First Evidence of Same-sign WW Vector Boson Scattering Process at ATLAS

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Outline

• Introduction to Quartic Gauge Coupling and Vector Boson Scattering
• Previous studies with QGC and VBS
• Same-sign WW VBS studies at ATLAS using 20.3 fb\(^{-1}\) of data
  (arXiv:1405.6241, accepted by PRL as a PRL Editor’s Suggestion)
  – First evidence for \(W^\pm W^\pm \rightarrow W^\pm W^\pm\) scattering process
  – First set of limits on WWWWW aQGCs
• Summary
Introduction

• SM is based on SU(3)×SU(2)×U(1) gauge symmetry
• The SM Lagrangian for the EW sector can be written as:

\[ \mathcal{L}_{\text{EW}} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_{HHV} + \mathcal{L}_Y + \mathcal{L}_{HHH/H} \]
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$$\mathcal{L}_C +$$

$$\mathcal{L}_{\text{WWV}} +$$

$$\mathcal{L}_{\text{WWVV}} +$$

$$\mathcal{L}_{\text{HVV}} +$$

$$\mathcal{L}_Y +$$

$$\mathcal{L}_{\text{HHH/H}}$$
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\[
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\]
Introduction

- SM is based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry
- The SM Lagrangian for the EW sector can be written as:

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_{HVV} + \mathcal{L}_Y + \mathcal{L}_{HHH/H}$$

- Well known mass terms
- Precise measurements from LEP, SLD, Tevatron and LHC experiments
- Related to today’s topics
- Recently observations at the LHC, $H \rightarrow WW, H \rightarrow ZZ^*, H \rightarrow \tau \tau$ ($H \rightarrow t\bar{t}$), $H \rightarrow bb$ from the Tevatron
- Not yet seen, waiting for sLHC or ILC

Four QGC couplings: $WWW, WW\gamma\gamma, WWZ\gamma, WWZZ$
Processes with Quartic Gauge Couplings

- QGC process: process where a QGC vertex contributes
  - No reaction is ever mediated by a QGC vertex alone
  - Even a gauge-invariant definition of the QGC-alone contribution is not possible!

- Two classes of QGC processes are measurable:
  - Triboson production (WWZ as one example)
  - Vector boson scattering/fusion (VBS/VBF, $W^+W^-$ as one example)
QGC Studies at the LEP

- Search for $W^+W^-\gamma\gamma$ and $W^+W^-Z\gamma$ processes with $e^+e^- \rightarrow \nu\nu\gamma\gamma$, $WW\gamma$, or $qq\gamma\gamma$

Data are found to be consistent with SM background predictions within ISR/FSR uncertainties (no strong indications for the existence of QGC contributions)
QGC Studies at the LHC

- CMS: $pp \rightarrow W(\rightarrow \ell \nu)V(\rightarrow jj)\gamma$

\[ \sigma(pp \rightarrow WV\gamma) < 311 \text{ fb} \] compared to the SM prediction of $91.6 \pm 21.7 \text{ fb}$

\[ \sigma(pp \rightarrow WV\gamma) < 311 \text{ fb} \]

arXiv:1404.4619, submitted to PRD
QGC Studies at the LHC

- CMS: $pp \rightarrow p(*)WWp(*) \rightarrow p(*)e\nu\mu\nu p(*)$

- High-$p_T$ dilepton ($e\mu$) and two forward scattered protons not detected, no other tracks associated with the PV, large $p_T(e\mu)$ and $m(e\mu)$

$\sigma(pp \rightarrow p(*)WWp(*)) \rightarrow p(*)e\nu\mu\nu p(*)) < 10.6$ fb compared to the SM prediction of $4.0 \pm 0.7$ fb

No real observations of any QGC processes at the LEP, Tevatron and LHC so far
Vector Boson Scattering (VV → VV)

$W^+W^-$ scattering/fusion without a SM Higgs

The unitarity can be restored by adding a Higgs scalar with exactly the SM HWW coupling

Unitarity violation

$M \propto s$  

$s, t - M_H^2$

Lee, Quigg, Thacker, PRD 16, 1519 (1977)

$M \propto \frac{s^2}{s-M_H^2} + \frac{t}{t-M_H^2}$

$\sigma(VV \rightarrow VV)$, no Higgs

Alboteanu et al.  
JHEP: 0811.010 (2008)

$\sigma(VV \rightarrow VV)$ with $m_h = 120$ GeV

Alboteanu et al.  
JHEP: 0811.010 (2008)

$\Rightarrow$ center-of-mass energy for VV system
High Mass Resonances

- The Higgs boson is the most economic solution to restore the unitarity, but it is not the only choice (new physics, or new physics + (non)-SM Higgs).

