Electroweak Boson interactions at the LHC

Alexander Kupco
Institute of Physics of the Czech Academy of Sciences, Prague

Slides prepared by
J.F. Laporte
CEA/IRFU, Paris-Saclay University

On behalf of the ATLAS and CMS Collaborations

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Outline

• Introduction

• Multibosons studies at LHC
  • Data, Signatures and backgrounds
  • Three Bosons interactions
    • Diboson production
  • Four Bosons interactions
    • Triboson production
    • Vector Boson Scattering

• Conclusions
LHC cross-sections measurements

**Standard Model Production Cross Section Measurements**

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

14 orders of magnitude

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SW/
Bosons production

August 2017

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

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

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

Production Cross Section, $\sigma [pb]$
Electroweak Boson couplings in the SM

\[ SU_L(2) \times U(1)_Y \] Gauge theory defines uniquely Gauge Boson Couplings

No other couplings allowed e.g. no neutral TGC such as \( ZZZ \)

TGC: Triple Gauge Couplings

\( \gamma/Z \)

No other couplings allowed e.g. no neutral TGC such as \( ZZZ \)

QGC: Quartic Gauge Couplings

\( \gamma/Z \)

Definite couplings insuring “delicate” cancellations between divergent diagrams

Interplay between QGC, TGC and boson couplings to Higgs boson gives theory a proper high energy behaviour

Multi-boson processes provide a direct probe of this mechanism

Deviations from SM predictions would give hints to new Physics beyond SM
Comparison to predictions requires both QCD and EWK higher order corrections.
QCD-NLO corrections long known: large ~60% for WZ production.
QCD-NNLO only available over past couple of years (arxiv: 1604.08576): ~10 to 20%.

QCD-NNLO corrections have improved agreement with data.
Comparison to predictions requires both QCD and EWK higher order corrections
QCD-NLO corrections long known: large \( \approx 60 \% \) for WZ production
QCD-NNLO only available over past couple of years (arxiv: 1604.08576) : \( \approx 10 \) to 20%

QCD-NNLO corrections have improved agreement with data

2015:
WW production @ 8TeV
Tension data/QCD NLO

\[ \text{JHEP 09 (2016) 029} \]
Anomalous Couplings

“Traditional” approach
Add terms to the SM Lagrangian with minimal constrains
(minimal number of derivatives, 2 bosons on-shell)

For **Charged TGC** (WWγ and WWZ), this leads to 14 independent terms/couplings
reduced to 5 if U(1)_{em} and CP conservation required: Δg_{1Z}, Δκ_{Z}, λ_{Z}, Δκ_{γ}, λ_{γ}
K. Hagiwara et al. PhysRevD.48.2182

\[
\begin{align*}
&i g_1^V \left( W_{\mu\nu}^+ W^{\mu-} - W_{\mu\nu}^- W^{\mu+} \right) Y + i \bar{\kappa}_V W_\mu^+ W_\nu^- Y^{\mu\nu} + \frac{i \bar{\lambda}_V}{M_W^2} Y^{\mu\nu} W_{\nu}^+ W_{\rho}^- Y^{\mu\rho}, \\
&\lambda_{\gamma} = \lambda_{Z} \\
&\Delta g_{1Z} = \Delta \kappa_{Z} + \tan^2 \theta_W \Delta \kappa_{\gamma}
\end{align*}
\]
(V= γ or Z)

Very often complemented with the “LEP scenario”
⇒ 3 independent parameters

For **Neutral TGC** (ZZγ, ZZZ and Zγγ), Lagrangian
somewhat more complicated G. J. Gounaris et al. PRD 61, 073013
⇒ 12 independent parameters

<table>
<thead>
<tr>
<th>Vertex</th>
<th>ZZZ</th>
<th>ZZγ</th>
<th>Zγγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two boson production</td>
<td>ZZ</td>
<td>Zγ</td>
<td></td>
</tr>
<tr>
<td>CP-even</td>
<td>f_5^Z</td>
<td>f_5^γ</td>
<td>h_3,4 Z</td>
</tr>
<tr>
<td>CP-violating</td>
<td>f_4^Z</td>
<td>f_4^γ</td>
<td>h_{1,2} Z</td>
</tr>
</tbody>
</table>

