VV + jets and vector boson scattering at the CMS experiment

Riccardo Bellan
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On behalf of the CMS Collaborations

EPS2017: The European Society Conference on High Energy Physics
Venezia, Italy, 5 July – 12 July, 2017
Top and electroweak physics session
Stairway to Heaven or Highway to Hell?

- Standard Model cross sections successfully tested over 9 orders of magnitude
- We discovered a Higgs boson
- **Still** we have to understand **in detail** the Electroweak Symmetry Breaking Mechanism (*and if there is new physics beyond the SM*)

It is crucial to deeply understand the final states *mediated by heavy gauge boson pair production*: do we *master* them, using our $N^n$LO computations?

- Measure with high precision the differential cross sections
- Measure exclusive multi boson production mechanisms, such as **VV scattering** and **QGC mediated**
- Investigate the high VV mass region

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7th July 2017 – VV+jets and VBS at CMS
What interesting EW features can the VV production probe?

- **Triple gauge couplings (TGC)**
  
  - \( W^+ \rightarrow W^- W^+ \)
  - \( W^- \rightarrow W^+ W^- \)

- **Quartic gauge couplings (QGC)**
  
  - \( W^+ \gamma \rightarrow W^- \gamma \)
  - \( W^- \gamma \rightarrow W^+ \gamma \)
  - \( W^+ Z \rightarrow W^- Z \)
  - \( W^- Z \rightarrow W^+ Z \)
  - \( W^+ W^- \rightarrow W^+ W^- \)
  - \( W^- W^+ \rightarrow W^- W^+ \)
What interesting EW features can the VV production probe?

- **Triple gauge couplings (TGC)**

- **Quartic gauge couplings (QGC)**

Anomalous couplings + what forbidden in SM
Experimental and theoretical challenges

non-VBS diagrams, with \((\alpha_{\text{EW}}^6)\) at tree level

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ZZ+jets analysis

Search for two on-shell \((60 < m_{\ell\ell} < 120 \text{ GeV})\) Z bosons decaying into electrons or muons pairs, consider jets if their \(p_T\) is > 30 GeV

- Final state can be fully reconstructed
  - all kinematic variables are accessible

- Very clean final state
  - low reducible background

- Low \(\sigma \times \text{BR}\) compared to other channels
  - maximize the selection efficiency (minimal cuts on lepton mainly driven by trigger thresholds, detector acceptance)

- ZZ + QCD-induced jets (irreducible background) highly dominant compared to pure EW production
  - understanding of the irreducible background is paramount

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Understanding the irreducible background: differential cross sections of ZZ+jets (I)

Number of jets ($|\eta^{\text{jet}}| < 4.7$) | Fiducial cross section [fb] | Theo. cross section [fb]
--- | --- | ---
0 | $28.3 \pm 1.3 \text{ (stat)}^{+1.7}_{-1.6} \text{ (syst)} \pm 0.7\text{ (lumi)}$ | $23.6^{+0.8}_{-0.9}$
1 | $8.1 \pm 0.8 \text{ (stat)}^{+0.8}_{-0.8} \text{ (syst)} \pm 0.2\text{ (lumi)}$ | $9.7^{+0.4}_{-0.4}$
2 | $3.0 \pm 0.5 \text{ (stat)}^{+0.3}_{-0.4} \text{ (syst)} \pm 0.1\text{ (lumi)}$ | $4.0^{+0.3}_{-0.2}$
$\geq 3$ | $1.3 \pm 0.4 \text{ (stat)}^{+0.3}_{-0.2} \text{ (syst)}$ | $1.7^{+0.1}_{-0.1}$
Understanding the irreducible background: differential cross sections of ZZ+jets (I)

CMS Preliminary

35.9 fb\(^{-1}\) (13 TeV)

Unfolded data + stat. uncertainty
Total uncertainty
MadGraph5_aMCatNLO+MCFM+Pythia8
Powheg+MCFM+Pythia8

\( \frac{d\sigma_{\text{fid}}}{dN_{\text{jets}}} \) [fb]

N_{\text{jets}} (|\eta_{\text{jet}}| < 4.7)

Data/MC

MadGraph5_aMCatNLO+MCFM+Pythia8. p-value = 0.033
Powheg+MCFM+Pythia8. p-value = 0.114

SMP-16-019
Understanding the irreducible background: differential cross sections of ZZ+jets (I)

