Vector Boson Scattering: Status and Prospects

Diogo Buarque Franzosi, Richard Ruiz, Michele Gallinaro

- Introduction
- VBS at the LHC
- Cross section and polarization
- VBS and BSM at Run3-5
- Future prospects beyond LHC

Planet Earth
Year 2022

= only

Community Summer Study
SN WMASS
July 17-26 2022, Seattle
Introduction

• Observation of the Higgs boson
  – Consistent with SM, within current uncertainties
  – W and Z acquire longitudinal polarization via the Brout-Englert-Higgs mechanism

• Is the Higgs the only player for the EWSB mechanism?
  – VBS is key process to test EWSB
  – Complementary to direct Higgs measurements

• LHC as a gauge boson collider to study VBS/VBF processes

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arXiv:2106.01393
VBS and VBF

- VBF and VBS processes provide key measurements to probe the mechanism of EWK symmetry breaking and test effect of BSM models.
- $V_L V_L \rightarrow V_L V_L$ scattering is unitarized by the interference with the H exchange.

\[ q \xrightarrow{W^\pm} q' \]

\[ q \xrightarrow{W^\pm} \nu \]

\[ q \xrightarrow{W^\pm} \ell^\pm \]

\[ q \xrightarrow{W^\pm} \ell^\pm \]

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Motivation

- Electroweak process characterized by VVjj (V=γ, W, Z) final state
- The physics potential
  - Precision test of EWSB at high energies
  - Probe the Higgs mechanism
  - Non-standard Higgs couplings
  - Higgs portal: New Higgs sector physics
- Probes nature of SM:
  - Direct access to triple/quartic gauge couplings
  - Sensitive to couplings btw Higgs and gauge bosons
  - Complementary to Higgs measurements at scales >m_H
- Portal to BSM:
  - Model-independent via EFTs (dim-6 and dim-8)
  - Constraints on aQGCs
Signal and background

- **VV production via vector boson scattering** ($V=W,Z,\gamma$)
  - Purely EW process
  - QCD induced diagrams are treated as background
- **V self-interactions** (and with H) precisely predicted
- Deviations from predictions may signal new physics in EW sector
- **Experimental challenges**: rare process, precision?

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Experimental signature

- **Event topology**
  - 2 vector bosons produced centrally
  - 2 energetic forward jets in opposite hemispheres
  - Large $m_{jj}$ and $\Delta \eta_{jj}$

- **Signature defined on diboson final state**
  - Fully leptonic: 4 e/μ + 2 jets
  - Semi-leptonic/hadronic: 1(2) e/μ + jets
  - Fully hadronic: 4 or 6 jets

- **Tree-level contributions to final state**
  - EWK: signal component $O(\alpha_{EW}^4)$
  - QCD: background, $O(\alpha_{EW}^2 \alpha_S^2)$, suppressed at high $m_{jj}$, high $|\Delta \eta_{jj}|$ region
  - Interference: $O(\%)$ of signal
Study VVjj processes

- **WWjj:**
  - EW production dominant over QCD
  - Distinct same-sign (SS) lepton final state with low bkg (“golden channel”)

- **WZjj:**
  - Sensitive to charged resonances or couplings
  - Clean signature, larger bkg

- **ZZjj:**
  - Fully reconstructed final state provides maximal information

Absolute and normalized differential cross section measurements:

- EW WZ: $6.8(5.3)\sigma$
- EW WW: far above $5\sigma$
- EW ZZ: far above $5.5(3.9)\sigma$
Polarization: VBS WW

