Multiboson measurements from CMS

Senka Đurić
(University of Wisconsin-Madison)

On behalf of the CMS Collaboration
Importance of multiboson measurements

So far New Physics has not been directly seen at the LHC

→ Precision measurements are more important then ever!

Higher order perturbative corrections?
- Inclusive and differential cross section measurements

Nature of electroweak symmetry breaking?
- Electroweak diboson production via vector boson scattering

Signature of physics beyond SM above directly reachable energy?
- Search for accesses in high energy/mass tails of diboson production
Multiboson cross section at LHC

March 2017

Production Cross Section, \(\sigma\) [pb]

Inclusive (QCD) diboson production

Probing:
- higher order QCD (and QED) perturbative corrections
- SM gauge structure: triple gauge couplings (TGC)

Electroweak (QED) diboson production

Probing:
- higher order QED perturbative corrections
- the nature of EWSB via EWK vector boson scattering production
- SM gauge structure: triple and quartic gauge couplings (TGC and QGC)

Inclusive (QCD) triboson production

Probing:
- higher order QCD (and QED) perturbative corrections
- SM gauge structure: quartic gauge couplings (QGC)

One of the consequences of non-Abelian gauge theories are the self-interactions of gauge bosons
- Multiboson measurements are probing weak boson self-interactions
Multiboson decay channels

**Fully leptonic channels:**
→ Most precise measurements of the bulk of multiboson signal
→ Total and differential cross section measurements

**ZZ-4l:**
✓ Clean signal signature
✓ Low background
  ▪ Small BR

**ZZ-2l2ν and V- jj channels:**
→ Access to higher pT/mass of the multiboson system
→ Valuable for cross section measurement in high pT phase space and NP searches

**ZZ-2l2ν and ZZ-2l2j:**
- Not clean signal signature
  ▪ Large experimental systematic uncertainties
- Low signal to background except at high energy
✓ Larger BR

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![Graphs and tables showing data distributions for ZZ-4l, ZZ-2l2ν, ZZ-2l2j channels, and other multiboson decay channels.](attachment:image.png)

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DIS 2017
Inclusive diboson cross section measurement summary (I/II)

ZZ→4l measurement statistical uncertainty: 6.5% (8 TeV) -> 3.3% (13 TeV)
Now, all diboson inclusive cross section measurements are already systematics dominated!

From theory side: NNLO QCD calculations now available for all diboson processes, including differential calculations!

ZZ→4l: First diboson measurement with full 2016 dataset!
Inclusive diboson cross section measurement summary (II/II)

Uncertainties in inclusive diboson measurements:

<table>
<thead>
<tr>
<th>Channel (fully leptonic)</th>
<th>√s (TeV)</th>
<th>Dominant systematic uncertainty source</th>
<th>Syst/stat uncertainty w/o lumi (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>8</td>
<td>uncertainty on background estimate</td>
<td>6.7 / 3.6</td>
</tr>
<tr>
<td>ZZ</td>
<td>13</td>
<td>lepton/trigger efficiency</td>
<td>3.6 / 3.3</td>
</tr>
<tr>
<td>WW</td>
<td>8</td>
<td>higher order corrections, UE, lepton efficiency</td>
<td>5.3 (exp) + 5.2 (theory) / 1.5</td>
</tr>
<tr>
<td>Wγ</td>
<td>7</td>
<td>uncertainty on background estimate</td>
<td>10.8 / 2.2</td>
</tr>
<tr>
<td>Zγ</td>
<td>8</td>
<td>uncertainty on background estimate</td>
<td>4.8 / 1.0</td>
</tr>
</tbody>
</table>

ZZ->4l: First diboson measurement with full 2016 dataset!
Importance of differential cross section measurements

Jet related observables allow direct probe of higher order corrections \(\leftrightarrow\) \textit{Differential measurements}

- \textbf{Look for differences of shape in sensitive observables}
- \textbf{Absolute measurement}: measurement of absolute cross section per bin
- \textbf{Normalized measurement}: measurement of shape (significant cancelation of systematic uncertainties)
- \textbf{More possibilities with larger statistics}: ratios of production processes

