WW and ZZ production at NNLO

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ATLAS (N)NLO meeting, CERN, december 18 2014

*On leave of absence from INFN, Sezione di Firenze

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Outline

- Introduction
- pp→WW+X at NNLO
  - The q_T-subtraction method
  - the inclusive cross section
  - 4FNS vs 5FNS
  - **NEW:** the fully exclusive calculation
  - NNLO vs NLO merging and NLO matching
- Summary

Introduction

WW production is one of the most important diboson processes:

- Background to Higgs and new physics searches
- It allows detailed studies of the gauge structure of EW interactions

The cross section is larger than ZZ and WZ and the $ll\nu\nu$ final state cannot be fully reconstructed due to the presence of neutrinos

Delicate subtraction of top contamination and extrapolation procedure

The recent observation by ATLAS of an excess of events over the SM prediction has triggered intense discussions

- New physics effects ?
- Need for jet-veto/p_T resummation ?
- Mis-modelling of jet-veto efficiency ?

Curtin et al. (2014)
J.S.Kim et al. (2014)
H.Luo et al. (2014)....

P.Jaiswal, T.Okui (2014)
P.Meade et al. (2014)

P.Monni, G.Zanderighi (2014)

→ We want to bring the SM prediction to a new level of accuracy by computing the QCD corrections at NNLO

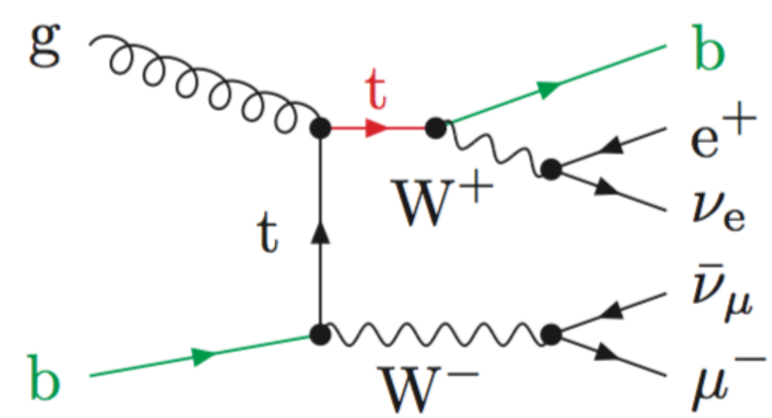
The WW cross section at NNLO

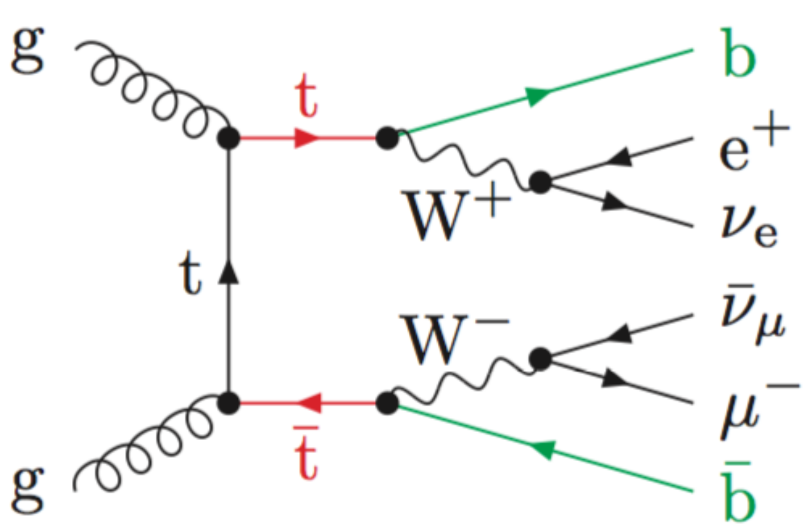
T. Gehrmann, S. Kallweit, P. Maierhofer, A. von Manteuffel,
S. Pozzorini, D. Rathlev, L. Tancredi, MG (2014)

The 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 $g \rightarrow b\bar{b}$ 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

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 integrals and allows a fast evaluation of tree-level and one-loop amplitudes within the SM