CMS Preliminary

Unfolded data + stat. uncertainty
Total uncertainty
MadGraph5_aMC@NLO+MCFM+Pythia8
Powheg+MCFM+Pythia8

SMP-16-019

CMS Preliminary

Data + stat. unc.
Stat. + syst. unc.
POWHEG+MCFM
MG5_aMC@NLO+MCFM

SMP-16-017

$N_{\text{jets}}$ ($|\eta^{\text{jet}}| < 4.7$)

Data/MC

MadGraph5_aMC@NLO+MCFM+Pythia8. p-value = 0.033

Powheg+MCFM+Pythia8. p-value = 0.114

$\mu_{\text{data}}$ [fb]

$\frac{d\sigma}{dN_{\text{jets}}}$ [fb]

35.9 fb$^{-1}$ (13 TeV)
Summary of VV+jets measurements

May 2017

Production Cross Section, $\sigma$ [pb]

- 7 TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
- 13 TeV CMS measurement ($L \leq 35.9$ fb$^{-1}$)
- Theory prediction

All results at: http://cern.ch/go/pNj7

Fiducial: $W$, $Z$, and $H$ as $W\rightarrow l\nu$, $Z\rightarrow ll$, $H\rightarrow gg$, and kinematic selection

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Understanding the irreducible background: differential cross sections of ZZ+jets (II)
as a function of the leading-$p_T$ jet variables

Overall **good** agreement with two type of MC sets

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7th July 2017 – VV+jets and VBS at CMS
Understanding the irreducible background: differential cross sections of ZZ+jets (III) as a function of the subleading-$p_T$ jet variables

Overall good agreement with two type of MC sets

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Understanding the irreducible background: differential cross sections of ZZ+jets (IV)
as a function of the dijet variables

$m_{jj}$ in good agreement with MC while $|\Delta \eta_{jj}|$ seems steeper in data than in MC
Search for the ZZ+jets EW production

Overall very good data-theory agreement
Little discrimination on individual variables
Few expected signal events

BDT optimized to separate EW ZZ+jets from QCD-induced jet production
7 inputs: \( m_{jj}, \Delta \eta_{jj}, z_1^*, z_2^*, R(p_T), \) dijet \( p_T \) balance, \( m_{4l} \)

Signal extracted via template fit of full BDT spectrum
Constrains background normalization with data

Validation of background model in a QCD-enriched region → good agreement

Measured signal strength: \( \mu = 1.39^{+0.72}_{-0.57} \, (\text{stat})^{+0.46}_{-0.31} \, (\text{syst}) \)
With an observed significance of 2.7 \( \sigma \) (1.6 \( \sigma \), expected)

Measured fiducial cross section \( \sigma \left( EW \ pp \rightarrow ZZ + jets \rightarrow lll' l' + jets \right) = 0.40^{+0.21}_{-0.16} \, (\text{stat})^{+0.13}_{-0.09} \, (\text{syst}) \, fb \)
Search for a pair of same charge lepton (μ, e) with $p_T^{1,2} > 25\, (20)\, \text{GeV}$, $m_{ll} > 20\, \text{GeV}$, vetoing additional leptons (including τ’s) in the event.

Two jets with $p_T > 30\, \text{GeV}$, leading jets taken as tagging jets, $m_{jj} > 500\, \text{GeV}$, $|\Delta\eta_{jj}| > 2.5$, max $(z_1^*) < 0.75$

Low background contamination compared to other VBS search channels (thanks to its quite large $\sigma\times\text{BR}$) → # signal events ~ half of all background events.

Background from $W\pm W\pm$+jets induced by QCD very small compared to the signal. Main background from multi non-prompt leptons in the event and $WZ \rightarrow 3l\nu$ where a charged lepton is lost:

- To suppress $DY \rightarrow E_T^{\text{miss}} > 40\, \text{GeV}$ and $Z \rightarrow e^+e^-$ veto
- To reduce top background: anti b-tagging, $m_{ll} > 20\, \text{GeV}$
• Signal event yield extracted using a 2D fit of $m_{jj}$ and $m_{ll}$

• EW production observed with a significance of $5.5 \sigma$ (expected $5.7 \sigma$)

\[
\sigma \left( EW \, pp \rightarrow W^\pm W^\pm + jets \rightarrow l^\pm l'^\pm \nu \bar{\nu} + jets \right) = 3.83 \pm 0.66 \text{(stat)} \pm 0.35 \text{(syst)} \, fb
\]