Expecting sizable effect from NNLO QCD and NLO QED in high pT and angular distributions of the diboson system

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New differential measurements: ZZ->4l

<table>
<thead>
<tr>
<th>Cross section measurement</th>
<th>Fiducial requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common requirements</td>
<td>$p_T^{\ell_1} &gt; 20$ GeV, $p_T^{\ell_2} &gt; 10$ GeV, $p_T^{\ell_3} &gt; 5$ GeV,</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
</tbody>
</table>

**ZZ -> 4\ell**

- 60 < $m_{Z_1}$, $m_{Z_2}$ < 120 GeV

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### Shape comparison

- QCD NLO
- QED LO

**ZZ-PAS-SMP-16-017**

- Possible indication of softer $p_T^{4\ell}$ then predicted by NLO QCD
- Data elsewhere are well reproduced by the simulation
**ZZ production modes**

- Dominant 4l production at Z resonance
- Dominant 4l production above the Z resonance

\[ \sigma_d^{4l} \]

+ small contribution from qq VBS production

**M_{4l} spectrum** is essential for the study of the different production mechanisms!

\[ \pm \] + VBF, VH, tth higgs production (<15% to higgs production)

Higgs boson production

- Large destructive interference of ggH with ggF processes (high mass \( m_{4l} \))

\[ \sqrt{s} = 8 \text{ TeV} \]

**ATLAS Simulation**

- \( \sigma_d^{4l} \)
- \( m_{4l} \) spectrum is essential for the study of the different production mechanisms!
New differential measurements: ZZ->4l

Cross section measurement  
Fiducial requirements

Common requirements  
\[ p_T^{\ell_1} > 20 \text{ GeV} \ , \ p_T^{\ell_2} > 10 \text{ GeV} \ , \ p_T^{\ell_3} > 5 \text{ GeV} \ , \]
\[ |\eta^{\ell}| < 2.5 \ , \ m_{\ell^+\ell^-} > 4 \text{ GeV} \] (any opposite-sign same-flavor pair)

\[ ZZ \rightarrow 4\ell \]
\[ 60 < m_{\ell_1}, m_{\ell_2} < 120 \text{ GeV} \]

dominated by the resonant Higgs boson contribution

- Other then ZZ on-shell, including contributions from the Z and Higgs boson resonances and continuum ZZ production
- With full 2016 dataset starting to be sensitive to differences in shape

ATLAS Simulation

Shape comparison
QCD NLO
QED LO
New differential measurements: WZ→3lν (8 TeV)

- Overall (non significant) higher yield in agreement with expected NNLO QCD corrections (~11%) is observed
- Decrease in uncertainties needed to probe differences in shape
Due to large \( t\bar{t} \) background, **WW measurement is performed applying a jet veto** (0- or 1-jet events only)

- Veto enhances the contribution of the soft gluons to the \( p_T(WW) \) distribution
- **Jet veto efficiency is sensitive to higher-order QCD corrections** → Large theoretical uncertainty!

Differential distributions show good agreement with several predictions from NLO perturbative QCD calculations. Some differences observed in \( \Delta\phi_{ll} \) distributions.
Rare processes: Triboson measurements

First observation of triboson production: Zγγ!

Wγγ and Zγγ:
- Measurements dominated by systematic uncertainty on background (jets misidentified as photons)
- New in Wγγ: added electron channel

Production Cross Section, $σ$ [pb]

<table>
<thead>
<tr>
<th>Triboson measurements</th>
<th>CMS (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WVV→lvjjγ</td>
<td>Upper limit on cross section and aQGC measurement</td>
</tr>
<tr>
<td>Wγγ→lγγ</td>
<td>Cross section and aQGC measurement signal significance 2.6σ</td>
</tr>
<tr>
<td>Zγγ→llγγ</td>
<td>Observation: signal significance 5.9σ</td>
</tr>
</tbody>
</table>

- 7 TeV CMS measurement (L ≤ 5.0 fb$^{-1}$)
- 8 TeV CMS measurement (L ≤ 19.6 fb$^{-1}$)
- 13 TeV CMS measurement (L ≤ 2.7 fb$^{-1}$)
- Theory prediction
- CMS 95%CL limit