A.Denner, S.Dittmaier, L.Hofer (2014)

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 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

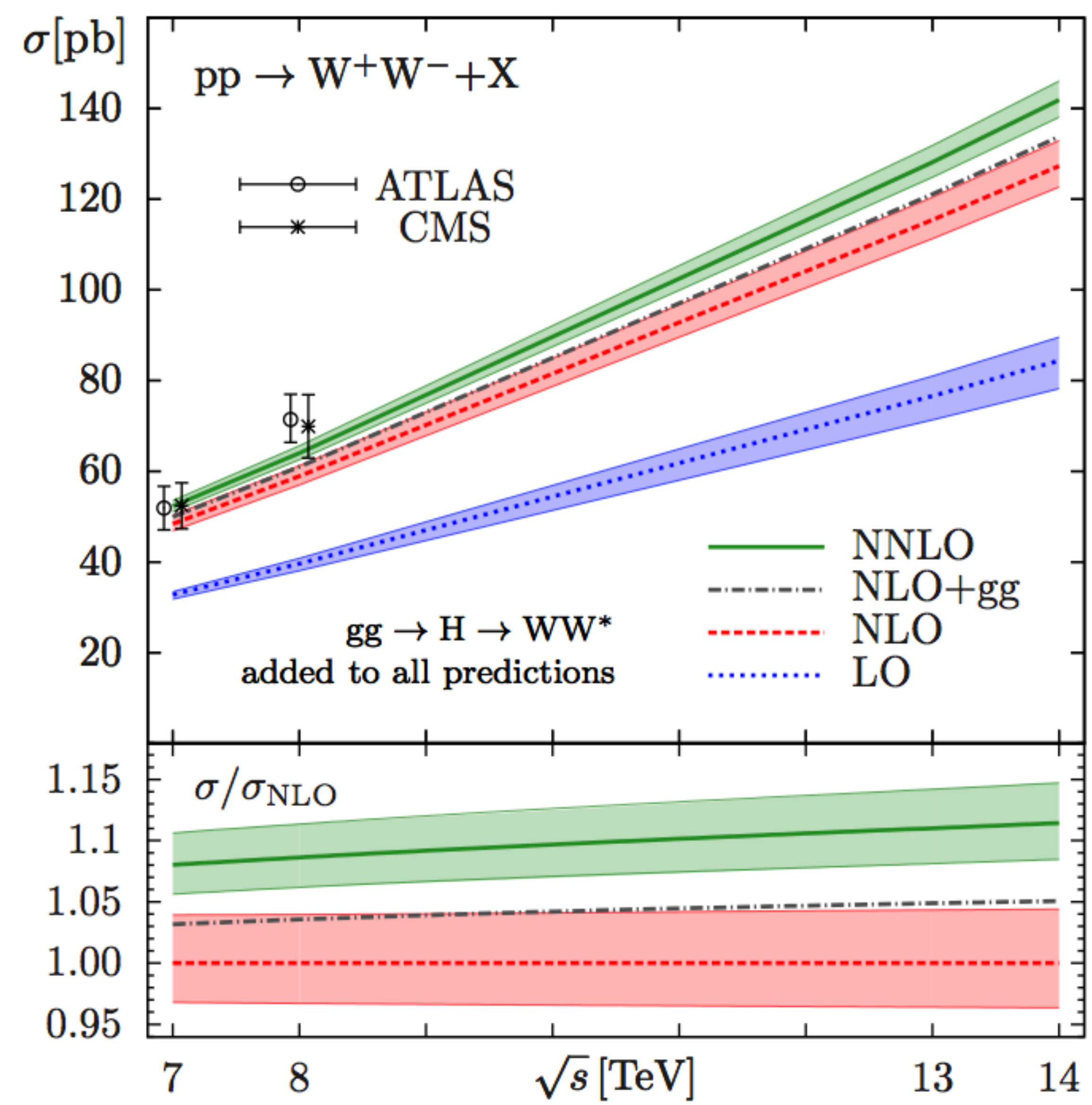
The WW cross section at NNLO

