Vector boson scattering and anomalous quartic couplings from ATLAS and CMS

Ezio Torassa
INFN Padova
On behalf of CMS and ATLAS collaborations
Overview

• Vector boson scattering
• VBS background
• VBS signature
• LHC results: same-sign $W^\pm W^\pm$ jj
• LHC results: $W^\pm Z$ jj
• LHC results: ZZ jj
• Anomalous quartic coupling
• Conclusions
Vector boson scattering $VV \rightarrow VV$

Within the Standard Model (SM), cancellations between Feynman amplitudes involving

(a) trilinear gauge boson couplings,
(b) Higgs exchange,
(c) quartic gauge boson interactions,

lead to scattering amplitudes which do not grow with energy and which respect bounds derived from unitarity.

Trilinear couplings are well constrained by LEP, Tevatron and LHC measurements. Deviation in the SM coupling of the Higgs boson to the gauge bosons or anomalous quartic gauge couplings (QGC) break this delicate cancellation. These measurements can test the electroweak symmetry breaking mechanism and can provide limits for new physics.
VBS background

EW irreducible contributions at $O(\alpha^6)$ with 2V and 2 jets but not VBS

QCD induced contributions at $O(\alpha_s^2\alpha^4)$

Interference of the EW and QCD amplitudes contributes at $O(\alpha_s\alpha^5)$
VBS signature

Signature of VBS events:

• 2 energetic jets (from q_3 and q_4) with
  - high di-jet invariant mass (m_{jj})
  - large rapidity Δy_{jj} (or Δη_{jj}) separation

• Central rapidity region with only VV decays
  - WW 2 leptons + MET
  - WZ 3 leptons + MET
  - ZZ 4 leptons

Cross sections differential distributions in the variables (m_{jj}, |Δy_{jj}|) for the three LO contributions to the process pp → μ^+ ν_μ e^+ ν_e jj at √s = 13 TeV


σ (fb) per bin (m_{jj}, |Δy_{jj}|): $O(\alpha^6)$

σ (fb) per bin (m_{jj}, |Δy_{jj}|): $O(\alpha_s^2\alpha^4)$

σ (fb) per bin (m_{jj}, |Δy_{jj}|): $O(\alpha_s\alpha^5)$

EW  
QCD  
Interference

m_{jj}(GeV)  
|Δy_{jj}|

m_{jj}(GeV)  
|Δy_{jj}|

m_{jj}(GeV)  
|Δy_{jj}|

5 November 26^{th}-30^{th} 2018 HC 2018 Ryogoku, Tokyo, Japan
Measurements of EW production of same sign $W^+W^\pm jj$ by ATLAS and CMS:

**ATLAS**: ATLAS-CONF-2018-030 (July 2018)  
**CMS**: PRL 120, 081801 (Nov. 2017)

$\sqrt{s}$, Integr. Luminosity  
- 13 TeV, 36.1 fb$^{-1}$ (2015+2016)  
- 13 TeV, 35.9 fb$^{-1}$ (2016)

The selection of same-sign lepton events (from leptonic decays of same-sign WW):
- reduces the contribution form the strong production of WW bosons
- and suppresses background contributions with opposite-sign lepton final state ($t\bar{t}$).

VBS signal in the s-channel ($W^+W^- \rightarrow Z/H \rightarrow W^+W^-$) are absent processes.
LHC results: same sign $W^\pm W^\pm jj$

Event selection:
2 same sign leptons (e, or $\mu$) and 2 jets

<table>
<thead>
<tr>
<th>Requirements</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{l} &gt;$ (GeV)</td>
<td>27/27</td>
<td>25/20</td>
</tr>
<tr>
<td>$p_T^{j} &gt;$ (GeV)</td>
<td>65/35</td>
<td>30/30</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;$</td>
</tr>
</tbody>
</table>