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

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13
EWK (QED) diboson production

- **VV+2jets production is dominated** by $O(\alpha_s^2)$ QCD processes
- **EWK VV+2jets production** is essential to probe the nature of the EWSB
  - $V_L V_L$ scattering linked to the mechanism responsible for the EWSB

**VBS characteristic signature:**
- Two high $p_T$ jets in the forward-backward region
- Large rapidity separation between jets ($\Delta\eta_{jj}$)
  - Low hadronic activity in-between
- Large di-jet invariant mass ($M_{jj}$)

**HL-LHC prospects:**
**EWK (QED) diboson production: results**

**EWK measurements: VV+2jets**

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS (8 TeV)</th>
</tr>
</thead>
</table>
| $W^\pm W^\pm \rightarrow l\nu l\nu$ | PRL 114 (2015) 051801  
EWK signal significance 1.9σ (exp 2.9σ) |
| $W\gamma \rightarrow l\nu\gamma$      | CMS-PAS-SMP-14-011 
EWK signal significance 2.7σ (exp 1.5σ) |
| $Z\gamma \rightarrow l\nu l\nu$       | CMS-PAS-SMP-14-018 
Evidence: EWK signal significance 3.0σ (exp 2.1σ) |

- First evidence of EWK VV production with 8 TeV data
- First observation for VV right around the corner (with 13 TeV data)?
Anomalous couplings as a search for New Physics?

Parametrization: extend SM Lagrangian (effective Lagrangian or effective field theory) with additional operators and anomalous parameters, measure parameters:

\[
EFT: \quad L_{SM} \longrightarrow L_{eff} = L_{SM} + \sum_{n=1}^{\infty} \sum_{i} c_i^{(n)} Q_i^{(n+4)}
\]
Anomalous couplings: variety of measurements

Measurements performed in numerous production channels:

- inclusive diboson and triboson measurements
- EWK production offers a complementary test of anomalous couplings

Limiting factor: observed statistics in the tail (primary), systematic and statistical uncertainty on the signal/bkg model (secondary)

No significant deviation of data from SM expectation is observed

Anomalous couplings result in an increase of cross section at high energies

- invariant mass of the diboson system and the boson $p_T$ are particularly sensitive
Anomalous couplings: results

LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) tighter than LEP results.

- Anomalous coupling sensitivity depends on the diboson channel
- Sensitivity is defined by the reach of diboson system invariant mass
  - Best sensitivity from channels with larger BR (semileptonic decays in boosted topology)
  - Large gain in sensitivity with increase of $\sqrt{s}$

### March 2017

<table>
<thead>
<tr>
<th>Channel</th>
<th>CMS</th>
<th>ATLAS</th>
<th>ATLAS+CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_4^\gamma$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_4^\gamma$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_4^Z$</td>
<td></td>
<td></td>
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<tr>
<td>$f_4^Z$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$f_5^\gamma$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$f_5^\gamma$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$f_5^Z$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_5^Z$</td>
<td></td>
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</tr>
</tbody>
</table>

Recent measurement with 13 TeV data!
Anomalous couplings: results

LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) comparable to LEP results.

Recent measurement with 8 and 13 TeV data!
The present and the future of multiboson physics

LHC Run2 is ongoing, so far ~40 fb\(^{-1}\) of data collected by CMS experiments

- Variety of multiboson measurements performed: inclusive and differential cross sections
  - Measurements are pushing for more precise theoretical calculations (NNLO or 3NLO QCD, NLO EWK, ...)
  - Future prospects: increase in sensitivity to higher order perturbative corrections and different production mechanisms, self-consistency check and combinations for anomalous couplings
- Expect sensitivity for first observation of the diboson EWK production with 2016/2017 data
- Significant increase of sensitivity for indirect search for New Physics (aTGC, aQGC)
- Await for vast of new diboson results in next few months!
- Continue to probe the nature of EWSB!