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

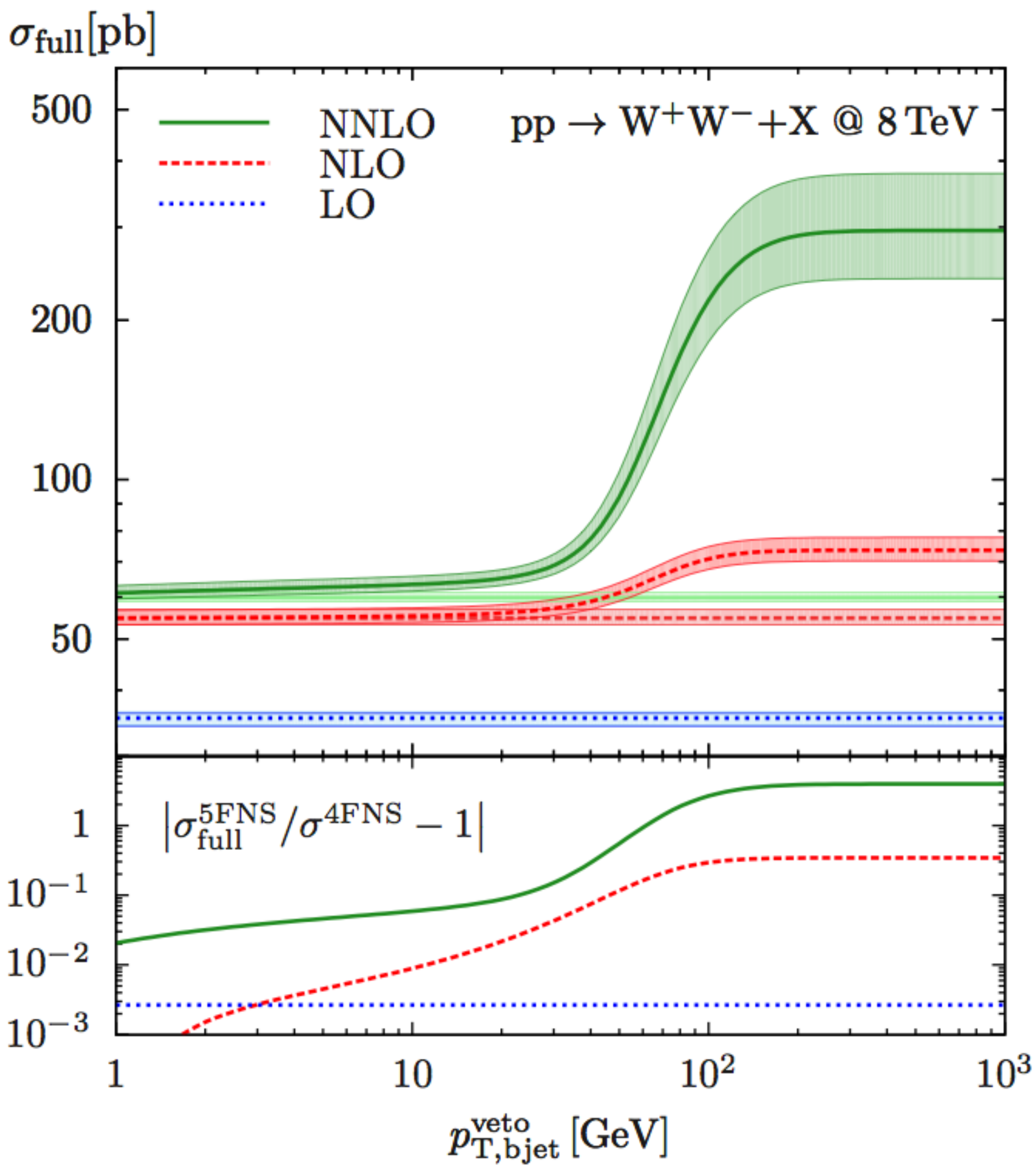
$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$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