Traditional too: anomalous couplings lead to divergent cross-sections
cured by Form Factors
\[
\zeta(s) = \frac{\zeta_0}{(1 + \hat{s}/\Lambda_{FF}^2)^n}
\]
EFT: Effective Field Theory

“New” approach
The Standard Model is the low energy limit of a more fundamental theory at a scale \( \Lambda \gg \sqrt{s} \)

Beyond SM Theory

Low Energy limit

At low energy
interactions between SM fields only
(similar to Fermi 4-fermions theory)

Limited range theory: \( E \ll \Lambda \)
\( \Rightarrow \) no Form Factor

Build with SM fields, operators of dimension \( d > 4 \) invariant under \( SU(3) \times SU(2) \times U(1) \)

\[
L_{EFT} = L_{SM} + \sum_{d \geq 5} L_{EFT}^d \text{ with } L_{EFT}^d = \sum_i \frac{C_i^d}{\Lambda^{d-4}} O_i^d
\]

Challenging theory/experiment project: operators bases, loop calculations, best observables

We gain - more consistent approach with no additional form factors allowing us to combine the gauge and Higgs bosons sectors

Scott Willenbrock, Cen Zhang arxiv: 1401.0470
EFT: anomalous Triple Gauge Couplings

For **Charged TGC**, first contributing operators have dimension 6 $\Rightarrow$ coupling parameters $c/\Lambda^2$

5 operators
3 CP conserving +2 CP violating

\[
\begin{align*}
O_{WWW} & = \text{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho\mu}] \\
O_W & = (D_{\mu}\Phi)^\dagger W^{\mu\nu}(D_{\nu}\Phi) \\
O_B & = (D_{\mu}\Phi)^\dagger B^{\mu\nu}(D_{\nu}\Phi)
\end{align*}
\]

Traditional $\Leftrightarrow$ EFT

\[
\begin{align*}
g_1^Z & = 1 + c_w \frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma & = 1 + (c_w + c_B) \frac{m_W^2}{2\Lambda^2} \\
\kappa_Z & = 1 + (c_w - c_B\tan^2\theta_W) \frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma & = \lambda_Z = c_{WWW} \frac{3g^2m_W^2}{2\Lambda^2}
\end{align*}
\]

“LEP scenario” justified (actually long known)

For **Neutral TGC**, first contributing operators have dimension 8 $\Rightarrow$ coupling parameters $c/\Lambda^4$

4 operators
all CP violating but one

\[
\begin{align*}
O_{BW} & = iH^\dagger B_{\mu\nu}W^{\mu\rho}\{D_\rho, D^{\nu}\}H \\
O_{BB} & = iH^\dagger B_{\mu\nu}B^{\mu\rho}\{D_\rho, D^{\nu}\}H \\
O_{WW} & = iH^\dagger W_{\mu\nu}W^{\mu\rho}\{D_\rho, D^{\nu}\}H \\
O_{BW} & = iH^\dagger \tilde{B}_{\mu\nu}W^{\mu\rho}\{D_\rho, D^{\nu}\}H
\end{align*}
\]

Independent parameters reduced from 12 to just 4

C. Degrande et al. arXiv:1205.4231

C. Degrande JHEP 1402 (2014) 101
Searches of anomalous QGC always assume aTGC=0 since best measured in TGC searches

The first operators leading to aQGC but no aTGC have dimension 8 $\Rightarrow$ coupling parameters $c/\Lambda^4$

18 dimension-8 operators

Three types of operators:

Scalar : $O_{S,i}$ Higgs doublet Derivatives

Tensor : $O_{T,i}$ Gauge Fields Tensors

Mixed : $O_{M,i}$ Both

Now the framework for ~all LHC analyses

Michael Rauch arXiv:1610.08420
O. J. P. Éboli and M. C. Gonzalez–Garcia PRD93, 093013 (2016)
EFT: anomalous Couplings and more