Looking forward: HL-LHC (starting 2023)

http://hilumilhc.web.cern.ch/about/hl-lhc-project
Backup
### Diboson inclusive measurements: overview

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\rightarrow 4l$</td>
<td>PRL 112, 231806 (2014)</td>
<td>PLB 763 (2016) 280, CMS-PAS-SMP-16-017 Cross section, differential and aTGC measurement</td>
</tr>
<tr>
<td>$ZZ\rightarrow 2l2\nu$</td>
<td>JHEP01, 099 (2017) Cross section, differential, aTGC</td>
<td>EPJC 75 (2015) 511 Cross section and aTGC measurement</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow ll\gamma$</td>
<td>PRD 93, 112002 (2016) Cross section, differential and aTGC measurement</td>
<td>PLB 760 (2016) 448 Cross section and aTGC measurement</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow \nu\nu\gamma$</td>
<td>JHEP 09 (2016) 029 (WW+0jet) Cross section, differential and aTGC measurement</td>
<td>CMS-PAS-SMP-16-004 Cross section</td>
</tr>
<tr>
<td>$WW\rightarrow ll\nu\nu$</td>
<td>PLB 763 (2016) 114 (WW+1jet) Cross section measurement</td>
<td>EPJC 76 (2016) 401 (WW+0- or 1-jet) Cross section, differential and aTGC measurement</td>
</tr>
<tr>
<td>$WZ\rightarrow 3l\nu$</td>
<td>PRD 93, 092004 (2016) Cross section, differential, upper limit on EWK WZ, aTGC, aQGC measurement</td>
<td>CMS-SMP-14-014, arXiv:1609.05721 Cross section, differential and aTGC measurement</td>
</tr>
<tr>
<td>$WV\rightarrow lvjj$</td>
<td>-</td>
<td>arXiv:1703.06095 aTGC measurement</td>
</tr>
</tbody>
</table>

- Large cross section of multiboson production at LHC in pp collisions
- Clean signature and small branching ratio for vector bosons decaying leptonically
- Not clean signature but large branching ratio for hadronic decays
# Triboson and rare processes measurements: overview

<table>
<thead>
<tr>
<th>Triboson measurements</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WVγ→lνjjγ</td>
<td>-</td>
<td>PRD 90 (2014) 032008 Upper limit on cross section and aQGC measurement</td>
</tr>
<tr>
<td>Wγγ→lνγγ</td>
<td>PRL 115, 031802 (2015) Cross section (inclusive and exclusive) and aQGC measurement <strong>Evidence</strong>: signal significance &gt;3σ</td>
<td>CMS-PAS-SMP-15-008, arxiv:1704.00366 Cross section and aQGC measurement signal significance 2.6σ</td>
</tr>
<tr>
<td>Zγγ→lνγγ</td>
<td>PRD 93, 112002 (2016) <strong>Observation</strong>: signal significance 6.3σ</td>
<td>CMS-PAS-SMP-15-008 <strong>Observation</strong>: signal significance 5.9σ</td>
</tr>
<tr>
<td>WWW→lνlνjj, lνlνlν</td>
<td>ATLAS-STDM-2015-07 Upper limit on cross section and aQGC measurement</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rare processes</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W⁺W⁺→γγ→lνlν exclusive</td>
<td>-</td>
<td>JHEP 08 (2016) 119 <strong>Evidence</strong>: signal significance 3.4σ (exp 2.8σ) aQGC measurement</td>
</tr>
<tr>
<td>8 TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W⁺W⁺→γγ→lνlν exclusive</td>
<td>PRD 94 (2016) 032011 <strong>Evidence</strong>: signal significance 3σ aQGC measurement, search for exclusive Higg production</td>
<td>-</td>
</tr>
</tbody>
</table>

For the first time, evidence and observations of triboson and exclusive WW production!

