Karlsruher Institut für Technologie

WW production at high transverse momenta beyond NLO

in collaboration with F. Campanario and S. Sapeta, Nucl.Phys. B879 (2014) 65-79 [arXiv:1309.7293]

Michael Rauch | Mar 27, 2014

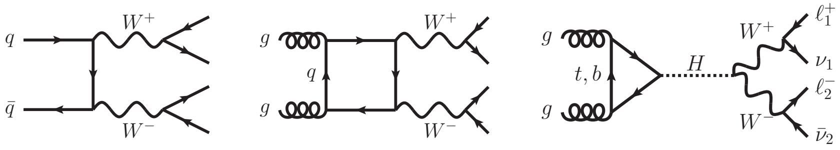
INSTITUTE FOR THEORETICAL PHYSICS

Motivation

WW pair production at the LHC

$$pp \to W^+W^- + X \to \ell_1^+ \nu_1 \ell_2^- \bar{\nu}_2 + X$$

- Neutrinos in the final state $\to$ invariant W mass cannot be reconstructed
- $\to$ background for many LHC measurements:
  Higgs searches/measurements,
  BSM physics (often contains light stable particle $\to$ missing energy)
- signal process in its own right: anomalous triple gauge couplings
- Experiment: exclusive cross section measurements
  from ATLAS (7 TeV run only) and CMS (7 TeV and 8 TeV, 5 fb^{-1})
  $\to$ reasonable agreement, $\sim 2\sigma$ excess observed



State of the Art

Available higher-order corrections:

- *WW*
  - NLO QCD: $\mathcal{O}(50\%)$ for inclusive cuts, phase-space dependent [Dixon, Kunszt, Signer; Campbell, Ellis, Williams]
  - soft-gluon resummation of threshold logarithms [Dawson, Lewis, Zeng]
  - NNLO QCD: work started [Gehrmann, Tancredi, Weihs; Chachamis]
  - NLO EW up to double-pole approximation [Bierweiler, Kasprzik, Kühn, Uccirati, Gieseke; Baglio, Ninh, Weber; Billoni, Dittmaier, Jäger, Speckner]
  - gluon-initiated contributions: [Ametller, Gava, Paver, Treleani; Dicus, Kao, Repko; Glover, van der Bij; Binoth, Ciccolini, Kauer, Krämer; Bonvini, Caola, Forte, Melnikov, Ridolfi]
    formally NNLO, numerically enhanced due to large gluon PDFs:
    3-5% inclusive, 10% in Higgs analyses
- *WWj*
  - NLO QCD plus gluon-initiated contributions [Dittmaier, Kallweit, Uwer; Melia, Melnikov, Rontsch, Schulze, Zanderighi]
    $\mathcal{O}(40\%)$ for inclusive cuts, phase-space dependent
- *WWjj*
  - NLO QCD: $\mathcal{O}(10\%)$, greatly reduced scale dependence [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]

Large QCD corrections for *WW* and *WWj*
$\rightarrow$ assess size of NNLO QCD corrections $\leftrightarrow$ lack of explicit calculation
$\rightarrow$ combine *WW* and *WWj* consistently with simulated 2-loop contributions

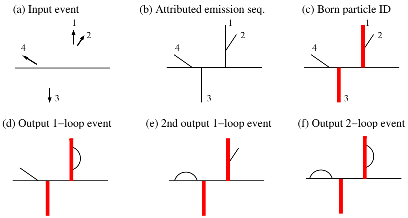
(see also [Cascioli, Hoeche, Krauss, Maierhöfer, Pozzorini, Siegert]
for similar approach with different physics focus)

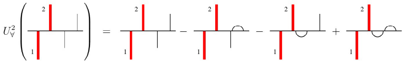
LoopSim

LoopSim approach

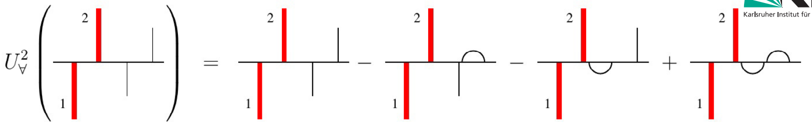
[Rubin, Salam, Sapeta]

- based on unitarity
- assign angular-ordered branching structure to each event (C/A algorithm with radius R_{LS}) until number of particles identical to Born number
- hard structure of event determined $\rightarrow$ remaining particles marked as “Born”
- construct virtual “loop” events: recombine particles j not marked as “Born”:
  - clustered with particle i: spread j momentum over i and all particles emitted after j
  - clustered with beam: remove j and apply transverse boost
  - no secondary emitters looped (particles which emit another particle) $\leftrightarrow$ no divergence for emission from internal line





LoopSim (cont.)