With the discovery of a SM-like Higgs boson, we need to know if this boson is fully or only partially responsible for the EWSB in the whole energy regime.

- Observe or exclude strong VV scattering
- Determine the dynamics of EWSB

Alboteanu et al.
JHEP: 0811.010 (2008)
VVjj: Electroweak Production (EW VVjj)

- **VBS processes**
- EW production of VVjj: No QCD vertices involved
- Non-VBS processes: Not gauge invariantly separable from VBS
  - Gauge invariantly separable from VBS

\[ \text{VBS processes} = \text{Non-VBS processes} \]

August 27, 2014
Strong production of VVjj: QCD vertices involved

VBS processes are interesting processes to study. Many literature papers available for the investigations of different selection criteria (forward jets, large $m_{jj}$, $\Delta y_{jj}$, central-jet veto etc) to separate interesting EW production from strong production and non-VBS production.
VBS Studies at the LHC

- CMS: EW production of Zjj final state at 7 TeV
- Tight cuts on $p_T(j_1)$, $p_T(j_2)$, $m_{jj}$, $\Delta\eta_{jj}$ to increase the signal-to-background ratio

$2.6\sigma$ significance for EW production of Zjj
$\sigma = 154 \pm 24 \pm 53$ fb compared to the SM prediction of 166 fb
VBS Studies at the LHC

• ATLAS and CMS performed similar studies for EW production of Zjj final state at 8 TeV

5σ significance for EW production of Zjj

\[ \sigma_{\text{fid}} = 54.7 \pm 4.6 \pm 10.5 \text{ fb} \]

compared to the SM prediction of 46.1 fb

5.9σ significance for EW production of Zjj

\[ \sigma_{\text{fid}} = 226 \pm 26 \pm 35 \text{ fb} \]

compared to the SM prediction of 239 fb
VBS Studies at the LHC

• Both ATLAS and CMS have searched for $H \rightarrow \gamma \gamma$, $ZZ^*$, $WW^*$, $\tau \tau$, $bb$ production in VBF modes

• No $3\sigma$ evidence observed in each individual channel yet

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### ATLAS Prelim.

$m_H = 125.5$ GeV

| $H \rightarrow \gamma \gamma$ | $\frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+gH}}}$ | $\frac{\sigma(\text{stat})}{\sigma(\text{sys inc.})}$ | Total uncertainty
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.2^{+0.8}_{-0.6}$</td>
<td>$\pm 1\sigma$</td>
<td>$\pm 2\sigma$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$H \rightarrow ZZ^* \rightarrow 4l$</th>
<th>$\frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+gH}}}$</th>
<th>$\pm 1\sigma$</th>
<th>$\pm 2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow WW^* \rightarrow lvlv$</td>
<td>$\frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+gH}}}$</td>
<td>$\pm 1\sigma$</td>
<td>$\pm 2\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow \tau \tau$</td>
<td>$\frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+gH}}}$</td>
<td>$\pm 1\sigma$</td>
<td>$\pm 2\sigma$</td>
</tr>
</tbody>
</table>

| Combined                           | $\frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+gH}}}$ | $\pm 1\sigma$ | $\pm 2\sigma$ |

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### CMS Preliminary

**ATLAS-CONF-2014-009**

**CMS-PAS-HIG-13-005**

$\sqrt{s} = 7 \text{ TeV}, L \leq 5.1 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}, L \leq 19.6 \text{ fb}^{-1}$

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$\mu_{\text{VBF+VH}}$ vs $\mu_{\text{ggF+ttH}}$
Vector Boson Scattering

- No evidences for QGC processes (no studies with $VV \rightarrow VV$, $V=W,Z$) so far
- Only observed the $Zjj$ VBS process with $WW \rightarrow Z$ (TGC) at the LHC
- Not an easy task to observe VBS process with QGCs:
  - We do not have W/Z beams
  - Large reducible and irreducible SM backgrounds
  - Often could not fully reconstruct the final states W and/or Z bosons
  - Hard to do with photons due to ISR and FSR