Signal selection: $m_{jj}$, $\Delta \eta_{jj}$, $E_T^{\text{miss}}$

<table>
<thead>
<tr>
<th>Requirements</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{jj} &gt;$ (GeV)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y_{jj}</td>
<td>,</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}, p_T^{\text{miss}} &gt;$ (GeV)</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>$m_{ll} &gt;$ (GeV)</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Measurement performed in ee, $\mu\mu$, and $e\mu$ final states

Major backgrounds (estimated from data):
- non-prompt leptons  control region: QCD enriched sample, ratio tight/loose lepton ID
- $WWjj$ QCD induced  control region: low $m_{jj}$
- EW WZ                control region: 3 leptons

Other backgrounds (estimated from data):
- Electron charge mis-reconstruction measured from $Z \rightarrow ee$ events

Other backgrounds (estimated from MC):
- ZZ, $V\gamma$, VVV, ttV

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LHC results: same sign $W^\pm W^\pm jj$

Data, $W^\pm W^\pm jj$ EW signal and backgrounds after signal selection.

**ATLAS**: $m_{jj}$ distribution

**CMS**: $m_{jj}$ and $m_{ll}$ distributions

---

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36.1 $fb^{-1}$

- Data
- $W^+W^-jj$ EW
- $W^+W^-jj$ QCD
- Non-prompt
- $e/\gamma$ conversions
- WZ
- Other prompt
- Total uncertainty

---

**CMS**

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

- Data
- EW WW
- WZ
- Nonprompt
- Others
- Bkg. unc.

---

**e/γ conversion**: Electron charge misreconstr. + $V_\gamma$

**Others**: QCD WW + e/γ conversion
LHC results: same sign $W^\pm W^\pm jj$

$W^\pm W^\pm jj$ EW signal significances:

**ATLAS**: 6.9 $\sigma$ observed (4.6 $\sigma$ expected)

**CMS**: 5.5 $\sigma$ observed (5.7 $\sigma$ expected)

Signal extraction:

**ATLAS**
- MC signal: SHERPA (LO)
- Data: Fit $m_{jj}$ shape in 6 categories
  - $e^+e^- e^-e^- e^+\mu^+ \mu^- \mu^+\mu^- \mu^-\mu^-$

**CMS**
- MC signal: MADGRAPH5_aMC@NLO (LO)
- Data: 2D fit $m_{ll}$ - $m_{jj}$ shape

Fiducial regions:

Defined by the selection criteria.
The main difference between ATLAS and CMS is the jet selection.
The measured cross section is corrected for the acceptance in this fiducial region using Monte Carlo generator.
LHC results: same sign $W^+W^\pm jj$

Fiducial cross sections:

**ATLAS**

$\sigma^{\text{fid}}(W^\pm W^\pm jj) = 2.91 \pm 0.51 \text{ (stat.) } \pm 0.27 \text{ (sys.) fb}$

$\sigma^{\text{th}}(W^\pm W^\pm jj) = 2.01^{+0.33}_{-0.23} \text{ fb @ LO (SHERPA) }$

$\sigma^{\text{th}}(W^\pm W^\pm jj) = 3.08^{+0.45}_{-0.46} \text{ fb @ LO (POWHEG) }$

**CMS**

$\sigma^{\text{fid}}(W^\pm W^\pm jj) = 3.83 \pm 0.66 \text{ (stat.) } \pm 0.35 \text{ (sys.) fb}$

$\sigma^{\text{th}}(W^\pm W^\pm jj) = 4.25 \pm 0.27 \text{ fb @ LO (MADGRAPH) }$

The SHERPA MC systematic uncertainty includes:

- variation of renormalization and factorization scales: $\pm 14\%$ $\pm 11\%$
- PDF uncertainties: $\pm 8\%$ $\pm 1\%$
- parton shower modeling: $\pm 2.5\%$ $\pm 1.5\%$

The MADGRAPH MC systematic uncertainty: $+6.3\%$ $-6.3\%$

Fiducial cross sections are compatible with SM expectations.
LHC results: same sign $W^\pm W^\pm jj$

Higher order corrections are not negligible.