• Analysis also used to constrain the $\sigma \times BR$ for the production of doubly charged Higgs boson decaying into two same sign W, resulting in a limit at 95% CL well below 100 fb for a large range of the $H^{\pm\pm}$ mass
Cross sections summary

May 2017

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

- 7 TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
- 13 TeV CMS measurement ($L \leq 35.9$ fb$^{-1}$)
- Theory prediction
- CMS 95%CL limits at 7, 8 and 13 TeV

All results at: http://cern.ch/go/pNj7

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7th July 2017 – VV+jets and VBS at CMS
Anomalous vector boson couplings

- Search for **new physics while doing EW measurements**
- Look for deviations from SM in tail of distributions \((m_{VV}, m_{ll}, m_{jj}, p_{T,V}, \ldots)\)
- Parametrize the new physics **adding terms to the SM lagrangian**
- Parameters are varied **one-by-one**.
Main variables for the search of anomalous quartic gauge couplings

→ no evidence found so far
## aQGC Summary Table

<table>
<thead>
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<th>May 2017</th>
<th>CMS</th>
<th>ATLAS</th>
<th>Channel</th>
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7th July 2017 – VV+jets and VBS at CMS
Conclusions

- We discovered a Higgs boson, yet **the comprehension of the Electroweak Symmetry Breaking is not completed**
  
  → **Understanding the Multi-boson production in association with jets is the key point!**
  
  - **Complementary** to Higgs boson properties studies and high mass searches

- Observation of Electroweak production of two same sign W and two jets
  
  - **Hint** of the production of ZZ+jets through EW process

Time of multi-boson production is now, the **New Frontier will be:**

  VV + jets, Vector Boson Scattering and triboson production

  → they will be ones of the hot topic of LHC Run II!

**Details on results** can be found in the public pages of the CMS experiment:

More Material
### ZZ+jets Complete Cut List

#### Fiducial region (baseline)

- $p_T^e > 5 \text{ GeV}$, $|\eta^e| < 2.5$
- $p_T^\mu > 5 \text{ GeV}$, $|\eta^\mu| < 2.5$
- $p_T^{\ell_3,4} > 5 \text{ GeV}$
- $p_T^{\ell_1} > 20 \text{ GeV}$, $p_T^{\ell_2} > 10 \text{ GeV}$
- $m_{\ell^+\ell^-} > 4 \text{ GeV}$ (any opposite-sign same-flavor pair)
- $60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}$

#### Fiducial region (VBS)

- $m_{jj} > 100 \text{ GeV}$

#### Search region (baseline)

- $|\eta^e| < 2.5$ $p_T^e > 7 \text{ GeV}$, $|\eta^\mu| < 2.4$ $p_T^\mu > 5 \text{ GeV}$, relative isolation < 0.35 in a cone of $\Delta R = 0.3$, CMS tight ID and SIP= $|\text{IP}/\sigma_{IP}| < 4$

- At least a lepton with $p_T > 20 \text{ GeV}$ and a $\mu(e)$ with $p_T > 10(12) \text{ GeV}$
- $60 < m_Z < 120 \text{ GeV}$ (On shell), $m_{\ll\text{ crossed}}$ (Opposite sign same flavour) $> 4 \text{ GeV}$
- Loosely ID jets, reco with anti-$k_T 0.4$; $|\eta_{\text{jet}}| < 4.7$ and $p_T > 30 \text{ GeV}$

- $m_{jj} > 100 \text{ GeV}$

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**R.Bellan**

7th July 2017 – VV+jets and VBS at CMS
## ZZ+jets systematic uncertainties

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<th>Systematic source</th>
<th>Absolute</th>
<th>Normalized</th>
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<td>Trigger</td>
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<tr>
<td>Muon ID, ISO and Tracking</td>
<td>0.9 - 1.0 %</td>
<td>&lt;0.1 - 0.1 %</td>
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<tr>
<td>Electron ID, ISO and Tracking</td>
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<td>0.1 - 0.7 %</td>
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<td>2.1 - 8.4 %</td>
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<td>4.6 - 17.6 %</td>
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<td>$\alpha_S$</td>
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ZZ njets differential cross section

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Total uncertainty
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Powheg+MCFM+Pythia8. p-value = 0.078

35.9 fb$^{-1}$ (13 TeV)