Because EFT works with “before EWK breaking fields”
[i.e. the H, $W^3$ and B fields, not the h, Z and the $\gamma$ fields]

- it connects different aspects of Gauge Bosons vertices, i.e. reduces the number of independent parameters

- it connects also different processes involving Gauge Bosons and Higgs boson couplings

  e.g. a same operator contributes to

  ⇒ Combined analysis of all EWK measurements

Combination of Higgs LHC and LEP TGC measurements

A. Falkowski et al. PRL 116, 011801 (2016)
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LHC and Experiments Data

Outstanding LHC performance

- Run 1:
  - 2011: 5 fb$^{-1}$ @ 7TeV
  - 2012: 20 fb$^{-1}$ @ 8TeV

- Run 2: aim for 100 fb$^{-1}$ @ 13TeV
  - 2015-2016: ~36 fb$^{-1}$
  - 2017: Restarted in May; now >20 fb$^{-1}$

- Most analyses @7+8TeV have now used the full Run 1 dataset
- Analyses @13 TeV use part of or the complete Run 2 dataset ≤ 2016

Very High Pileup

Challenging for Trigger and Reconstruction

Z$\rightarrow$ $\mu\mu$ in 2016

103 vertices!
Multibosons: Signatures and Backgrounds

EWK cross-sections small wrt to background processes (jet, heavy quarks,...)

⇒ Use leptonic decay of W and Z: small Branching Ratio but clean signature

Signatures
- High-\(p_T\) isolated photons, muons and/or electrons
- When \(\nu\) involved require high missing \(E_T\)
- High-\(p_T\) jets

Backgrounds
- Irreducible backgrounds ⇒ Estimated from MC
- Leptons from heavy quarks
- Jet mis-identified as an electron or a photon ⇒ From Data Driven methods (Control Regions)
Dibosons production

Channels shown today
- ZZ
- WW
- WZ
- WV

There are interesting results on $W\gamma$ and $Z\gamma$ as well.
CMS and ATLAS: full 13TeV Run 2 dataset ≤ 2016 (~36 fb\(^{-1}\)) in the ZZ\(\rightarrow\)4\(\ell\) channel with \(\ell = \text{e or } \mu\)

Very clean signature
Full reconstruction of the final state with good resolution

Small background < 5%
- Irreducible with ≥ 4 \(\ell\) (ttV, VVV) from MC
- Misid. \(\ell\) (Z+jets) from Data Driven methods

Small uncertainties ~5% (combined stat. + syst.)

Comparable statistical and systematics uncertainties

Main systematics is from lepton efficiency
ZZ\to\ell^+\ell^- \ell'^+\ell'^- \ @ 13 \ TeV

Not reviewed, for internal

Measured Cross-sections at 7, 8 and 13 TeV are consistent with NNLO predictions

Good agreement between experiments

Still statistically dominated measurements

ATLAS Preliminary \( \sqrt{s} = 13 \) TeV, 36.1 fb\(^{-1} \)

Data
SM stat. + syst. uncertainty
\( q\bar{q} \to ZZ \)
\( gg \to ZZ \)
\( pp \to ZZjj \) (EWK)
Non-ZZ background
SM + aTGC, \( \zeta' = 0.0038 \)
SM + aTGC, \( \zeta' = 0.0038, \zeta'' = 0.0033 \)

\( \sigma_{pp \to ZZ} \) (pb)

\( \sqrt{s} \) (TeV)

SM + aTGC

aTGC contributes mainly at high mass or \( p_T \)

aTGC limits extracted from \( p_{TZ} \) (ATLAS) or \( m_{ZZ} \) (CMS) spectra

Best currents limits on neutral TGC
Neutral aTGC Limits

- No deviation from SM
- LHC limits for neutral anomalous TGC are far stricter than LEP and Tevatron ones
- Large gain from increased $\sqrt{s}$
- Gain Expected from ZZ→2l2ν channel