Same sign $WW$ is the only diboson process with full NLO computation (EW and QCD) (B. Biedermann, A. Denner, and M. Pellen JHEP 1710 (2017) 124)

\[
\begin{align*}
\text{LO} & \quad \mathcal{O}(\alpha^7) \quad \mathcal{O}(\alpha_s \alpha^6) \quad \mathcal{O}(\alpha_s^2 \alpha^5) \quad \mathcal{O}(\alpha_s^3 \alpha^4) \\
\text{NLO} & \quad \mathcal{O}(\alpha^7) \quad \mathcal{O}(\alpha_s \alpha^6) \quad \mathcal{O}(\alpha_s^2 \alpha^5) \quad \mathcal{O}(\alpha_s^3 \alpha^4)
\end{align*}
\]

NLO computation (EW and QCD) for $pp \rightarrow e^+\nu_e \mu^+\mu^-jj$

<table>
<thead>
<tr>
<th>Order</th>
<th>$\mathcal{O}(\alpha^7)$</th>
<th>$\mathcal{O}(\alpha_s \alpha^6)$</th>
<th>$\mathcal{O}(\alpha_s^2 \alpha^5)$</th>
<th>$\mathcal{O}(\alpha_s^3 \alpha^4)$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta\sigma_{NLO}$ [fb]</td>
<td>$-0.2169(3)$</td>
<td>$-0.0568(5)$</td>
<td>$-0.00032(13)$</td>
<td>$-0.0063(4)$</td>
<td>$-0.2804(7)$</td>
</tr>
<tr>
<td>$\delta\sigma_{NLO}/\sigma_{LO}$ [%]</td>
<td>$-13.2$</td>
<td>$-3.5$</td>
<td>$0.0$</td>
<td>$-0.4$</td>
<td>$-17.1$</td>
</tr>
</tbody>
</table>

The expected NLO cross section is 17% lower than $\sigma_{LO}$ (the dominant contribution is -13% due to NLO EW corrections)

ATLAS

$\sigma^{\text{fid}}(W^\pm W^\pm jj) = 2.91 \pm 0.51$ (stat.) $\pm 0.27$ (sys.) fb

$\sigma^{\text{th}}(W^\pm W^\pm jj) = 1.67^{+0.27}_{-0.19}$ fb @ NLO (SHERPA)

CMS

$\sigma^{\text{fid}}(W^\pm W^\pm jj) = 3.83 \pm 0.66$ (stat.) $\pm 0.35$ (sys.) fb

$\sigma^{\text{th}}(W^\pm W^\pm jj) = 3.52 \pm 0.22$ fb @ NLO (MADGRAPH)
LHC results: same sign $W^\pm W^\pm jj$

Limits in the Georgi-Machacek (GM) model:

- complex isospin doublet $Y=1\ (\phi^+, \phi^0)$
- real triplet with $Y=0\ (\zeta^+, \zeta^0, \zeta^-)$
- complex triplet with $Y=2\ (\chi^{++}, \chi^+, \chi^0)$

$s_H = \sin \theta_H$, mixing angle of vevs

$s_H \equiv \sin \theta_H = \frac{2\sqrt{2}v_{\chi}}{v}$.

