Observation and Measurements of Vector-Boson Scattering at the ATLAS Detector

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on behalf of ATLAS Collaboration
Motivation

Vector boson scattering (massive bosons)
- Test of Standard Model (SM) gauge structure
- QGC becomes accessible (i.e. WWWW)
- Better understanding of the nature of EWSB mechanism since involves Higgs boson
- BSM anomalous QGC limits

VBS as Goldstone boson scattering (Goldstone Boson Equivalence Theorem)
- $W^\pm$ and $Z$ bosons acquire mass spending three Goldstone bosons (angular fields)
- Parametrisation of weak isodoublet ($a = 1, 2, 3$)

$$
\Phi(x) = \exp\left( \frac{i}{v} \pi^a(x) \tau^a \right) \begin{pmatrix}
0 \\
\frac{1}{\sqrt{2}} (v + H(x))
\end{pmatrix}
$$

Effective field theory
- Addition of higher order operators to SM
- SM as the limit case of the new model
- Scales beyond the reach of the LHC

$$
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d \geq 4} \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}
$$

Effect of D8 operators for QGC
(arXiv:1408.6207)
Protons interact electro-weakly

Vector Boson Scattering Diagrams

Protons interact electro-weakly

Vector Boson Scattering

QCD WW production

EWK VV production
Object Selection

• Leptonic signatures
  • $WWjj$
    • $\nu \ell + \nu \ell + jj$
  • $WZjj$
    • $\nu \ell + \ell \ell + jj$
  • $ZZjj$
    • $\ell \ell + \ell \ell + jj$
    • $\nu \nu + \ell \ell + jj$

• Semi-leptonic signatures
  • $VVjj$
    • $\ell \ell + jj + jj$
    • $\nu \ell + jj + jj$
    • $\nu \nu + jj + jj$
Object Selection

• Leptonic signatures
  • $WWjj$
    • $\nu_\ell + \nu_\ell + jj$
  • $WZjj$
    • $\nu_\ell + \ell\ell + jj$
  • $ZZjj$
    • $\ell\ell + \ell\ell + jj$
    • $\nu\nu + \ell\ell + jj$

• Semi-leptonic signatures
  • $VVjj$
    • $\ell\ell + jj + jj$
    • $\nu_\ell + jj + jj$
    • $\nu\nu + jj + jj$
Object Selection

- Transverse momentum
- Detector limit in pseudorapidity (\(\eta\))
- Impact parameter
  - Cosmic rejection
  - Secondary vertex
- Overlap removal
  - Electrons, Muons, Jets
- Lepton quality and isolation
- Jet reconstruction
  - Anti-\(k_T\)
  - Standard jet (\(\Delta R = 0.4\))
  - Large jet (\(\Delta R = 1.0\))
  - Track jet (\(\Delta R = 0.2\))
- Pileup jet tagging
- Missing transverse momentum
  - Negative global vector sum of all identified objects and unclassified tracks and calorimeter clusters

max lepton \(\eta\)
- \(>2.47\) (electrons)
- \(>2.7\) (muons)

lepton isolation

lepton separation

impact parameters

jet pseudo-rapidity
- \(>4.5\)

pileup jet treatment

missing \(E_T\)

proton

proton

anti-\(k_T\)
\(\Delta R = 0.4\)

jet

\(d_0\)

\(z_0\)
Object Selection

- Transverse momentum
- Detector limit in pseudorapidity ($\eta$)
- Impact parameter
  - Cosmic rejection
  - Secondary vertex
- Overlap removal
  - Electrons, Muons, Jets
- Lepton quality and isolation
- Jet reconstruction
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  - Standard jet ($\Delta R = 0.4$)
  - Large jet ($\Delta R = 1.0$)
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  - Pileup jet tagging
- Missing transverse momentum
  - Negative global vector sum of all identified objects and unclassified tracks and calorimeter clusters
Event Selection

- Leptonic W boson
  - High quality lepton plus missing transverse momentum
  - Additional lepton veto
  - bJet veto
- Leptonic Z boson
  - Same flavour opposite charge di-lepton (SFOC)
  - Di-lepton mass window
- Hadronic boson
  - Two small jets
  - One large jet and jet substructure
  - Di-jet mass window
- Invisible boson
  - Large missing transverse energy
- Tagging di-jet selection
  - Hardest jet from opposite side of detector
  - Di-jet separation in rapidity
  - High di-jet mass requirement
  - Jet-lepton centrality

\[ m_T = \sqrt{2p_T^e p_T^{\text{miss}}(1 - \cos \Delta\phi)} \]
Event Selection

- Leptonic W boson
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Aug 29, 2019

