Anomalous couplings in WZ production beyond NLO QCD

Robin Roth | 14.06.2016
in collaboration with Francisco Campanario, Sebastian Sapeta, Dieter Zeppenfeld

LHCP 2016, LUND
Introduction

Goal
- test the Standard Model (SM) at the LHC with the highest possible precision
- look for deviations from the SM in a model independent way

Methods
- more precise SM prediction, reduced theory error ⇒ \( \bar{n}\)NLO
- parametrize beyond-SM effects ⇒ Anomalous Couplings (AC) / EFT
- improve analyses ⇒ better cuts and observables, dynamical jet veto

Tools
- VBFNLO: diboson production at NLO QCD with AC
- LoopSim: \( \bar{n}\)NLO based on VBFNLO input
Diboson production at the LHC

Why Diboson
- leptonic decays: “easy” to tag, precise knowledge of final state
- access to triple gauge couplings, deviations in EW sector

Observables
- new resonances
- enhanced production at high energy ⇒ AC
- $m_T$, $p_{TV}$, $p_{TI}$
- decay angles, spin information

Motivation: Diboson production at LHC
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD
Current state of diboson production at the LHC

Motivation: Diboson production at LHC
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD

Dec. 2015

CMS measurements vs. NLO (NNLO) theory

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS Preliminary</th>
<th>7 TeV CMS measurement (stat,stat+sys)</th>
<th>8 TeV CMS measurement (stat,stat+sys)</th>
<th>13 TeV CMS measurement (stat,stat+sys)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$, (NNLO th.)</td>
<td>$1.06 \pm 0.01 \pm 0.12$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>$1.16 \pm 0.03 \pm 0.13$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
<td>$19.5 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW+WZ$</td>
<td>$1.05 \pm 0.13 \pm 0.15$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td>$1.11 \pm 0.04 \pm 0.10$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW$, (NNLO th.)</td>
<td>$1.01 \pm 0.02 \pm 0.08$</td>
<td>$19.4 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.17 \pm 0.07 \pm 0.07$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.12 \pm 0.03 \pm 0.07$</td>
<td>$19.6 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WZ$</td>
<td>$0.86 \pm 0.11 \pm 0.17$</td>
<td>$1.34 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.99 \pm 0.14 \pm 0.07$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$1.00 \pm 0.06 \pm 0.08$</td>
<td>$19.6 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$1.00 \pm 0.16 \pm 0.06$</td>
<td>$1.34 \text{ fb}^{-1}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All results at:
http://cern.ch/go/pNj7

Production Cross Section Ratio: $\frac{\sigma_{\text{exp}}}{\sigma_{\text{theo}}}$
Anomalous Couplings

### SM as Effective Field Theory
- only use SM fields and preserve symmetries
- add higher-dimensional terms to Lagrangian $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$
- contributions to WWZ vertex at dim 6 from 3 operators:
  \[ \mathcal{O}_W = (D_\mu \Phi) \dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \quad \mathcal{O}_{WWW} = \text{Tr} \left[ \hat{W}^{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\mu}_\rho \right], \]
  \[ \mathcal{O}_B = (D_\mu \Phi) \dagger \hat{B}^{\mu\nu} (D_\nu \Phi) \]

### Relation to $\kappa$ Framework
- To first order: $\Delta \kappa_\gamma = \frac{M_W^2}{2\Lambda^2} (f_B + f_W)$, $\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2} f_W$, \ldots
- EFT inherently gauge invariant, works consistently beyond LO

### Limited Validity of EFT
- low-energy expansion of unknown higher-energy model
- only valid if expansion parameter small
  validity depends on phase space region/kinematics
Anomalous Couplings

Example operator: \[ \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \quad \mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \ldots \]

WWH vertex: \[ igm_W g^{\mu\nu} \left( \frac{1}{2} \frac{f_W}{\Lambda^2} g_{\mu\nu} \right) \left( -g^{\mu\nu} (p_h \cdot p_- + p_h \cdot p_+) + p_h^\nu p_-^\mu + p_h^\mu p_-^\nu \right) \]