Limits on $\sigma_{\text{VBF}}(H^{\pm\pm})B(H^{\pm\pm} \rightarrow W^\pm W^\pm)$

Limits on $s_H$ vs $m_{H^{\pm\pm}}$

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HC 2018

Ryogoku, Tokyo, Japan
LHC results: $W^\pm Z \ jj$

Measurements of EW production of $W^\pm Z \ jj$ by ATLAS and CMS:

**ATLAS**: ATLAS-CONF-2018-033 (July 2018)  

**CMS**: CMS-PAS-SMP-18-001(July 2018)

$s$, Integr. Luminosity 13 TeV, 36.1 fb$^{-1}$ (2015+2016)  

13 TeV, 35.9 fb$^{-1}$ (2016)

Event selection:
3 leptons (e, or $\mu$) and 2 jets

<table>
<thead>
<tr>
<th>Requirements</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$p_T^l &gt;$ (GeV)</td>
<td>27/20/20</td>
<td>25(Zl1)/15(Zl2)/20(W)</td>
</tr>
<tr>
<td>2l from Z</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T^j &gt;$ (GeV)</td>
<td>40/40</td>
<td>50/50</td>
</tr>
<tr>
<td>$</td>
<td>\eta_j</td>
<td>&lt;$</td>
</tr>
</tbody>
</table>

Signal selection: $m_{jj}$, $\Delta \eta_{jj}$, $E_T^{\text{miss}}$

<table>
<thead>
<tr>
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<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{jj} &gt;$ (GeV)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>-(\eta_{j1} \cdot \eta_{j2}),</td>
<td>$\Delta \eta_{jj}</td>
<td>&gt;</td>
</tr>
<tr>
<td>$m_{T,W}$, $p_T^{\text{miss}} &gt;$ (GeV)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$m_{3l} &gt;$ (GeV)</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Measurement performed in $e^+e^-\mu^\pm$, $e^+e^-e^\pm$, $\mu^+\mu^-\mu^\pm$, and $\mu^+\mu^-e^\pm$ final states

**Major backgrounds (estimated from data):**
- $WZjj$ QCD induced control region: low $m_{jj}$

**Other backgrounds (estimated from data):**
- $ZZ$ control region: 1 additional loose ID lepton
- $t\bar{t} + V$ control region: b-tagged jets

**Other backgrounds (estimated from MC):**
- $VVV$, $tZj$
LHC results: $W^\pm Z jj$

$W^\pm Z jj$ EW signal significances:

**ATLAS**: 5.6 $\sigma$ observed (3.3 $\sigma$ expected)

**CMS**: 1.9 $\sigma$ observed (2.7 $\sigma$ expected)
LHC results: $W^\pm Zjj$

Signal extraction:

**ATLAS**
- MC signal: SHERPA (LO)
- Data: BDT trained to separate

**CMS**
- MC signal: MADGRAPH5_aMC@NLO (LO)
- Data: 2D fit $m_{jj} - |\Delta\eta_{jj}|$ shape

Fiducial cross sections:

**ATLAS**
- $\sigma_{fid,EW}(W^\pm Zjj) = 0.57^{+0.14}_{-0.13} (\text{stat.})^{+0.05}_{-0.04} (\text{sys.})^{+0.04}_{-0.03} (\text{th.}) \text{ fb}$
- $\sigma_{th,EW}(W^\pm Zjj) = 0.32\pm0.03 \text{ fb @ LO (SHERPA)}$
- $\sigma_{th,EW}(W^\pm Zjj) = 0.366\pm0.004 (\text{stat.}) \text{ fb @ LO (MADGRAPH)}$

**CMS**
- $\sigma_{fid}(W^\pm Zjj) = 2.91^{+0.53}_{-0.49} (\text{stat.})^{+0.41}_{-0.34} (\text{sys.}) \text{ fb}$
- $\sigma_{th}(W^\pm Zjj) = 3.27^{+0.39}_{-0.32} (\text{scale}) \pm0.15 (\text{PDF}) \text{ fb @ LO (MADGR.)}$

ATLAS and CMS $\sigma_{fid}$ are different because ATLAS measured the EW component, CMS the total.

Fiducial cross sections are compatible with SM expectations, for ATLAS small discrepancy of $1.7\sigma$.