<table>
<thead>
<tr>
<th>Final state</th>
<th>Process</th>
<th>$VVjj$-EW</th>
<th>$VVjj$-QCD</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell^+ \nu \ell'^- \nu' jj$ (same sign, arbitrary flavor)</td>
<td>$W^+ W^-$</td>
<td>19.5 fb</td>
<td>18.8 fb</td>
<td>1.04</td>
</tr>
<tr>
<td>$\ell^+ \nu \ell'^- \nu' jj$ (opposite sign)</td>
<td>$W^+ W^+$</td>
<td>91.3 fb</td>
<td>3030 fb</td>
<td>0.03</td>
</tr>
<tr>
<td>$\ell^+ \ell^- \nu' \nu' jj$</td>
<td>$ZZ$</td>
<td>2.4 fb</td>
<td>162 fb</td>
<td>0.015</td>
</tr>
<tr>
<td>$\ell^+ \ell^- \ell^+ \ell^- jj$</td>
<td>$W^\pm Z$</td>
<td>30.2 fb</td>
<td>687 fb</td>
<td>0.04</td>
</tr>
<tr>
<td>$\ell^+ \ell^- \ell^+ \ell^- jj$</td>
<td>$ZZ$</td>
<td>1.5 fb</td>
<td>106 fb</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Sherpa prediction (8 TeV) with two leptons $p_T > 5$ GeV, $M_{ll} > 4$ GeV and at least two jets with $p_T > 10$ GeV

Two same-sign leptons in the final state will also greatly reduce other SM backgrounds
ss WW VBS Event Display

\[ \mu^+\mu^+jj \] Candidate Event

\[ m_{jj} = 2800 \text{ GeV} \quad |\Delta y_{jj}| = 6.3 \]

Run Number: 207490, Event Number: 33152138
Date: 2012-07-26 04:16:35 UTC
Event Selection

- Exactly two SS isolated leptons with $p_T > 25$ GeV and $|\eta| < 2.5$
- MET $> 40$ GeV
- At least two jets with $p_T > 30$ GeV and $|\eta| < 4.5$
- **WZ veto**: veto a third lepton with lower $p_T$ and looser quality requirements
- **Z veto**: $|m_{ee} - m_Z| > 10$ GeV to suppress the $Z \rightarrow ee$ contribution with the charge of one electron misidentified
- **ttbar veto**: no b-tagged jets in each event
- **Inclusive region**: $m_{jj} > 500$ GeV
- **VBS region**: $m_{jj} > 500$ GeV and $|\Delta y_{jj}| > 2.4$ → enhance the contribution from electroweak production
Backgrounds

- **MC-based estimation:**
  - WZ + jets (Sherpa)
  - Wγjj, tt+W/Z, ZZ (Alpgen+Sherpa/Madgraph/Sherpa)
  - Double parton scattering (negligible)

- **Data-driven estimation:**
  - Z + jets for ee and eμ channels (charge misID bkg)
  - Background with one or two jets mis-reconstructed as isolated leptons (non-prompt bkg)
Charge misID Background

- Muon charge misID rate is negligible
- Charge misID rate measured using $Z \rightarrow ee$ events in data
- Likelihood and tag-and-probe methods used
- Excellent MC closure test for both methods
- OS events are scaled by the charge misID rate to estimate charge misID background in the SS signal region
- Electrons that suffer charge misID tend to have a lower reconstructed energy due to bremsstrahlung, average electron energy loss corrected based on MC studies
- Several CRs defined to check charge misID rate and bkg estimation method

<table>
<thead>
<tr>
<th>Region name</th>
<th>Charge misID (OS-scaled)</th>
<th>Other backgrounds</th>
<th>Observed</th>
<th>Expected / Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS Z</td>
<td>$11419 \pm 12$ (stat.)</td>
<td>108 ± 16</td>
<td>11820</td>
<td>0.98 ± 0.01</td>
</tr>
<tr>
<td>Low $N_{\text{jet}}$ CF</td>
<td>$1924.5 \pm 5.0$ (stat.)</td>
<td>301 ± 56</td>
<td>2370</td>
<td>0.94 ± 0.03</td>
</tr>
<tr>
<td>VBF-like SS Z</td>
<td>$313.4 \pm 2.4$</td>
<td>12.1 ± 1.8</td>
<td>348</td>
<td>0.94 ± 0.05</td>
</tr>
<tr>
<td>SS Incl.</td>
<td>$1021.7 \pm 3.7$</td>
<td>261 ± 41</td>
<td>1318</td>
<td>0.97 ± 0.04</td>
</tr>
<tr>
<td>Top</td>
<td>$21.5 \pm 0.5$</td>
<td>20.2 ± 4.6</td>
<td>46</td>
<td>0.91 ± 0.17 (0.5σ)</td>
</tr>
</tbody>
</table>
Charge misID Background