- weight for each loop diagram: $(-1)^{\text{number of loops}}$
- double counting from exact 1-loop diagrams removed
- fully inclusive: cross section unmodified
- also electro-weak particles looped $\rightarrow$ removed by final-state requirements
- cuts applied to each (simulated) part separately $\rightarrow$ integrated cross sections differ

$\Rightarrow$ Exact tree-level and one-loop parts, singular part of two-loop diagrams
$\leftrightarrow$ constant term of two-loop diagrams missing

Cross-checks:

- $\bar{n}$LO vs. NLO calculation
- Drell-Yan: $\bar{n}NLO$ vs. NNLO calculation

$\rightarrow$ good agreement

Generation of $WW + X$ events: VBFNLO
(NLO QCD WW, NLO QCD WWj, LO GF-WW) [Zeppenfeld, MR *et al.*]

Numerical Results

Integrated cross sections for LHC 8 TeV

$\mu_{F,R} = \mu_0 = \frac{1}{2}\left(\sum p_{T,\text{partons}} + \sqrt{p^2_{T,W^+} + m^2_{W^+}} + \sqrt{p^2_{T,W^-} + m^2_{W^-}}\right)$, $R_{LS} = 1$

MSTW NNLO 2008 PDF for all cross sections used

	c.s. [fb] without jet veto	c.s. [fb] with jet veto
σ_{LO}	$247.49\ ^{+5.40}_{-7.60}$	$247.49\ ^{+5.40}_{-7.60}$
$\sigma_{\text{box+Higgs}}$	$19.02\ ^{-3.70}_{+4.86}$	$19.02\ ^{-3.70}_{+4.86}$
$\sigma_{\text{pure-NLO}}$	$334.64\ ^{-6.36}_{+6.49}$	$253.05\ ^{+2.98}_{-4.75}$
$\sigma_{\text{pure-}\bar{n}\text{NLO}}$	$345.17\ ^{-7.06}_{+7.03}\ (\mu)\ ^{+5.24}_{-3.33}\ (R_{\text{LS}})$	$236.63\ ^{-1.16}_{+1.45}\ (\mu)\ ^{+5.31}_{-3.27}\ (R_{\text{LS}})$
σ_{NLO}	$353.67\ ^{-10.06}_{+11.35}$	$272.07\ ^{-8.45}_{+7.84}$
$\sigma_{\bar{n}\text{NLO}}$	$364.19\ ^{-10.76}_{+11.89}\ (\mu)\ ^{+5.24}_{-3.33}\ (R_{\text{LS}})$	$255.72\ ^{-4.86}_{+6.31}\ (\mu)\ ^{+5.31}_{-3.27}\ (R_{\text{LS}})$

- scale variation between $2\mu_0$ (upper value) and $\mu_0/2$ (lower value)
- R_{LS} variation between 1.5 (upper) and 0.5 (lower)
- σ_{NLO}, $\sigma_{\bar{n}\text{NLO}}$ contains gluon-fusion (box+Higgs) part (errors added linearly)
- $\rightarrow$ Large negative corrections for vetoed results (Sudakov logarithms)
- $\leftrightarrow$ Missing finite part of 2-loop virtuals

Cuts:
(follows CMS analysis)

- $p_{T,\ell} > 20$ GeV
- $|\eta_\ell| < 2.5$
- different-flavour: $E^{\text{projected}}_{T,\text{miss}} > 20$ GeV
- same-flavour: $E^{\text{projected}}_{T,\text{miss}} > 45$ GeV
  $m_{\ell\ell} > 12$ GeV
  $|m_{\ell\ell} - m_Z| > 15$ GeV
  $p_{T,\ell\ell} > 45$ GeV
  $\Delta\phi(\ell\ell, j_1) < 165^\circ$

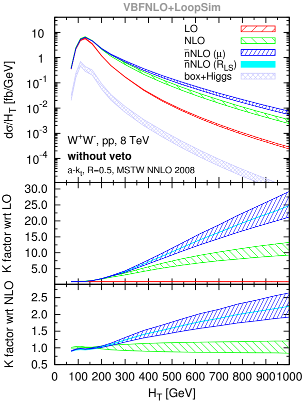
Jet veto: no jets with

- $p_{T,\text{jet}} > 30$ GeV
- $|\eta_{\text{jet}}| < 4.7$

Distributions

Effective mass observable H_T (commonly used in new-physics searches)

$$H_T = \sum p_{T,\text{jets}} + \sum p_{T,\ell} + E_{T,\text{miss}}$$



- very sensitive to additional radiation from further partons and soft or collinear emission of the W bosons
- $\rightarrow$ giant K factors for large H_T
- $\rightarrow$ well described by LoopSim method
- $\leftrightarrow$ small dependence on R_{LS} parameter
- cross-check:
  comparison of $\bar{n}$LO and NLO results
  $\rightarrow$ very close for $H_T \gtrsim 200$ GeV

