Latest Results on VBF and VBS Processes at CMS

Jakob Salfeld-Nebgen
on behalf of the CMS Collaborations
Princeton University

QCD@LHC 2018
Dresden, August 27th - 31st, 2018
Overview

• Introduction
  ▶ Triple- and Quartic Gauge Couplings

• Single Boson Production via Vector Boson Fusion
  ▶ EW Z production at 13 TeV

• Electroweak Diboson Production and Vector Boson Scattering
  ▶ EW same-sign WW production at 13 TeV
  ▶ EW ZZ production at 13 TeV
  ▶ EW WZ production at 13 TeV

• Conclusions
Introduction

- Electroweak single- and diboson production modes are important measurements at LHC to precisely explore EWSB mechanism

Electroweak Diboson Production (VBS)

Electroweak Single Boson Production (VBF)

- TGC and QGC precisely predicted in Standard Model
  - Slightest deviation from SM prediction leads to unitarity violation and thereby hints for New Physics
  - QGC: first measurements performed at LHC, TGC: studied at LEP and Tevatron
- VBS and VBF processes important background for New Physics
Electroweak (Di-)Boson Production

- VBS and VBF signal processes defined via EW and strong coupling constants involved at LO, e.g.

- NLO EW corrections for VBS can be as large as 10-20% on cross section

See Mathieu's talk

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{EW} \propto \mathcal{O}(\alpha_{EW}^4)$</th>
<th>$\sigma_{EW \times QCD} \propto \mathcal{O}(\alpha_{EW}^3 \alpha_S)$</th>
<th>$\sigma_{QCD} \propto \mathcal{O}(\alpha_{EW}^2 \alpha_S^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW Signal</td>
<td>Interference, added to background or scaled according to signal $\mathcal{O}(10%)$</td>
<td>Background (QCD induced)</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Interference, uncertainty or added to background, usually $\mathcal{O}(1\%)$
Experimental Signature

- VBF and VBS type events at LHC have distinct event topology in the detector
  - Two high-pT forward jets, with:
    - large pseudorapidity separation
    - high di-jet invariant mass
  - Suppressed central hadronic activity
  - “Centrality” of (di-)boson system with respect to dijet-system

- Observables used to EW from QCD induced processes

- In CMS, the QCD and EW production mechanisms are simulated with aMC@NLO
  - QCD⊗EW interference contributions are cross-checked using PHANTOM generator
LHC Experimental Status

- Experiments have accumulated \( \sim 25 \text{ fb}^{-1} \) at 7/8 TeV and \( 130 \text{ fb}^{-1} \) at 13 TeV
- Expect \( \sim 150 \text{ fb}^{-1} \) at 13 TeV by end of 2018, full Run-2
- Measuring cross sections of \( O(1\text{fb}) \) for VBS, and \( O(100\text{fb}) \) for VBF
- Current results based on Run-1 dataset and 36 fb\(^{-1}\) of Run-2 collected in 2016
VBF Z (13 TeV)

- CMS EW Z production cross section measurement performed on 2016 dataset, 36 fb⁻¹

- Event selection: two same-flavour leptons (ee or $\mu\mu$), mass within 15 GeV of Z, $p_T>$30/20 GeV, two jets with $p_T>$50/30 GeV, $m_{JJ}>$ 200 GeV

- Signal extraction performed using dedicated boosted decision tree, usual VBF variables used ($m_{JJ}$, $|\Delta\eta_{JJ}|$, $z^*$, $R_T$ and g/q discriminator)
VBF Z (13 TeV) arxiv:1712.09814

- Cross section measurement performed using template fit of BDT discriminant
  - excellent agreement with the SM prediction (MG LO), ee and $\mu\mu$ combined to find
    \[
    \mu = 0.98 \pm 0.04 \text{ (stat)} \pm 0.10 \text{ (syst)} = 0.98 \pm 0.11 \text{ (total)} \\
    \sigma(\text{EW } \ell\ell jj) = 534 \pm 20 \text{ (stat)} \pm 57 \text{ (syst)} \text{ fb} = 534 \pm 60 \text{ (total) fb}
    \]
  - Note interference term contribution scaled according to signal strength modifier