WH production
\( \Lambda = 1 \text{ TeV} \)
Anomalous Couplings

Example operator: \( \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \quad \mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \ldots \)

WWH vertex: \( igm_W g^{\mu\nu}_{SM} \left[ -\frac{1}{2} \frac{f_W}{\Lambda^2} g_{\mathcal{O}_W} \left( -g^{\mu\nu} (p_+ p^- + p_- p_+) + p_+^\nu p_-^\mu + p_-^\nu p_+^\mu \right) \right] \)

WH production
\( \Lambda = 1 \text{ TeV} \)
**LoopSim**

**Idea**
- “Giant QCD K-factors beyond NLO” [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states $X@NLO + Xj@NLO = X@\bar{nNLO}$
- parton level
- use NLO events, interface to existing Monte Carlos programs

**Properties**
- misses finite 2-loop contributions
- include dominant contributions from extra emissions, $O(\alpha_s \ln^2 p_{T,jet}/m_Z)$
- preserve NLO total cross section
- nearly NNLO in high-$p_T$ tails
**Idea**

- "Giant QCD K-factors beyond NLO" [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states
  \[ X@NLO + Xj@NLO = X@\bar{n}NLO \]
- parton level
- use NLO events, interface to existing Monte Carlos programs

**Properties**

- misses finite 2-loop contributions
- include dominant contributions from extra emissions, \( O(\alpha_s \ln^2 p_{T\text{jet}}/m_Z) \)
- preserve NLO total cross section
- nearly NNLO in high-\( p_T \) tails
LoopSim

Idea

- “Giant QCD K-factors beyond NLO” [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states
  \[ X@NLO + \bar{X}j@NLO = X@\bar{nNLO} \]
- parton level
- use NLO events, interface to existing Monte Carlos programs

Properties

- misses finite 2-loop contributions
- include dominant contributions from extra emissions, \( \mathcal{O}(\alpha_s \ln^2 p_T/m_Z) \)
- preserve NLO total cross section
- nearly NNLO in high-\( p_T \) tails

\[
\begin{array}{cccccc}
  & & & 2 & & \\
  & & \sigma_0^{(2)} & \sigma_1^{(2)} & \cdots & \\
0 & \sigma_0^{(1)} & \sigma_1^{(1)} & \sigma_2^{(1)} & \cdots & \\
1 & \sigma_0^{(0)} & \sigma_1^{(0)} & \sigma_2^{(0)} & \sigma_3^{(0)} & \cdots & \\
2 & & & & & \\

k (legs)
\end{array}
\]
**Idea**
- “Giant QCD K-factors beyond NLO” [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states $X_{\text{NLO}} + X_{j\text{NLO}} = X_{\tilde{n}\text{NLO}}$
- parton level
- use NLO events, interface to existing Monte Carlos programs

**Properties**
- misses finite 2-loop contributions
- include dominant contributions from extra emissions, $O(\alpha_s \ln^2 p_{T\text{jet}}/m_Z)$
- preserve NLO total cross section
- nearly NNLO in high-$p_T$ tails
LoopSim

**Idea**
- “Giant QCD K-factors beyond NLO” [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states
  \[ X@NLO + Xj@NLO = X@\bar{n}NLO \]
- parton level
- use NLO events, interface to existing Monte Carlos programs

**Properties**
- misses finite 2-loop contributions
- include dominant contributions from extra emissions,
  \[ O(\alpha_s \ln^2 p_{Tjet}/m_Z) \]
- preserve NLO total cross section
- nearly NNLO in high-\(p_T\) tails

\[ \sigma_0^{(0)} \quad \sigma_1^{(0)} \quad \sigma_2^{(0)} \quad \sigma_3^{(0)} \quad \ldots \]

\[ \sigma_0^{(1)} \quad \sigma_1^{(1)} \quad \sigma_2^{(1)} \quad \ldots \]

\[ \sigma_0^{(2)} \quad \sigma_1^{(2)} \quad \ldots \]

\[ l \ (\text{loops}) \]

\[ k \ (\text{legs}) \]

