Higher Order Corrections to Diboson Production and anomalous Triple Gauge Couplings

Robin Roth | 01.09.2016
in collaboration with Francisco Campanario, Sebastian Sapeta, Dieter Zeppenfeld
Motivation

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 ⇒ $\bar{nNLO}$
- parametrize beyond-SM effects ⇒ Anomalous Couplings (AC) / EFT
- improve analyses ⇒ better cuts and observables, dynamical jet veto

Tools
- $\text{VBFNLO}$: diboson production at NLO QCD with AC
- $\text{LoopSim}$: $\bar{nNLO}$ based on $\text{VBFNLO}$ input
LHC Cross Sections

Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

Theory
Data $4.5 - 4.9$ fb$^{-1}$
Data $20.3$ fb$^{-1}$
Data $0.08 - 14.8$ fb$^{-1}$

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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
Corrections to diboson production

- NLO QCD first reliable prediction and scale variation uncertainty
  LO only depends on factorization scale

- NNLO QCD needed for **precision measurements**
  first order to include **all partonic channels**
  now available for all diboson processes  [Grazzini, Kallweit et al.; Ellis et al.; ]
  corrections to gg initial state large  [Caola, Melnikov, et al.]
  coming soon: more differential results, public codes

- NLO EW sizeable in tails of distributions
  work ongoing towards automation and combination with QCD corrections
  [Baglio et al.; Bierweiler, Kühn et al.; Biedermann et al.; Denner, Dittmaier et al.]

- matching to parton shower:
  established schemes for NLO QCD
  first results for DY NNLO QCQ + PS  [Hoeche, Li, Prestel; Karlberg, Re, Zanderighi]
Recent results

EW corrections to WW production
[Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder, 1605.03419]

NNLO QCD corrections to $V\gamma$ production
[Grazzini, Kallweit, Rathlev, 1601.06751]
## Anomalous Couplings

### SM as Effective Field Theory
- only use SM fields and preserve symmetries
- add higher-dimensional terms to Lagrangian $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$

### Building Blocks
- Higgs field $\Phi$
- (covariant) derivative $\partial^\mu, D^\mu$
- fermion fields $\psi$
- field strength tensors $G^{\mu\nu}, W^{\mu\nu}, B^{\mu\nu}$

### Contributions to WWZ vertex
At dimension 6 only 3 linear independent operators:

$\mathcal{O}_W = (D_\mu \Phi)\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)$, $\mathcal{O}_{WWW} = \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right]$, $\mathcal{O}_B = (D_\mu \Phi)\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$

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

WWH vertex: \( \frac{i g m_W g^{\mu\nu}}{2 \Lambda^2} \mathcal{O}_W \) 

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

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

WWH vertex:
\[
\text{SM} \quad \frac{i g m_W g^{\mu \nu}_{SM}}{2 \Lambda^2} g m_W \left( -g^{\mu \nu} (p_h \cdot p_- + p_h \cdot p_+) + p_h^\nu p^\mu_- + p_h^\mu p^\nu_+ \right)
\]

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

- preserve NLO total cross section
- exact tree-level and one-loop
- only singular two-loop contributions
- include dominant contributions from extra emissions, \(\mathcal{O}(\alpha_s \ln^2 p_T^{\text{jet}}/m_Z)\)
- nearly NNLO in high-\(p_T\) tails
LoopSim

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Beyond NLO: LoopSim
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LoopSim

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  extra emissions, \( \mathcal{O} ( \alpha_s \ln^2 p_{T \text{jet}} / m_Z ) \)
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\[ X@\text{NLO} \]
LoopSim

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$\bar{n}$NLO for WZ production

$e^+\nu_e\mu^+\mu^- + X$, LHC@13 TeV, inclusive cuts

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

$\sigma/\text{SM NLO}$

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

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

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

WZ production with a dynamical jet veto

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AC for diboson production

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

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

FW = -5
FW = -3
FW = +10
SM (NLO)

\[ \frac{\sigma}{\sigma_{\text{SM NLO}}} \]

\[ p_{T_{l,\text{max}} / \text{GeV}} \]

WZ production with a dynamical jet veto

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AC for diboson production

\[ \frac{d\sigma}{dp_{T\ell,\text{max}}} / \text{fb/GeV} \]

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FW = -5

FW = -3

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SM (NLO)

SM (nNLO)

WZ production with a dynamical jet veto
AC for diboson production

\[ \frac{d\sigma}{d\frac{p_{T_{1,\text{max}}}}{\text{GeV}}} \]

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

\[ \frac{\sigma}{\text{SM NLO}} \]

WZ production with a dynamical jet veto
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Jet vetos

want $V V + \text{jets}$, not $V j + V$

Traditional (fixed) jet veto

- don’t allow any jets above a fixed $p_T$ threshold
- introduces large logs $\log \frac{p_{T\text{veto}}}{m_{VV}}$
- cuts away relevant phase space: $m_{VV} \approx 1 \, \text{TeV} \iff p_{T\text{jet}} = 50/300 \, \text{GeV}$

Dynamical veto

[Campanario, RR, Zeppenfeld, 1410.4840]

