Vector Boson Scattering

as a portal to new physics

Iro Koletsou
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Introduction

- Already many years of proton-proton collisions in LHC
- Higgs discovery in 2012
- Deep study of the electroweak symmetry breaking

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

higgs mass

higgs decay ratios
Introduction

• Already many years of proton-proton collisions in LHC

• Higgs discovery in 2012

• Deep study of the electroweak symmetry breaking

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

• What else is out there?
Introduction

• Already many years of proton-proton collisions in LHC
• Higgs discovery in 2012
• Deep study of the electroweak symmetry breaking

Could it be... nothing?

• What else is out there?

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
Time for rare processes

Vector Boson Scattering (VBS)
Vector Boson Scattering: EW symmetry breaking

- The cross section computation includes interactions with the Higgs boson
- These interactions unitarize the scattering amplitude

- Important test of the **EW** symmetry breaking
- Complementary to direct Higgs studies
VBS: Quartic Gauge boson Couplings (QGC)

- VBS process can give us access to quartic gauge boson couplings
- Anomalous QGCs could lead to deviation in the VBS cross section

➢ and allow new physics to appear
VBS: Quartic Gauge boson Couplings (QGC)

- Anomalous QGC in a EFT framework:

\[
\mathcal{L} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j.
\]

### SM effective Lagrangian

Gauge boson interactions as described by the SM

Valid below an energy scale \( \Lambda \)

### dim-6:

Operators describing aTGCs and aQGCs

VBS processes not really competitive for their constraint

### dim-8:

Lowest order operators describing only aQGCs

Can be constrained by VBS

Three different types of parameters:

- **Only neutral couplings can be induced**

\[
\begin{align*}
\mathcal{L}_{T,0} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \text{Tr} \left[ \hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right] \\
\mathcal{L}_{T,1} &= \text{Tr} \left[ \hat{W}_{\alpha\nu} \hat{W}^{\mu\alpha} \right] \times \text{Tr} \left[ \hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right] \\
\mathcal{L}_{T,2} &= \text{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\nu\beta} \right] \times \text{Tr} \left[ \hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right] \\
\mathcal{L}_{T,3} &= \text{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha} \right] \times B_{\beta\nu} \\
\mathcal{L}_{T,4} &= \text{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\nu\beta} \hat{W}^{\nu\alpha} \right] \times B_{\beta\mu} B^{\alpha\beta} \\
\mathcal{L}_{T,5} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \text{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\beta} \hat{W}^{\nu\alpha} \right] \times B_{\beta\nu} B^{\nu\alpha} \\
\mathcal{L}_{T,7} &= \text{Tr} \left[ \hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\beta\nu} \right] \times B_{\beta\nu} B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu} B^{\nu\mu} B_{\alpha\beta} B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} \\
\end{align*}
\]

\[
\begin{align*}
\mathcal{L}_{M,0} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times (D_{3\beta} \Phi)^{\dagger} D^{3\beta} \\
\mathcal{L}_{M,1} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\beta} \right] \times (D_{3\beta} \Phi)^{\dagger} D^{\mu} \\
\mathcal{L}_{M,2} &= [B_{\mu\nu} B^{\mu\nu}] \times (D_{3\beta} \Phi)^{\dagger} D^{3\beta} \\
\mathcal{L}_{M,3} &= [B_{\mu\nu} B^{\mu\beta}] \times (D_{3\beta} \Phi)^{\dagger} D^{\mu} \\
\mathcal{L}_{M,4} &= (D_{\mu} \Phi)^{\dagger} \hat{W}_{\beta\mu} D^{3\beta} \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= (D_{\mu} \Phi)^{\dagger} \hat{W}_{\beta\mu} D^{\nu} \times B^{3\beta} \\
\mathcal{L}_{M,6} &= (D_{\mu} \Phi)^{\dagger} \hat{W}_{\beta\mu} \hat{W}^{\beta\nu} D^{3\nu} \\
\mathcal{L}_{M,7} &= (D_{\mu} \Phi)^{\dagger} \hat{W}_{\beta\mu} \hat{W}^{\beta\nu} D^{\nu} \\
\end{align*}
\]

\[
\begin{align*}
\mathcal{L}_{S,0} &= \left[ (D_{\mu} \Phi)^{\dagger} D_{\nu} \Phi \right] \times \left[ (D_{\mu} \Phi)^{\dagger} D_{\nu} \Phi \right] \\
\mathcal{L}_{S,1} &= \left[ (D_{\mu} \Phi)^{\dagger} D^{\nu} \Phi \right] \times \left[ (D_{\nu} \Phi)^{\dagger} D^{\nu} \Phi \right] \\
\end{align*}
\]

Pure Higgs field \(f_3\) (cannot induce couplings with photons)

**VVjj final state**

<table>
<thead>
<tr>
<th>ZZ</th>
<th>Zy</th>
<th>W+W-</th>
<th>W-+W-</th>
<th>W-</th>
<th>W#</th>
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31/03/2018