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$f_{L}^{dd}$</th>
<th>$f_{S}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ (4421v)</td>
<td>[-1.5e-02, 1.5e-02]</td>
<td>4.6 fb⁻¹</td>
<td>7 TeV</td>
</tr>
<tr>
<td>ZZ (4421v)</td>
<td>[-3.8e-03, 3.8e-03]</td>
<td>20.3 fb⁻¹</td>
<td>8 TeV</td>
</tr>
<tr>
<td>ZZ (441)</td>
<td>[-1.8e-03, 1.8e-03]</td>
<td>36.1 fb⁻¹</td>
<td>13 TeV</td>
</tr>
<tr>
<td>ZZ (441)</td>
<td>[-5.0e-03, 5.0e-03]</td>
<td>19.6 fb⁻¹</td>
<td>8 TeV</td>
</tr>
<tr>
<td>ZZ (221v)</td>
<td>[-3.8e-03, 3.2e-03]</td>
<td>24.7 fb⁻¹</td>
<td>7.8 TeV</td>
</tr>
<tr>
<td>ZZ (441v)</td>
<td>[-3.0e-03, 2.6e-03]</td>
<td>24.7 fb⁻¹</td>
<td>7.8 TeV</td>
</tr>
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<td>[-1.3e-03, 1.3e-03]</td>
<td>35.9 fb⁻¹</td>
<td>13 TeV</td>
</tr>
<tr>
<td>ZZ (4121v)</td>
<td>[-1.0e-02, 1.0e-02]</td>
<td>9.6 fb⁻¹</td>
<td>7 TeV</td>
</tr>
</tbody>
</table>

13 TeV limits

EFT interpretation

dim-8 parameter $\sqrt{\Lambda^4/c} \sim 0.6-0.7$ TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC
CMS and ATLAS: part of the 13TeV Run 2 dataset (resp. 2.3 fb\(^{-1}\) and 3.2 fb\(^{-1}\))

2 isolated leptons, opposite charges, different flavors + missing \(E_T\)
Jet veto (ATLAS) or 0 or 1 jet (CMS)

Background \(~30\%\): Top, W+jets, Drell-Yan

Cross-sections agree with NNLO predictions

\(~10\%\) uncertainty dominated by systematics (jets)

No aTGC studies @13 TeV yet
(aTGC @8TeV completed)
CMS and ATLAS: part of the 13TeV Run 2 dataset 
(resp. 2.3 fb-1 and 13.3 fb⁻¹)

3 isolated leptons (2 ones from a Z) 
+ missing $E_T$

Background < 20%
  • Irreducible with ≥ 3 $\ell$ (Vt, VV, VVV) from MC
  • Misid. $\ell$ (Z+jets) from Data Driven methods

Cross-sections uncertainties ~10%
  Systematics getting larger than statistics

Main systematics:
  lepton efficiency, misid. $\ell$ backgrounds, $E_{T,\text{Miss}}$
Measured Cross-sections at 7, 8 and 13 TeV are consistent with NNLO predictions

Some tension between ATLAS and CMS

- 8 TeV and 13 TeV ATLAS limits combined
- Limits @8TeV completed for both experiments
Semi-leptonic $W/V \rightarrow \ell \nu \, q\bar{q}$ ($V=W, Z$)

CMS and ATLAS: full 8TeV Run 1 dataset (~20 fb$^{-1}$)

- Isolated lepton + missing $E_T$ +
  - two resolved jets
  - or one boosted (large radius) jet

- Larger background than fully-leptonic channels
- But 6 times higher branching ratio (for $Z$)
- Probe higher $p_T(V)$ → Improve sensitivity to aTGC

Main uncertainty from Background modeling
Semi-leptonic $WV \rightarrow \ell\nu \ q\bar{q}$ $(V= W, Z)$

**The Boosted topology increases sensitivity to aTGC (higher $p_T$ reached)**

**Gain factors:**
- 1.85x boosted vs. resolved
- 2.17x boosted vs. fully lept.

**The semileptonic channel provides some of the tightest limits**

**CMS**

CMS has used part of the Run 2 dataset

2.3 fb-1 @ 13 TeV

aTGC limits less stringent than the 8 TeV limits but statistics can be increased by more than 20 times
Charged aTGC Limits