- Generator comparisons performed for hadronic activity, results interpreted in terms of dim-6 EFT operators (LEP parametrization)

Compatible with WZ inclusive sensitivity.
CMS VBS Studies

- WW largest EW cross section and signal to background ratio
  ➤ So far the only VBS process experimentally confirmed
- WZ and ZZ processes become feasible with the full Run-2 dataset
  ➤ larger QCD VV background, controlled in 2-jet side bands

<table>
<thead>
<tr>
<th>sqrt(s)</th>
<th>VBS process</th>
<th>CMS</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td>EW $W^\pm W^\pm$ (l\nu\nu)</td>
<td>PRL 114 (2015) 051801</td>
<td>CMS finds 2.0 $\sigma$</td>
</tr>
<tr>
<td></td>
<td>EW $Z\gamma$ (v\nu/\nu\gamma)</td>
<td>Phys.Lett. B770 (2017) 380-402</td>
<td>CMS finds evidence</td>
</tr>
<tr>
<td></td>
<td>EW $W\gamma$ (l\nu\nu)</td>
<td>JHEP 1706 (2017) 106</td>
<td>CMS finds 2.7 $\sigma$</td>
</tr>
<tr>
<td></td>
<td>EW WZ (3\nu)</td>
<td>PRL 114 (2015) 051801</td>
<td>CMS meas. QCD+EW xsec</td>
</tr>
<tr>
<td>13 TeV</td>
<td>EW $W^\pm W^\pm$ (2l\nu\nu)</td>
<td>PRL 120, 081801</td>
<td>CMS first observation</td>
</tr>
<tr>
<td></td>
<td>EW ZZ (4l)</td>
<td>Phys. Lett. B 774 (2017) 682</td>
<td>CMS finds 2.7 $\sigma$</td>
</tr>
<tr>
<td></td>
<td>EW WZ (3\nu)</td>
<td>SMP-18-001</td>
<td>CMS finds 1.9 $\sigma$, aQGC constraints and limits on H$^+$ are derived</td>
</tr>
</tbody>
</table>
\( W^\pm W^\pm \) VBS (Observation 13 TeV)

- Measurement performed inclusively in \( ee, e\mu, \mu\mu \) channel, two same-sign leptons
  - Major backgrounds estimated from the data: Fake leptons (60%), WZ (QCD+EW), charge flip (for electrons (sub) per mille level)
  - Major syst. unc.: jet energy scale, fake background, theory unc. on the (factorization scale) signal modelling
- Fit performed to extract best-fit signal strength modifier with experimental and theoretical uncertainties, enhances sensitivity

First observation of VBS process

\[
\sigma^{EW}_{LO} = 4.25 \pm 0.27 \text{fb}
\]

\[
\sigma^{EW}_{NLO} \approx \sigma^{EW}_{LO} - 13\%
\]

\[
\sigma^{\text{meas.}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst}) \text{fb}
\]
**WZ VBS (13 TeV)**

- EW WZ cross section measurement performed on 2016 dataset, 36 fb$^{-1}$
  - 3-lepton final-state (electron/muon)

- QCD WZ process controlled in background enriched side-band
  - **Signal region:** events pass the VBS cuts $m_{jj} > 500$ GeV, $|\Delta\eta_{jj}|>2.5$, $|z^*|<2.5$
  - **Control region:** events pass $m_{jj} > 100$ GeV and fail either of the VBS cuts

