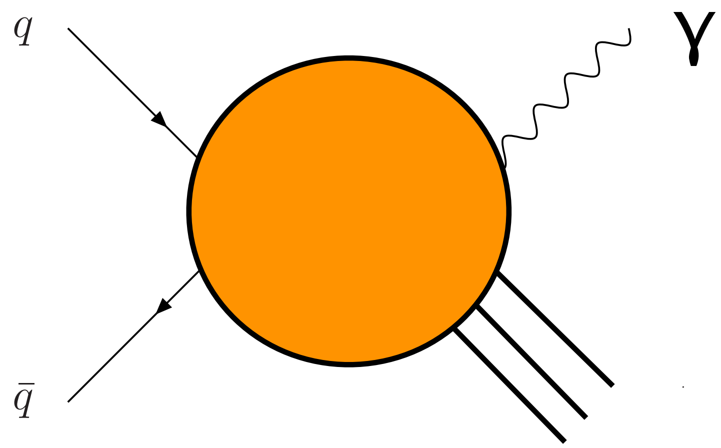
Summary & Outlook

- We have recently extended the NNLO calculation for WW production to the fully differential level by considering the W decays and off-shell effects
- All contributions are included exactly except the two-loop matrix element for which we use an on-shell projection: excellent approximation
- I have presented preliminary results for the fiducial cross section in the $e^+\mu^- + e^- \mu^+$ channel and for the jet veto efficiency
- I have presented a comparison of these results with what obtained with a NLO matched and an NLO merged simulation with Sherpa+Openloops
- The computation of the helicity amplitudes will make possible the exact fully exclusive NNLO calculations of ZZ, WW and WZ including leptonic decays and off-shell effects

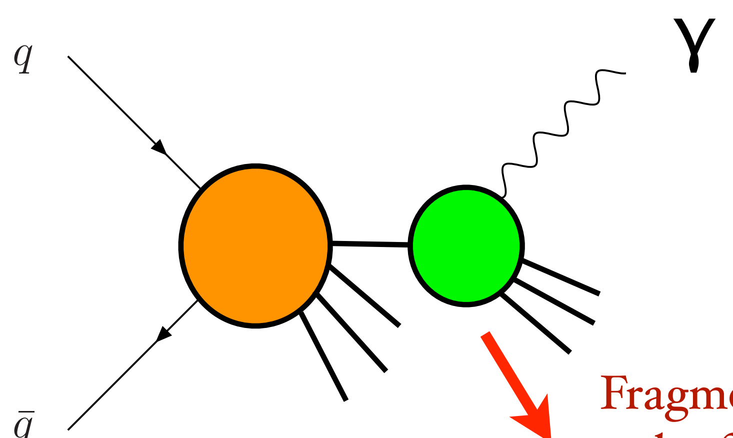
Backup slides

Photon isolation

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



Direct component: photon directly produced through the hard interaction

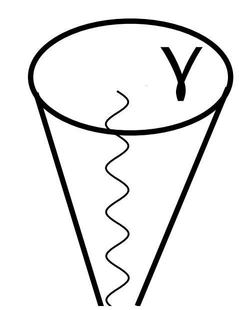


Fragmentation component: photon produced from non-perturbative fragmentation of a hard parton (like a hadron)

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