- Polarization measurements allow important tests of EWSB mechanism
  - Challenging since low expected yields for $W_LW_L$
  - four-momentum of W boson unknown
- EW production cross section of polarized WW
  - $W$ and $Z$ bosons have a spin 1 and can be longitudinally polarized as they are massive
- Polarization: simultaneous production of $W/Z$ allows study fundamental interactions btw them

$$\text{obs (exp) significance } (W_LW_X): 2.3(3.1)\sigma$$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma B$ (fb)</th>
<th>Theoretical prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_L^\pm W_L^\pm$</td>
<td>0.32$^{+0.42}_{-0.40}$</td>
<td>0.44$^{+0.05}_{-0.05}$</td>
</tr>
<tr>
<td>$W_X^\pm W_T^\pm$</td>
<td>3.06$^{+0.51}_{-0.48}$</td>
<td>3.13$^{+0.35}_{-0.35}$</td>
</tr>
<tr>
<td>$W_L^\pm W_X^\pm$</td>
<td>1.20$^{+0.56}_{-0.53}$</td>
<td>1.63$^{+0.18}_{-0.18}$</td>
</tr>
<tr>
<td>$W_T^\pm W_T^\pm$</td>
<td>2.11$^{+0.49}_{-0.47}$</td>
<td>1.94$^{+0.21}_{-0.21}$</td>
</tr>
</tbody>
</table>

In the WW CoM frame

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Advanced analysis methods

- Polarization in VBS
- Discriminating power of $W_T$ vs $W_L$ in jet substructure
  - $W_T$ decay products preferentially anti-parallel to $W$ momentum
  → asymmetry in $p_T$ btw sub-jets
• Good agreement with SM
• Important to model QCD contribution: a challenging task
Final processes with taus in the final state

• Not yet studied in VBS processes
• Cross section measurements including $\tau s$
• Includes only 3rd generation quarks/leptons
• Syst unc: tauId, fakes
• If special role in EWK symmetry breaking, couplings to W may change
• Charged Higgs may alter coupling to W

Use $R$ for signal extraction:
binned maximum likelihood fit

$R_\tau = \frac{p_{\tau}^{track}}{p_{\tau h}}$
• **Search for charged Higgs in GM model:**
  - $H^+$ and $H^{++}$

• **Search for resonant production**
  - Only fermiophobic $H^+$ considered
  - Require 2/3 leptons
  - Good bkg description of data in SR
Exotic searches

High mass sensitivity at LHC driven by $W\gamma$ and $W^±W^±$

- Type I seesaws hypothesize a new scalar singlet $ν_R$
  - Sterile neutrino $N$ and mixing $|V_{lN}|^2$ accessible with VBF/VBS
  - Probe heavy neutrinos
  - Test dim-5 Weinberg operators

- Isolated photon + invisible
- SM: $Z(→νν)γjj$
  - $O(α_{EW}^5)$ process
- BSM
  - $H→γ+γ_D$
  - $H→invisible +γ$
Anomalous couplings

- Searches for BSM may be parametrized in the **Effective Field Theory (EFT)** approach
- Limits on aQGCs set using EFT. Dim-6 and dim-8 operators may modify VVjj production
  - Dim-5 operator may probe $0\nu\beta\beta$ and Lepton Number Violation (see prev. slide)

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots \]

- EFT amplitudes grow with $M_{VV}$ and the growth is non-physical above a scale $\Lambda$. Sets limits on validity of EFT approach
- Replace EFT amplitudes with SM in $>\Lambda$ region ("clipping")
Gauge boson self-interactions

- SM precisely predicts strength of EWK gauge boson interactions
- Studied several processes sensitive to TGCs/QGCs
  - Charged TGCs/QGCs consistent with SM predictions
  - Neutral TGCs/QGCs forbidden
  - Processes may occur through higher-order diagrams at very low rates
- LHC provides the most sensitive limits
Physics w/ forward protons

Study photon-mediated processes
- Tag leading protons w/forward det.
- Small expected SM production
- Search for (non-)resonant excess in high-mass tails (AQGC/EFT)

Exclusive diphotons
CMS-EXO-20-007
Light-by-light scattering: \( \gamma\gamma \to \gamma\gamma \), sensitive to ALPs, probe neutral QGC

Exclusive top quark pairs
CMS-TOP-21-007
Search for central exclusive production of ttbar pairs in pp interactions with tagged protons

Z\(\gamma\)+X production
CMS-PAS-EXO-19-009
Search for anomalous Z/\(\gamma^\ast\) central production