<table>
<thead>
<tr>
<th></th>
<th>Electroweak Signal</th>
<th>Higgs Signal</th>
<th>Tight Fiducial</th>
<th>Loose Fiducial</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(l_2,l_3)$ [GeV]</td>
<td>&gt; 25</td>
<td>&gt; 25</td>
<td>&gt; 25</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>$p_T(l_2,l_3)$ [GeV]</td>
<td>&gt; 15</td>
<td>&gt; 15</td>
<td>&gt; 15</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>$p_T(l_1)$ [GeV]</td>
<td>&gt; 20</td>
<td>&gt; 20</td>
<td>&gt; 20</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>$</td>
<td>\eta(l_1)</td>
<td>$</td>
<td>&lt; 2.4</td>
<td>&lt; 2.4</td>
</tr>
<tr>
<td>$</td>
<td>\eta(l_2)</td>
<td>$</td>
<td>&lt; 2.5</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>$m_{Z} - m_{Z_{\text{MC}}}$ [GeV]</td>
<td>&gt; 15</td>
<td>&gt; 15</td>
<td>&gt; 15</td>
<td>&gt; 15</td>
</tr>
<tr>
<td>$m_{W}$ [GeV]</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>$m_{l_1}$ [GeV]</td>
<td>&gt; 4</td>
<td>&gt; 4</td>
<td>&gt; 4</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>$p_T^{miss}$ [GeV]</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$p_T(l_1)$ [GeV]</td>
<td>&lt; 4.7</td>
<td>&lt; 4.7</td>
<td>&lt; 4.7</td>
<td>&lt; 4.7</td>
</tr>
<tr>
<td>$p_T(l_2)$ [GeV]</td>
<td>&gt; 50</td>
<td>&gt; 30</td>
<td>&gt; 50</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>$</td>
<td>\Delta R(l_1,l_2)</td>
<td>$</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>$m_{l_1}$</td>
<td>&gt; 2</td>
<td>&gt; 2</td>
<td>&gt; 2</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>$p_T(b)$ [GeV]</td>
<td>&gt; 30</td>
<td>&gt; 30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$m_{b_{\text{jet}}}$</td>
<td>= 0</td>
<td>= 0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>\Delta R(b_{l_1},b_{l_2})</td>
<td>$</td>
<td>&gt; 500</td>
<td>&gt; 500</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{b_{\text{jet}}}-\frac{1}{2}(\eta_{l_1}+\eta_{l_2})</td>
<td>$</td>
<td>&gt; 2.5</td>
<td>&gt; 2.5</td>
</tr>
</tbody>
</table>
WZ VBS (13 TeV)

- Signal extraction using 2d $m_{jj}$ vs $|\Delta\eta_{jj}|$ distribution
  - Observed (Expected) significance: $1.9\sigma$ ($2.7\sigma$)
  - $\mu_{EW} = 0.64^{+0.45}_{-0.37}$

- Also EW+QCD contribution measured in signal region
  - $\sigma_{WZjj}^{\text{fid}} = 2.91^{+0.53}_{-0.49}$ (stat) $^{+0.41}_{-0.34}$ (syst) = $2.91^{+0.67}_{-0.60}$ fb
  - Predicted: $3.27^{+0.39}_{-0.32}$ (scale) $\pm 0.15$ (PDF) fb

<table>
<thead>
<tr>
<th>Process</th>
<th>µµµ</th>
<th>µµe</th>
<th>eeeµ</th>
<th>eee</th>
<th>Total Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD WZ</td>
<td>14.1 ± 0.9</td>
<td>9.4 ± 0.5</td>
<td>7.1 ± 0.4</td>
<td>4.8 ± 0.3</td>
<td>35.4 ± 1.1</td>
</tr>
<tr>
<td>$t+V/VVV$</td>
<td>6.0 ± 0.4</td>
<td>3.4 ± 0.2</td>
<td>2.6 ± 0.2</td>
<td>1.8 ± 0.1</td>
<td>13.7 ± 0.5</td>
</tr>
<tr>
<td>Nonprompt VV</td>
<td>5.1 ± 2.1</td>
<td>2.3 ± 1.0</td>
<td>1.4 ± 0.6</td>
<td>0.7 ± 0.3</td>
<td>9.5 ± 2.4</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>0.9 ± 0.1</td>
<td>1.7 ± 0.2</td>
<td>0.5 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>Pred. Background</td>
<td>26.0 ± 2.2</td>
<td>18.9 ± 1.6</td>
<td>11.6 ± 0.8</td>
<td>8.0 ± 0.5</td>
<td>64.5 ± 2.9</td>
</tr>
<tr>
<td>Data</td>
<td>38</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>75</td>
</tr>
</tbody>
</table>