Beyond NLO: LoopSim
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD
LoopSim

Idea

- “Giant QCD K-factors beyond NLO” [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states
  \[ X@NLO + Xj@NLO = X@\bar{nNLO} \]
- parton level
- use NLO events, interface to existing Monte Carlos programs

Properties

- misses finite 2-loop contributions
- include dominant contributions from extra emissions, \( O(\alpha_s \ln^2 p_{T_{jet}}/m_Z) \)
- preserve NLO total cross section
- nearly NNLO in high-\( p_T \) tails

\[ X+\text{jet@NLO} \]
Idea

- “Giant QCD K-factors beyond NLO” [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states
  \( X@NLO + Xj@NLO = X@\bar{n}NLO \)
- parton level
- use NLO events, interface to existing Monte Carlos programs

Properties

- misses finite 2-loop contributions
- include dominant contributions from extra emissions,
  \( \mathcal{O}(\alpha_s \ln^2 p_{T\text{jet}}/m_Z) \)
- preserve NLO total cross section
- nearly NNLO in high-\( p_T \) tails
nNLO for WZ production

LHC, 13 TeV, inclusive cuts

WZ production with a dynamical jet veto
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD
AC for diboson production

\[
\frac{d\sigma}{dp_{T_{l,max}}} / \text{fb/GeV}
\]

\[
\mu = 2^{\pm 1}\mu_0 \text{ (NLO)}
\]

\[
\text{FW = -5}
\]

\[
\text{FW = -3}
\]

\[
\text{FW = +10}
\]

\[
\text{SM (NLO)}
\]

WZ production with a dynamical jet veto
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD

14.06.2016 9/13
AC for diboson production

WZ production with a dynamical jet veto

Robin Roth – Anomalous couplings in WZ production beyond NLO QCD

14.06.2016 9/13
AC for diboson production

\[ \frac{d\sigma}{d\rho_{T_{l,max}}}/\text{fb/GeV} \]

\[ \mu = 2^{1+1} \mu_0 \text{ (NLO)} \]
\[ \mu = 2^{1+1} \mu_0 \text{ (nNLO)} \]
\[ R_{LS} = \{0.5, 1.5\} \]
\[ \text{FW} = +10 \]
\[ \text{FW} = -5 \]
\[ \text{FW} = -3 \]

SM (NLO)
SM (nNLO)

WZ production with a dynamical jet veto
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD
Jet vetos

want $VV + \text{jets}$, not $Vj + V$

Traditional (fixed) jet veto
- don’t allow any jets above a fixed $p_T$ threshold
- introduces large logs $\log p_T^{\text{veto}}/m_{VV}$
- cuts away relevant phase space:
  $m_{VV} \approx 1 \text{ TeV} \leftrightarrow p_T^{\text{jet}} = 50/300 \text{ GeV}$

Dynamical veto
- veto scaled depending on overall scale $\Rightarrow$ smaller logs
- allow more QCD radiation in tails of EW distributions

$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$$

[Campanario, RR, Zeppenfeld, 1410.4840]
Observable \( x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}} \)

\( \rho_{\text{TZ}} > 200 \text{ GeV} \)
Dynamical veto to improve AC sensitivity

$\frac{d\sigma}{dp_{T_{l,max}}}/fb/GeV$

$R_{LS} = \{0.5, 1.5\}$

$\mu = 2^{\pm 1}\mu_0$ (nNLO)

$\mu = 2^{\pm 1}\mu_0$ (NLO)

SM (NLO)

SM (nNLO)

FW = -5

FW = -3

FW = +10

WZ production with a dynamical jet veto
Dynamical veto to improve AC sensitivity

$\frac{d\sigma}{dpT_{l,\text{max}}}$ / fb/GeV

- $R_{LS} = \{0.5, 1.5\}$
- $\mu = 2^{\pm 1}\mu_0$ (nNLO)
- $\mu = 2^{\pm 1}\mu_0$ (NLO)
- SM (NLO)
- SM (nNLO)
- FW = -5
- FW = -3
- FW = +10