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LHC results: $W^\pm Zjj$

NLO computation (EW and QCD) for $pp \rightarrow e^+\nu_e \mu^+\mu^-jj$

\[
\begin{array}{c}
\text{LO} \quad O(\alpha^6) \\
\text{EW} \quad \Rightarrow \quad \text{QCD} \quad O(\alpha_s^6)
\end{array}
\]

\[
\begin{array}{c}
\text{NLO} \quad O(\alpha^7) \\
\text{EW} \quad \Rightarrow \quad \text{QCD} \quad O(\alpha_s^7)
\end{array}
\]

\[
\begin{array}{c}
\text{Phys. Rev. D 75, 073004 (2007)} \\
\sigma_{LO}^{\text{cut}}(\mu_0 = m_V) \quad \sigma_{NLO}^{\text{cut}}(\mu_0 = m_V)
\end{array}
\]

\[
\begin{array}{c|c|c}
& W^+ Zjj & W^- Zjj \\
\hline
\sigma_{LO}^{\text{cut}} & 0.224 fb & 0.217 fb \\
\sigma_{NLO}^{\text{cut}} & 0.122 fb & 0.120 fb
\end{array}
\]

Preliminary $O(\alpha^7)$ from like sign WW expected to have large contribution

(Christopher Schwan, Ansgar Denner, Stefan Dittmaier, Philipp Maierhöfer, Mathieu Pellen)

(High Precision for Hard Processes 2018 Freiburg 1-3 October 2018)

\[
\begin{array}{c|c|c|c}
\text{LO [fb]} & \text{NLO [fb]} & \delta = \frac{O(\alpha^7)}{O(\alpha^6)} [\%] \\
\hline
0.2362_{-8.022\%}^{+9.433\%} & 0.1899_{-7.575\%}^{+8.356\%} & -19.6\%
\end{array}
\]
LHC results: ZZ jj

Measurements of EW production of ZZ jj by CMS:


\( \sqrt{s} \), Integr. Luminosity 13 TeV, 35.9 fb\(^{-1} \) (2016)

Event selection: 4 leptons (e, or \( \mu \)) and 2 jets

<table>
<thead>
<tr>
<th>Requirements</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T^{l_1} &gt; ) (GeV)</td>
<td>20 (Z( l_1 ))/12 (Ze( e_2 )), 10 (Z( \mu_2 ))</td>
</tr>
<tr>
<td>4l from ZZ</td>
<td>✓</td>
</tr>
<tr>
<td>( p_T^{l_2} &gt; ) (GeV)</td>
<td>30/30</td>
</tr>
<tr>
<td>(</td>
<td>\eta_j</td>
</tr>
</tbody>
</table>

Signal selection: \( m_{jj}, \Delta \eta_{jj}, E_T^{\text{miss}} \)

<table>
<thead>
<tr>
<th>Requirements</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{jj} &gt; ) (GeV)</td>
<td>400</td>
</tr>
<tr>
<td>(</td>
<td>\Delta \eta_{jj}</td>
</tr>
</tbody>
</table>

Major backgrounds (estimated from data):
- ZZjj QCD induced control region: low \( m_{jj} \)

Other backgrounds (estimated from data):
- Z+jets control region: inverted lepton ID criteria

Other backgrounds (estimated from MC):
- ttZ + jets
- WWZ + jets
LHC results: ZZ jj

ZZjj EW signal significances:

CMS: 2.7 $\sigma$ observed (1.6 $\sigma$ expected)

Signal extraction:

MC signal: MADGRAPH5_aMC@NLO (LO)
Data: BDT trained to separate ZZ EW signal from other processes

Fiducial cross sections:

$$\sigma^{\text{fid,EW}}_{\text{ZZjj}} = 0.40^{+0.21}_{-0.16} \text{ (stat.)}^{+0.13}_{-0.09} \text{ (sys.) fb}$$

$$\sigma^{\text{th}}_{\text{ZZjj}} = 0.29^{+0.02}_{-0.03} \text{ fb @ LO (MADGRAPH)}$$