Ondřej Penc, Acad. of Sciences of the Czech Rep.
arXiv:1906.03203
\( W^\pm W^\pm \) - VBS “Discovery” Channel

- VBS final state: \( \nu \ell^\pm \nu \ell^\pm + jj \)
- Dataset: 36.1 fb\(^{-1}\), 13 TeV
- Expected significance: 6.5 \( \sigma \) (Powheg-Box) and 4.4 \( \sigma \) (Sherpa)
- Same sign requirement suppress \( q\bar{q} \) production

- Prompt background (MC modeled)
  - \( WZ+\)jets (dominant), \( WW+\)jets (QCD), \( ZZ+\)jets, and VVV

Non-prompt background (data driven)
- \( t\bar{t} \), \( WW+\)jets (QCD), \( Vy+\)jets, \( W+\)jets, \( t+\)jets
- Lepton misidentification (photon misidentified as electron)
- Charge misidentification (same sign leptons)

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

Control regions

\begin{align*}
\text{Events / bin} \\
\hline
F \rightarrow \ell^\pm \ell^\pm & \quad 250 \\
\ell^+\ell^- \rightarrow e^+e^- & \quad 200 \\
e^+\mu^- \rightarrow e^+\mu^- & \quad 150 \\
\mu^+\mu^- \rightarrow \mu^+\mu^- & \quad 100 \\
\mu^+\mu^- \rightarrow \mu^+\mu^- & \quad 50 \\
\ell^+\ell^- \rightarrow e^+e^- & \quad 10 \\
\ell^+\ell^- \rightarrow \mu^+\mu^- & \quad 5 \\
\hline
\end{align*}

\( WZ \) CR

low \( m_{jj} \) CRs

Data
- \( W^\pm W^\pm jj \) electroweak
- \( W^\pm W^\pm jj \) strong
- Non-prompt
- \( e^+/\gamma \) conversions
- \( WZ \)
- Other prompt
- Total uncertainty

arXiv:1906.03203
MC simulations for $W^\pm W^\pm$ VBS

- Extensive MC studies for VBS first evidence channel
- Predicted cross-section and kinematic distribution comparison studies
- Low di-jet mass disagreement

**Comparison settings**

- Generators: MadGraph5_aMC@NLO, Powheg-Box 2, Sherpa 2
- Parton showering: Pythia 8, Herwig 7, Sherpa 2
- Factorization and renormalization scales effects

$W$ mass, di-boson invariant mass, $\sqrt{p_T^1 p_T^2}$

Non-optimal setting of the color flow for the Sherpa parton shower
**W±W±** - Results

- Signal strength (compared to Sherpa)
  \[ 1.44^{+0.26}_{-0.24} \text{(stat.)}^{+0.28}_{-0.22} \text{(syst.)} \]

- Background only hypothesis rejected with significance 6.5 \(\sigma\) (expected 4.4/6.5 \(\sigma\))

- EWK Fiducial cross-section
  \[ 2.89^{+0.51}_{-0.48} \text{(stat.)}^{+0.29}_{-0.28} \text{(syst.)} \text{ fb} \]

- No deviation from SM observed in \(W±W±jj\) EWK

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**ATLAS**

\(\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}\)

\(W^±W^±jj\) EW

- Gauge dependent non-SM calculations
- no HWW vertex
- no WWWW vertex
- Unitary gauge
- no WWWW vertex
- Feynman gauge

**ATLAS**

\(\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}\)

\(W^±W^±jj\) EW

- Data - Background
- \(W^±W^±jj\) EW in the SM

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W\(^{\pm}Z\) – VBS “Mix” Channel

- VBS final state: \(\nu\nu\nu\nu + jj\)
- Dataset: 36.1 fb\(^{-1}\), 13 TeV
- Expected significance: 3.2 \(\sigma\)
- MVA: TMVA BDT, 15 variables
- W and Z reconstruction using Resonant Shape algorithm

- Fourth lepton veto
- Prompt background
  - WZ+jets (QCD), ZZ+jets, t\(\bar{t}\)V, VVV, tZ+jets
- Non-Prompt background
  - Z+jets, Z\(\gamma\)+jets, t\(\bar{t}\), Wt+jets, WW+jets
  - Misidentified leptons (data driven)

Example of BDT Input

![Example of BDT Input](image)

BDT Score

![BDT Score](image)

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W$^\pm$Z – Results

- EWK Signal strength
  
  $1.77^{+0.44}_{-0.40} \text{ (stat.)}^{+0.26}_{-0.21} \text{ (syst.)}$

- Background only hypothesis rejected with significance 5.3 $\sigma$ (expected 3.2 $\sigma$)

- EWK fiducial cross-section
  
  $0.57^{+0.14}_{-0.13} \text{ (stat.)}^{+0.07}_{-0.06} \text{ (syst.)} \text{ fb}$