**ATLAS**

20.3 fb⁻¹, \( \sqrt{s} = 8 \) TeV

- Data 2012
- Syst. Uncertainty
- W⁺W⁻jj ewk+strong
- OS prompt leptons
- W⁺γ
- Other non-prompt
- t⁺t⁻W/Z

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Non-prompt Background

- Fake factor method:
  - Measure a correction factor based on two definitions of leptons
    - Tight: normal lepton definition
    - Loose: failing isolation cuts and passing looser quality criteria
  - \( f = \frac{N_{\text{tight}}}{N_{\text{loose}}} \) determined from a dijet sample
  - Scale the tight+loose data sample by the fake factor to estimate the non-prompt background in the signal region

Lepton, jet \( p_T > 25 \text{ GeV} \)
\( \Delta \phi(l, j) > 2.8 \)
\( M_T < 40 \text{ GeV} \)
Non-prompt Background

• Due to tight lepton definition used, not easy to find a region dominated by non-prompt background

• Use same-sign ttbar events with at least one tagged b-jet
**WZ+jets Background**

- Dominant background source for the two signal regions
- The generator-level $Z/\gamma^*$ mass is required to be greater than 1 GeV (30% off-shell contribution to the total background after the final selection)
- Normalized to QCD NLO calculation using VBFNLO
- Sherpa MC simulation checked using events with three leptons and $m_{jj}$ and $\Delta y_{jj}$ cuts removed
Signal Simulation

- Several MC event generators available to produce $W^\pm W^\pm jj$ events (Sherpa, VBFNLO, Powheg-box, WHIZARD etc)
- Sherpa sample normalized to Powheg-box predicted cross sections
- Inclusive and VBS fiducial regions defined at the generator level using similar cuts as applied at the reconstruction level

<table>
<thead>
<tr>
<th>Process</th>
<th>Inclusive SR (fb)</th>
<th>VBS SR (fb)</th>
<th>Dominant uncertainty sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW $W^\pm W^\pm jj$</td>
<td>$1.00 \pm 0.06$</td>
<td>$0.88 \pm 0.05$</td>
<td>Generator/PDF/parton shower/scale uncertainties</td>
</tr>
<tr>
<td>Strong $W^\pm W^\pm jj$</td>
<td>$0.35 \pm 0.05$</td>
<td>$0.098 \pm 0.018$</td>
<td>Scale dependence/Generator/parton shower MC statistics</td>
</tr>
</tbody>
</table>

- Interference effects between EW and strong production studied using Sherpa, increase the inclusive SR cross section by $(12\pm6)\%$ and the VBS SR cross section by $(7\pm4)\%$
- Inclusive: EW+strong+interference as the signal
- VBS: EW+interference as the signal
Background Compositions in CRs

- Check both yields and shape distributions between data and MC for four control regions:
  - **Low $m_{jj}$ CR:** $m_{jj} < 500$ GeV
  - **Trilepton CR:** events with three leptons, $m_{jj}$ and $\Delta y_{jj}$ cuts removed
  - **b-tag CR:** at least one b-tagged jet
  - **$\leq 1$ jet CR:** events with $\leq 1$ jet
Low $m_{jj}$ Control Region

<table>
<thead>
<tr>
<th>Source</th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^{\pm}W^{\pm}jj$ ewk-strong</td>
<td>6.5 ± 0.7</td>
<td>18.8 ± 1.9</td>
<td>11.4 ± 1.2</td>
<td>37 ± 4</td>
</tr>
<tr>
<td>$WZ/\gamma^*,ZZ$</td>
<td>25 ± 4</td>
<td>54 ± 9</td>
<td>18.4 ± 3.1</td>
<td>98 ± 16</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>14 ± 4</td>
<td>20 ± 6</td>
<td>-</td>
<td>34 ± 10</td>
</tr>
<tr>
<td>$t\bar{t} + W/Z$</td>
<td>1.7 ± 0.7</td>
<td>3.8 ± 1.6</td>
<td>2.4 ± 1.0</td>
<td>7.9 ± 3.4</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>19.4 ± 2.3</td>
<td>8.4 ± 1.4</td>
<td>-</td>
<td>27.8 ± 3.4</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>9 ± 4</td>
<td>21 ± 8</td>
<td>8 ± 4</td>
<td>39 ± 10</td>
</tr>
<tr>
<td><strong>Total Predicted</strong></td>
<td><strong>76 ± 9</strong></td>
<td><strong>127 ± 16</strong></td>
<td><strong>40 ± 6</strong></td>
<td><strong>243 ± 27</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>78</td>
<td>120</td>
<td>30</td>
<td>228</td>
</tr>
</tbody>
</table>
Trilepton Control Region

\[ \int L \, dt = 20.3 \, fb^{-1}, \frac{\sqrt{s}}{\sqrt{s}} = 8 \, TeV \]