Source of systematic uncertainty | Relative systematic uncertainty [%] $\sigma_{WZjj}$ | EW WZ Significance
--- | --- | ---
Jet energy scale | +9.8/-9.2 | 7.5
Jet energy resolution | +1.1/-1.9 | < 0.1
QCD WZ modeling | - | 0.9
Other background theory | +2.5/-2.2 | 0.2
Nonprompt normalization | +2.1/-2.4 | 1.1
Nonprompt stat. | +6.1/-5.8 | 6.2
Lepton energy scale and eff. | +3.5/-2.7 | < 0.1
b-tagging | +1.7/-1.9 | < 0.1
Luminosity | +3.1/-3.4 | < 0.1

![Events in bin](image)
ZZ VBS (13 TeV)

- ZZjj production measurement performed in fully leptonic final state
- Exploit boosted decision tree to enhance sensitivity (7 most performant variables used)
  - $m_{jj}$, $\Delta\eta_{jj}$, $m_{ZZ}$, $Z_{1,2}$-centrality, vector/scalar sum of VBF-jets and of ZZ+jets
- 2.7 (1.6) observed (expected) over bkgd-only hypothesis
  \[
  \sigma_{EW}(pp \rightarrow ZZjj \rightarrow \ell\ell\ell\ell jj) = 0.40^{+0.21}_{-0.16} \text{(stat)}^{+0.13}_{-0.09} \text{(syst)} \text{ fb}.
  \]
  \[
  \sigma_{EW}^{LO} = 0.29^{+0.02}_{-0.03} \text{ fb}.
  \]
- Good sensitivity to EFT operators
  - $-0.46 < f_{T0}/\Lambda^4 < 0.44$
  - $-0.61 < f_{T1}/\Lambda^4 < 0.61$
  - $-1.2 < f_{T2}/\Lambda^4 < 1.2$
  - $-0.84 < f_{T8}/\Lambda^4 < 0.84$
  - $-1.8 < f_{T9}/\Lambda^4 < 1.8$
Anomalous Quartic Gauge Couplings

- Important to probe all diboson processes to cover all possible EFT operators
  - Indirectly probing mass scales above 1 TeV
- Gain in sensitivity can be obtained by combination, if two analyses have similar sensitivity
VBF Diboson Resonances (13 TeV)

- CMS performed searches for VBF H++ and H+ production at 13 TeV
- Higgs triplet models give rise to doubly-charged Higgs bosons
- Search performed in fully leptonic final-states
- VBF/VBS dijet topology cuts
- W±W± analysis most performant when interpreted in Georgi-Machacek Model

arxiv:1705.02942
The Summary

- VBS and VBF processes key measurements to fully explore EWSB
- $W^\pm W^\pm, WZ, ZZ$ VBS measurements performed at 13 TeV with 36 fb$^{-1}$
  - First VBS ($W^\pm W^\pm$) process observed directly with $>5\sigma$
- Expect 150 fb$^{-1}$ by end of year $\Rightarrow$ many more measurements
  - Clear evidence for WZ and ZZ VBS processes, and hadronic decays will be investigated
- VBS and VBF processes place strong limits on aTGCs and aQGCs
Additional Material
Beyond The SM Interpretation

1.) Effective Field Theory (Eboli basis, orthogonal to aTGC)

Operators ordered terms of covariant derivatives only (Scalar), field strength tensors only (Tensor) or both (Mixed)

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=WWW,WW,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,i}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j} \]

2.) Direct diboson resonance searches reach (M_X \sim 1-2 \, \text{TeV})

\[ \text{Depends on: spin 0/1/2, charge, fermion/boson couplings} \]

possible to map onto specific model

---

<table>
<thead>
<tr>
<th>( I )</th>
<th>( J = 0 )</th>
<th>( J = 1 )</th>
<th>( J = 2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( \sigma^0 ) (&quot;Higgs&quot;)</td>
<td>( [\omega^0] ) (( \gamma'/Z' ))</td>
<td>( f^0 ) (KK graviton)</td>
</tr>
<tr>
<td>1</td>
<td>( [\pi^\pm, \pi^0] ) (2HDM)</td>
<td>( \rho^\pm, \rho^0 ) (( W'/Z' ))</td>
<td>( [a^\pm, a^0] )</td>
</tr>
<tr>
<td>2</td>
<td>( \phi^\pm, \phi^0 ) (Higgs triplet)</td>
<td>---</td>
<td>( t^\pm, t^\pm, t^0 )</td>
</tr>
</tbody>
</table>