- WZjj EWK production observed

- Distributions sensitive to anomalous QGC

- Inclusive fiducial phase space (EWK + QCD)
VV Semi-leptonic – VBS “Jet” Channel

- VBS final states: $\ell\ell jj + jj$, $\ell\nu jj + jj$, $\nu\nu jj + jj$ (2-, 1-, and 0-lepton channel)
- Dataset: 35.5 fb$^{-1}$, 13 TeV
- Expected significance: 2.5 $\sigma$
- MVA: TMVA BDT, 4 – 16 variables
- 9 signal regions, 12 control regions
  - Working points: resolved, high/low purity merged jets
- Dominant background
  - 2-lepton channel
    - $Z$+jets
  - 1-lepton channel
    - $W$+jets, $t\bar{t}$
  - 0-lepton channel
    - $V$+jets, $t\bar{t}$
- Minor background (all channels)
  - $VVjj$ (QCD), $t$+jets, multijet

arXiv:1905.07714
VV Semi-leptonic – Results

- **EWK signal strength**
  \[ 1.05^{+0.20}_{-0.20} \text{(stat.)}^{+0.37}_{-0.34} \text{(syst.)} \]
- Background only hypothesis rejected with significance 2.7 \( \sigma \) (expected 2.5 \( \sigma \))
- **EWK fiducial cross-section**
  \[ 45.1^{+8.6}_{-8.6} \text{(stat.)}^{+15.9}_{-14.6} \text{(syst.)} \text{ fb} \]
- Extensive combined fit (21 signal/control regions)
- Still waiting for evidence

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**ATLAS**

<table>
<thead>
<tr>
<th>Events / 0.1</th>
</tr>
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<tbody>
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<td>0-lepton, Merged high-purity SR</td>
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arXiv:1905.07714
NEW!

- VBS final states: $\ell\ell\ell\ell + jj$, $\nu\nu\ell\ell + jj$
- Dataset: 139 fb$^{-1}$, 13 TeV
  - First VBS analysis of full Run 2 of LHC
- Expected significance: 4.3 $\sigma$
- MVA: TMVA Gradient BDT, 14 variables
- 2 signal regions, 1 control region (only $\ell\ell\ell\ell$)

**Background**

- $\ell\ell\ell\ell$
  - Dominant: ZZ+jets (QCD)
  - Otherwise very clean channel (3%): misidentified leptons, Z+jets, $t\bar{t}$, WZ+jets
- $\nu\nu\ell\ell$
  - Dominant: ZZ+jets (QCD), WZ+jets, WW+jets
  - $t\bar{t}$, Z+jets

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**Diagrams:**

- **ATLAS Preliminary** $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
  - QCD Control Region
  - Signal Region

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**ATLAS Conference**

13
ZZ – Results

• EWK signal strength \(1.35 \pm 0.21\)
• Background only hypothesis rejected with significance 5.5 \(\sigma\) (expected 4.3 \(\sigma\))
• EWK fiducial cross-section \(0.82 \pm 0.34\) fb
• ZZjj EWK production observed

ATLAS Preliminary
\(\sqrt{s} = 13\) TeV, 139 fb\(^{-1}\)
\(\ell\ell\ell\ell jj\) Signal Region
Summary

• ATLAS Vector Boson Scattering
  • Observation in all leptonic channels WW, WZ, ZZ
  • Waiting for evidence in VV semi-leptonic channel
  • Latest observation in the ZZ channel in full Run 2 (139 fb\(^{-1}\))

• Beyond the Standard Model
  • No obvious disagreement with standard model observed
  • Limit settings of the anomalous Quartic Gauge Couplings are ongoing

• Outlook
  • Full Run 2 still offers the further studies and measurements of the VBS phenomena
    • Semi-leptonic channel
    • Channels including gamma
    • Polarization studies
BACKUP
Resonant Shape Algorithm

• Used for WZ VBS channel
• arXiv:1603.02151

• Based on value of the following estimator

\[
P = \left| \frac{1}{m^2_{(\ell^+, \ell^-)} - \left(m^{\text{PDG}}_Z\right)^2 + i \Gamma^{\text{PDG}}_Z m^{\text{PDG}}_Z} \right|^2 \times \left| \frac{1}{m^2_{(\ell', \nu_{\ell'})} - \left(m^{\text{PDG}}_W\right)^2 + i \Gamma^{\text{PDG}}_W m^{\text{PDG}}_W} \right|^2
\]

• Input
  • Mass of all possible di-lepton and neutrino-lepton pairs
  • PDG mass and width of W and Z bosons
• The best evaluated triplet is the WZ candidate
  • Highest \( P \) value
• Monte Carlo independent method