WZ production with a dynamical jet veto

Robin Roth – Anomalous couplings in WZ production beyond NLO QCD

14.06.2016 12/13
Conclusion

Beyond NLO: Loopsim
- method to combine multiplicities consistently at parton level
  \[ X@NLO + Xj@NLO = X@\bar{nNLO} \]
- captures log enhanced terms of real emission
- nearly NNLO in high-\(p_T\) region

Anomalous couplings
- diboson production interesting channel to study triple gauge couplings
- validity depends on coupling and phase space region
- increase sensitive \(\Rightarrow\) dynamical jet veto
  \[ x_{jet} = \frac{\sum_{jets} E_{T,i}}{\sum_{jets} E_{T,i} + E_{T,W} + E_{T,Z}} \]

VBFNLO: https://www.itp.kit.edu/vbfnlo [0811.4559, 1107.4038, 1404.3940]
VBFNLO


- Monte Carlo program for hadron collider cross sections at NLO QCD
- focus on processes with EW bosons: VBF, VV, VVV (+jets)
- includes leptonic decay of vector bosons with full off-shell effects
- anomalous triple/quartic gauge couplings
- efficient by reusing electroweak part of diagrams in terms of leptonic tensors
- BLHA interface to event generators: NLO event output
Validity of EFT approach

EFT assumptions
- all NP scales well above observables, no resonances at measurable scales
- $f/\Lambda^2$ “small”, depends on coupling: $\mathcal{O}(1)$ or $\mathcal{O}(\alpha_{\text{QED}})$

Power counting in $\Lambda$

\[
\mathcal{M} = \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{AC}}^{d=6} + \mathcal{M}_{\text{AC}}^{d=8} \\
|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \underbrace{2\text{Re}\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=6}}_{1/\Lambda^2} + \underbrace{|\mathcal{M}_{\text{AC}}^{d=6}|^2}_{1/\Lambda^4} + \underbrace{2\text{Re}\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=8}}_{1/\Lambda^4} + \underbrace{|\mathcal{M}_{\text{AC}}^{d=8}|^2}_{1/\Lambda^8}
\]

- power-counting $\Lambda^{-4}$: $|\mathcal{M}_{\text{AC}}^{d=6}|^2$, $\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=8}$?
- conservative: experimental fit only in range where $|\mathcal{M}_{\text{AC}}|^2 \ll \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{SM}}$
- but: $\mathcal{M}_{\text{SM}}$ accidentally small (phase space, weak coupling compared to $\mathcal{M}_{\text{AC}}$)
  \Rightarrow $\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}$ suppressed, $|\mathcal{M}_{\text{AC}}^{d=6}|^2$ leading $1/\Lambda^4$ term
ATLAS WZ $\rho_{TZ}$

ATLAS Preliminary

\( \sqrt{s} = 8 \text{ TeV}, \int L \, dt = 13 \, \text{fb}^{-1} \)
## Event Selection

### Cuts

<table>
<thead>
<tr>
<th>$p_T^j$</th>
<th>&gt; 30 GeV</th>
<th>$p_T^l$</th>
<th>&gt; 15 GeV</th>
<th>$p_T$</th>
<th>&gt; 30 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta_j</td>
<td>&lt; 4.5$</td>
<td>$</td>
<td>\eta_l</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$60 \text{ GeV} &lt; m_{ll} &lt; 120 \text{ GeV}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

_boosted: $p_{TZ} > 200 \text{ GeV}$

---

### Input values

- EW constants: VBFNLO default
- PDF: NNPDF23
Different $x_{\text{jet}}$ cuts

$\frac{d\sigma}{dp_{T_{\text{l,max}}}} / \text{fb/GeV}$

$\mu = 2^{\pm 1}\mu_0$ (NLO)

$\mu = 2^{\pm 1}\mu_0$ (nNLO)