- No deviations from SM
- LHC limits for charged anomalous TGC are now better than LEP and Tevatron ones
- Run 2 statistics has been only partially exploited up to now (and more is coming)
- Boosted semi-leptonic channel increased sensitivity

EFT interpretation

\[ \sqrt{\Lambda^2/c} \sim 0.6 \text{ TeV} \]
Summary of Diboson cross-sections

- Overall good agreement with the Standard Model
- Almost all recent ATLAS and CMS measurements are limited by systematics uncertainties
- NNLO QCD improves agreement with data substantially
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Tribosons production

EWK Triboson production involves interplay between boson-radiation, TGC and QGC

Experimentally very challenging - asking at least for one photon in the final state helps
Tribosons: $W_{\gamma\gamma}$ and $Z_{\gamma\gamma}$

CMS and ATLAS: full 8TeV Run 1 dataset (~20 fb$^{-1}$)

CMS search in $W(\rightarrow \ell\nu)\gamma\gamma$ and $Z(\rightarrow \ell\ell)\gamma\gamma$ channels
(ATLAS included also $Z\rightarrow \nu\nu$)

Dominated by syst. uncertainty on background (jets misidentified as photons)

$Z_{\gamma\gamma}$ observation - $6.3\sigma$ (ATLAS) and $5.9\sigma$ (CMS)

$W_{\gamma\gamma}$ evidence - >$3\sigma$ (ATLAS) and $2.6\sigma$ (CMS)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured fiducial cross section</th>
</tr>
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<tbody>
<tr>
<td>$W_{\gamma\gamma} \rightarrow e^+e^-\gamma\gamma$</td>
<td>$4.2 \pm 2.0$ (stat) $\pm 1.6$ (syst) $\pm 0.1$ (lumi) fb</td>
</tr>
<tr>
<td>$W_{\gamma\gamma} \rightarrow \mu^+\mu^-\gamma\gamma$</td>
<td>$6.0 \pm 1.8$ (stat) $\pm 2.3$ (syst) $\pm 0.2$ (lumi) fb</td>
</tr>
<tr>
<td>$W_{\gamma\gamma} \rightarrow \ell^+\ell^-\gamma\gamma$</td>
<td>$4.9 \pm 1.4$ (stat) $\pm 1.6$ (syst) $\pm 0.1$ (lumi) fb</td>
</tr>
<tr>
<td>$Z_{\gamma\gamma} \rightarrow e^+e^-\gamma\gamma$</td>
<td>$12.5 \pm 2.1$ (stat) $\pm 2.1$ (syst) $\pm 0.3$ (lumi) fb</td>
</tr>
<tr>
<td>$Z_{\gamma\gamma} \rightarrow \mu^+\mu^-\gamma\gamma$</td>
<td>$12.8 \pm 1.8$ (stat) $\pm 1.7$ (syst) $\pm 0.3$ (lumi) fb</td>
</tr>
<tr>
<td>$Z_{\gamma\gamma} \rightarrow \ell^+\ell^-\gamma\gamma$</td>
<td>$12.7 \pm 1.4$ (stat) $\pm 1.8$ (syst) $\pm 0.3$ (lumi) fb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
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<tr>
<td>$W_{\gamma\gamma} \rightarrow \ell^+\ell^-\gamma\gamma$</td>
<td>$4.8 \pm 0.5$ fb</td>
</tr>
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<td>$Z_{\gamma\gamma} \rightarrow \ell^+\ell^-\gamma\gamma$</td>
<td>$13.0 \pm 1.5$ fb</td>
</tr>
</tbody>
</table>

Fiducial CMS Cross-sections consistent with NLO predictions
Tribosons: \( WV_\gamma \) (\( V= W, Z \))

CMS and ATLAS: full 8TeV Run 1 dataset (~20 fb\(^{-1}\))

ATLAS search in 2 channels
- Fully leptonic: \( WW_\gamma \rightarrow \ell \ell' \nu \nu' \) (different flavour leptons to reduce background)
- Semi-leptonic: \( WV_\gamma \rightarrow \ell \nu jj \gamma \)