Exclusive WW/ZZ
CMS-SMP-21-004
Search for \( \gamma\gamma \to WW/ZZ \) with forward protons
Theoretical predictions

- Steady progress in computational techniques for VBS/VBF
  - NLO in EW, NLO in EW+QCD, PS beyond LL/N_C
  - EW@NLO in event generators
  - Include EW corrections in PS

- EW PDFs and their extrapolation to high-energy lepton colliders
  - Estimate PDFs for a high-energy muon beam
  - At Q=1 TeV, overall size of EW corrections is ~10-20% (much larger for specific final states)

- Significant progress in computing helicity-polarized cross sections
  - Diboson at NLO in EW+QCD
  - Diboson at NNLO in QCD

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Prospects for HL-LHC

- Prospects for the study of VBS WW/WZ channels
  - Inclusive and polarized EW WW production

Based on existing 13 TeV results extrapolated to 14 TeV at HL-LHC
Detector upgrades @ HL-LHC

- **Timing detectors:** a new paradigm in HEP for PU rejection
- **Improve particle reconstruction/ID**
  - Increase object-ID efficiency and isolation
  - Improve missing transverse momentum resolution
  - Reduce fake jet reconstruction
  - Will help forward jet reconstruction in high PU
- **10%-20% gain in S/B in many Higgs decay channels**

### HH production sensitivity (sigmas) at 3 ab$^{-1}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>No MTD</th>
<th>$\langle \sigma \rangle$ 35 ps</th>
<th>$\langle \sigma \rangle$ 50 ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>0.89</td>
<td>0.95</td>
<td>0.94</td>
</tr>
<tr>
<td>bbtt</td>
<td>1.3</td>
<td>1.58</td>
<td>1.48</td>
</tr>
<tr>
<td>bbvv</td>
<td>1.7</td>
<td>1.85</td>
<td>1.83</td>
</tr>
<tr>
<td>bbWW</td>
<td>0.53</td>
<td>0.579</td>
<td>0.576</td>
</tr>
<tr>
<td>bbZZ</td>
<td>0.38</td>
<td>0.423</td>
<td>0.418</td>
</tr>
<tr>
<td>Combined</td>
<td>2.4</td>
<td>2.71</td>
<td>2.63</td>
</tr>
</tbody>
</table>

**Luminosity gain**
- +26%
- +20%

HL-LHC@140PU
Lepton colliders with $\sqrt{s} \sim$ few TeVs have advantages to measure VBS processes:
- well defined initial state, separate spin, polarization, quantum numbers, etc.

An $e^+e^-$ collider (ILC or CLIC) can cover energies up to a few TeVs.

Photon-induced EW production of VBF/VBS becomes dominant at high $\sqrt{s}$. 

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**VBS at $e^+e^-$ colliders**

- **Signal**: triple gauge couplings, Higgs $VV$ couplings, quartic gauge couplings

- **Backgrounds**
VBS at $e^+e^-$ colliders: sensitivity

- Polarized beams offer enhancement in sensitivity
  - Well defined initial state, clean final state
  - vs. EFT expansion parameters

- Differential cross sections with SM and non-SM values
  - Can probe dim-8 operators (ex. $F_{S,0,1}$)

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Multi-boson production $WW/ZH$ production

- same physics at $e^+e^-$ & $\mu^+\mu^-$ colliders (except $m_e$ vs $m_\mu$)
- VBS takes over at $\sqrt{s}\sim2$-3 TeV
- $WW$ parton luminosities exceed those at pp collider
- $WW$ at 14 TeV with 20ab$^{-1}$ can probe dim-6 operators

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Higgs pair production: VBF

- Higgs pair production gives access to Higgs self-coupling
- HH is one of the main goals @LHC and beyond
  - ggF and VBF production
  - Rare process
  - Both non-resonant (SM) and resonant (BSM) production
- 4-5σ sensitivity can be reached at HL-LHC
- 1% (?) precision can be achieved at 100TeV

