Multiboson production at ATLAS and CMS

Louis Helary – Heidelberg University, Physikalisches Institut

On the behalf of the ATLAS and CMS collaborations

Moriond QCD 2019 - 03/27/2019
Outline

• Introduction
• Precision measurements
• Rare processes
• Limits on new physics
• Conclusions
Introduction

- Introduction
- Precision measurements
- Rare processes
- Limits on new physics
- Conclusions
Introduction – EWK measurements

Multiboson program at the LHC:

- Precision measurements in 2 bosons:
  - Comparisons to higher order predictions.
  - Extraction of SM parameters.

- Sensitivity to new final states never observed before!
  - Double parton interactions.
  - 3 bosons production
  - Vector Boson Scattering

- Probe new physics.


CMS ZZ: EPJC 78 165 (2018)

ATLAS ZZ: arXiv:1902.05759

CMS ssWW: PRL. 120 (2018) 081801
Model independent cross section measurements

- Cross-sections measured in fiducial volumes and extrapolated to total phase space:

\[ \sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{L \times C} \]

\[ \sigma_{\text{tot}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{L \times A \times C} \]

- Where:
  - C corrects for detector inefficiency and resolution.
  - A is signal acceptance in the fiducial volume.

- Differential measurements performed to provide kinematic distributions of data subtracted from backgrounds, and corrected from detector effect.

\[ \sigma_{f} = \frac{N_{f}}{L \times C} \]

\[ \sigma_{t} = \frac{N_{t}}{L \times A \times C} \]
Interpretation on Boson Gauge Couplings or other BSM theory

- Trilinear and Quartic Gauge boson couplings (TGC, QGC) precisely determined by SU(2)xU(1) gauge symmetry.
  - Neutral coupling forbidden.
  - TGC:
    - VBF and VV production.
  - QGC:
    - VBS and VVV production.
- Anomalous Gauge Coupling results in large production cross-section at high energy.
  - aTGCs and aQGCs parameterised with effective theory.
  - Limits provided as functions of operators.
  - Also probe new physics in less generic interpretation and provide limits on model such as (H++, H+, W', etc.).

<table>
<thead>
<tr>
<th>coupling</th>
<th>parameters</th>
<th>channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW\gamma$</td>
<td>$\lambda_\gamma, \Delta k_\gamma$</td>
<td>$WW, W\gamma$</td>
</tr>
<tr>
<td>$WWZ$</td>
<td>$\lambda_Z, \Delta k_Z, \Delta q_1^Z$</td>
<td>$WW, WZ$</td>
</tr>
<tr>
<td>$ZZ\gamma$</td>
<td>$h_3^Z, h_4^Z$</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td>$Z\gamma\gamma$</td>
<td>$h_3^\gamma, h_4^\gamma$</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td>$Z\gamma Z$</td>
<td>$f_4^\gamma, f_5^\gamma$</td>
<td>$ZZ$</td>
</tr>
<tr>
<td>$ZZZ$</td>
<td>$f_4^Z, f_5^Z$</td>
<td>$ZZ$</td>
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</table>

<table>
<thead>
<tr>
<th>O_{S.0}, O_{S.1}</th>
<th>WWW</th>
<th>WWZZ</th>
<th>ZZZZ</th>
<th>WWAZ</th>
<th>WWAA</th>
<th>ZZZA</th>
<th>ZZAA</th>
<th>ZAAA</th>
<th>AAAA</th>
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<tbody>
<tr>
<td>O_{M.0}, O_{M.1}, O_{M.6}, O_{M.7}</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>O_{M.2}, O_{M.3}, O_{M.4}, O_{M.5}</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>O_{T.0}, O_{T.1}, O_{T.2}</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>O_{T.5}, O_{T.6}, O_{T.7}</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>O_{T.8}, O_{T.9}</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

aQGC (dim 8) operators
Precision measurements

- Introduction
- Precision measurements
  - $WZ \rightarrow \ell\ell\ell\nu$
  - $4\ell$ final state
  - $\nu\nu\gamma$
- Rare process
- Limits on new physics
- Conclusions
WZ→ℓℓℓν inclusive measurement

- WZ→3ℓν selection:
  - 3ℓ (e,μ) compatible with a Z and a W.

