Diboson production at NNLO

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Outline

- Introduction
- The q_T-subtraction method
- $pp \to WW+X$ at NNLO
  - jet veto efficiency
- $pp \to ZZ+X$ 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

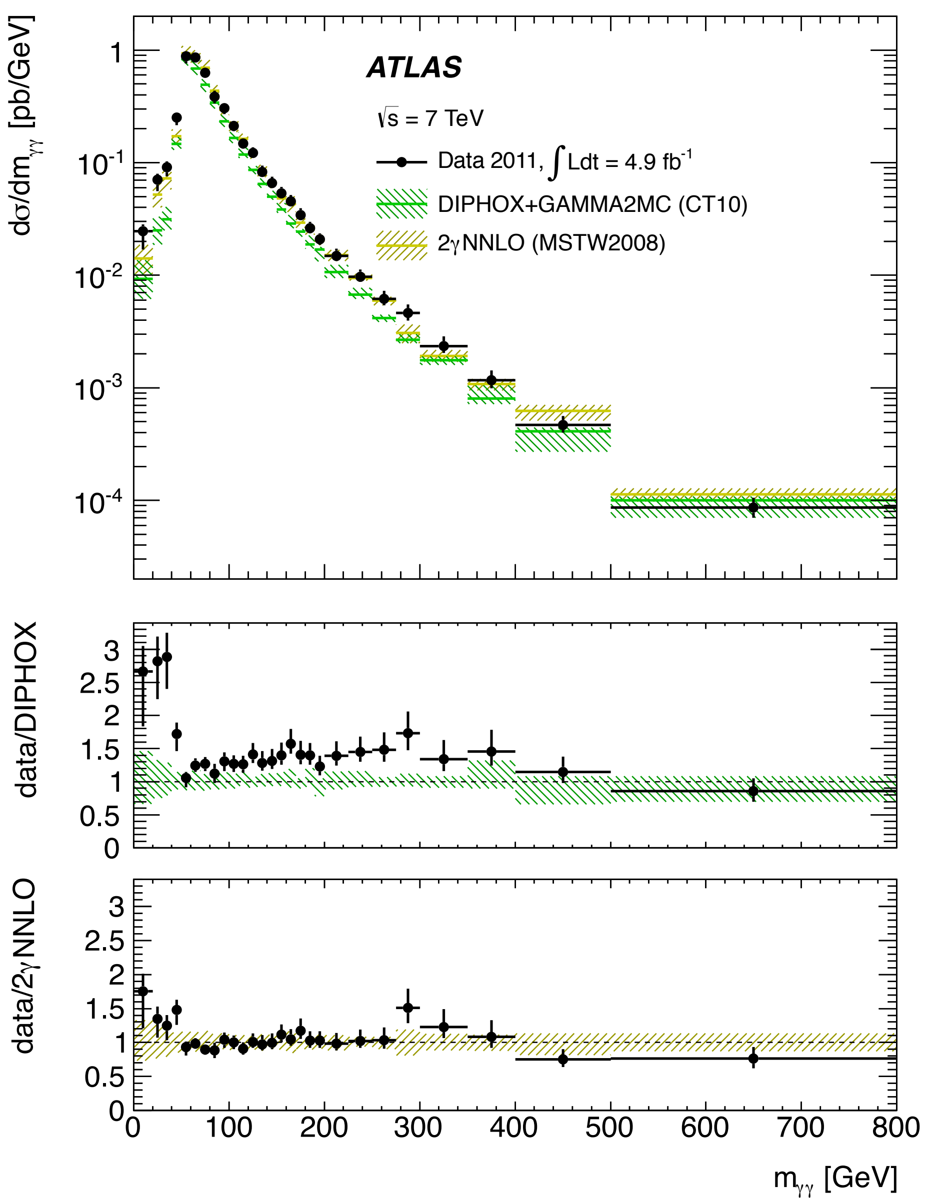
Up to very recently the accuracy was limited to NLO QCD

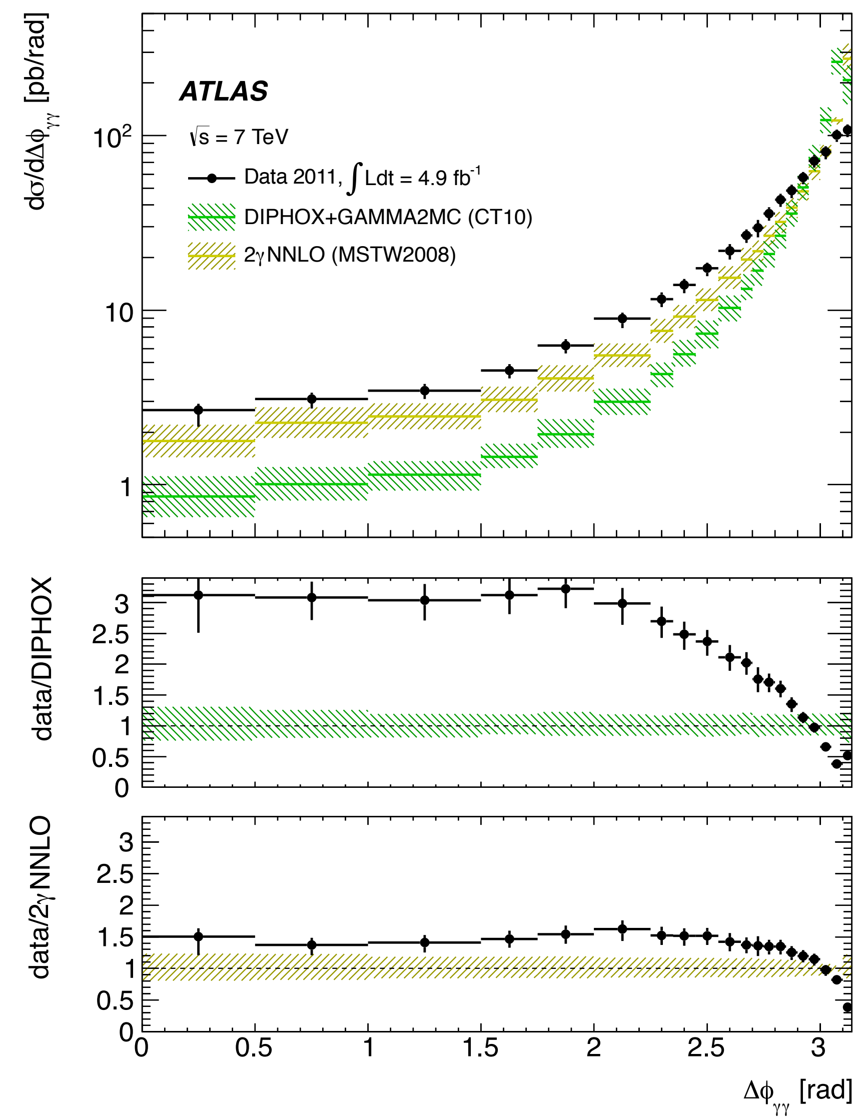
→ Extension to NNLO highly desirable

Introduction

Up to about two years 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

Wγ,Zγ,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 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)