$N_{\text{jets}} (|\eta_{\text{jet}}| < 4.7)$
ZZ+jets, Pseudorapidity distributions
ZZ+jets MVA input variables

\[ Z_j^* = \eta_{Z_j} - (\eta_{jet,1} + \eta_{jet,2})/2 \]

\[ R(p_T^{\text{hard}}) = \frac{\|p_T^{jet,1} + p_T^{jet,2} + p_T^{Z_1} + p_T^{Z_2}\|}{p_T^{jet,1} + p_T^{jet,2} + p_T^{Z_1} + p_T^{Z_2}} \]
ZZ+jets: ROC Curve
ZZ+jets: Event Display

| $m_{4\ell}$ [GeV] | $m_{Z1}$ [GeV] | $m_{Z2}$ [GeV] | $m_{jj}$ [GeV] | $|\Delta\eta_{jj}|$ | $\eta^*_Z$ | $\eta^*_Z$ | BDT score |
|------------------|---------------|---------------|---------------|----------------|-----------|-----------|-----------|
| 365.8            | 91.4          | 101.1         | 844.1         | 3.4            | -0.7      | 0.0       | 0.97      |
| 325.1            | 93.1          | 96.3          | 1332.9        | 5.2            | 0.0       | -1.8      | 0.98      |
| 263.8            | 91.9          | 88.0          | 829.7         | 2.2            | -0.5      | 1.1       | 0.94      |
| 562.8            | 93.7          | 88.0          | 947.3         | 2.8            | 0.6       | 0.6       | 0.93      |
| 248.8            | 91.5          | 89.2          | 1340.9        | 5.4            | -0.5      | 0.2       | 0.98      |
| 375.2            | 89.4          | 98.5          | 1052.5        | 3.8            | 0.7       | -0.2      | 0.96      |
| 482.1            | 95.0          | 95.6          | 1543.1        | 4.8            | -1.6      | 2.5       | 0.99      |

$m_{W_W} = 89.2$ GeV
$m_{ee} = 91.5$ GeV
$m_{jj} = 1.3$ TeV
$\Delta\eta_{jj} = 5.4$
### ZZ+jets: aQGC Limits

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<th>Exp. upper</th>
<th>Obs. lower</th>
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<td>$0.51$</td>
<td>$-0.46$</td>
<td>$0.44$</td>
<td>$0.6$</td>
</tr>
<tr>
<td>$f_{T_1}/\Lambda^4$</td>
<td>$-0.72$</td>
<td>$0.71$</td>
<td>$-0.61$</td>
<td>$0.61$</td>
<td>$0.6$</td>
</tr>
<tr>
<td>$f_{T_2}/\Lambda^4$</td>
<td>$-1.4$</td>
<td>$1.4$</td>
<td>$-1.2$</td>
<td>$1.2$</td>
<td>$0.6$</td>
</tr>
<tr>
<td>$f_{T_8}/\Lambda^4$</td>
<td>$-0.99$</td>
<td>$0.99$</td>
<td>$-0.84$</td>
<td>$0.84$</td>
<td>$2.8$</td>
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<tr>
<td>$f_{T_9}/\Lambda^4$</td>
<td>$-2.1$</td>
<td>$2.1$</td>
<td>$-1.8$</td>
<td>$1.8$</td>
<td>$2.9$</td>
</tr>
</tbody>
</table>
ssWW+jets Complete Cut List

Search region

- **Two same charge lepton** ($\mu$, e) with $p_{T,1(2)}> 25$ (20) GeV, $|\eta|< 2.4$ (2.5), $m_{ll}> 20$ GeV
- **Veto events with additional leptons** if $p_T$ of a 3rd loosely ID lepton is $> 10$ GeV or the $p_T$ of an identified $\tau$ (to hadrons) is $> 18$ GeV
- **Two jets** (anti-$k_T$ 0.4) with $p_T> 30$ GeV, $|\eta|< 5$ leading jets taken as tagging jets, $m_{jj}> 500$ GeV, $|\Delta \eta_{jj}|> 2.5$, max ($z^*_l$) $< 0.75$ $Z^*_l=|\eta_l-(\eta_{jet,1}+\eta_{jet,2})/2|/|\Delta \eta_{jj}|$
- $E_T^{miss}> 40$ GeV, $Z \rightarrow e^+e^-$ veto (requiring $|m_{ll}-m_Z|> 15$ GeV), anti b-tag, $m_{ll}> 20$ GeV