Fiducial cross section is compatible with SM expectation
Effective Field Theory

Add additional operators to the SM Lagrangian density with dimension larger than $E^4$:

$$L_{\text{eff}} = L_{SM} + \sum_n \frac{c_n}{\Lambda_n^4} \mathcal{O}^{(n+4)}$$

Coupling constants $c_n/\Lambda_n$ with dimensions $E^{-n}$

Operators are constructed by defining particle content

Operators are suppressed if the accessible energy is low compared to mass scale

All possible dimension 6 operators (*):

Only 5 operators affect Vector Boson Self interactions:
3 with C and P conserved
2 with C and/or P violated

(*) Only even-dimensional operators conserve both lepton and baryon number
Anomalous quartic coupling (aQGC)

All possible dimension 8 operators:

Only from dimension 8 there are operators contributing to QGC but not to trilinear gauge coupling (TGC)

\[
L_{S0} = \frac{f_{S0}}{\Lambda^4} [(D_\mu \Phi)\dagger D_\nu \Phi] \times [(D_\mu \Phi)^\dagger D_\nu \Phi],
\]

\[
L_{S1} = \frac{f_{S1}}{\Lambda^4} [(D_\mu \Phi)\dagger D_\rho \Phi] \times [(D_\rho \Phi)^\dagger D_\nu \Phi],
\]

\[
L_{M0} = \frac{f_{M0}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \sigma}^\dagger] \times [(D_\beta \Phi)\dagger D_\beta \Phi],
\]

\[
L_{M1} = \frac{f_{M1}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \beta}^\dagger] \times [(D_\beta \Phi)^\dagger D_\beta \Phi],
\]

\[
L_{M2} = \frac{f_{M2}}{\Lambda^4} [B_{\mu \nu}B_{\rho \beta}^\dagger] \times [(D_\beta \Phi)^\dagger D_\beta \Phi],
\]

\[
L_{M3} = \frac{f_{M3}}{\Lambda^4} [B_{\mu \nu}B_{\rho \beta}^\dagger] \times [(D_\beta \Phi)^\dagger D_\beta \Phi],
\]

\[
L_{M4} = \frac{f_{M4}}{\Lambda^4} [(D_\mu \Phi)^\dagger W_{\beta \nu}D_\rho \Phi] \times B_{\beta \nu},
\]

\[
L_{M5} = \frac{f_{M5}}{\Lambda^4} [(D_\mu \Phi)^\dagger W_{\beta \nu}D_\rho \Phi] \times B_{\beta \nu},
\]

\[
L_{M6} = \frac{f_{M6}}{\Lambda^4} [(D_\mu \Phi)^\dagger W_{\beta \nu}W_{\beta \nu}^\dagger D_\rho \Phi] ,
\]

\[
L_{M7} = \frac{f_{M7}}{\Lambda^4} [(D_\mu \Phi)^\dagger W_{\beta \nu}W_{\beta \nu}^\dagger D_\rho \Phi] ,
\]

\[
L_{T0} = \frac{f_{T0}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \sigma}^\dagger] \times \text{Tr}[W_{\alpha \beta}W_{\alpha \beta}^\dagger],
\]

\[
L_{T1} = \frac{f_{T1}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \beta}^\dagger] \times \text{Tr}[W_{\mu \rho}W_{\nu \beta}],
\]

\[
L_{T2} = \frac{f_{T2}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \beta}^\dagger] \times \text{Tr}[W_{\mu \rho}W_{\nu \beta}],
\]

\[
L_{T5} = \frac{f_{T5}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \sigma}^\dagger] \times B_{\alpha \beta}B_{\alpha \beta},
\]

\[
L_{T6} = \frac{f_{T6}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \sigma}^\dagger] \times B_{\alpha \beta}B_{\alpha \beta},
\]

\[
L_{T7} = \frac{f_{T7}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \sigma}^\dagger] \times [B_{\alpha \beta}B_{\alpha \beta}],
\]

\[
L_{T8} = \frac{f_{T8}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \sigma}^\dagger] \times B_{\alpha \beta}B_{\alpha \beta},
\]

\[
L_{T9} = \frac{f_{T9}}{\Lambda^4} \text{Tr}[W_{\mu \nu}W_{\rho \sigma}^\dagger] \times B_{\alpha \beta}B_{\alpha \beta}.
\]
# Anomalous quartic coupling (aQGC)