### Table: Trilepton Control Region

<table>
<thead>
<tr>
<th>Process</th>
<th>$e^\pm e^\pm \ell^\mp$</th>
<th>$e^\pm \mu^\pm \ell^\mp$</th>
<th>$\mu^\pm \mu^\pm \ell^\mp$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\pm jj$</td>
<td>$0.01 \pm 0.01$</td>
<td>$0.11 \pm 0.02$</td>
<td>$0.00 \pm 0.00$</td>
<td>$0.12 \pm 0.02$</td>
</tr>
<tr>
<td>$WZ/\gamma^*$</td>
<td>$32 \pm 5$</td>
<td>$96 \pm 16$</td>
<td>$57 \pm 10$</td>
<td>$186 \pm 31$</td>
</tr>
<tr>
<td>$ZZ \rightarrow 4l$</td>
<td>$2.2 \pm 0.6$</td>
<td>$5.3 \pm 1.3$</td>
<td>$1.8 \pm 0.5$</td>
<td>$9.2 \pm 2.1$</td>
</tr>
<tr>
<td>$t\bar{t} + W/Z$</td>
<td>$0.65 \pm 0.28$</td>
<td>$2.4 \pm 1.0$</td>
<td>$1.0 \pm 0.5$</td>
<td>$4.1 \pm 1.7$</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>$0.48 \pm 0.32$</td>
<td>$6 \pm 5$</td>
<td>$0.00 \pm 0.00$</td>
<td>$7 \pm 5$</td>
</tr>
<tr>
<td>Total Predicted</td>
<td>$36 \pm 6$</td>
<td>$110 \pm 18$</td>
<td>$60 \pm 10$</td>
<td>$206 \pm 33$</td>
</tr>
<tr>
<td>Data</td>
<td>$40$</td>
<td>$104$</td>
<td>$48$</td>
<td>$192$</td>
</tr>
</tbody>
</table>
# b-tag Control Region

**ATLAS**

<table>
<thead>
<tr>
<th>Process</th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\pm jj$ ewk+strong</td>
<td>$0.81 \pm 0.10$</td>
<td>$2.57 \pm 0.28$</td>
<td>$1.55 \pm 0.18$</td>
<td>$4.9 \pm 0.5$</td>
</tr>
<tr>
<td>$WZ\gamma^*, ZZ$</td>
<td>$2.3 \pm 0.5$</td>
<td>$4.9 \pm 0.9$</td>
<td>$2.2 \pm 0.4$</td>
<td>$9.4 \pm 1.6$</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>$1.7 \pm 0.7$</td>
<td>$2.3 \pm 0.9$</td>
<td>$-$</td>
<td>$4.0 \pm 1.4$</td>
</tr>
<tr>
<td>$t\bar{t} + W/Z$</td>
<td>$7.1 \pm 3.1$</td>
<td>$18 \pm 8$</td>
<td>$11 \pm 4$</td>
<td>$36 \pm 15$</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>$22 \pm 5$</td>
<td>$27 \pm 6$</td>
<td>$-$</td>
<td>$49 \pm 11$</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>$6.7 \pm 2.5$</td>
<td>$20 \pm 8$</td>
<td>$10 \pm 5$</td>
<td>$37 \pm 10$</td>
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<tr>
<td><strong>Total Predicted</strong></td>
<td>$40 \pm 6$</td>
<td>$75 \pm 13$</td>
<td>$25 \pm 7$</td>
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<tr>
<td><strong>Data</strong></td>
<td>$46$</td>
<td>$82$</td>
<td>$36$</td>
<td>$164$</td>
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$\leq 1$ jet Control Region