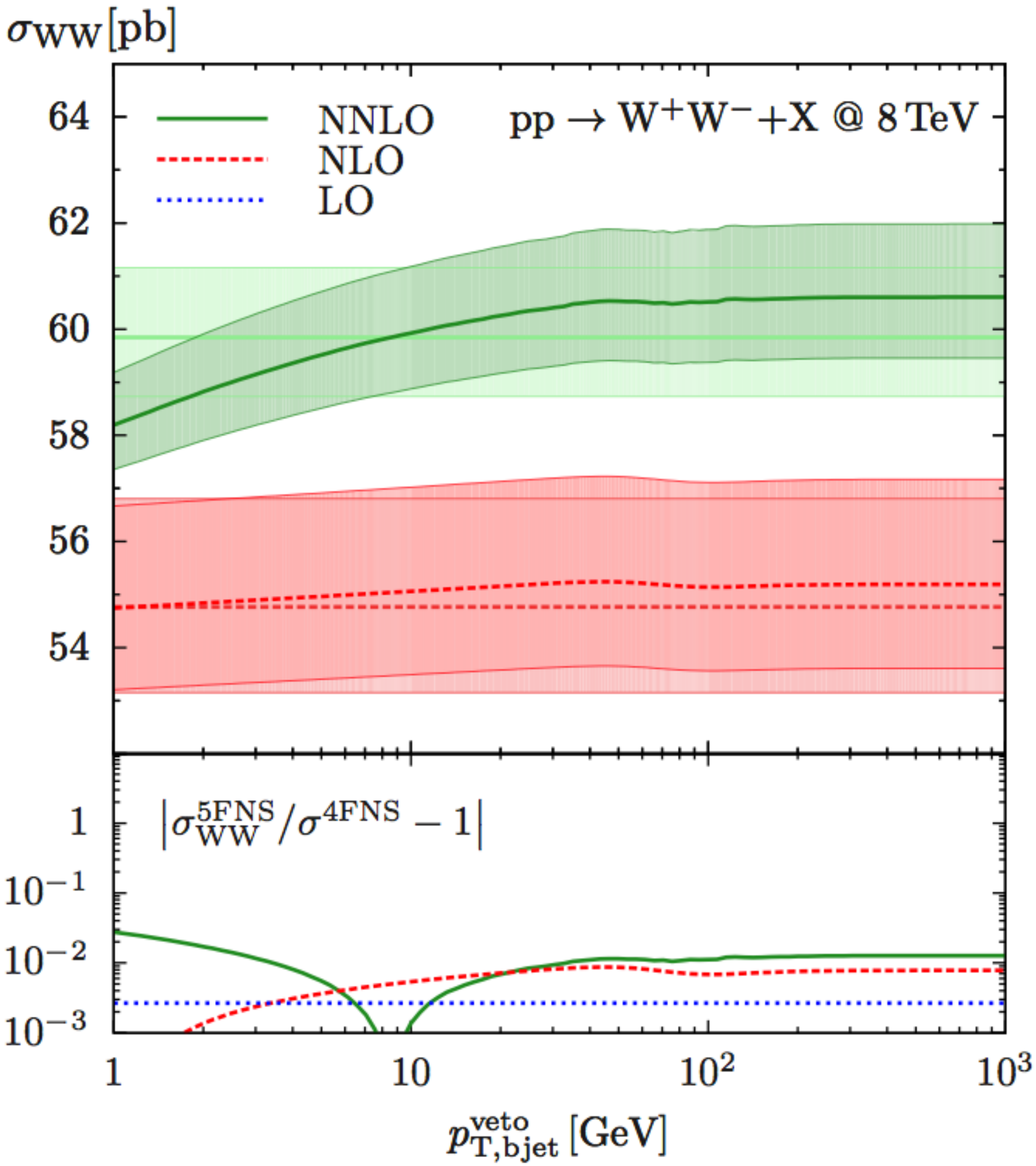
At large values of $p_{\rm T,bjet}^{\rm veto}$ the 5FNS result suffers from a huge contamination from top resonances

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

NEW: Beyond the inclusive cross section

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

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 !