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Senka Đurić  
DIS 2017  
23
### EWK results: overview

<table>
<thead>
<tr>
<th>VBS measurements (VV+2jets)</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8 TeV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EWK W⁺W⁻ → lνlν</strong></td>
<td>PRL 113, 141803</td>
<td>PRL 114 (2015) 051801</td>
</tr>
<tr>
<td>Cross section (EWK, EWK+QCD) and aQGC measurement</td>
<td>Cross section (EWK+QCD) and aQGC measurement</td>
<td></td>
</tr>
<tr>
<td><strong>Evidence</strong></td>
<td>EWK signal significance 3.6σ (exp 2.8σ)</td>
<td>EWK signal significance 1.9σ (exp 2.9σ)</td>
</tr>
<tr>
<td></td>
<td>arxiv:1611.02428</td>
<td></td>
</tr>
<tr>
<td>Updated aQGC limits</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>EWK W⁺γ → lνγ</strong></th>
<th>CMS-PAS-SMP-14-011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section (EWK+QCD) and aQGC measurement</td>
<td>Cross section (EWK, EWK+QCD) and aQGC measurement</td>
</tr>
</tbody>
</table>

| **Evidence** | EWK signal significance 1.9σ (exp 2.9σ) |

<table>
<thead>
<tr>
<th><strong>EWK Z⁺γ → llγ</strong></th>
<th>STDM-2015-21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section (EWK, EWK+QCD), aQGC measurement</td>
<td>Cross section (EWK, EWK+QCD) and aQGC measurement</td>
</tr>
</tbody>
</table>

| **Evidence** | EWK signal significance 2.0σ (exp 1.8σ) |

<table>
<thead>
<tr>
<th><strong>EWK WZ → lνll</strong></th>
<th>Phys. Rev. D 93, 092004 (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section (EWK, EWK+QCD) measurement</td>
<td>Cross section (EWK+QCD) measurement</td>
</tr>
</tbody>
</table>

| **Evidence** | EWK signal significance 2.7σ (exp 1.5σ) |

<table>
<thead>
<tr>
<th><strong>EWK WV→ lνjj</strong></th>
<th>PRD 95 (2017) 032001</th>
</tr>
</thead>
<tbody>
<tr>
<td>aQGC measurement</td>
<td></td>
</tr>
</tbody>
</table>

| **Evidence** | EWK signal significance 3.0σ (exp 2.1σ) |

### VBF measurements (V+2jets)

<table>
<thead>
<tr>
<th>VBF measurements (V+2jets)</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8 TeV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EWK Z(II)</strong></td>
<td>JHEP 04 (2014) 031</td>
<td>EPJC 75 (2015) 66</td>
</tr>
<tr>
<td>Cross section (EWK) and aTGC measurement</td>
<td>Cross section (EWK) measurement</td>
<td></td>
</tr>
<tr>
<td><strong>Observation</strong></td>
<td>EWK signal significance ~5σ ()</td>
<td></td>
</tr>
</tbody>
</table>

| Cross section (EWK, EWK+QCD), differential (EWK, EWK+QCD), aTGC measurement | Cross section (EWK) measurement |
| **Observation** | EWK signal significance >5σ |

| **Evidence** | EWK signal significance ~4σ |

+ some measurements also with 7 TeV !
LHC experiments
CMS experiment
LHC performance

- Wonderful performance of LHC accelerator in past years

  - Large amount of data collected by ATLAS and CMS experiments of proton-proton collisions at a center-of-mass energies of $\sqrt{s} = 7$, 8 and 13 TeV

  - Huge amount of measurements performed, including milestone discovery of Higgs boson!
ZZ normalized differential with full 2016 data
New differential measurements: ZZ

qq→4l: NLO in QCD with Powheg/aMC@NLO_MG5
qg→4l: LO
gg→ZZ: LO with MCFM
EWK ZZ production in association with two jets is generated with PHANTOM
gg→H→ZZ: NLO with POWHEG 2.0

Scaled to NNLO (k-factor=1.1)
scaled to NLO (k-factor=1.7)
scaled to NNLO (k-factor=1.7)
ZZ normalized differential with full 2016 data

Table 4: Fiducial definitions for the reported cross sections. The common requirements are applied for both measurements.