Only upper limits could be derived for semi-leptonic case

ATLAS fiducial cross-section measured in the fully leptonic channel

\[
\sigma_{\text{fid}}^{\ell \ell' \nu \nu'} = 1.5 \pm 0.9\text{(stat.)} \pm 0.5\text{(syst.)} \text{ fb},
\]

in agreement with NLO prediction \( 2.0 \pm 0.1 \text{ fb} \)

Observed significance: \( 1.4 \sigma \) (for \( 1.6 \sigma \) expected)
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Incoming quarks act as sources of colliding boson beams

**Signature**

\( VV + 2 \) tagging high \( p_T \) jets in the forward-backward regions with large \( m_{jj} \), large rapidity gap and low hadronic activity in between

**\( \mu^+\mu^+jj \) Candidate Event**

\( m_{jj} = 2800 \text{ GeV} \)

\( |\Delta y_{jj}| = 6.3 \)
Vector Boson Scattering: $VVjj$

Search for EWK $VVjj$ production suffers from a huge background of QCD induced $VVjj$

- Look in clean final states $Z\gamma jj$, $ZZjj$
- Cleanest channel: same sign $WW$, $W^+W^\pm jj$
  - no LO $gg$ or $gq$ initial states, highest EWK/QCD ratio

- Other channels:
  - $W\gamma jj$ by CMS with $2.7\sigma$ significance, JHEP 06 (2017) 106
  - $WZjj$ by ATLAS with 95% CL limit $>0.63fb$ (SM: 0.13fb), PRD93, 092004 (2016)
  - Exclusive $WW$ production ($\gamma\gamma \rightarrow WW$) PRD94 (2016) 032011, JHEP 08 (2016) 119
VBS: $Z\gamma jj$

CMS and ATLAS: full 8TeV Run 1 dataset (~20 fb⁻¹)

2 channels
$Z\gamma\rightarrow\ell\ell\gamma$ (ATLAS/CMS) and $Z\gamma\rightarrow\nu\nu\gamma$ (ATLAS)

ATLAS for the 1st time made use of $Z\rightarrow\nu\nu$ to provide better constraints on neutral aQGC via $Z\gamma$ VBS

- Cross-sections extracted comparing different $M_{jj}$ regions to constraint QCD background
- Expected significance $\sim 2\sigma$

Observed significance $3\sigma$ for CMS, $2\sigma$ for ATLAS
CMS evidence for EWK $Z\gamma jj$ production!

Cross-sections consistent with NLO predictions
aQGC limits from $Z\gamma jj$

![Graph showing aQGC limits @95% C.L. [TeV⁻⁴]](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSM#aQGC_Results)
CMS: full 13TeV Run 2 dataset ≤ 2016 (~36 fb⁻¹)

Fully leptonic channel: ZZ→4ℓ + 2 jets \( m_{jj} > 100 \text{ GeV} \)

Large background from QCD induced ZZ

Boosted Decision Tree (built on \( m_{jj}, |\Delta\eta_{jj}|, M_{ZZ}, \ldots \))

to separate EWK and QCD

Includes use of advanced q/g MVA tagging

$$\sigma_{\text{fid.}}(\text{EW} \, pp \to ZZjj \to \ell\ell\ell'jj) = 0.40^{+0.21}_{-0.16} \text{(stat.)}^{+0.13}_{-0.09} \text{(syst.)} \, \text{fb}$$

Compatible with SM prediction: 0.29 ± 0.03 fb

The most stringent limits on the dim-8 parameters \( f_{T,8} \) and \( f_{T,9} \), accessible only via neutral gauge bosons final states

aQGC limits are well within Unitarity Violation bound

Big milestone!