Fiducial region

- $p_T> 20$ GeV, $|\eta|< 2.5$, for both leptons
- $p_T> 30$ GeV, $|\eta|< 5$ for the two leading jets and $m_{jj}> 500$ GeV, $|\Delta \eta_{jj}|> 2.5$
- Taus decay into leptons are excluded from this definition
• **Fiducial region**

• $p_T > 20$ GeV, $|\eta| < 2.5$, for both leptons

• $p_T > 30$ GeV, $|\eta| < 5$ for the two leading jets and $m_{jj} > 500$ GeV, $|\Delta \eta_{jj}| > 2.5$

• Taus decay into leptons are excluded from this definition
### ssWW+jets: Yields

<table>
<thead>
<tr>
<th></th>
<th>$\mu^+\mu^+$</th>
<th>$e^+e^+$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^-\mu^-$</th>
<th>$e^-e^-$</th>
<th>$e^-\mu^-$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>40</td>
<td>14</td>
<td>63</td>
<td>26</td>
<td>10</td>
<td>48</td>
<td>201</td>
</tr>
<tr>
<td><strong>Signal+Total bkg.</strong></td>
<td>44.1 ± 3.4</td>
<td>19.0 ± 1.9</td>
<td>67.6 ± 3.8</td>
<td>23.9 ± 2.8</td>
<td>11.8 ± 1.8</td>
<td>38.9 ± 3.3</td>
<td>204.8 ± 7.2</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>18.3 ± 0.4</td>
<td>6.2 ± 0.2</td>
<td>24.7 ± 0.4</td>
<td>6.5 ± 0.2</td>
<td>2.5 ± 0.1</td>
<td>8.7 ± 0.2</td>
<td>66.9 ± 0.7</td>
</tr>
<tr>
<td><strong>Total bkg.</strong></td>
<td>25.7 ± 3.4</td>
<td>12.8 ± 1.9</td>
<td>42.9 ± 3.8</td>
<td>17.4 ± 2.8</td>
<td>9.4 ± 1.8</td>
<td>30.2 ± 3.3</td>
<td>137.9 ± 7.1</td>
</tr>
<tr>
<td><strong>Non-prompt</strong></td>
<td>18.4 ± 3.3</td>
<td>5.6 ± 1.7</td>
<td>24.9 ± 3.6</td>
<td>14.2 ± 2.8</td>
<td>5.0 ± 1.6</td>
<td>19.9 ± 3.2</td>
<td>87.9 ± 6.9</td>
</tr>
<tr>
<td><strong>WZ</strong></td>
<td>4.4 ± 0.2</td>
<td>3.0 ± 0.2</td>
<td>8.5 ± 0.3</td>
<td>2.2 ± 0.1</td>
<td>1.9 ± 0.2</td>
<td>5.2 ± 0.3</td>
<td>25.1 ± 0.6</td>
</tr>
<tr>
<td><strong>QCD WW</strong></td>
<td>1.3 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>1.7 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>4.8 ± 0.2</td>
</tr>
<tr>
<td><strong>$W\gamma$</strong></td>
<td>0.2 ± 0.2</td>
<td>1.4 ± 0.5</td>
<td>3.6 ± 0.9</td>
<td>-</td>
<td>0.8 ± 0.4</td>
<td>2.3 ± 0.7</td>
<td>8.3 ± 1.3</td>
</tr>
<tr>
<td><strong>Tribozon</strong></td>
<td>1.2 ± 0.3</td>
<td>0.8 ± 0.2</td>
<td>2.2 ± 0.4</td>
<td>0.5 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>0.9 ± 0.3</td>
<td>5.8 ± 0.7</td>
</tr>
<tr>
<td><strong>Wrong sign</strong></td>
<td>-</td>
<td>1.5 ± 0.6</td>
<td>1.4 ± 0.4</td>
<td>-</td>
<td>1.1 ± 0.5</td>
<td>1.2 ± 0.4</td>
<td>5.2 ± 1.0</td>
</tr>
</tbody>
</table>
ssWW+jets: charged Higgs limits