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

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

$$E_T = E \frac{|\vec{p}_T|}{|\vec{p}|}$$
Observable $x_{jet} = \frac{\sum_{jets} E_{T,i}}{\sum_{jets} E_{T,i} + E_{T,W} + E_{T,Z}}$
Dynamical veto to improve AC sensitivity

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

\[ R_{LS} = \{0.5, 1.5\} \]

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

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

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

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

\[ \text{FW} = 5 \]

\[ \text{FW} = 3 \]

\[ \text{FW} = 10 \]

\[ \sigma / \text{SM NLO} \]

\[ p_{T_{l,\text{max}}} / \text{GeV} \]

inclusive
Dynamical veto to improve AC sensitivity

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

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SM (NLO)

SM (nNLO)

FW = -5

FW = -3

FW = +10

\[ \sigma / \text{SM NLO} \]

\[ p_{T_{l,\text{max}}} / \text{GeV} \]

inclusive

\[ x_{\text{jet}} < 0.2 \]

WZ production with a dynamical jet veto

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Conclusion

Beyond NLO: Loopsim

- Method to combine multiplicities consistently at parton level
  \( X@NLO + Xj@NLO = X@\tilde{nNLO} \)
- 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

\[
 x_{\text{jet}} = \frac{\sum_{\text{jets}} E_T,i}{\sum_{\text{jets}} E_T,i + E_T,W + E_T,Z}
\]

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


- 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: $O(1)$ or $O(\alpha_{\text{QED}})$

### Power counting in $\Lambda$

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

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

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

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

### Cuts

- $p_T^j > 30$ GeV
- $p_T^l > 15$ GeV
- $p_T > 30$ GeV
- $|\eta_j| < 4.5$
- $|\eta_l| < 2.5$
- $R_{l,j} > 0.4$
- $60$ GeV $< m_{ll} < 120$ GeV
- boosted: $p_T^Z > 200$ GeV

### Input values

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

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

\[ \mu = 2^{\pm1}\mu_0 \text{ (NLO)} \]
\[ \mu = 2^{\pm1}\mu_0 \text{ (nNLO)} \]
\[ R_{\text{LS}} = \{0.5, 1.5\} \]
\[ \text{FW} = +10 \]
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\[ \text{SM (NLO)} \]
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Different $x_{\text{jet}}$ cuts

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

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

$\sigma / \text{SM NLO}$

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

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

$1.0 \quad 1.5 \quad 2.0 \quad 2.5 \quad 3.0$

$\sigma / \text{SM NLO}$

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

$p_{T_{l,\text{max}}} / \text{GeV}, x_{\text{jet}} < 0.4$
Observable: $x_{\text{jet}}, x_Z$

Motivation

- 3 particle final state (WZj)
- the transverse momenta can be parametrized using only two variables
  6 d.o.f. ($p_T^W, p_T^Z, p_T^{\text{jet}}$) - 2 (total $p_T = 0$) - 1 (no $\phi$ dependence) - 1 (rescaling at high $p_T$)
- dalitz-like construction

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

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

$$\frac{d^2\sigma}{dx_{\text{jet}}^p x_H^p} \ [\text{fb}]$$
PS effects on $x_{\text{jet}}$
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

\[ \text{Campanario, Rauch, Sapeta, 1309.7293} \]
Anomalous Couplings

$WHj$ with inclusive cuts and several values of $f_W/\Lambda^2$ in TeV$^{-2}$ and no form factor.
Anomalous Couplings
with form factor \( \left( \frac{\Lambda^2}{\Lambda^2+m_{\text{WH}}^2} \right)^2 \), \( \Lambda = 2 \text{ TeV} \)
# Current state of diboson production at the LHC

**Dec. 2015**

### CMS measurements vs. NLO (NNLO) theory

<table>
<thead>
<tr>
<th>System</th>
<th>Theory</th>
<th>Experiment</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>$0.12^{+0.01}_{-0.01} \pm 0.06$</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>$0.13^{+0.03}_{-0.03} \pm 0.16$</td>
<td>$1.16 \pm 0.03 \pm 0.13$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
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<tr>
<td>$Z\gamma$</td>
<td>$0.05^{+0.01}_{-0.01} \pm 0.98$</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
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</tr>
<tr>
<td>$Z\gamma$</td>
<td>$0.05^{+0.01}_{-0.01} \pm 0.98$</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
<td>$19.5 \text{ fb}^{-1}$</td>
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<td></td>
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<tr>
<td>$WW+WZ$</td>
<td>$0.08^{+0.02}_{-0.02} \pm 1.01$</td>
<td>$1.05 \pm 0.13 \pm 0.15$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
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<td>$WW$, (NNLO th.)</td>
<td>$0.07^{+0.07}_{-0.03} \pm 1.14$</td>
<td>$1.01 \pm 0.02 \pm 0.08$</td>
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<tr>
<td>$WZ$</td>
<td>$0.07^{+0.11}_{-0.07} \pm 1.17$</td>
<td>$0.86 \pm 0.11 \pm 0.17$</td>
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All results at: http://cern.ch/go/pNj7

**Production Cross Section Ratio:** $\sigma_{\text{exp}} / \sigma_{\text{theo}}$

Backup

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