SM+aQGC

aQGC limits from \( m_{ZZ} \) spectrum
VBS: $W^\pm W^\pm jj$

CMS: full 13 TeV Run 2 dataset $\leq 2016$ ($\sim 36$ fb$^{-1}$)

Same sign $W^\pm W^\pm jj$ has the highest EW/QCD ratio

Clean signature in fully leptonic mode $W \rightarrow \ell\nu, \ell = e, \mu, \tau$ ($\tau$ in $e, \mu$)

Other backgrounds: WZ and non-prompt constrained by control regions

- Cross-section from a 2D Fit in $(m_{jj}, m_{ll})$ plane

$$\sigma_{\text{fid}}(W^\pm W^\pm jj) = 3.83 \pm 0.66 \text{ (stat)} \pm 0.35 \text{ (syst)} \text{ fb}$$

in agreement with LO prediction $4.25 \pm 0.21$ fb

Observed Significance $5.7 \sigma$ (exp. $5.5 \sigma$)

Not only the first ever observation of a EWK-WWjj with a VBS signature!
Also the first ever observed VBS singature of all!
aQGC limits from $m_\parallel$ distributions

<table>
<thead>
<tr>
<th></th>
<th>Observed limits (TeV$^{-4}$)</th>
<th>Expected limits (TeV$^{-4}$)</th>
<th>Run-I limits (TeV$^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{S_0}/\Lambda$</td>
<td>[-7.7, 7.7]</td>
<td>[-7.0, 7.2]</td>
<td>[-38, 40] [11]</td>
</tr>
<tr>
<td>$f_{M_0}/\Lambda$</td>
<td>[-6.0, 5.9]</td>
<td>[-5.6, 5.5]</td>
<td>[-4.6, 4.6] [29]</td>
</tr>
<tr>
<td>$f_{M_1}/\Lambda$</td>
<td>[-8.7, 9.1]</td>
<td>[-7.9, 8.5]</td>
<td>[-17, 17] [29]</td>
</tr>
<tr>
<td>$f_{M_6}/\Lambda$</td>
<td>[-11.9, 11.8]</td>
<td>[-11.1, 11.0]</td>
<td>[-65, 63] [11]</td>
</tr>
<tr>
<td>$f_{M_7}/\Lambda$</td>
<td>[-13.3, 12.9]</td>
<td>[-12.4, 11.8]</td>
<td>[-70, 66] [11]</td>
</tr>
<tr>
<td>$f_{T_0}/\Lambda$</td>
<td>[-0.62, 0.65]</td>
<td>[-0.58, 0.61]</td>
<td>[-3.8, 3.4] [30]</td>
</tr>
<tr>
<td>$f_{T_1}/\Lambda$</td>
<td>[-0.28, 0.31]</td>
<td>[-0.26, 0.29]</td>
<td>[-1.9, 2.2] [11]</td>
</tr>
<tr>
<td>$f_{T_2}/\Lambda$</td>
<td>[-0.89, 1.02]</td>
<td>[-0.80, 0.95]</td>
<td>[-5.2, 6.4] [11]</td>
</tr>
</tbody>
</table>

Data used also to set limits on BSM model

Doubly charged Higgs bosons $H^{\pm\pm}$ are predicted in some BSM models

First limits placed on $H^{\pm\pm} \rightarrow W^\pm W^\pm$ cross-section using a 2D Fit in $(m_{jj}, m_\parallel)$ plane

The aQGC limits are greatly improved w.r.t. 8TeV limits

These are the most stringent limits for almost all the dim-8 parameters

VBS: $W^\pm W^\pm jj$

The CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)
aQGC Limits \( f_T \) parameters

- No deviation from the SM
- The 13 TeV VBS results have greatly improved the limits
aQGC Limits $f_M$ parameters

- No deviation from the SM
- The 13 TeV VBS results have greatly improved the limits
- Improvements to be expected from other VBS such as $\gamma\gamma\rightarrow WW$ (exclusive WW)

Some of the limits on the parameters $f/\Lambda^4$ are now $<1$ TeV$^{-4}$

If one takes $f \sim 1$ then $\Lambda > 1$ TeV!
Summary of multiboson cross-sections