Two-loop helicity amplitudes for WW,WZ and ZZ production recently evaluated

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

→ NNLO calculation now possible

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

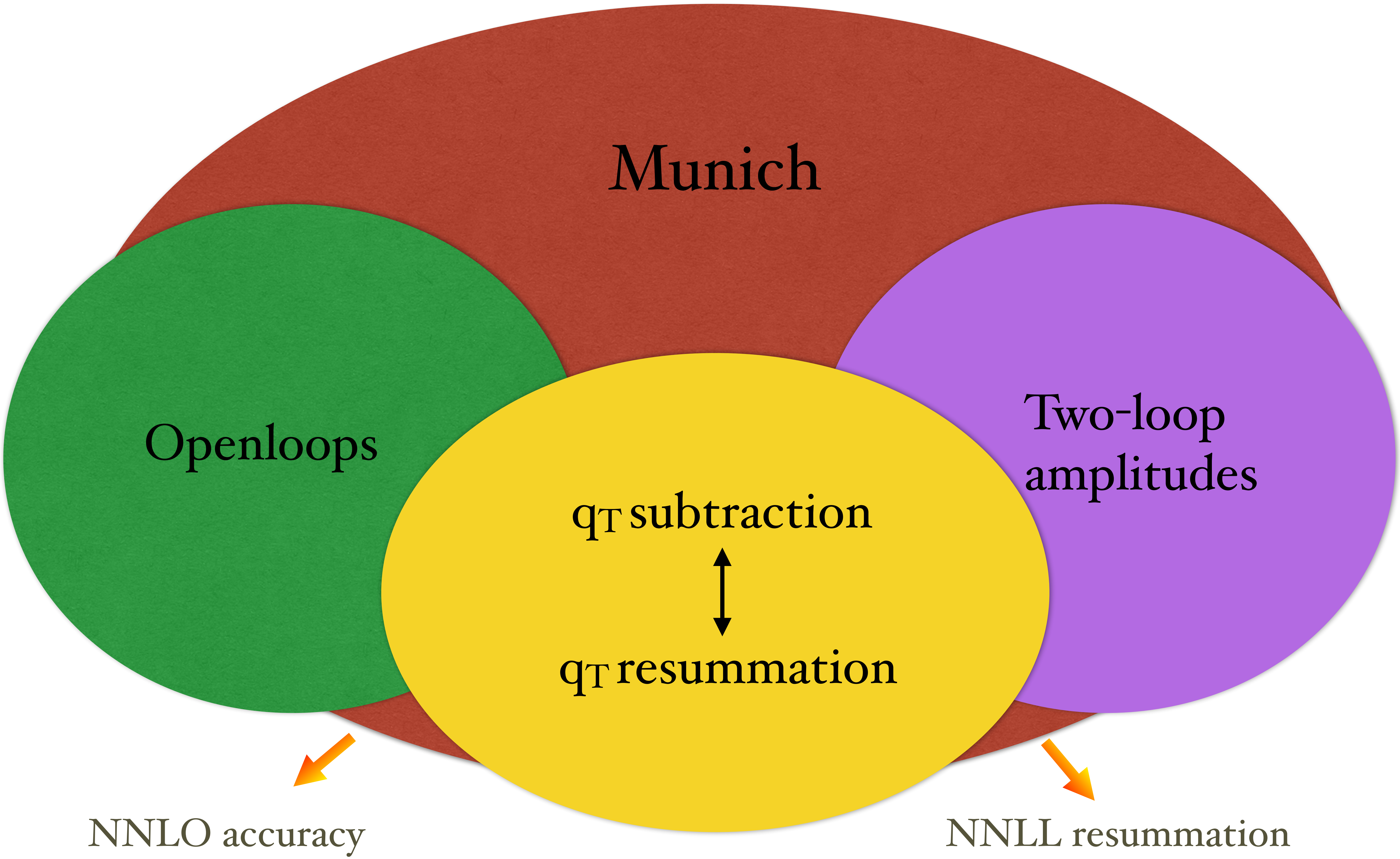
S. Catani, MG (2010)
S. Catani, L.Cieri, D. de Florian, G.Ferrera, MG (2013)

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

Our framework

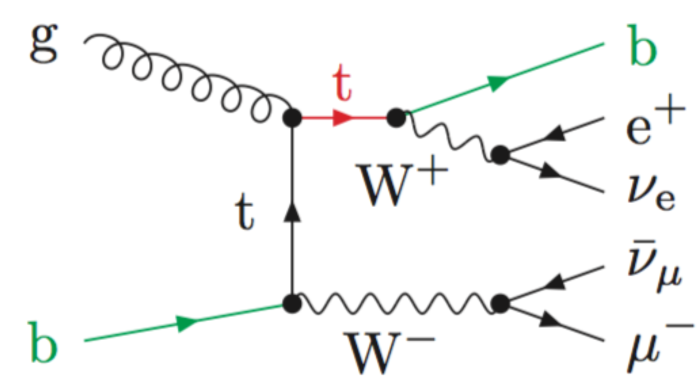


The WW cross section at NNLO

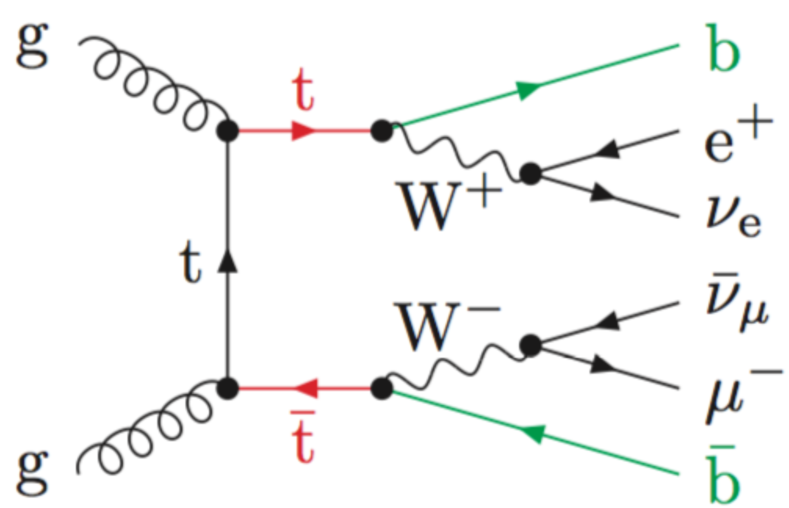
T. Gehrmann, S. Kallweit, P. Maierhofer, A. von Manteuffel,
S. Pozzorini, D. Rathlev, L. Tancredi, MG (2014)

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)