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<tr>
<th>Source</th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
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<tr>
<td>$W^\pm W^\mp jj$ ewk+strong</td>
<td>$2.72 \pm 0.30$</td>
<td>$8.2 \pm 0.8$</td>
<td>$4.2 \pm 0.4$</td>
<td>$15.1 \pm 1.5$</td>
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<tr>
<td>$WZ/\gamma^*, ZZ$</td>
<td>$46 \pm 8$</td>
<td>$130 \pm 23$</td>
<td>$75 \pm 13$</td>
<td>$250 \pm 40$</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>$39 \pm 11$</td>
<td>$59 \pm 17$</td>
<td>$-$</td>
<td>$98 \pm 29$</td>
</tr>
<tr>
<td>$t\bar{t} + W/Z$</td>
<td>$0.34 \pm 0.15$</td>
<td>$0.8 \pm 0.4$</td>
<td>$0.56 \pm 0.25$</td>
<td>$1.7 \pm 0.7$</td>
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<tr>
<td>OS prompt leptons</td>
<td>$152 \pm 17$</td>
<td>$24 \pm 4$</td>
<td>$-$</td>
<td>$177 \pm 21$</td>
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<td>Other non-prompt</td>
<td>$38 \pm 15$</td>
<td>$65 \pm 26$</td>
<td>$8 \pm 5$</td>
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<tr>
<td>Total Predicted</td>
<td>$278 \pm 28$</td>
<td>$290 \pm 40$</td>
<td>$88 \pm 14$</td>
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<td>Data</td>
<td>$288$</td>
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<td>$717$</td>
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Inclusive Signal Region

$e^\pm e^\pm$

$\mu^\pm \mu^\pm$

Combined
VBS Signal Region

**ATLAS**
20.3 fb⁻¹, √s = 8 TeV

VBS SR ee

- Data 2012
- Syst. Uncertainty
- W⁺W⁻jj Electroweak
- WZ/γ⁺, ZZ, t̅t+W/Z
- OS prompt leptons
- W+γ
- W⁺W⁻jj Strong
- Other non-prompt

VBS SR eμ

- Data 2012
- Syst. Uncertainty
- W⁺W⁻jj Electroweak
- WZ/γ⁺, ZZ, t̅t+W/Z
- W⁺W⁻jj Strong
- Other non-prompt
- W+γ
- OS prompt leptons

VBS SR μμ

- Data 2012
- Syst. Uncertainty
- W⁺W⁻jj Electroweak
- WZ/γ⁺, ZZ, t̅t+W/Z
- W⁺W⁻jj Strong
- Other non-prompt

m_{jj} > 500 GeV

Combined

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<tr>
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<table>
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<th>Δy_{jj}</th>
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<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

August 27, 2014

University of Michigan - Junjie Zhu
Lepton centrality

- Lepton centrality: \( \zeta = \min\{\eta(j_1) - \eta(l_1), \eta(l_2) - \eta(j_2)\} \) where \( \eta(j_1) > \eta(j_2) \) and \( \eta(l_1) > \eta(l_2) \)
# Signal Region Numbers

## Inclusive Signal Region

<table>
<thead>
<tr>
<th></th>
<th>( e^\pm e^\pm )</th>
<th>( e^\pm \mu^\pm )</th>
<th>( \mu^\pm \mu^\pm )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W^\pm W^\pm jj ) Electroweak</td>
<td>3.07 ± 0.30</td>
<td>9.0 ± 0.8</td>
<td>4.9 ± 0.5</td>
<td>16.9 ± 1.5</td>
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<tr>
<td>( W^\pm W^\pm jj ) Strong</td>
<td>0.89 ± 0.15</td>
<td>2.5 ± 0.4</td>
<td>1.42 ± 0.23</td>
<td>4.8 ± 0.8</td>
</tr>
<tr>
<td>( WZ/\gamma^*, ZZ, t\bar{t} + W/Z )</td>
<td>3.0 ± 0.7</td>
<td>6.1 ± 1.3</td>
<td>2.6 ± 0.6</td>
<td>11.6 ± 2.5</td>
</tr>
<tr>
<td>( W + \gamma )</td>
<td>1.1 ± 0.6</td>
<td>1.6 ± 0.8</td>
<td>–</td>
<td>2.7 ± 1.2</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>2.1 ± 0.4</td>
<td>0.77 ± 0.27</td>
<td>–</td>
<td>2.8 ± 0.6</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>0.61 ± 0.30</td>
<td>1.9 ± 0.8</td>
<td>0.41 ± 0.22</td>
<td>2.9 ± 0.8</td>
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<tr>
<td>Total Predicted</td>
<td>10.7 ± 1.4</td>
<td>21.7 ± 2.6</td>
<td>9.3 ± 1.0</td>
<td>42 ± 5</td>
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<tr>
<td>Data</td>
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<td>26</td>
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## VBS Signal Region