## CMS WWjj

PRL 120, 081801 (Nov. 2017)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Observed limits (TeV$^{-4}$)</th>
<th>Expected limits (TeV$^{-4}$)</th>
<th>Previously observed limits (TeV$^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{50}/\Lambda^4$</td>
<td>$[-7.7, 7.7]$</td>
<td>$[-7.0, 7.2]$</td>
<td>$[-58, 40]$</td>
</tr>
<tr>
<td>$f_{51}/\Lambda^4$</td>
<td>$[-21.6, 21.8]$</td>
<td>$[-19.9, 20.2]$</td>
<td>$[-118, 120]$</td>
</tr>
<tr>
<td>$f_{M0}/\Lambda^4$</td>
<td>$[-6.0, 5.9]$</td>
<td>$[-5.6, 5.5]$</td>
<td>$[-4.6, 4.6]$</td>
</tr>
<tr>
<td>$f_{M1}/\Lambda^4$</td>
<td>$[-8.7, 9.1]$</td>
<td>$[-7.9, 8.5]$</td>
<td>$[-17, 17]$</td>
</tr>
<tr>
<td>$f_{M6}/\Lambda^4$</td>
<td>$[-11.9, 11.8]$</td>
<td>$[-11.1, 11.0]$</td>
<td>$[-65, 63]$</td>
</tr>
<tr>
<td>$f_{M7}/\Lambda^4$</td>
<td>$[-13.3, 12.9]$</td>
<td>$[-12.4, 11.8]$</td>
<td>$[-70, 66]$</td>
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<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>$[-0.62, 0.65]$</td>
<td>$[-0.58, 0.61]$</td>
<td>$[-0.46, 0.44]$</td>
</tr>
<tr>
<td>$f_{T1}/\Lambda^4$</td>
<td>$[-0.28, 0.31]$</td>
<td>$[-0.26, 0.29]$</td>
<td>$[-0.61, 0.61]$</td>
</tr>
<tr>
<td>$f_{T2}/\Lambda^4$</td>
<td>$[-0.89, 1.02]$</td>
<td>$[-0.80, 0.95]$</td>
<td>$[-1.2, 1.2]$</td>
</tr>
</tbody>
</table>

## CMS WZjj

CMS-PAS-SMP-18-001 (July 2018)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Expected limit (TeV$^{-4}$)</th>
<th>Observed limit (TeV$^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{M0}/\Lambda^4$</td>
<td>$[-10.7, 10.7]$</td>
<td>$[-8.80, 8.55]$</td>
</tr>
<tr>
<td>$f_{M1}/\Lambda^4$</td>
<td>$[-10.1, 10.6]$</td>
<td>$[-8.25, 8.85]$</td>
</tr>
<tr>
<td>$f_{S0}/\Lambda^4$</td>
<td>$[-31.5, 33.5]$</td>
<td>$[-25.7, 27.5]$</td>
</tr>
<tr>
<td>$f_{S1}/\Lambda^4$</td>
<td>$[-50.5, 51.5]$</td>
<td>$[-40.5, 41.5]$</td>
</tr>
<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>$[-0.85, 0.85]$</td>
<td>$[-0.72, 0.75]$</td>
</tr>
<tr>
<td>$f_{T1}/\Lambda^4$</td>
<td>$[-0.55, 0.55]$</td>
<td>$[-0.48, 0.52]$</td>
</tr>
<tr>
<td>$f_{T2}/\Lambda^4$</td>
<td>$[-2.98, 2.92]$</td>
<td>$[-1.42, 1.83]$</td>
</tr>
</tbody>
</table>