The relative contribution of the finite part of the two-loop is suppressed by a factor O(10) with respect to the corresponding NLO contribution

→ **the calculation is essentially exact**

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 $\quad p_{T2} > 20$ 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

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

  $\Delta\phi$=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: $\mu_0/2 < \mu_F, \mu_R < 2\mu_0 \qquad 0.5 < \mu_F/\mu_R < 2$

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:

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

NLO merging (MEPS@NLO): the merging scale is taken to be Q_{cut} =20 ± 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

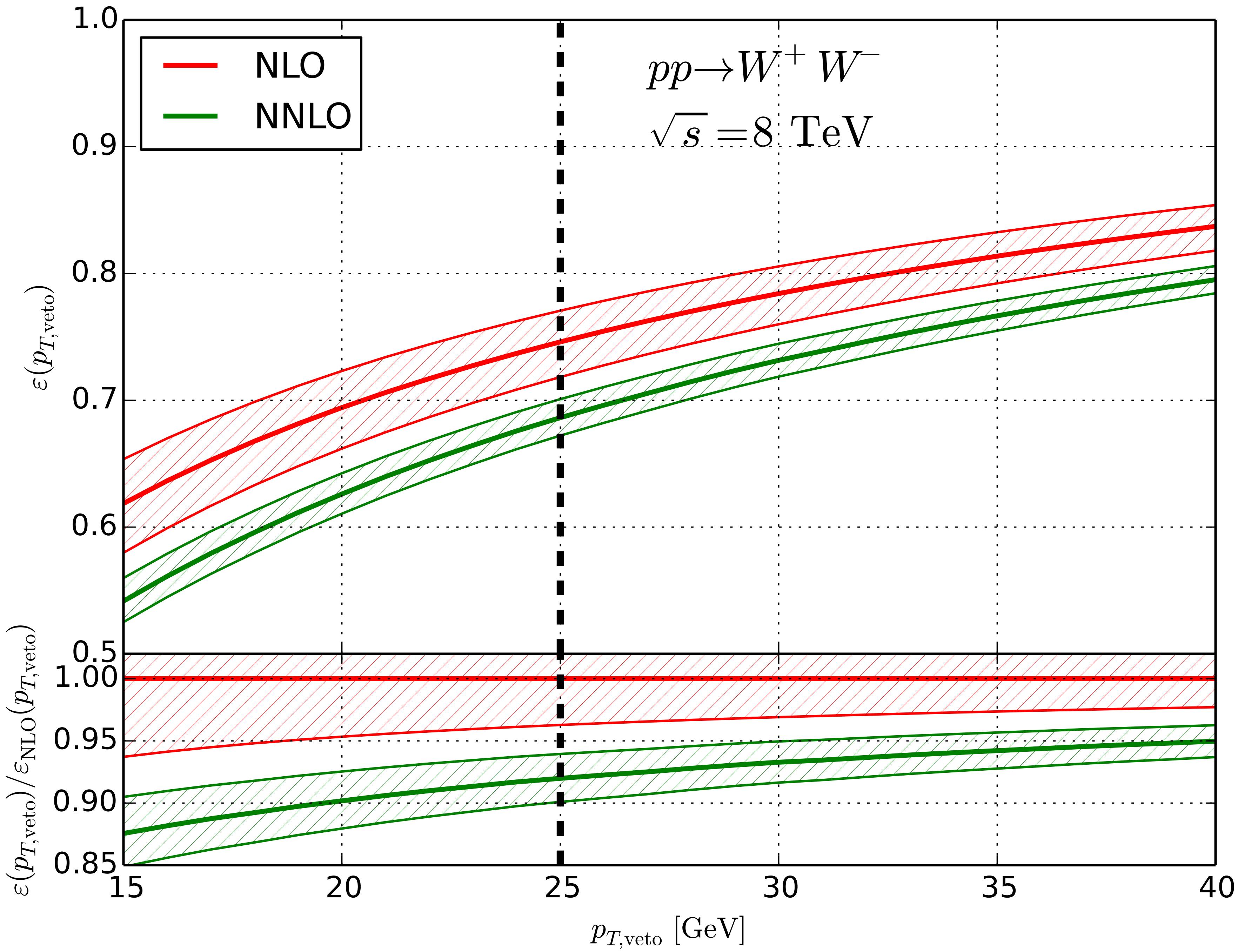
Total:	$340.5^{+2.0\%}_{-1.6\%}$	$328.6^{+4.2\%}_{-2.5\%}$	$330.6^{+6.7\%}_{-2.6\%}$