- Using 36 fb⁻¹ of data (2015-2016).

- Measure integrated cross section:
  - Prediction NNLO: \( \sigma_{WZ}^{tot} = 49.98^{+2.2\%}_{-2.0\%} \) pb
  - ATLAS: \( \sigma_{WZ}^{tot} = 51.0 \pm 2.4 \) pb
  - CMS: \( \sigma_{WZ}^{tot} = 48.09^{+2.98}_{-2.78} \) pb

- Also measure ratio W+Z/W-Z.

- Find good agreement with predictions everywhere.

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Both experiments have unfolded distributions:

- CMS: $p_T^Z$, $p_T^{j_1}$, $M_{WZ}$.
- ATLAS: $p_T^Z$, $p_T^W$, $M_{WZ}^Z$, $\Delta \phi_{WZ}$, $p_T^\nu$, $|y_Z-y_W|$, $N_{jets}$, $M_{jj}$.

CMS publish limits of aTGCs.

ATLAS provides a first measurement of the W and Z polarisations at hadrons collider.
ZZ → 4ℓ differential measurement

- ZZ → 4ℓ selection:
  - 4ℓ (e,μ) compatible with 2 Zs: 2 SFOS pairs.
  - Investigate: 70 < m_4ℓ < 1200 GeV
  - ATLAS Using 36 fb^{-1} of data (2015-2016).

- Explore multiple production mode Z → 4ℓ , H → 4ℓ , ZZ → 4ℓ continuum, gg → 4ℓ.

- Provide unfolded m_4ℓ, p_T^{4ℓ}, y^{4ℓ} and a matrix element discriminant.

- Measurement compared to different order of predictions.

- Use these measurements to make reinterpretations.
  - μ_{gg4ℓ} = 1.3 ± 0.5 (compare to NLO).

- Constraint off-shell Higgs boson signal strength.

- Modified Higgs coupling gluon and top.

![ATLAS m4l: arXiv:1902.05892](image)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( B_{Z \rightarrow 4\ell}/10^{-6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, ( \sqrt{s} = 7 ) TeV and ( \sqrt{s} = 8 ) TeV [8]</td>
<td>( 4.31 \pm 0.34 \text{(stat)} \pm 0.17 \text{(syst)} )</td>
</tr>
<tr>
<td>CMS, ( \sqrt{s} = 13 ) TeV [6]</td>
<td>( 4.83 \pm 0.23 \text{(stat)} \pm 0.32 \text{(syst)} \pm 0.08 \text{(theo)} \pm 0.12 \text{(lumi)} )</td>
</tr>
<tr>
<td>ATLAS, ( \sqrt{s} = 13 ) TeV</td>
<td>( 4.70 \pm 0.32 \text{(stat)} \pm 0.21 \text{(syst)} \pm 0.14 \text{(lumi)} )</td>
</tr>
</tbody>
</table>

ZZ→4ℓ selection:

- 4 lepton (e, μ) consistent with ZZ: (i.e., 2 pair SFOS).
- 60 < M_{Z1,2} < 120 GeV.
- CMS Analyses 2016, 2017 and 2018 Data!
- Good agreement with NNLO predictions.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fiducial cross section, fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>40.9 ± 1.3 (stat) ± 1.4 (syst) ± 1.0 (lumi)</td>
</tr>
<tr>
<td>2017</td>
<td>39.1 ± 1.2 (stat) ± 1.2 (syst) ± 1.0 (lumi)</td>
</tr>
<tr>
<td>2018</td>
<td>39.2 ± 1.0 (stat) ± 1.3 (syst) ± 1.0 (lumi)</td>
</tr>
<tr>
<td>Combined</td>
<td>39.9 ± 0.7 (stat) ± 1.0 (syst) ± 0.7 (lumi)</td>
</tr>
</tbody>
</table>


First multiboson full run2 measurement!!