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

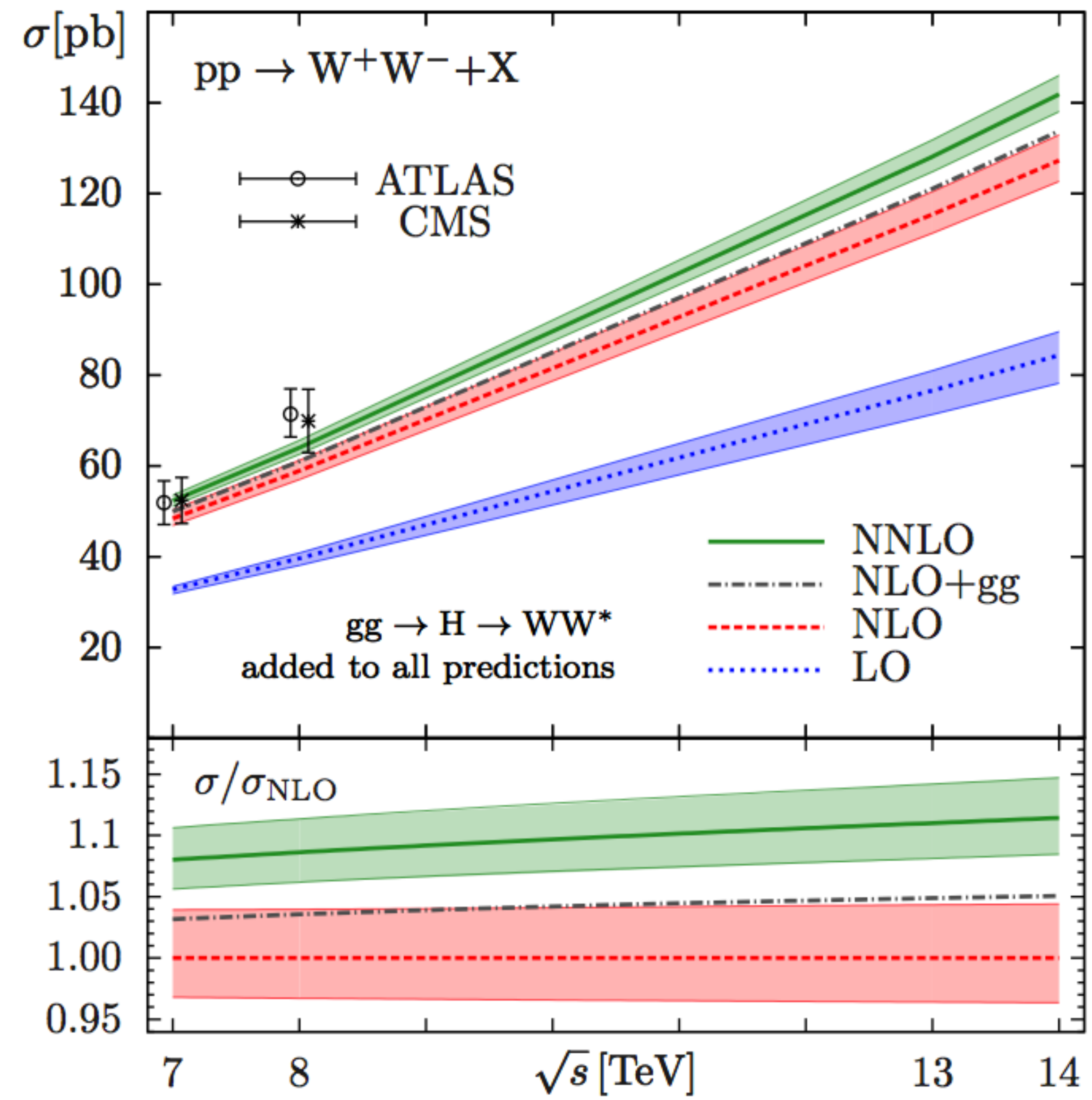
The WW cross section at NNLO

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

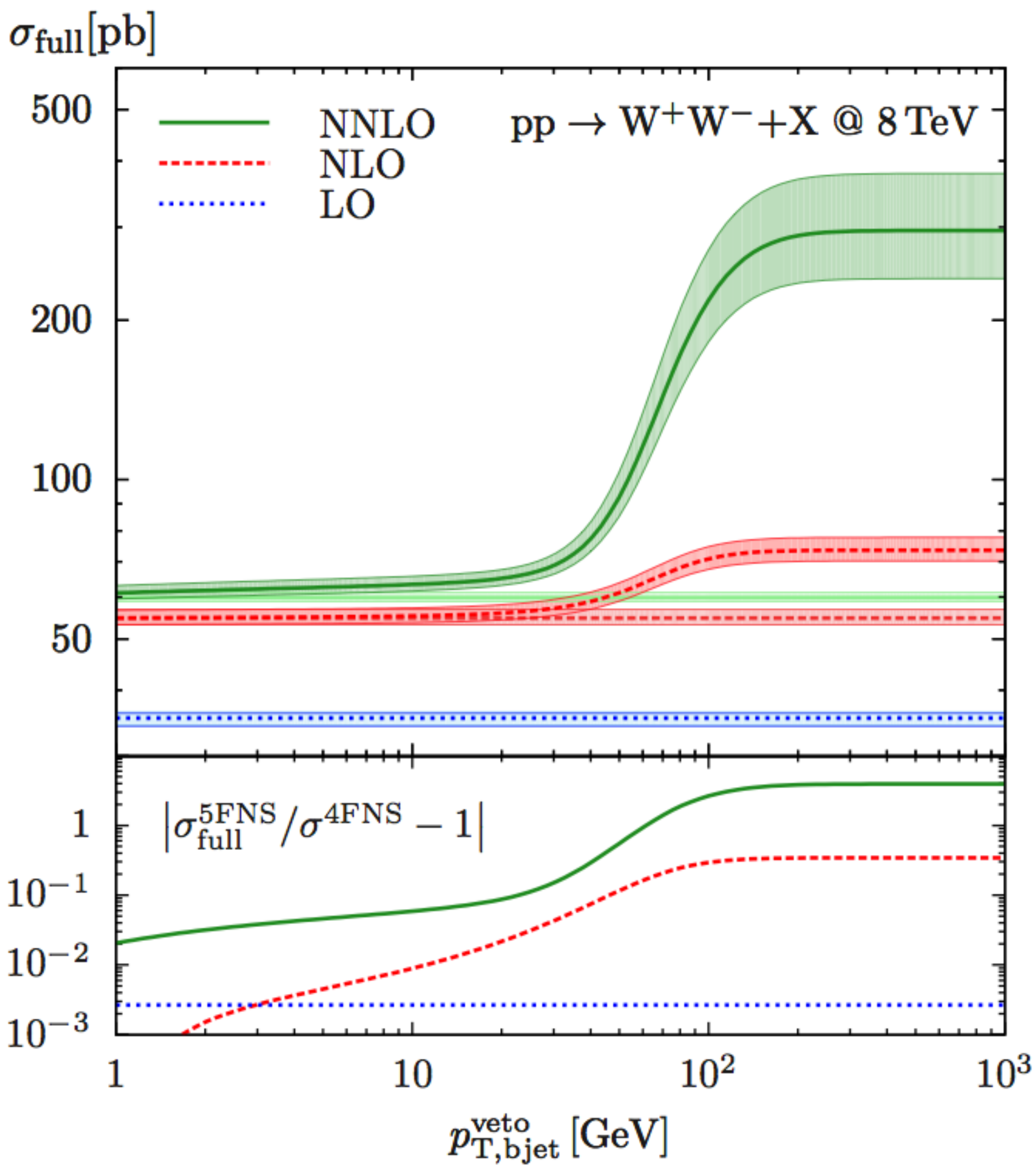
$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$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