<table>
<thead>
<tr>
<th>Cross section measurement</th>
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<td>$Z \rightarrow 4\ell$</td>
<td>$m_{Z_1} &gt; 40\text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$80 &lt; m_{4\ell} &lt; 100\text{ GeV}$</td>
</tr>
<tr>
<td>$ZZ \rightarrow 4\ell$</td>
<td>$60 &lt; m_{Z_1}, m_{Z_2} &lt; 120\text{ GeV}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$Z \rightarrow 4\ell$</th>
<th>$ZZ \rightarrow 4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton efficiency</td>
<td>6–10%</td>
<td>2–6%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2–4%</td>
<td>2%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Background</td>
<td>0.6–1.3%</td>
<td>0.5–1%</td>
</tr>
<tr>
<td>Pileup</td>
<td>1–2%</td>
<td>1%</td>
</tr>
<tr>
<td>PDF</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>QCD Scales</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.6%</td>
<td>2.6%</td>
</tr>
</tbody>
</table>

\[
\sigma_{\text{fid}}(pp \rightarrow Z \rightarrow 4\ell) = 29.7 \pm 1.4 \text{ (stat)}^{+2.0}_{-1.8} \text{ (syst)} \pm 0.8 \text{ (lumi)} \text{ fb},
\]
\[
\sigma_{\text{fid}}(pp \rightarrow ZZ \rightarrow 4\ell) = 42.2 \pm 1.4 \text{ (stat)}^{+1.6}_{-1.5} \text{ (syst)} \pm 1.1 \text{ (lumi)} \text{ fb}.
\]
\[
\sigma(pp \rightarrow ZZ) = 17.8 \pm 0.6 \text{ (stat)}^{+0.7}_{-0.6} \text{ (syst)} \pm 0.4 \text{ (theo)} \pm 0.5 \text{ (lumi)} \text{ pb}.
\]
EWK production via vector boson scattering

Probing the nature of the Electroweak Symmetry Breaking (EWSB)!
aTGC couplings: variety of measurements

Future Prospects

• Full 2016 data will provide significantly stronger limits than our 8 TeV results

• Combination of anomalous coupling limits using inclusive diboson measurements and Higgs measurements (and ATLAS and CMS combination)
  ✷ Improvement in sensitivity

Falkowski et al, 1508.00581
Anomalous couplings: results
LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) comparable to LEP results.

Future prospects under discussion:

Self-Consistency Check
- perturbativity of physical expansion
- deriving limits with extra cut on $\sqrt{s} < M_{cutoff}$
  $\rightarrow$ limits in the $(c,M)$ plane

Combination of anomalous coupling limits with Higgs measurements
$\rightarrow$ Improvement in sensitivity

Limits are set on $c_i^{(n)}/\Lambda^n \rightarrow$ probing energies of $\Lambda^n = c_i^{(n)}/\text{limit}$
In the limit of strong coupling ($c_i = 4\pi$) $\rightarrow$ limit on $\Lambda$ up to 2 TeV!
Source & Uncertainty (%)
---
Statistical uncertainty & 1.5 
Lepton efficiency & 3.8 
Lepton momentum scale & 0.5 
Jet energy scale & 1.7 
$E_T$ resolution & 0.7 
tt+W normalization & 2.2 
W+jets normalization & 1.3 
$Z/\gamma^* \rightarrow \ell^+\ell^-$ normalization & 0.6 
$Z/\gamma^* \rightarrow \tau^+\tau^-$ normalization & 0.2 
Wγ normalization & 0.3 
Wγ* normalization & 0.4 
VV normalization & 3.0 
H → W+W− normalization & 0.8 
Jet counting theory model & 4.3 
 PDFs & 1.2 
MC statistical uncertainty & 0.9 
Integrated luminosity & 2.6 
Total uncertainty & 7.9 

- jet counting model uncertainty includes the renormalization and factorization scales, and underlying event uncertainties