---

\text{arxiv.1307.8170}

---

<table>
<thead>
<tr>
<th>( \mathcal{O}<em>{S,0}, \mathcal{O}</em>{S,1} )</th>
<th>( \mathcal{O}<em>{M,0}, \mathcal{O}</em>{M,1}, \mathcal{O}<em>{M,6}, \mathcal{O}</em>{M,7} )</th>
<th>( \mathcal{O}<em>{M,2}, \mathcal{O}</em>{M,3}, \mathcal{O}<em>{M,4}, \mathcal{O}</em>{M,5} )</th>
<th>( \mathcal{O}<em>{T,0}, \mathcal{O}</em>{T,1}, \mathcal{O}_{T,2} )</th>
<th>( \mathcal{O}<em>{T,5}, \mathcal{O}</em>{T,6}, \mathcal{O}_{T,7} )</th>
<th>( \mathcal{O}<em>{T,8}, \mathcal{O}</em>{T,9} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWW</td>
<td>WWZZ</td>
<td>ZZZZ</td>
<td>WWAZ</td>
<td>WWAA</td>
<td>ZZZA</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

---

\text{arxiv.1309.7890}

18
VBF W at 8 TeV

• EW W boson production cross section measurement performed on 8 TeV dataset (19.2 fb⁻¹)
  ▶ QCD W+2jet sample normalized in background control region
  ▶ QCD⊗EW term treated as background (~12%)

• Analytic fit to mJJ distribution performed to extract EW W production cross section

### Event Selection Criteria

<table>
<thead>
<tr>
<th>W → ℓν Lepton requirements</th>
<th>Jet requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton trigger</td>
<td>( p_{T1} &gt; 60,\text{GeV}, \ p_{T2} &gt; 50,\text{GeV} )</td>
</tr>
<tr>
<td>High-quality lepton ID and isolation</td>
<td>(</td>
</tr>
<tr>
<td>Electron (muon) ( p_{T} &gt; 30 ) (25) GeV</td>
<td>( m_{jj} &gt; 1000 ,\text{GeV} )</td>
</tr>
<tr>
<td>( \not{E}_T &gt; 30 ) (25) GeV for electron (muon) channels</td>
<td>-</td>
</tr>
<tr>
<td>W transverse mass &gt; 30 GeV</td>
<td>-</td>
</tr>
<tr>
<td>Veto second lepton</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>0.41 ± 0.04 (stat) ± 0.09 (syst) ± 0.01 (lumi) pb</td>
</tr>
<tr>
<td>Muon</td>
<td>0.43 ± 0.04 (stat) ± 0.10 (syst) ± 0.01 (lumi) pb</td>
</tr>
<tr>
<td>Combined</td>
<td>0.42 ± 0.04 (stat) ± 0.09 (syst) ± 0.01 (lumi) pb</td>
</tr>
</tbody>
</table>

predicted LO cross section:

0.50 ± 0.02 (scale) ± 0.02 (PDF) pb

\[
\mathcal{F} = \frac{1}{m_{jj} a_0 + a_1 \ln (m_{jj}/8000)}
\]
Unitarity

- After discovery of W and Z boson at SPS 1983
  - How to restore unitarity in quartic massive gauge boson interactions?
  - How do gauge bosons acquire mass?