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<th>( e^\pm \mu^\pm )</th>
<th>( \mu^\pm \mu^\pm )</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>( W^\pm W^\pm jj ) Electroweak</td>
<td>2.55 ± 0.25</td>
<td>7.3 ± 0.6</td>
<td>4.0 ± 0.4</td>
<td>13.9 ± 1.2</td>
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<tr>
<td>( W^\pm W^\pm jj ) Strong</td>
<td>0.25 ± 0.06</td>
<td>0.71 ± 0.14</td>
<td>0.38 ± 0.08</td>
<td>1.34 ± 0.26</td>
</tr>
<tr>
<td>( WZ/\gamma^*, ZZ, t\bar{t} + W/Z )</td>
<td>2.2 ± 0.5</td>
<td>4.2 ± 1.0</td>
<td>1.9 ± 0.5</td>
<td>8.2 ± 1.9</td>
</tr>
<tr>
<td>( W + \gamma )</td>
<td>0.7 ± 0.4</td>
<td>1.3 ± 0.7</td>
<td>–</td>
<td>2.0 ± 1.0</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>1.39 ± 0.27</td>
<td>0.64 ± 0.24</td>
<td>–</td>
<td>2.0 ± 0.5</td>
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<tr>
<td>Other non-prompt</td>
<td>0.50 ± 0.26</td>
<td>1.5 ± 0.6</td>
<td>0.34 ± 0.19</td>
<td>2.3 ± 0.7</td>
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<tr>
<td>Total Predicted</td>
<td>7.6 ± 1.0</td>
<td>15.6 ± 2.0</td>
<td>6.6 ± 0.8</td>
<td>29.8 ± 3.5</td>
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<td>18</td>
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## Inclusive SR Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic Uncertainties $ee/\mu\mu/\mu\mu$ (%)</th>
<th>Inclusive SR</th>
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</thead>
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<tr>
<td><strong>Background</strong></td>
<td>$ee/\mu\mu/\mu\mu$</td>
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<tr>
<td>Jet uncertainties</td>
<td>11/13/13</td>
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<tr>
<td>Theory $WZ/\gamma^*$</td>
<td>5.6/7.7/11</td>
</tr>
<tr>
<td>MC statistics</td>
<td>8.2/5.9/8.4</td>
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<tr>
<td>Fake rate</td>
<td>3.5/7.1/7.2</td>
</tr>
<tr>
<td>OS lepton bkg/</td>
<td>5.9/4.2/−</td>
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<tr>
<td>Conversion rate</td>
<td>2.8/2.6/−</td>
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<tr>
<td>Theory $W + \gamma$</td>
<td>2.2/2.4/1.8</td>
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<tr>
<td>$E_T^{miss}$ reconstruction</td>
<td>1.7/2.1/2.4</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.6/1.2/1.2</td>
</tr>
<tr>
<td>Lepton reconstruction</td>
<td>1.0/1.1/1.0</td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>0.1/0.2/0.4</td>
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## VBS SR Systematic Uncertainties

<table>
<thead>
<tr>
<th>Background</th>
<th>ee / eμ / μμ (%)</th>
<th>Signal</th>
<th>ee / eμ / μμ (%)</th>
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<tbody>
<tr>
<td>Jet uncertainties</td>
<td>13 / 15 / 15</td>
<td>Theory $W^\pm W^\pm jj$-ewk</td>
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<td>Theory $WZ/\gamma^*$</td>
<td>4.5 / 5.4 / 7.8</td>
<td>Jet uncertainties</td>
<td>5.1</td>
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<td>MC statistics</td>
<td>8.9 / 6.4 / 8.4</td>
<td>Luminosity</td>
<td>2.8</td>
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<tr>
<td>Fake rate</td>
<td>4.0 / 7.2 / 6.8</td>
<td>MC statistics</td>
<td>4.5 / 2.7 / 3.7</td>
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<tr>
<td>OS lepton bkg/Conversion rate</td>
<td>5.5 / 4.4 / -</td>
<td>$E_T^{miss}$ reconstruction</td>
<td>1.1</td>
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<tr>
<td>$E_T^{miss}$ reconstruction</td>
<td>2.9 / 3.2 / 1.4</td>
<td>Lepton reconstruction</td>
<td>1.9 / 1.0 / 0.7</td>
</tr>
<tr>
<td>Theory $W+\gamma$ Luminosity</td>
<td>3.1 / 2.6 / -</td>
<td>b-tagging efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Theory $W^\pm W^\pm jj$-strong</td>
<td>0.9 / 1.5 / 2.6</td>
<td>trigger efficiency</td>
<td>0.1 / 0.3 / 0.5</td>
</tr>
<tr>
<td>Lepton reconstruction</td>
<td>1.7 / 1.1 / 1.1</td>
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<tr>
<td>b-tagging efficiency</td>
<td>0.8 / 0.9 / 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.1 / 0.2 / 0.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cross Section Extraction