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 %

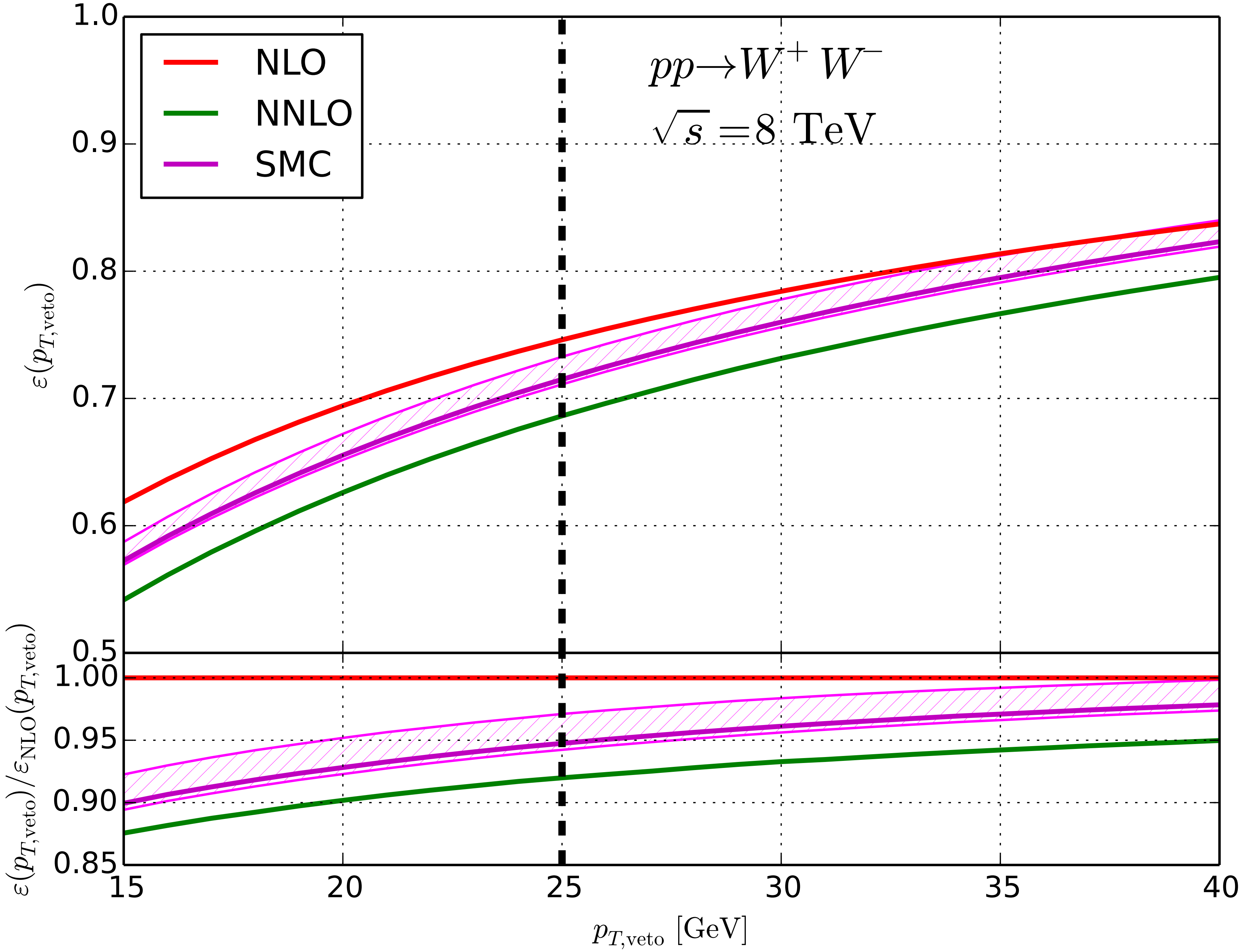
Suppression is driven by the suppression of QCD corrections in the jet vetoed cross section

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)