Distributions

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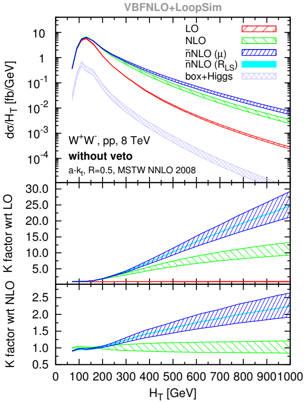
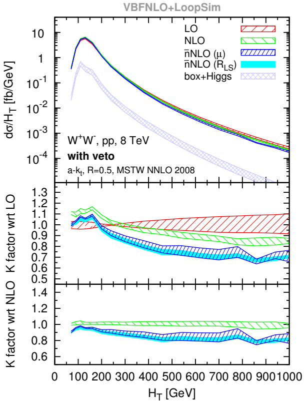
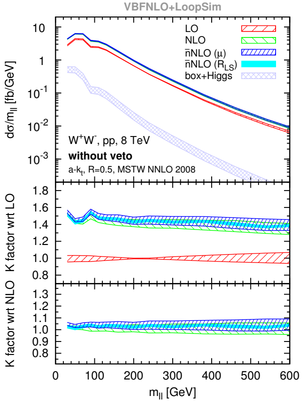


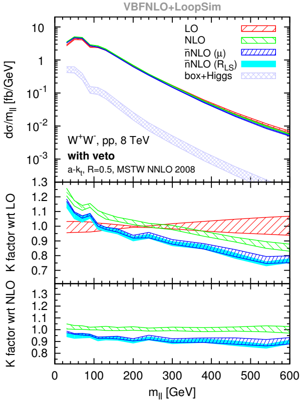


- large negative corrections when applying jet veto (Sudakov logs) $\mathcal{O}(-15\%)$ for NLO compared to LO, $\mathcal{O}(-20\%)$ for $\bar{n}$NLO compared to NLO
- $\leftrightarrow$ finite two-loop contributions missing
- $\leftrightarrow$ same effect in WH@NNLO: $\mathcal{O}(-15\%)$ for NNLO/NLO [Ferrera, Grazzini, Tramontano]

Distributions (cont.)

Invariant mass of the lepton pair $m_{\ell\ell}$





- shape unchanged by $\bar{n}$NLO effects, normalization differs for vetoed case
- large $m_{\ell\ell} \leftrightarrow$ back-to-back leptons dominate
  $\rightarrow$ not particularly sensitive to new topologies opening up

Conclusions

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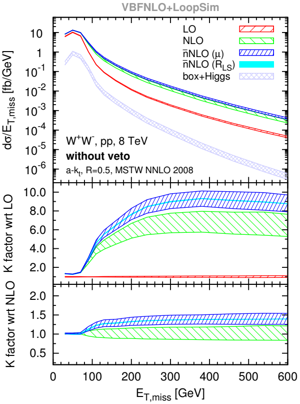
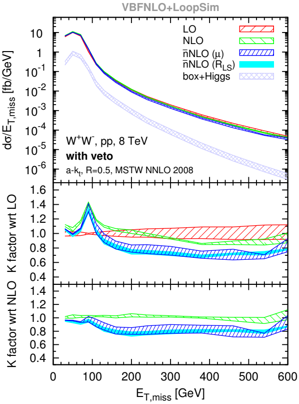
- Calculation of *WW* including leptonic decays at $\bar{n}$NLO
  using LoopSim approach
  combining NLO QCD *WW*, NLO QCD *WWj* and LO GF-*WW*
- large additional corrections beyond NLO outside scale variation bands
  for observables sensitive to QCD radiation (like H_T or $E_{T,\text{miss}}$)

  $m_{\ell\ell}$ or m_{WW} distribution on the other hand hardly affected
- jet veto like in exp. setup leads to large negative corrections
  $\rightarrow$ large Sudakov logarithms
  $\leftrightarrow$ finite 2-loop virtual term

Distributions (cont.)

Missing transverse energy $E_{T,\text{miss}}$





- large K factors for unvetoed results
- negative $\mathcal{O}(-20\%)$ correction for vetoed results
- outside scale variation bands