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CMS full run2 ZZ: PAS-SMP-19-001
**vνγ measurement**

- **vνγ selection:**
  - $E_{T\gamma}>150$ GeV and $E_{T\text{Miss}}$.
  - ATLAS Using 36 fb$^{-1}$ of data (2015-2016).
- Channel not sensitive to FSR.
- Higher stat at high energy than $\ell\ell\gamma$ channels.
- Measurement in inclusive, and exclusive jet requirements.
- Provide unfolded $E_{T\gamma}$, $N_{\text{jets}}$, $p_{T\nu\nu}$.
- Provide limits on $aTGC$.
- No deviation observed from the predictions.

<table>
<thead>
<tr>
<th>$\sigma_{\text{ext. fid.}}$ [fb]</th>
<th>$\sigma_{\text{ext. fid.}}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement</strong></td>
<td><strong>NNLO MCFM Prediction</strong></td>
</tr>
<tr>
<td>$\frac{N_{\text{jets}}}{78.1 \pm 0.2(\text{stat.}) \pm 0.7(\text{syst.})}$</td>
<td>$78.1 \pm 0.2(\text{stat.}) \pm 0.7(\text{syst.})$</td>
</tr>
<tr>
<td>$\frac{N_{\text{jets}}}{55.9 \pm 0.1(\text{stat.}) \pm 0.3(\text{syst.})}$</td>
<td>$55.9 \pm 0.1(\text{stat.}) \pm 0.3(\text{syst.})$</td>
</tr>
</tbody>
</table>

**ATLAS vnu gamma:**
JHEP 12 (2018) 010

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Rare process: VBS & VVV

- Introduction
- Precision measurements
- Rare processes
  - Double parton interactions
  - $WZjj \rightarrow \ell\ell\nu jj$
  - $VVjj \rightarrow \ell\nu jj$ or $\ell\ell\nu jj$
  - $WWW \rightarrow \ell\ell\nu jj$ or $\ell\ell\ell\nu

and $VVV \rightarrow \ell\ell\nu jj$, $\ell\ell\ell\nu$

- Limits on new physics
- Conclusions
**Double Parton Interaction**

**CMS DPS WW → ℓ±ℓ±:**
- First evidence for DPS!
- Sensitivity: $3.9\sigma$
- Measure cross section: $1.41\pm0.28$ (stat)±0.28 (syst) pb
- Extract $\sigma_{\text{eff}} = 12.7^{+5}_{-2.9}$ mb

**ATLAS DPS ZZ → 4ℓ:**
- 8 TeV data (2012).
- No sensitivity to process.
- Extract 95% CL limit: $\sigma_{\text{eff}} > 1$ mb.

New result!!

Will be discussed in detail in Merijn Van De Klundert talk tomorrow!
VBS $WZjj \rightarrow \ell\ell\nu\nu$

- $WZjj \rightarrow 3\ell$ selection:
  - 3\ell (e,\mu) compatible with a Z and a W
  - 2 high $p_T$ jets, with high $m_{jj}$.
  - Using 36 fb$^{-1}$ of data (2015-2016).

- Use BDT approach in ATLAS, cut based approach for CMS fitting $m_{jj}$.

- Sensitivity:
  - ATLAS: 5.3 (3.2) $\sigma$
  - CMS: 2.2 (2.5) $\sigma$

- Measure cross section in fiducial space for both EWK and QCD+EWK.

ATLAS:
\[ \sigma_{\text{fid}}^{WZ-\text{EWK}} = 0.57^{+0.16}_{-0.14} \text{ fb} \]

Sherpa:
\[ \sigma_{\text{fid-LO}}^{WZ-\text{EWK}} = 0.32 \pm 0.03(\text{scale}) \text{ fb} \]
ATLAS also measured differential distributions for WZjj QCD+EWK:

- Sensitive to aQGCs: \( \sum p_{T}, (b) \Delta \phi(W,Z) \) and (c) \( m_{WZ} \)

- For modelling: \( \Delta y_{jj}, m_{jj}, N_{\text{jet}^\text{gap}}, \Delta \phi_{jj} \).

CMS also provides limits on aQGCs and charged Higgs.