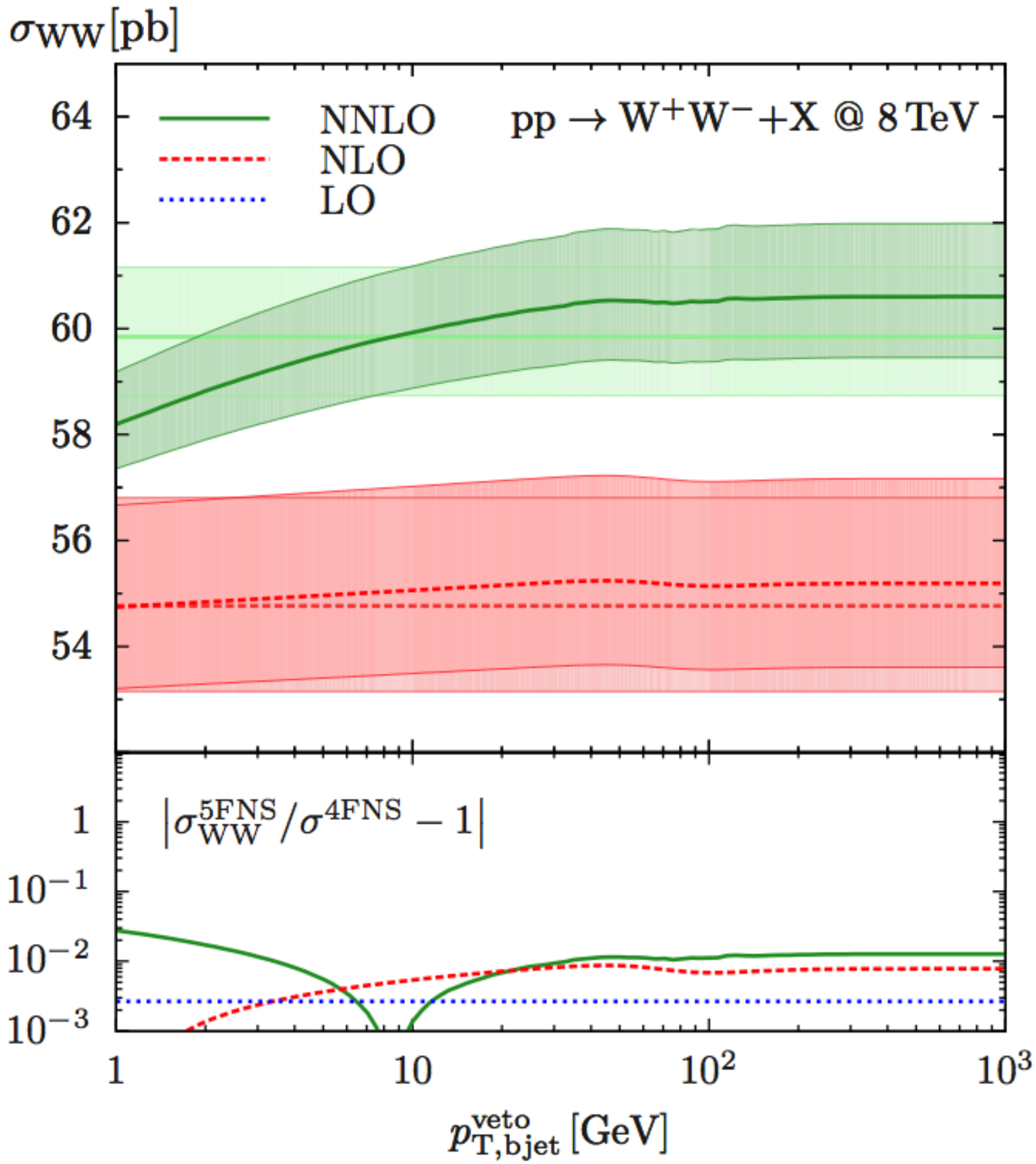
At large values of $p_{\rm T,bjet}^{\rm veto}$ the 5FNS result suffers from a huge contamination from top resonances

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

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

➡ This sensitivity to $p_{\rm T,bjet}^{\rm veto}$ 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

Jet veto efficiency

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

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

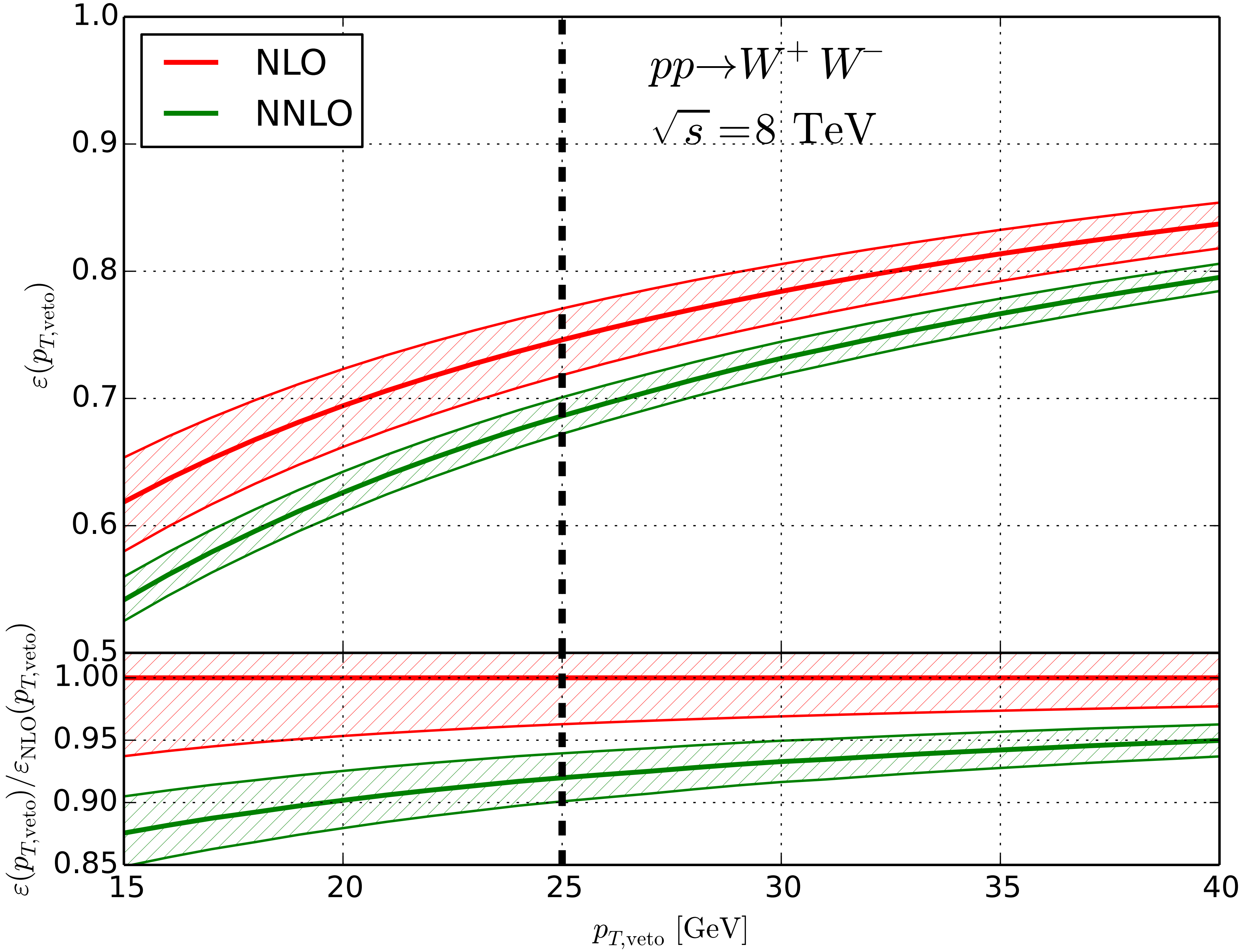
A preliminary estimate of scale uncertainties is obtained by varying factorisation (μ_F), renormalisation (μ_R) and resummation (μ_Q) scales in the following way:

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

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

Jet veto efficiency: NNLO

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



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

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

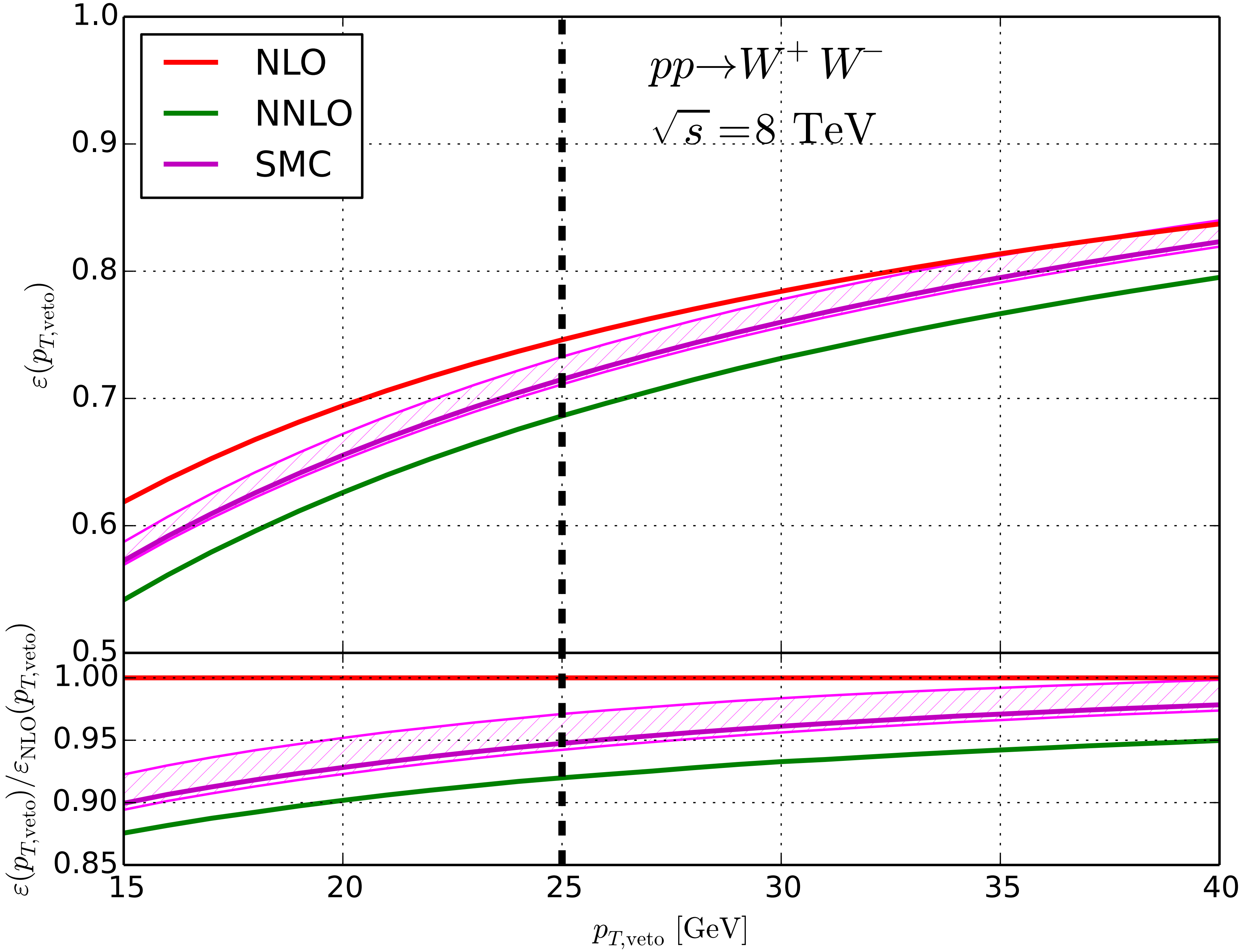
Suppression is driven by the suppression of QCD corrections in the jet vetoed cross section

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 (preliminary)