<table>
<thead>
<tr>
<th>Process</th>
<th>zero-jet category</th>
<th>one-jet category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Different-flavor</td>
<td>Same-flavor</td>
</tr>
<tr>
<td>$qq \rightarrow W^+W^-$</td>
<td>3516 ± 271</td>
<td>1390 ± 109</td>
</tr>
<tr>
<td>$gg \rightarrow W^+W^-$</td>
<td>162 ± 50</td>
<td>91 ± 28</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>3516 ± 271</td>
<td>1390 ± 109</td>
</tr>
<tr>
<td>ZZ + WZ &amp; 84 ± 10 &amp; 89 ± 11 &amp; 86 ± 4 &amp; 42 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VVV &amp; 33 ± 17 &amp; 17 ± 9 &amp; 28 ± 14 &amp; 14 ± 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>top quark (Bt-tag) &amp; 248 ± 26 &amp; 1398 ± 156 &amp; 562 ± 128</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell^+\ell^-$</td>
<td>30 ± 4</td>
<td>141 ± 63</td>
</tr>
<tr>
<td>Wγ* &amp; 54 ± 22 &amp; 12 ± 5 &amp; 18 ± 8 &amp; 3 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wγ &amp; 54 ± 20 &amp; 20 ± 8 &amp; 36 ± 14 &amp; 9 ± 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets(e) &amp; 189 ± 68 &amp; 46 ± 17 &amp; 114 ± 41 &amp; 16 ± 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets(µ) &amp; 81 ± 40 &amp; 19 ± 9 &amp; 63 ± 30 &amp; 17 ± 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higgs boson &amp; 125 ± 25 &amp; 53 ± 11 &amp; 75 ± 22 &amp; 22 ± 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total bkg. &amp; 1179 ± 123 &amp; 643 ± 73 &amp; 1954 ± 168 &amp; 749 ± 133</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W^+W^- +$ total bkg. &amp; 4857 ± 302 &amp; 2124 ± 134 &amp; 3128 ± 217 &amp; 1162 ± 142</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data &amp; 4847 &amp; 2233 &amp; 3114 &amp; 1198</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### WW CMS 13TeV

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Propagation to cross section (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental uncertainties</td>
<td>4.9</td>
</tr>
<tr>
<td>QCD scales and higher order effects</td>
<td>3.2</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.4</td>
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<tr>
<td>Underlying event and parton shower</td>
<td>3.7</td>
</tr>
<tr>
<td>Non-prompt normalization</td>
<td>3.0</td>
</tr>
<tr>
<td>Top-quark normalization</td>
<td>2.0</td>
</tr>
<tr>
<td>Wγ* normalization</td>
<td>0.3</td>
</tr>
<tr>
<td>Simulation and data control regions sample size</td>
<td>1.4</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>7.4</td>
</tr>
<tr>
<td>Total statistical uncertainty</td>
<td>5.0</td>
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<tr>
<td>Luminosity</td>
<td>3.0</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>9.5</td>
</tr>
</tbody>
</table>

- reweighting the spectrum obtained using POWHEG to the analytical prediction obtained using the pT-resummation at next-to-next-to-leading logarithm precision
  - uncertainties in the theoretical modeling of the signal efficiency are estimated by varying independently the resummation, the factorization, and the renormalization scales in the analytical calculation of the $pT_{WW}$ spectrum
- The uncertainty in the efficiency of the $gg \rightarrow W W$ component is determined by the variation of the renormalization and factorization scales in the theoretical calculation of this process. The propagation of these uncertainties in the signal acceptance, together with the effect of scale variations in the background simulations, yield an uncertainty of 3.2% in the measurement of the $W+W-$ cross section.
- Experimental uncertainties: lepton reconstruction and identification efficiencies, efficiency to discriminate jets from b-quarks and jets from light quarks, uncertainties in the electron and muon energy scales, jet energy scale, and $E_{\text{miss}}$ energy scale and resolution
• This measurement is performed at relatively low WW pT.
• This region cannot be properly simulated by a fixed-order MC because of the importance of large \( \log(p_{T_{WW}}/m_{WW}) \) terms. There are analytical calculations available that resum these logs: arXiv:1507.02565 (NNLL + NNLO), arXiv:1407.4481 (NLL + approx NNLO).
• We use the WW pT as a proxy for these corrections and reweight the POWHEG events comparing the out-of-the-box distribution with the result of the most precise (NNLL + NNLO) analytical calculation.
Figure 5: The transverse-momentum spectrum of the $W^+W^-$ pair at NNLL+NNLO (a) in the low-$p_T$ region and (b) at high transverse momenta. The NNLL+NNLO result (red, dashed) is compared to the fixed-order NNLO prediction (grey, dash-dotted) and to the finite component of Eq. (4) (magenta, dash-double dotted). The lower insets show the NNLL+NNLO result normalized to NNLO.
### Integrated luminosity uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eee</td>
<td>eem</td>
</tr>
<tr>
<td>Renorm. and fact. scales</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>PDFs</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Lepton and trigger efficiency</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>—</td>
<td>0.6</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>1.9</td>
<td>0.8</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>3.7</td>
<td>3.4</td>
</tr>
<tr>
<td>ZZ cross section</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>$Z\gamma$ cross section</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>tf and Z+jets</td>
<td>2.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Other simulated backgrounds</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>6.1</td>
<td>7.8</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>13.5</td>
<td>13.9</td>
</tr>
<tr>
<td>Integrated luminosity uncertainty</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

### Sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{s} = 8$ TeV; $\mathcal{L} = 19.6$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Non-prompt leptons</td>
<td>$18.4 \pm 12.7$</td>
<td>$32.0 \pm 21.0$</td>
</tr>
<tr>
<td>ZZ</td>
<td>$2.1 \pm 0.3$</td>
<td>$2.4 \pm 0.4$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$3.4 \pm 1.3$</td>
<td>$0.4 \pm 0.4$</td>
</tr>
<tr>
<td>$W\gamma^*$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$VVV$</td>
<td>$6.7 \pm 2.2$</td>
<td>$8.7 \pm 2.8$</td>
</tr>
<tr>
<td>Total background ($N_{bkg}$)</td>
<td>$30.6 \pm 13.0$</td>
<td>$43.5 \pm 21.2$</td>
</tr>
<tr>
<td>WZ</td>
<td>$211.1 \pm 1.6$</td>
<td>$262.1 \pm 1.8$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$241.6 \pm 13.1$</td>
<td>$305.7 \pm 21.3$</td>
</tr>
<tr>
<td>Data ($N_{obs}$)</td>
<td>$258$</td>
<td>$298$</td>
</tr>
</tbody>
</table>

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Senka Đurić

DIS 2017

38
# Triboson and rare processes measurements: overview

<table>
<thead>
<tr>
<th>Triboson measurements</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WVγ→ lvjjγ</td>
<td>-</td>
<td>PRD 90 (2014) 032008 (WVγ→ lvjjγ) Upper limit on cross section and aQGC measurement</td>
</tr>
<tr>
<td>Wγγ→ lvγγ</td>
<td>PRL 115, 031802 (2015) (Wγγ→ lvγγ) Cross section (inclusive and exclusive) and aQGC measurement</td>
<td>CMS-PAS-SMP-15-008 (Wγγ→ lvγγ) Cross section and aQGC measurement signal significance 2.4σ</td>
</tr>
<tr>
<td>Zγγ→ llγγ</td>
<td>PRD 93, 112002 (2016) (Zγγ→ llγγ) Observation: signal significance 6.3σ</td>
<td>CMS-PAS-SMP-15-008 (Zγγ→ llγγ) Observation: signal significance 5.9σ</td>
</tr>
<tr>
<td>WWW→ lvlvjj, lvlvlv</td>
<td>ATLAS-STDM-2015-07 (WWW→ lvlvjj, lvlvlv) Upper limit on cross section and aQGC measurement</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rare processes</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>-</td>
<td>JHEP 08 (2016) 119 (W^+W^-→ γγ→ lvlv) exclusive (W^+W^-→ γγ→ lvlv) exclusive</td>
</tr>
<tr>
<td>8 TeV</td>
<td>PRD 94 (2016) 032011 (W^+W^-→ γγ→ lvlv) exclusive (W^+W^-→ γγ→ lvlv) exclusive</td>
<td>Evidence: signal significance 3σ aQGC measurement, search for exclusive Higg production</td>
</tr>
</tbody>
</table>

For the first time, evidence and observations of triboson and exclusive WW production!
The uncertainty in the modeling of the signal is taken from the difference in acceptance between MCFM and MADGRAPH predictions.