HEP 2018 NTUA
**VBS: a challenging process**

- Very low cross section ($\sim fb$) with a high background
- **Electroweak** diboson production (signal)
  
  > can be enhanced with an optimal choice of analysis phase space

- **QCD** diboson production
With a clear cinematic signature

• Two forward jets and suppressed hadronic activity in between (absence of color flow between interacting partons)

➢ Cinematic discriminative variables (D. Zeppenfeld et al.)

\[ d\sigma / dx \]

\[ m_{\text{inv}} \]  
\[ \hat{p}_T \]  
\[ \Delta \eta \]  

\[ \text{dijet invariant mass} \]  
\[ \text{dijet } \Delta \eta \]  
\[ \text{centrality} \]

\[ \text{arXiv:hep-ph/9605444} \]
## Diboson final states

- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP)
- [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults)

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td><strong>8 TeV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWss</td>
<td>limits on QGCs</td>
<td>only dim-6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>most optimal S/B</td>
</tr>
<tr>
<td>WZ</td>
<td>limits on QGCs</td>
<td>No ew</td>
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<tr>
<td>ZZ</td>
<td>-</td>
<td>No ew</td>
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<tr>
<td></td>
<td></td>
<td>low reducible background</td>
</tr>
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<td>Zγ</td>
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<tr>
<td>Wγ</td>
<td>-</td>
<td>limits on QGCs</td>
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<tr>
<td></td>
<td></td>
<td>largest cross section</td>
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<td><strong>13 TeV</strong></td>
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<tr>
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<td>limits on QGCs</td>
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<td></td>
<td></td>
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</tr>
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<td>limits on QGCs</td>
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Diboson final states

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<td>limits on QGCs</td>
</tr>
<tr>
<td>ZZ</td>
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<td>limits on QGCs</td>
</tr>
</tbody>
</table>
ATLAS Zγ Run 1 Analysis

- $M_{jj}$ variable used to
  - define a QCD control region
  - create a VBS enriched phase space

<table>
<thead>
<tr>
<th>Inclusive region</th>
<th>Control region $Z(l^+l^-)\gamma + \geq 2$ jets</th>
<th>Search region $Z(l^+l^-)\gamma + \geq 2$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 &lt; $m_{jj}$ &lt; 500 GeV</td>
<td>$m_{jj}$ &gt; 500 GeV</td>
<td></td>
</tr>
<tr>
<td>$e^+e^-\gamma jj$</td>
<td>$\mu^+\mu^-\gamma jj$</td>
<td>$e^+e^-\gamma jj$</td>
</tr>
<tr>
<td>Data</td>
<td>781</td>
<td>949</td>
</tr>
<tr>
<td>$Z$+jets bkg.</td>
<td>134 ± 36</td>
<td>154 ± 42</td>
</tr>
<tr>
<td>Other bkg. $(t\bar{t}\gamma, WZ)$</td>
<td>88 ± 17</td>
<td>91 ± 18</td>
</tr>
<tr>
<td>$N_{Z\gamma}$ QCD (SHERPA MC)</td>
<td>583 ± 41</td>
<td>671 ± 47</td>
</tr>
<tr>
<td>$N_{Z\gamma}$ EWK (SHERPA MC)</td>
<td>25.4 ± 1.5</td>
<td>27.3 ± 1.7</td>
</tr>
</tbody>
</table>

2 leptons: $P_T$>25 GeV, $|\eta|<$2.47 (2.5 for $\mu$) $m_{ll}$>40 GeV, $m_{ll}$>182 GeV
2 jets: $P_T$>30 GeV, $|\eta|<$4.5

Redducible background: extracted from data
Irreducible background: normalized in CR
Signal
ATLAS Zγ Run 1 Analysis

- **M_{jj}** variable used to
  - define a QCD control region
  - create a VBS enriched phase space

<table>
<thead>
<tr>
<th>Source of EWK yield [%]</th>
<th>QCD yield [%]</th>
<th>Bkg. yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>Source of EWK yield [%]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2

- **Z+ jets contribution in this table is taken as a fixed fraction,**
- **the uncertainties correspond to the statistical and systematic uncertainties added in quadrature.**

2 leptons: 
- \( P_{Tγ}>25 \text{ GeV}, |η|<2.47 \) (2.5 for \( μ \))
- \( m_γ>40 \text{ GeV}, m_{llγ}>182 \text{ GeV} \)
- 2 jets: \( P_{T}>30 \text{ GeV}, |η|<4.5 \)

### Trend

- **Reducible background: extracted from data**
- **Irreducible background: normalized in CR**
- **Signal**

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ATLAS Zγ Run 1 Analysis

• Centrality variable used as « template »

  ➢ Negative Log Likelihood ratio minimization
  ➢ Parameter of interest: \( \mu = \frac{\sigma_{\text{meas.}}}{\sigma_{\text{MC}}} \)

  \[-\ln(\lambda(\mu)) = -\ln \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}\]