**CMS**

**Preliminary**

- Observed
- Median expected
- Expected ± 1σ
- Expected ± 2σ

**σ_{VBF}(H^{±}) \times B(H^{±} \rightarrow W^{±}W^{±}) (fb)**

**m_{H^{±}} (GeV)**

- 200
- 300
- 400
- 500
- 600
- 700
- 800
- 900
- 1000

**CMS**

**Preliminary**

- Observed
- Median expected
- Expected ± 1σ
- Expected ± 2σ
- $\Gamma_{H^{±}} / m_{H^{±}} > 0.1$

**m_{H^{±}} (GeV)**

- 200
- 300
- 400
- 500
- 600
- 700
- 800
- 900
- 1000

35.9 fb$^{-1}$ (13 TeV)
ssWW+jets: aQGC limits

<table>
<thead>
<tr>
<th>Observed limits (TeV^{-4})</th>
<th>Expected limits (TeV^{-4})</th>
<th>Run-I limits (TeV^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{S0}/\Lambda$</td>
<td>[ -7.7, 7.7]</td>
<td>[ -7.0, 7.2]</td>
</tr>
<tr>
<td>$f_{S1}/\Lambda$</td>
<td>[-21.6,21.8]</td>
<td>[-19.9,20.2]</td>
</tr>
<tr>
<td>$f_{M0}/\Lambda$</td>
<td>[ -6.0, 5.9]</td>
<td>[ -5.6, 5.5]</td>
</tr>
<tr>
<td>$f_{M1}/\Lambda$</td>
<td>[ -8.7 ,9.1]</td>
<td>[ -7.9 ,8.5]</td>
</tr>
<tr>
<td>$f_{M6}/\Lambda$</td>
<td>[-11.9,11.8]</td>
<td>[-11.1,11.0]</td>
</tr>
<tr>
<td>$f_{M7}/\Lambda$</td>
<td>[-13.3,12.9]</td>
<td>[-12.4,11.8]</td>
</tr>
<tr>
<td>$f_{T0}/\Lambda$</td>
<td>[-0.62,0.65]</td>
<td>[-0.58,0.61]</td>
</tr>
<tr>
<td>$f_{T1}/\Lambda$</td>
<td>[-0.28,0.31]</td>
<td>[-0.26,0.29]</td>
</tr>
<tr>
<td>$f_{T2}/\Lambda$</td>
<td>[-0.89,1.02]</td>
<td>[-0.80,0.95]</td>
</tr>
</tbody>
</table>
Other WW Production Analyses

• CMS made two beautiful analyses aiming to observe the **first evidence of** $W^\pm W^\pm jj$ produced via **Electroweak** processes at 8 TeV
  
  - CMS: 114 (2015) 051801

• Production of **WW via photon-photon scattering** at 7 and 8 TeV
  
Why VV Scattering

In the symmetry breaking (EWSB) mechanism the $W$ and $Z$ bosons get their masses and acquire a longitudinal degree of polarization.

The mechanism responsible for the EWSB has to regulate the $V_L V_L \rightarrow V_L V_L$ cross section such that the unitarity is preserved above $m_{VV} \sim 1$-2 TeV

VV scattering is the key process to probe EWSB and high energy vector boson scattering will play a central role:

- both as a test of the Higgs boson nature
  - If the discovered Higgs boson contributes fully to the EWSB, then most probably the interaction among longitudinal weak bosons would remain weak at high energy
- and as a model independent research of alternative theory to explain EWSB
  - if the 125.5 GeV Higgs boson is only partially responsible for the EWSB, then the VV interaction could get strong at high energy.
- Also TGC and QGC processes may carry new physics phenomena
The Higgs Job

• If the cancellation of the Higgs diagrams is not complete, then we expect a $g_{HWW}$ coupling smaller than the SM.

• The $W_L W_L$ will keep growing with $\sqrt{s}$, up to the new resonance, or more generally to the new physics scale $\Lambda$.

• Suppose the Higgs-WW coupling is $\sqrt{\delta}$ of the SM value, then the amplitudes become

$$iM^{\text{gauge}} = -i \frac{g^2}{4m_W^2} u + \mathcal{O}((E/m_W)^0)$$

$$iM^{\text{higgs}} = i \frac{g^2}{4m_W^2} u \delta + \mathcal{O}((E/m_W)^0)$$

$$iM^{\text{all}} = -i \frac{g^2}{4m_W^2} u(1 - \delta) + \mathcal{O}((E/m_W)^0)$$

Measure with high precision both the HVV coupling and the $V_L V_L$ scattering.