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Exp. limit</th>
<th>Obs. limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{M0}/\Lambda^4 )</td>
<td>([-11.2, 11.6])</td>
<td>([-9.15, 9.15])</td>
</tr>
<tr>
<td>( f_{M1}/\Lambda^4 )</td>
<td>([-10.9, 11.6])</td>
<td>([-9.15, 9.45])</td>
</tr>
<tr>
<td>( f_{S0}/\Lambda^4 )</td>
<td>([-32.5, 34.5])</td>
<td>([-26.5, 27.5])</td>
</tr>
<tr>
<td>( f_{S1}/\Lambda^4 )</td>
<td>([-50.2, 53.2])</td>
<td>([-41.2, 42.8])</td>
</tr>
<tr>
<td>( f_{T0}/\Lambda^4 )</td>
<td>([-0.87, 0.89])</td>
<td>([-0.75, 0.81])</td>
</tr>
<tr>
<td>( f_{T1}/\Lambda^4 )</td>
<td>([-0.56, 0.60])</td>
<td>([-0.49, 0.55])</td>
</tr>
<tr>
<td>( f_{T2}/\Lambda^4 )</td>
<td>([-1.78, 2.00])</td>
<td>([-1.49, 1.85])</td>
</tr>
</tbody>
</table>

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**CMS WZjj:**
arXiv:1901.04060

**ATLAS WZjj:**
arXiv:1812.09740
VBS VVjj→ℓνJjj or ℓℓJjj

- Selection of VVjj→ℓνJjj or ℓℓJjj:
  - 1 or 2 leptons compatible with W or Z, 1 large R_{jet} compatible with W or Z, and 2 high p_T jets with high m_{jj}.
- CMS using 36 fb^{-1} of data (2015-2016).
- Analysis not sensitive to SM coupling.
- Set limit on aQGC.
- Sensitive to exotic charged Higgs scenario.

<table>
<thead>
<tr>
<th>Selection (WV)</th>
<th>Expected (WV)</th>
<th>Observed (ZV)</th>
<th>Expected (ZV)</th>
<th>Observed (TeV^{-1})</th>
<th>Expected (TeV^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_{S0}/Λ^4</td>
<td>-2.6,27</td>
<td>-4.0,40</td>
<td>-37,37</td>
<td>-29,29</td>
<td>-4.0,40</td>
</tr>
<tr>
<td>f_{S1}/Λ^4</td>
<td>-3.2,33</td>
<td>-4.9,49</td>
<td>-30,30</td>
<td>-23,23</td>
<td>-3.3,33</td>
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<tr>
<td>f_{MD}/Λ^4</td>
<td>-0.6,66,06</td>
<td>-0.95,95</td>
<td>-6.9,69</td>
<td>-5.1,51</td>
<td>-0.6,66,06,06</td>
</tr>
<tr>
<td>f_{M1}/Λ^4</td>
<td>-1.9,20</td>
<td>-2.8,28</td>
<td>-21,21</td>
<td>-15,15</td>
<td>-1.9,20</td>
</tr>
<tr>
<td>f_{M2}/Λ^4</td>
<td>-1.3,13</td>
<td>-1.9,19</td>
<td>-14,14</td>
<td>-10,10</td>
<td>-1.3,13</td>
</tr>
<tr>
<td>f_{M3}/Λ^4</td>
<td>-3.3,32</td>
<td>-4.8,48</td>
<td>-33,33</td>
<td>-24,24</td>
<td>-4.8,48</td>
</tr>
<tr>
<td>f_{T0}/Λ^4</td>
<td>-0.1,10</td>
<td>-0.16,05</td>
<td>-1.3,13</td>
<td>-0.95,95</td>
<td>-0.1,10</td>
</tr>
<tr>
<td>f_{T1}/Λ^4</td>
<td>-0.1,12</td>
<td>-0.17,17</td>
<td>-1.4,14</td>
<td>-0.98,09</td>
<td>-0.1,12</td>
</tr>
<tr>
<td>f_{T2}/Λ^4</td>
<td>-0.2,17</td>
<td>-0.38,03</td>
<td>-3.1,32</td>
<td>-2.3,23</td>
<td>-0.2,17</td>
</tr>
</tbody>
</table>

New result!!