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Precision Higgs physics

- Higgs boson couplings to EW gauge bosons
- At high energy, H and HH production rely on VBF topology

\[ \mu^+ \mu^- \rightarrow \nu_\mu \bar{\nu}_\mu \, H \quad (WW \, fusion) \]
\[ \mu^+ \mu^- \rightarrow \mu^+ \mu^- \, H \quad (ZZ \, fusion) \]

Muons collider vs other

<table>
<thead>
<tr>
<th>√s (lumi.)</th>
<th>3 TeV (1 ab⁻¹)</th>
<th>6 (4)</th>
<th>10 (10)</th>
<th>14 (20)</th>
<th>30 (90)</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWH (Δκ₁)</td>
<td>0.26%</td>
<td>0.12%</td>
<td>0.073%</td>
<td>0.050%</td>
<td>0.023%</td>
<td>0.1% [41] (68% C.L.)</td>
</tr>
<tr>
<td>\Lambda/\sqrt{c_i} (TeV)</td>
<td>4.7</td>
<td>7.0</td>
<td>9.0</td>
<td>11</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>ZZH (Δκ₂)</td>
<td>1.4%</td>
<td>0.89%</td>
<td>0.61%</td>
<td>0.46%</td>
<td>0.21%</td>
<td>0.13% [17] (95% C.L.)</td>
</tr>
<tr>
<td>\Lambda/\sqrt{c_i} (TeV)</td>
<td>2.1</td>
<td>2.6</td>
<td>3.2</td>
<td>3.6</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>WWHH (Δκ₃)</td>
<td>5.3%</td>
<td>1.3%</td>
<td>0.62%</td>
<td>0.415%</td>
<td>0.20%</td>
<td>5% [36] (68% C.L.)</td>
</tr>
<tr>
<td>\Lambda/\sqrt{c_i} (TeV)</td>
<td>1.1</td>
<td>2.1</td>
<td>3.1</td>
<td>3.8</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>HHHH (Δκ₄)</td>
<td>25%</td>
<td>10%</td>
<td>5.6%</td>
<td>3.9%</td>
<td>2.0%</td>
<td>5% [22, 23] (68% C.L.)</td>
</tr>
<tr>
<td>\Lambda/\sqrt{c_i} (TeV)</td>
<td>0.49</td>
<td>0.77</td>
<td>1.0</td>
<td>1.2</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

WWH/ZZHH couplings

HHH/WWHH couplings

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VBS @ 100 TeV

- **VV leptonic final states**
  - Final state fully reconstructed
  - Consider EFT dim-8 operators

- **pp→ ZZjj**
  - Sensitive to scalar resonances, background to VBF H production

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**$W_L W_L @ 100$ TeV**

- $W_L W_L$ scattering relevant for VVH coupling
- Longitudinal component extracted from angular distribution of the two leptons
- Extract HWW coupling mod. constraints $k_W$

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**VBS $W_L W_L$ Same Sign Cross Uncertainty**

| $|\eta| < 2.5$ | $|\eta| < 4.5$ | $p_T > 30$ GeV |
|---|---|---|
| $|\eta| < 4.0$ | $|\eta| < 6.0$ | $p_T > 30$ GeV |
| $|\eta| < 4.0$ | $|\eta| < 6.0$ | $p_T > 50$ GeV |

3% at 30ab$^{-1}$

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**FCC-hh Simulation (Delphes)**

- $m_{\gamma\gamma} > 1000$ GeV
- $m_{\gamma\gamma} > 500$ GeV
- $m_{\gamma\gamma} > 200$ GeV
- $m_{\gamma\gamma} > 50$ GeV

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Summary

• VBS to investigate SM and probe NP effects
  – Direct scrutiny of EWSB
  – Extensions to SM offer alternative EWSB mechanisms

• Several processes and final states investigated
  – Rare process, limited statistics
  – Indirect BSM studies with the EFT approach
  – Current and future studies at LHC and beyond

• VBS processes observed but need to be studied

⇒ Clean environment of lepton collider at highest energies is a fantastic opportunity for searches for NP in the EW sector