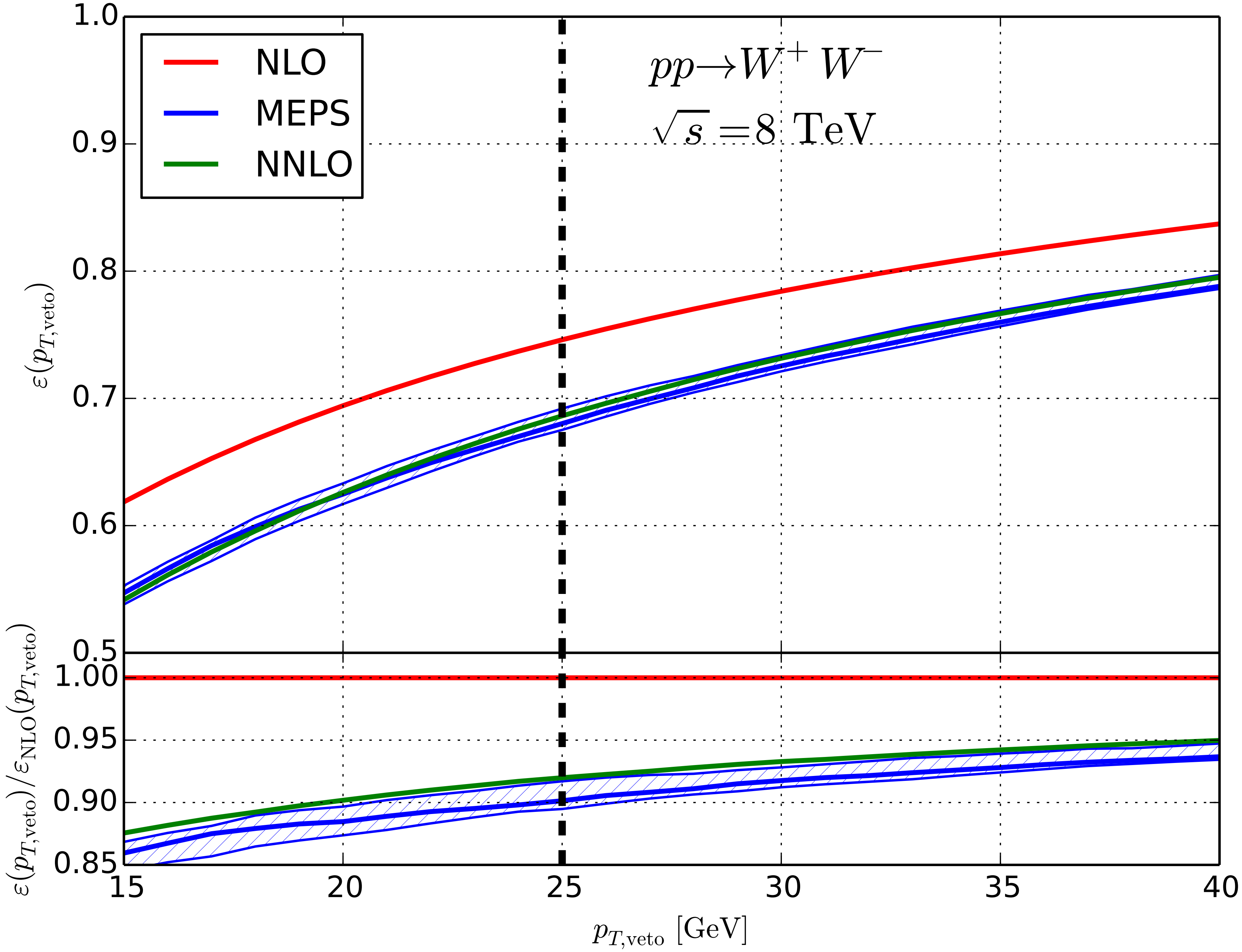
Only jet veto is applied here and gg channel is not included

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 (preliminary)



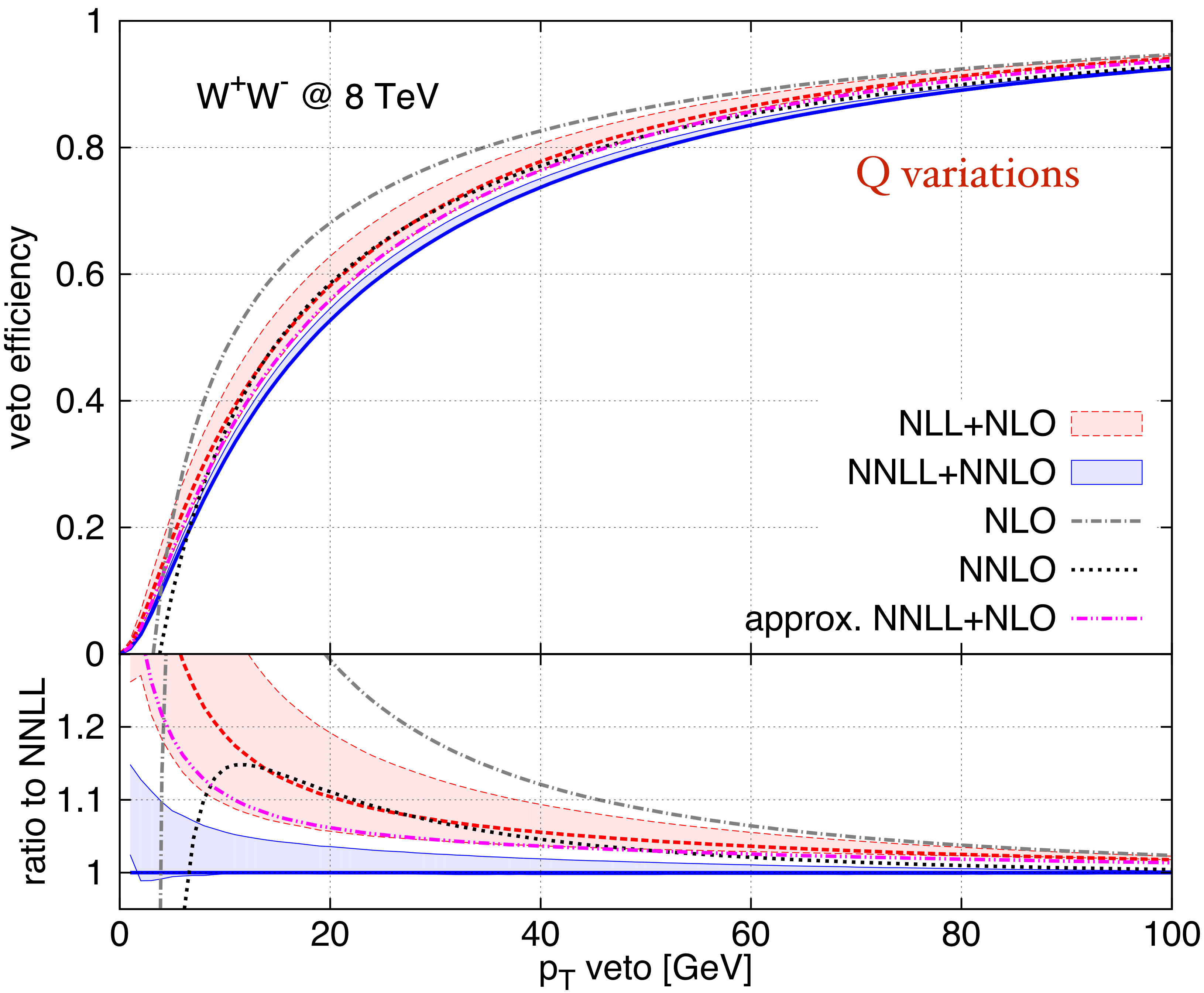
Only jet veto is applied here and gg channel is not included

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

NNLO and MEPS@NLO results consistent within uncertainties

NEW: p_T-veto efficiency

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



Use now p_T efficiency:

$$\epsilon(p_T^{\text{veto}}) = \sigma(p_T < p_T^{\text{veto}})/\sigma$$

In the recent CMS measurement the WW spectrum from POWHEG is reweighted to an approximate NNLL+NLO calculation