- Profile likelihood ratio method used to extract the final cross sections from all three channels taken into account correlated systematics

\[
L(\sigma_{W^\pm W^\pm jj}, \mathcal{L}, \alpha_j) = \text{Gaus}(\mathcal{L}_0|\mathcal{L}, \sigma_\mathcal{L}) \prod_{i \in \{ee, \mu\mu, e\mu\}} \text{Pois}(N_i^{\text{obs}}|N_i^{\text{exp}}) \prod_{j \in \text{syst}} \text{Gaus}(\alpha_j^0|\alpha_j, 1)
\]

- Inclusive SR: \(\sigma = 2.1 \pm 0.5 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ fb}, 4.5\sigma \text{ obs. (3.4}\sigma \text{ exp.)}\)
- VBS SR: \(\sigma = 1.3 \pm 0.4 \text{ (stat)} \pm 0.2 \text{ (syst)} \text{ fb}, 3.6\sigma \text{ obs. (2.8}\sigma \text{ exp.)}\)

- First ever evidence for EWK VV → VV scattering at the LHC
Anomalous QGCs

• Anomalous quartic couplings modify the expected cross sections
• We would like to set limits on possible new physics using the measured cross sections in a model-independent way
  – Use the effective Lagrangian:

\[ \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} \]
  – Can introduce unphysical predictions at high energies
  – Requires unitarization scheme
• Consider the chiral Lagrangian approach as implemented in WHIZARD (JHEP 11(2008) 010):
  – The terms that affect WWVV QGCs are \( \alpha_4 \) and \( \alpha_5 \)
• Indirect constraints from electroweak precision data (Eboli et al, PRD 74, 073005 (2006), 99% CL bounds):

\[-0.35 < \alpha_4 < 0.06 \text{ and } -0.87 < \alpha_5 < 0.15\]
• Unitarization: cut-off, form factor, K-matrix, inverse-amplitude method
• We use the K-matrix method as implemented in WHIZARD
  ❖ Projecting the scattering amplitude $A(s)$ onto the Argand circle → Saturation of the amplitude to achieve unitarity
  ❖ Amplitudes satisfying unitarity are invariant under K-matrix unitarization

\[ A_K(s) = \frac{1}{\text{Re}(\frac{1}{A(s)})-i} = \frac{A(s)}{1-iA(s)} \]

arXiv: 1310.6708
Theoretical cross sections in VBS SR with WHIZARD

aQGC limits on $\alpha_4$ and $\alpha_5$

1D aQGC limits:

$\alpha_4 \propto [-0.139, 0.157]$ obs. $[-0.104, 0.116]$ exp.

$\alpha_5 \propto [-0.229, 0.244]$ obs. $[-0.180, 0.199]$ exp.
Future $W^\pm W^\pm$ studies

- Tribons production ($W^\pm W^\pm W \rightarrow l^\pm l^\pm vjj$, ~7 fb at 8 TeV): relative low background, high branching ratio, and well-defined signal region

- VBS $\sigma(W^+W^+)/\sigma(W^-W^-)$ (the ratio is close to 4): can only perform this measurement at Run 2

- $W^\pm W^\pm$ VBS at 14 TeV: ATL-PHYS-PUB-2013-006

- $H^{\pm\pm}\rightarrow W^\pm W^\pm$: arXiv:1407.5053

Theorists’ interpretation of the same-sign WW VBS fiducial cross section we measured
Summary

- VV→VV scattering processes are important processes to understand the dynamics of EWSB
- QGCs predicted in the SM due to non-Abelian nature of the EW theory
- Presented a search for the same-sign WW VBS process using 20.3 fb\(^{-1}\) of data collected by the ATLAS detector
  - Provided a first evidence for the EW production of of \(W^\pm W^\pm \rightarrow W^\pm W^\pm\) at the LHC (4.5 \(\sigma\) observed for the inclusive SR, 3.6 \(\sigma\) observed for the VBS SR)
  - Provided a first set of aQGC limits on WWWWWW interactions
  - Opened a new section in the SM to experimentally study quartic W/Z interactions
- Studies with 13/14 TeV data will dramatically increase our understanding of WWVV and VV→VV scattering