Cheung, Chiang, Yuan
VV Scattering to test the EWSB

SILH:
- Higgs a pseudo Goldstone Boson of a new strong sector
- Both a light Higgs and Bosons strongly coupled
- Modified higgs coupling

\[ g_h \rightarrow g_h / \sqrt{1 + \xi c_H}, \quad \xi = \frac{v^2}{f^2} \]

\[ h \rightarrow h / \sqrt{1 + \xi c_H}, \quad \xi = \frac{v^2}{f^2} \]

Anomalous Quartic Gauge Couplings Modelling

- Extension of the SM Lagrangian by introducing additional **dimension-8 (or 6) operators**:

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i + ... \]

**desideratum**: \( \Lambda \sim 1-2 \text{ TeV} \)

- **Effective field theory** is useful as a methodology for studying possible new physics effects from massive particles that are **not directly detectable**.

  - Underlying assumption: scale \( \Lambda \) is large compared with the experimentally-accessible energy
  
  - These operators have **coefficients of inverse powers of mass** (\( \Lambda \)), and hence are suppressed if this mass is large compared with the experimentally-accessible energy
  
  - **Limit**: \( \Lambda \) so large that the effect is comparable to missing higher order corrections from SM
  
  - An effective field theory is the **low-energy approximation of the new physics**

- coefficients in **dimension-6** (i.e. \( c_i/\Lambda^2 \)) (e.g., hep-ph/9908254), **may affects 3 boson vertices too**:

  - \( C_{\phi W}/\Lambda^2 \) (VBFNLO), \( a_{0}^W/\Lambda^2 \), \( a_c^W/\Lambda^2 \) (CALCHEP)...

- coefficients in **dimension-8** (i.e. \( c_i/\Lambda^4 \)) (e.g., hep-ph/0606118), **modifies 4 boson vertices only**:

  - \( f_{S,0}^A/\Lambda^4 \), \( f_{T,0}^A/\Lambda^4 \)...
Future Projections

- Several final states investigated by both Collaborations (ATLAS-PHYS-PUB-2013-006 and CMS-PAS-FTR-13-006) for $\sqrt{s} = 14$ TeV and two luminosity scenarios, 300 fb$^{-1}$ and 3000 fb$^{-1}$:
  
  - $pp \rightarrow ZZqq \rightarrow 4ljj$ (VBS)
  - $pp \rightarrow WZqq \rightarrow 3lvjj$ (VBS)
  - $pp \rightarrow W^\pm W^\pm qq \rightarrow l^\pm v l^\pm v jj$ (VBS)
  - $pp \rightarrow Z\gamma\gamma \rightarrow ll\gamma\gamma$ (QGC)

- Results interpreted in terms of **Effective Lagrangian**, to estimate the sensitivity to new physics.
pp → WZqq → 3lνjj - VBS @ 14 TeV

CMS-13-PAS-FTR-006

- 300 fb⁻¹ (*Phase 1*) with 50 pile-up event and current detector
- 3000 fb⁻¹ (*Phase 2*) with 140 pile-up events and with the detector upgrade (new tracker and Ecal, mu-detection down to η < 4)
- Typical VBF/VBS cuts:
  - Lepton pₜ > 20 GeV, jet pₜ > 50 GeV, Δη(j,j) > 4, M(jj) > 600 GeV

<table>
<thead>
<tr>
<th>Significance</th>
<th>3σ</th>
<th>5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM EWK scattering discovery</td>
<td>75 fb⁻¹</td>
<td>185 fb⁻¹</td>
</tr>
<tr>
<td>f₉₁/Λ⁴ at 300 fb⁻¹</td>
<td>0.8 TeV⁻⁴</td>
<td>1.0 TeV⁻⁴</td>
</tr>
<tr>
<td>f₉₁/Λ⁴ at 3000 fb⁻¹</td>
<td>0.45 TeV⁻⁴</td>
<td>0.55 TeV⁻⁴</td>
</tr>
</tbody>
</table>

Additional contribution from aQGC with f₉₁/Λ⁴ = 1 TeV⁻⁴.
Final States and their Cross-sections

- Needs to simulate all $2 \rightarrow 6$ processes at least at the order $\mathcal{O}(\alpha_{EW}^6)$

- **Large interference** among same order diagrams

- **Signal has to be defined a posteriori**, using kinematic cuts [arXiv:0801.3359]