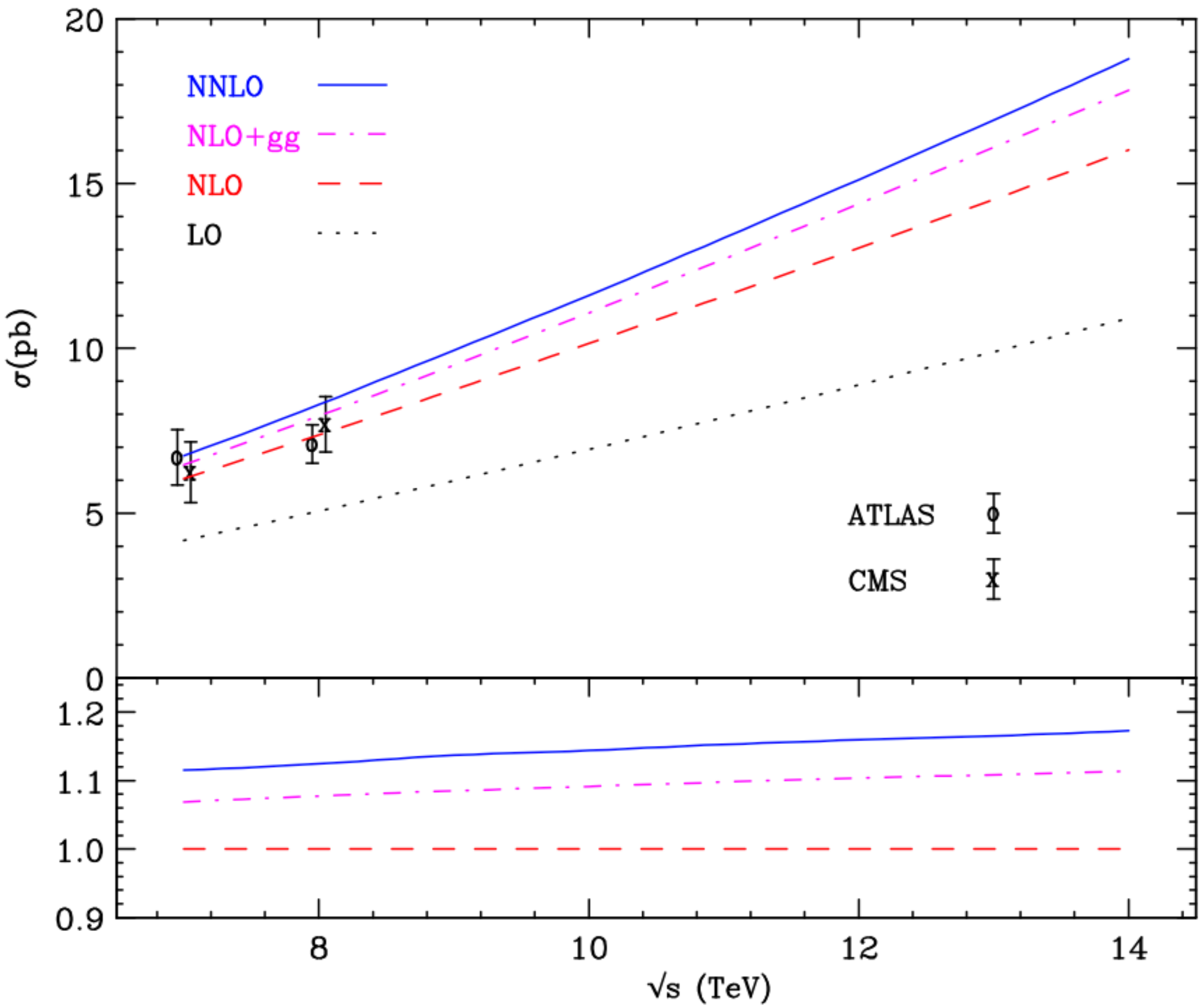
P.Meade, H.Ramani, M.Zeng (2014)

Full NNLL+NNLO calculation would lead to a decrease of the efficiency

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)

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)

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 $1/2\, m_Z < \mu_F, \mu_R < 2 m_Z$ and $1/2 < \mu_F/\mu_R < 2$

Scale uncertainties at NNLO remain at the ±3% level

NEW:

$pp \to ZZ+X$ at NNLO: lepton decays and off-shell effects

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

Consider $pp \to ZZ \to e^+e^- \mu^+\mu^-$ 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 $< m_{ll} <$ 116 GeV

σ(fb)	LO	NLO	NLO+gg	NNLO	ATLAS
2e2μ	$6.95^{+0.46}_{-0.61}$	$9.86^{+0.54}_{-0.35}$	$10.72^{+1.11}_{-0.76}$	$11.2^{+0.78}_{-0.60}$	11.1 ± 1.3

NNLO corrections further improve agreement with the data (but data have still large uncertainties)

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

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

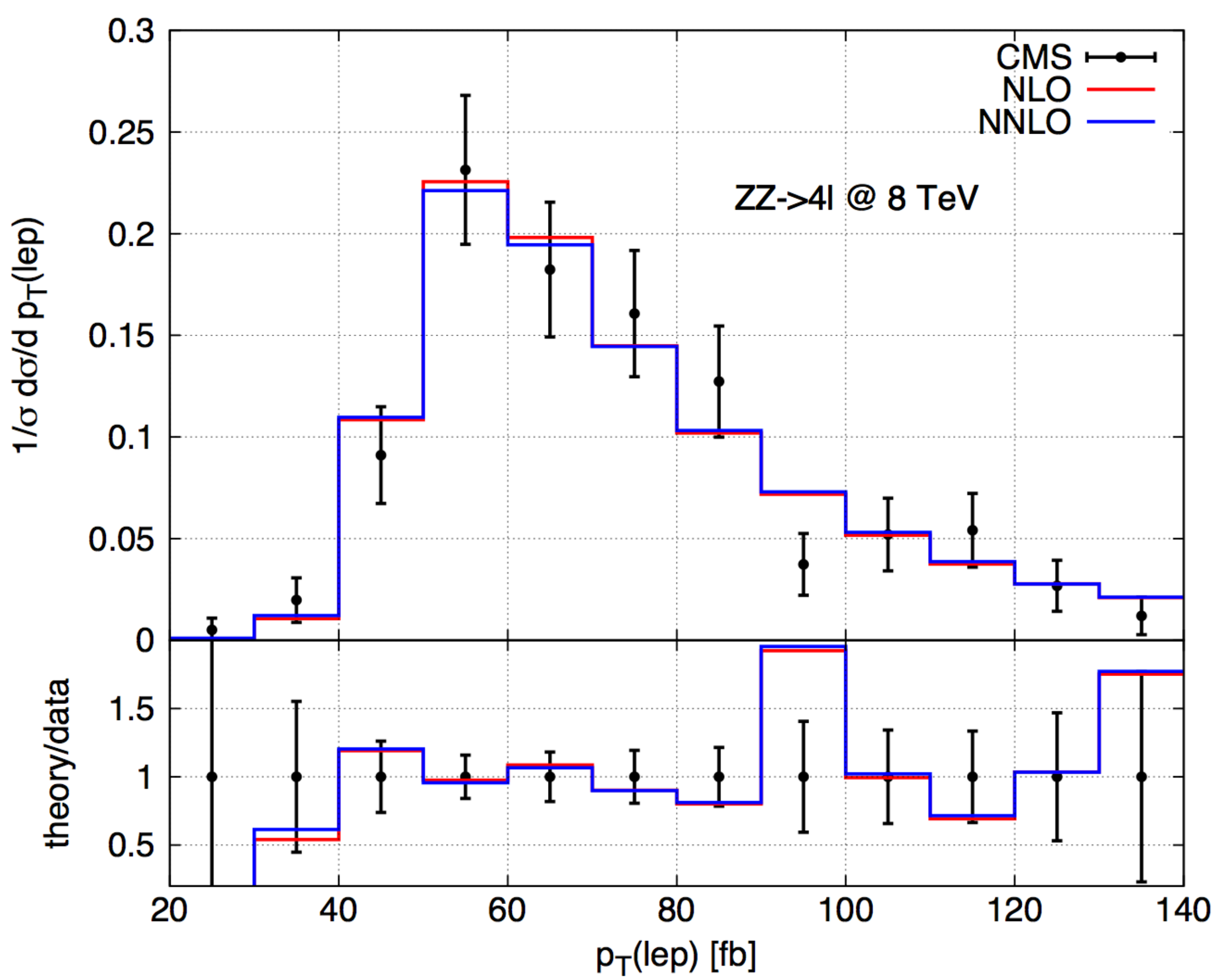
Consider $pp \to ZZ \to e^+e^- \mu^+\mu^-$ at 8 TeV