$R_{LS} = \{0.5, 1.5\}$

FW = +10

FW = -5

FW = -3

SM (NLO)

SM (nNLO)

$50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300$

$p_{T_{\text{l,max}}}$ / GeV

$1.0 \quad 1.5 \quad 2.0$

$\sigma/\text{SM NLO}$

Backup
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD

14.06.2016 5/13
Different $x_{\text{jet}}$ cuts

- $\mu = 2^{\pm 1}\mu_0$ (NLO)
- $\mu = 2^{\pm 1}\mu_0$ (nNLO)
- $R_{\text{LS}} = \{0.5, 1.5\}$
- FW = +10
- FW = -5
- FW = -3
- SM (NLO)
- SM (nNLO)

$p_{T_{\text{max}}}$ / GeV, $x_{\text{jet}} < 0.4$
$x_{\text{jet}}$ $\bar{\text{nNLO}}$ corrections

![Graphs showing $x_{\text{jet}}$ $\bar{\text{nNLO}}$ corrections with various parameters and comparisons to SM (NLO) and SM (nNLO).]
Motivation

- 3 particle final state (WZj)
- the transverse momenta can be parametrized using only two variables
  6 d.o.f. \((p_{TW}, p_{TZ}, p_{Tjet})\) - 2 (total \(p_T = 0\)) - 1 (no \(\phi\) dependence) - 1 (rescaling at high \(p_T\))
- Dalitz-like construction

\[
\begin{align*}
  x_{jet} &= \frac{\sum_{jets} E_{T,i}}{\sum_{jets} E_{T,i} + E_{T,W} + E_{T,Z}}, \\
  x_V &= \frac{E_{TV}}{\sum_{jets} E_{T,i} + E_{T,W} + E_{T,Z}} \\
  x_{jet} + x_W + x_Z &= 1 \\
  x_i &\leq 0.5 \quad \text{(at LO only)}
\end{align*}
\]

other choices: \(p_T\) instead of \(E_T\), partons instead of jets, ... 
Careful not to be (too) infrared-sensitive
Observable: $x_{jet}, x_{Z}$

\[ \frac{d^2\sigma}{dx_{jet}dx_{Z}} / \text{fb} \]

Image of a graph showing the distribution of $x_{jet}$ and $x_{Z}$ with the corresponding density. The axes range from 0 to 0.6 for $x_{jet}$ and 0 to 0.6 for $x_{Z}$. The color scale ranges from 0 to 54 fb.
PS effects on $x_{\text{jet}}$

$$d^2\sigma/dx_{\text{jet}}^p T x_{H}^p T [\text{fb}]$$

Backup
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD
14.06.2016 9/13
PS effects on $x_{\text{jet}}$

$$\frac{d^2\sigma}{dx_{\text{jet}}^p x_{H}^p} \; [\text{fb}]$$

Backup
Robin Roth – Anomalous couplings in WZ production beyond NLO QCD
14.06.2016 9/13
The LoopSim Method – “Looping”

- cluster by distance to get emission sequence (C/A algorithm)
- captures soft/collinear divergences
- subtract divergences by generating looped diagrams with negative weight
- Catani-Seymour like generation of looped kinematics
- Clustering radius $R_{LS}$ gives estimate of dependence on merging
- Scale dependence preserved for additional emissions, overestimates the NNLO scale dependence
Previous LoopSim results

W^+W^-, pp, 8 TeV
without veto
a-\kappa_t, R=0.5, MSTW NNLO 2008

K factor wrt NLO, K factor wrt LO

[Campanario, Rauch, Sapeta, 1309.7293]
Anomalous Couplings

\( WHj \) with inclusive cuts and several values of \( f_W/\Lambda^2 \) in \( \text{TeV}^{-2} \) and no form factor.
Anomalous Couplings

with form factor \( \left( \frac{\Lambda^2}{\Lambda^2 + m_{WH}^2} \right)^2 \), \( \Lambda = 2 \text{ TeV} \)