- Cross Sections for $\sqrt{s} = 14$ TeV from **Phantom Monte Carlo Generator**: full simulation of $2 \rightarrow 6$ at $\mathcal{O}(\alpha_{EW}^6) + \mathcal{O}(\alpha_{EW}^4\alpha_{QCD}^2)$

\[
\begin{align*}
\text{QQqQ\mu\nu/ee} & \quad \text{QQqQ\mu\nu/ee} \\
\text{no-Higgs} & \quad 500 \text{ GeV} & \quad \text{no-Higgs} & \quad 500 \text{ GeV} \\
\sigma (\text{fb}) & \quad \text{perc.} & \quad \sigma (\text{fb}) & \quad \text{perc.} & \quad \sigma (\text{fb}) & \quad \text{perc.} & \quad \sigma (\text{fb}) & \quad \text{perc.} \\
\text{total} & \quad 0.689 & \quad 100\% & \quad 0.718 & \quad 100\% & \quad 0.0305 & \quad 100\% & \quad 0.0350 & \quad 100\% \\
\text{signal} & \quad 0.158 & \quad 23\% & \quad 0.184 & \quad 26\% & \quad 0.0125 & \quad 41\% & \quad 0.0165 & \quad 47\% \\
\text{top} & \quad 0.495 & \quad 72\% & \quad 0.494 & \quad 69\% & \quad 0.0137 & \quad 45\% & \quad 0.0137 & \quad 39\% \\
\text{non resonant} & \quad 0.020 & \quad 3\% & \quad 0.023 & \quad 3\% & \quad 0.0030 & \quad 10\% & \quad 0.0035 & \quad 10\% \\
\text{three bosons} & \quad 0.016 & \quad 2\% & \quad 0.017 & \quad 2\% & \quad 0.0012 & \quad 4\% & \quad 0.0014 & \quad 4\% \\
\end{align*}
\]

\[
\begin{align*}
\text{EE+\nu\nu+\nu} & \quad \text{EE+\nu\nu+\nu} & \quad \text{EE+\nu\nu+\nu} \\
\text{no-Higgs} & \quad 500 \text{ GeV} & \quad \text{no-Higgs} & \quad 500 \text{ GeV} & \quad \text{no-Higgs} & \quad 500 \text{ GeV} \\
\sigma (\text{fb}) & \quad \text{perc.} & \quad \sigma (\text{fb}) & \quad \text{perc.} & \quad \sigma (\text{fb}) & \quad \text{perc.} \\
\text{total} & \quad 0.180 & \quad 100\% & \quad 0.310 & \quad 100\% & \quad 4.182 & \quad 100\% & \quad 4.152 & \quad 100\% \\
\text{signal} & \quad 0.120 & \quad 66.4\% & \quad 0.229 & \quad 74.1\% & \quad 1.317 & \quad 31.5\% & \quad 1.281 & \quad 30.8\% \\
\text{top} & \quad 0 & \quad 0\% & \quad 0 & \quad 0\% & \quad 1.817 & \quad 43.5\% & \quad 1.828 & \quad 44.01\% \\
\text{non resonant} & \quad 0.0364 & \quad 20.2\% & \quad 0.0533 & \quad 17.2\% & \quad 0.673 & \quad 16.1\% & \quad 0.651 & \quad 15.7\% \\
\text{three bosons} & \quad 0.0241 & \quad 13.4\% & \quad 0.0268 & \quad 8.66\% & \quad 0.375 & \quad 8.9\% & \quad 0.392 & \quad 9.5\% \\
\end{align*}
\]
• The VL are coupled to the Higgs and they are the ones sensitive to the EWSB.
• The behavior of the LL cross section only can give information on the scale at which the symmetry breaks.
• At large $M(VV)$ the TT cross section is of the same order as the LL (in the no-Higgs case)

If there is a new resonance at a scale $L$, the LL cross section will not decrease until $L$.

Experimentally we should enhance LL wrt TT and measure XS at the highest $M(VV)$

- The cross section decreases rapidly at high invariant masses due to PDF – Hard life for LHC @14 TeV!
- The invariant VV mass is the equivalent of the CM energy of the elastic VV scattering
R. Bellan

7th July 2017 – VV+jets and VBS at CMS

\( \sigma(VV \rightarrow VV) \) with \( m_h = 120 \text{ GeV} \)

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

\text{arxiv:0806.4145}