  ➢ θ: Nuisance parameters (systematics)

  \[\sigma^{\text{EWK}}_{Z\gamma jj} = 1.1 \pm 0.5 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ fb}\]
ATLAS Zγ Run 1 Analysis

- $E_T(\gamma)$ variable used to probe the QGC
  
  - High energy tails would be modified if aQGC
  - 7 effective operators varied one by one

<table>
<thead>
<tr>
<th>95% CL intervals</th>
<th>Measured [TeV$^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{T9}/\Lambda^4$</td>
<td>$[-6.9, 6.9] \times 10^4$</td>
</tr>
<tr>
<td>$f_{T8}/\Lambda^4$</td>
<td>$[-3.4, 3.3] \times 10^4$</td>
</tr>
<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>$[-7.2, 6.1] \times 10^1$</td>
</tr>
<tr>
<td>$f_{M0}/\Lambda^4$</td>
<td>$[-1.0, 1.0] \times 10^3$</td>
</tr>
<tr>
<td>$f_{M1}/\Lambda^4$</td>
<td>$[-1.6, 1.7] \times 10^3$</td>
</tr>
<tr>
<td>$f_{M2}/\Lambda^4$</td>
<td>$[-1.1, 1.1] \times 10^4$</td>
</tr>
<tr>
<td>$f_{M3}/\Lambda^4$</td>
<td>$[-1.6, 1.6] \times 10^4$</td>
</tr>
</tbody>
</table>

Non-zero $f_{T,8-9}$ only accessible by Zγ and ZZ channels

\[ L_{T,8} = B_{\mu\nu}B_{\mu\nu} B_{\alpha\beta}B_{\alpha\beta} \]
\[ L_{T,9} = B_{\alpha\mu}B_{\mu\beta}B_{\beta\nu}B_{\nu\alpha} \]

JHEP07(2017)107
CMS WWss Run 2 Analysis

- First (and only) Run 2 VBS analysis to appear
  - 35.9 fb^-1 with an optimal S/B
- Main background: WZ -> measured in dedicated CR asking for a 3\textsuperscript{rd} lepton

<table>
<thead>
<tr>
<th>Data</th>
<th>201</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal + total bkg.</td>
<td>205 ± 13</td>
</tr>
<tr>
<td>Signal</td>
<td>66.9 ± 2.4</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>138 ± 13</td>
</tr>
<tr>
<td>Nonprompt</td>
<td>88 ± 13</td>
</tr>
<tr>
<td>WZ</td>
<td>25.1 ± 1.1</td>
</tr>
<tr>
<td>QCD WW</td>
<td>4.8 ± 0.4</td>
</tr>
<tr>
<td>Wγ</td>
<td>8.3 ± 1.6</td>
</tr>
<tr>
<td>Triboson</td>
<td>5.8 ± 0.8</td>
</tr>
<tr>
<td>Wrong sign</td>
<td>5.2 ± 1.1</td>
</tr>
</tbody>
</table>

2 same sign leptons:
P_\text{T}^1>25 \text{ GeV}, P_\text{T}^2>20 \text{ GeV}, |\eta|<2.5 (2.4 for \mu)
2 jets: P_\text{T}>30 \text{ GeV}, |\eta|<5.0, m_{jj}>500 \text{ GeV}, |\Delta \eta_{jj}|>2.5
Centrality: |\eta_{l}(\eta_{j1}+\eta_{j2})/2|/|\Delta \eta_{jj}|<0.75

Reducible background: extracted from data

Main background: normalized in CR
CMS WWss Run 2 Analysis

- Cross section extraction:
  - 2-dimensionnal fit
  - 2 free parameters: $\mu_{WW}, \mu_{WZ}$
  - 2 regions: SR and WZ CR (only $m_{jj}$)

Results: $$\sigma_{W^\pm W^\pm}^{EWK} = 3.83 \pm 0.66 \text{ (stat)} \pm 0.35 \text{ (syst)} fb$$

$$\frac{\sigma_{fid}^{\text{meas}}}{\sigma_{fid}^{\text{SM}}} = 0.90 \pm 0.22 \text{ with a statistical significance of: } 5.5 \sigma$$
CMS WWss Run 2 Analysis

• $m_\|$ sensible to aQGC

➢ 9 effective operators varied one by one

Not accessible with Zg analysis

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

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

We need the complementarity of several analysis!
Summary of results: $f_T$
Summary of results: $f_M$
Summary

• *VBS* is the “new”, interesting chapter of indirect new physics searches
  
  • First observation with same sign WW (CMS)
  • Already used in Run 1 to set limits to aQGC – machinery in place

• To come:
  
  • New results with much more statistics and new analysis technics
  • Close ATLAS-CMS collaboration in order to combine their results
  • Close collaboration with theorists for the interpretation of the results

• We’re looking forward to this