- Without Higgs and/or BSM, unitarity violation in $\sigma(VV \rightarrow VV)$ above 1 TeV

- LHC was proposed in 1980`s to conclusively either find Higgs boson and/or yet unknown particles and interactions
aQGC EFT Operators

- Grouped in covariant derivatives, Field Strength Tensors and both (mixed)

\[ O_{S,0} = \left( (D_{\mu} \Phi)^\dagger D_{\nu} \Phi \right) \times \left( (D_{\mu} \Phi)^\dagger D_{\nu} \Phi \right), \]
\[ O_{S,1} = \left( (D_{\mu} \Phi)^\dagger D_{\mu} \Phi \right) \times \left( (D_{\nu} \Phi)^\dagger D_{\nu} \Phi \right), \]

\[ O_{M,0} = \text{Tr} \left[ W_{\mu\nu} W^{\mu\nu} \right] \times \left( (D_{\beta} \Phi)^\dagger D_{\beta} \Phi \right), \]
\[ O_{M,1} = \text{Tr} \left[ W_{\mu\nu} W^{\nu\beta} \right] \times \left( (D_{\beta} \Phi)^\dagger D_{\beta} \Phi \right), \]
\[ O_{M,2} = \left[ B_{\mu\nu} B^{\mu\nu} \right] \times \left( (D_{\beta} \Phi)^\dagger D_{\beta} \Phi \right), \]
\[ O_{M,3} = \left[ B_{\mu\nu} B^{\nu\beta} \right] \times \left( (D_{\beta} \Phi)^\dagger D_{\beta} \Phi \right), \]

\[ O_{T,0} = \text{Tr} \left[ W_{\mu\nu} W^{\mu\nu} \right] \times \text{Tr} \left[ W_{\alpha\beta} W^{\alpha\beta} \right], \]
\[ O_{T,1} = \text{Tr} \left[ W_{\alpha\nu} W^{\mu\beta} \right] \times \text{Tr} \left[ W_{\mu\beta} W^{\alpha\nu} \right], \]
\[ O_{T,2} = \text{Tr} \left[ W_{\alpha\mu} W^{\mu\beta} \right] \times \text{Tr} \left[ W_{\beta\nu} W^{\nu\alpha} \right], \]
\[ O_{T,3} = \text{Tr} \left[ W_{\mu\nu} W^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta}, \]
\[ O_{T,4} = \text{Tr} \left[ W_{\alpha\nu} W^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu}, \]
\[ O_{T,5} = \text{Tr} \left[ W_{\alpha\mu} W^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha}, \]
\[ O_{T,6} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}, \]
\[ O_{T,7} = B_{\alpha\beta} B^{\alpha\beta} B_{\beta\nu} B^{\nu\alpha}. \]
Higgs Couplings

- Cross section of VBS processes depend on Higgs vector boson couplings

- Example: Two Higgs Doublet Models

\[ \frac{g_{hVV}^{2HDM}}{g_{hVV}^{SM}} = \sin(\beta - \alpha) \]

\[ \frac{g_{HVV}^{2HDM}}{g_{HVV}^{SM}} = \cos(\beta - \alpha) \]

<table>
<thead>
<tr>
<th>Channels</th>
<th>$\sin(\beta - \alpha)$</th>
<th>0.7</th>
<th>0.9</th>
<th>SM ($C_V = 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$</td>
<td>0.51</td>
<td>0.46</td>
<td>0.40</td>
<td>0.39</td>
</tr>
<tr>
<td>$W^+W^+ \rightarrow \ell^+\nu\ell^+\nu$</td>
<td>0.20</td>
<td>0.17</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>$W^-W^- \rightarrow \ell^-\bar{\nu}\ell^-\bar{\nu}$</td>
<td>0.083</td>
<td>0.075</td>
<td>0.070</td>
<td>0.069</td>
</tr>
<tr>
<td>$W^+Z \rightarrow \ell^+\nu\ell^+\ell^-$</td>
<td>0.016</td>
<td>0.013</td>
<td>0.011</td>
<td>0.010</td>
</tr>
<tr>
<td>$W^-Z \rightarrow \ell^-\bar{\nu}\ell^+\ell^-$</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$8.5 \times 10^{-3}$</td>
<td>$7.6 \times 10^{-3}$</td>
<td>$7.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$</td>
<td>$8.4 \times 10^{-3}$</td>
<td>$6.4 \times 10^{-3}$</td>
<td>$4.6 \times 10^{-3}$</td>
<td>$4.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

arxiv:1307.7135

arxiv:1303.6335