1 or 2 leptons compatible with W or Z, 1 large R_{jet} compatible with W or Z, and 2 high p_T jets with high m_{jj}.

Analysis not sensitive to SM coupling.

Set limit on aQGC.

Sensitive to exotic charged Higgs scenario.
WWW$\rightarrow$ℓℓννjj or ℓℓℓννν

- Selection of WWW$\rightarrow$ℓℓννjj or ℓℓℓννν:
  - 3 leptons with missing ET or 2 leptons with 2 jets compatible with an extra W.

- CMS uses 36 fb$^{-1}$ of data, ATLAS 80 fb$^{-1}$.

- Significance: Observed (expected)
  - CMS: combined 0.6 (1.8)$\sigma$
  - ATLAS: combined 3.3 (2.4)$\sigma$

- Both experiments measured cross sections.

- CMS sets limits on aQGC and on axion like particles

<table>
<thead>
<tr>
<th>Anomalous coupling</th>
<th>Allowed range (TeV$^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{1,0}/\Lambda^4$</td>
<td>[-1.3, 1.3] [-1.2, 1.2]</td>
</tr>
<tr>
<td>$f_{1,1}/\Lambda^4$</td>
<td>[-3.7, 3.7] [-3.3, 3.3]</td>
</tr>
<tr>
<td>$f_{1,2}/\Lambda^4$</td>
<td>[-3.0, 2.9] [-2.7, 2.6]</td>
</tr>
</tbody>
</table>

CMS WWW: PAS- SMP-17-013
ATLAS WVV: arXiv:1903.10415

New result!!
WWW → ℓℓνjj or ℓℓℓνν
and WVV → ℓℓνjj or ℓℓℓνν or ℓℓℓjj : Evidence for WVV!

- Selection of WVV → ℓℓνjj or ℓℓℓνν or ℓℓℓjj:
  - 3 leptons with missing ET and 2j or 4 leptons with Missing ET.

- Sensitivities:

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>WWW combined</td>
<td>3.3σ</td>
</tr>
<tr>
<td>WWW → ℓνℓνqq</td>
<td>4.3σ</td>
</tr>
<tr>
<td>WWW → ℓℓνννν</td>
<td>1.0σ</td>
</tr>
<tr>
<td>WVZ combined</td>
<td>2.9σ</td>
</tr>
<tr>
<td>WVZ → ℓνqℓqℓq</td>
<td>–</td>
</tr>
<tr>
<td>WVZ → ℓνννννν</td>
<td>3.5σ</td>
</tr>
<tr>
<td>VVV combined</td>
<td>4.0σ</td>
</tr>
</tbody>
</table>

→ First evidence of massive 3boson production!!

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• Conclusions
Limits on aXGC

aQGC: Stringent limits are set on dim 8 operators $F_S$, $F_M$ and $F_T$ using VBS and VVV channels.

Stringent 95% Limits are derived on charged aTGCs.

LHC (CMS, ATLAS) Limits are compatible with Tevatron (D0) and LEP.

Release more modern parameterisation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>95% CI (expected) [TeV$^{-2}$]</th>
<th>95% CI (observed) [TeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_W/\Lambda^2$</td>
<td>$[-3.3, 2.0]$</td>
<td>$[-4.1, 1.1]$</td>
</tr>
<tr>
<td>$c_{WWW}/\Lambda^2$</td>
<td>$[-1.8, 1.9]$</td>
<td>$[-2.0, 2.1]$</td>
</tr>
<tr>
<td>$c_b/\Lambda^2$</td>
<td>$[-130, 170]$</td>
<td>$[-100, 160]$</td>
</tr>
</tbody>
</table>
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Conclusions

- The LHC multibosons recent results were presented.
  - No significant deviation from theoretical predictions have been observed.
    - Start to be sensitive to NNLO correction in some channels.
    - Able to measure for the first time polarisation in diboson events in the WZ final state.
  - New channels are now observed:
    - EWK VBS boson production, tri-bosons, and DPI.
  - Limits on aGCs are better than LEP results or Tevatron.
    - Move to more recent parameterisation.
- Lot more results will come soon! Stay tuned!