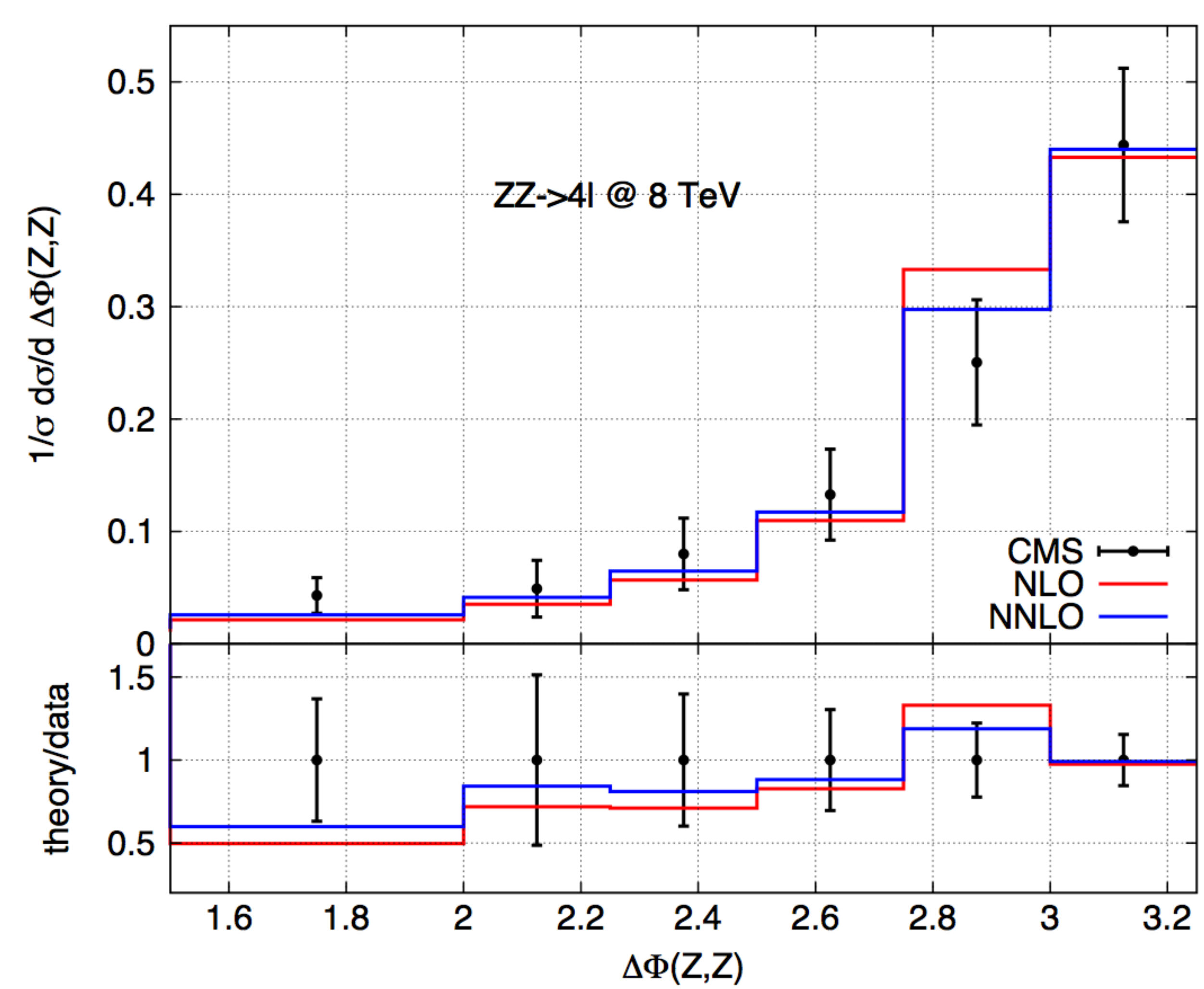
Use now CMS cuts

$p_{Te} > 7$ GeV $\quad |\eta_e| < 2.5$

$p_{T\mu} > 5$ GeV $\quad |\eta_\mu| < 2.4$

60 GeV $< m_{ll} <$ 120 GeV





Summary

- 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 now makes possible the exact fully exclusive NNLO calculations of ZZ, WW and WZ including leptonic decays and off-shell effects
- I have presented results for the inclusive ZZ and WW production

  - 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%
- For WW production I have presented preliminary results for the fiducial cross section in the $e^+\mu^- + e^-\mu^+$ channel and for the jet veto efficiency
- For ZZ production I have presented preliminary results for the fiducial cross section in the $ZZ \rightarrow e^+e^-\mu^+\mu^-$ channel and the distributions measured by CMS: small effect of NNLO corrections on the shapes

$\Rightarrow$ Ready to go off-shell and study Higgs backgrounds !

Backup

Beyond the inclusive cross section

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

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

Use cuts from ATLAS-CONF-2014-033

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

Jets: anti-kt with R=0.4

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

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

- $m_{ll} > 10$ GeV $\quad p_T^{miss} > 20$ GeV $\quad p_T^{rel} > 15$ GeV
- Jet veto: no jets with $p_T > 25$ GeV, $|\eta| < 4.5$ 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: $\mu_0/2 < \mu_F, \mu_R < 2\mu_0 \qquad 0.5 < \mu_F/\mu_R < 2$

Fiducial cross section

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

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