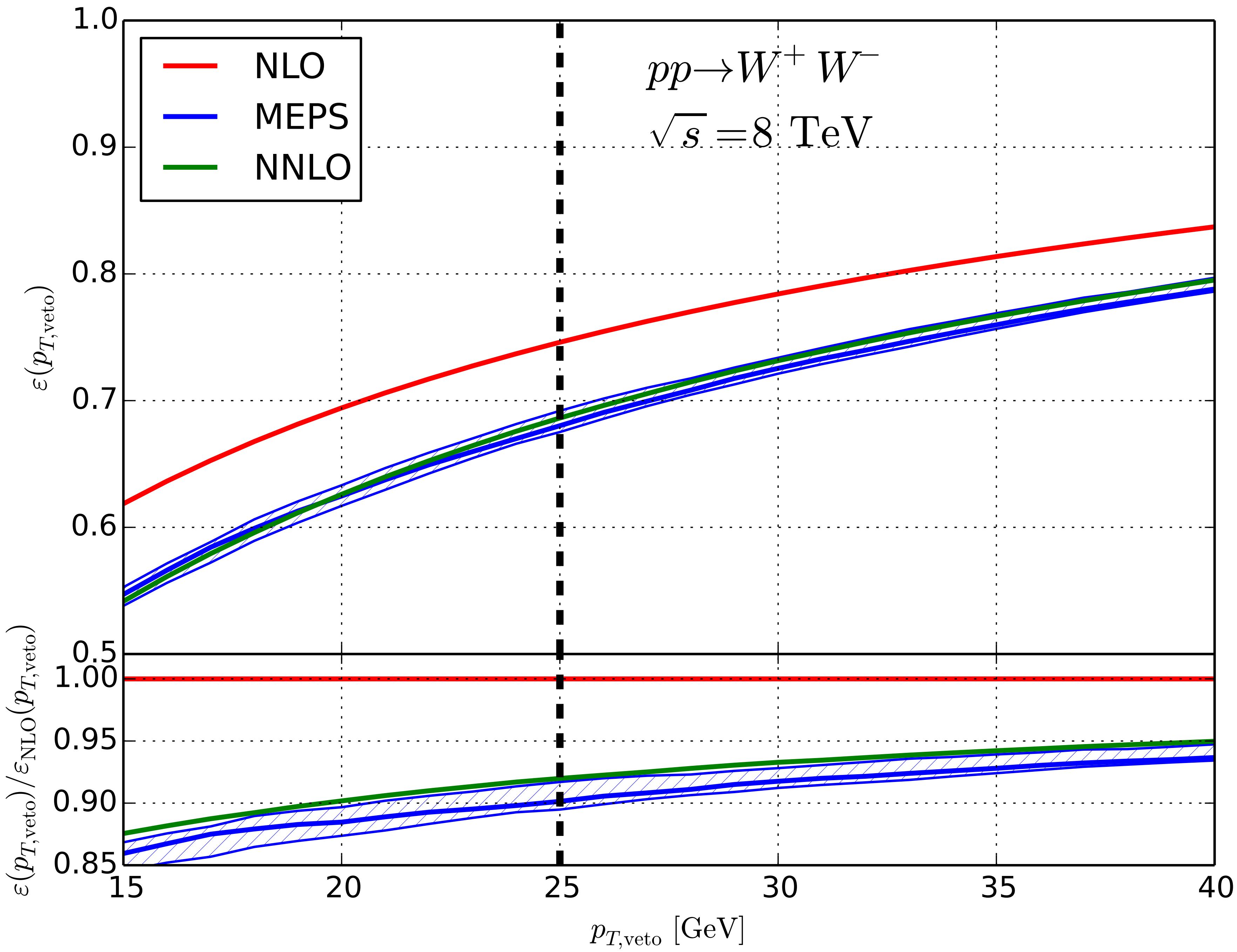
Only jet veto is applied here and gg channel is not included

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

- WW 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 the calculation of the inclusive cross section for on-shell WW pairs at the LHC: the NNLO effect ranges from 9 to 12 % when $\sqrt{s}$ varies from 7 to 14 TeV
- We have recently extended this calculation 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