## CMS ZZjj


<table>
<thead>
<tr>
<th>Coupling</th>
<th>Exp. lower (TeV$^{-4}$)</th>
<th>Exp. upper (TeV$^{-4}$)</th>
<th>Obs. lower (TeV$^{-4}$)</th>
<th>Obs. upper (TeV$^{-4}$)</th>
<th>Unitarity bound (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>$-0.53$</td>
<td>0.51</td>
<td>$-0.46$</td>
<td>0.44</td>
<td>2.5</td>
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<tr>
<td>$f_{T1}/\Lambda^4$</td>
<td>$-0.72$</td>
<td>0.71</td>
<td>$-0.61$</td>
<td>0.61</td>
<td>2.3</td>
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<tr>
<td>$f_{T2}/\Lambda^4$</td>
<td>$-1.4$</td>
<td>1.4</td>
<td>$-1.2$</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>$f_{T8}/\Lambda^4$</td>
<td>$-0.99$</td>
<td>0.99</td>
<td>$-0.84$</td>
<td>0.84</td>
<td>2.8</td>
</tr>
<tr>
<td>$f_{T9}/\Lambda^4$</td>
<td>$-2.1$</td>
<td>2.1</td>
<td>$-1.8$</td>
<td>1.8</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Anomalous quartic coupling (aQGC)

Strong improvement of aQGC limits with $\sqrt{s} = 13$ TeV data

July 2018
Anomalous quartic coupling (aQGC)

July 2018

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits (TeV⁻⁴)</th>
<th></th>
<th>Ldt</th>
<th>f₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>ss WW</td>
<td>[-3.8e+01, 4.0e+01]</td>
<td>19.4 fb⁻¹</td>
<td>8 TeV</td>
<td></td>
</tr>
<tr>
<td>ss WW</td>
<td>[-7.7e+00, 7.7e+00]</td>
<td>35.9 fb⁻¹</td>
<td>13 TeV</td>
<td></td>
</tr>
<tr>
<td>WZ</td>
<td>[-2.6e+01, 2.6e+01]</td>
<td>35.9 fb⁻¹</td>
<td>13 TeV</td>
<td></td>
</tr>
<tr>
<td>ss WW</td>
<td>[-1.2e+02, 1.2e+02]</td>
<td>19.4 fb⁻¹</td>
<td>8 TeV</td>
<td></td>
</tr>
<tr>
<td>ss WW</td>
<td>[-2.2e+01, 2.2e+01]</td>
<td>35.9 fb⁻¹</td>
<td>13 TeV</td>
<td></td>
</tr>
<tr>
<td>WZ</td>
<td>[-4.0e+01, 4.2e+01]</td>
<td>35.9 fb⁻¹</td>
<td>13 TeV</td>
<td></td>
</tr>
</tbody>
</table>

aQGC Limits @95% C.L. [TeV⁻⁴]
Conclusions

• Non-abelian gauge structure of Standard Model:
  - evidence of triple gauge coupling (TGC) by LEP
  - evidence of VBS (which includes QGC) by LHC

  We have done it!

• Fiducial cross sections of $W^\pm W^\pm jj$, $WZjj$ and $ZZjj$
  are compatible with standard model expectations
  Analyses have been performed with ~36 fb$^{-1}$ collected in 2016.
  Statistical errors are larger than systematic errors (twice for $W^\pm W^\pm jj$)
  they will be reduced with the full Run2 data sample ~150 fb$^{-1}$

• Limits on anomalous QGC have been strongly improved with respect to previous limits obtained with $\sqrt{s}=8$ TeV Run 1 data sample.