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS EWK measurements vs. Theory</th>
<th>7 TeV CMS measurement (stat,stat+sys)</th>
<th>8 TeV CMS measurement (stat,stat+sys)</th>
<th>13 TeV CMS measurement (stat,stat+sys)</th>
</tr>
</thead>
<tbody>
<tr>
<td>qqW</td>
<td></td>
<td>0.84 ± 0.08 ± 0.18</td>
<td></td>
<td>19.3 fb⁻¹</td>
</tr>
<tr>
<td>qqZ</td>
<td></td>
<td>0.93 ± 0.14 ± 0.32</td>
<td></td>
<td>5.0 fb⁻¹</td>
</tr>
<tr>
<td>qqZ</td>
<td></td>
<td>0.84 ± 0.07 ± 0.19</td>
<td></td>
<td>19.7 fb⁻¹</td>
</tr>
<tr>
<td>qqZ</td>
<td></td>
<td>1.02 ± 0.03 ± 0.10</td>
<td></td>
<td>35.9 fb⁻¹</td>
</tr>
<tr>
<td>γγ → WW</td>
<td></td>
<td>1.74 ± 0.00 ± 0.74</td>
<td></td>
<td>19.7 fb⁻¹</td>
</tr>
<tr>
<td>qqWγ</td>
<td></td>
<td>1.77 ± 0.67 ± 0.56</td>
<td></td>
<td>19.7 fb⁻¹</td>
</tr>
<tr>
<td>ss WW</td>
<td></td>
<td>0.69 ± 0.38 ± 0.18</td>
<td></td>
<td>19.4 fb⁻¹</td>
</tr>
<tr>
<td>ss WW</td>
<td></td>
<td>0.90 ± 0.16 ± 0.08</td>
<td></td>
<td>35.9 fb⁻¹</td>
</tr>
<tr>
<td>qqZγ</td>
<td></td>
<td>1.48 ± 0.65 ± 0.48</td>
<td></td>
<td>19.7 fb⁻¹</td>
</tr>
<tr>
<td>qqZZ</td>
<td></td>
<td>1.38 ± 0.64 ± 0.38</td>
<td></td>
<td>35.9 fb⁻¹</td>
</tr>
</tbody>
</table>

Production Cross Section Ratio: \( \sigma_{\text{exp}} / \sigma_{\text{theo}} \)

All results at: [http://cern.ch/go/pNj7](http://cern.ch/go/pNj7)
## Summary of multiboson cross-sections

### VBF, VBS, and Triboson Cross Section Measurements

**Status:** July 2017

<table>
<thead>
<tr>
<th>Process</th>
<th>Theory</th>
<th>Data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\gamma\gamma \rightarrow t\bar{t}\gamma\gamma$</td>
<td>MCFM NLO (theory)</td>
<td>ATLAS Preliminary</td>
<td>$\sqrt{s} = 7,8,13$ TeV</td>
</tr>
<tr>
<td>$W\gamma\gamma \rightarrow t\bar{t}\gamma\gamma$</td>
<td>MCFM NLO (theory)</td>
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<tr>
<td>$W\gamma \rightarrow ev\nu\gamma$</td>
<td>MADGRAPH + HERWIG (theory)</td>
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<tr>
<td>$WWW \rightarrow t\bar{t}t\bar{t}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Hjj$ (tot.)</td>
<td>LHC-HGG (theory)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H(\rightarrow WW)jj$</td>
<td></td>
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</tr>
<tr>
<td>$Wjj$ (M(jj) &gt; 1 TeV)</td>
<td>LHC pp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Zjj$ (M(jj) &gt; 500 GeV)</td>
<td>LHC pp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
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<tr>
<td>$Z\gamma j$</td>
<td></td>
<td></td>
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<tr>
<td>$W^+W^-jj$</td>
<td></td>
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<tr>
<td>$WZjj$</td>
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</table>

### References

- PRD 93, 112002 (2016)
- PRL 115, 031802 (2015)
- PRL 115, 031802 (2015)
- EPJC 77, 141 (2017)
- EPJC 77, 141 (2017)
- ATLAS-CONF-2017-047
- EPJC 76, 6 (2016)
- PRD 92, 012006 (2015)
- JHEP 04, 031 (2014)
- PRD 94 (2016) 032011
- arXiv: 1705.01966 [hep-ex]
- arXiv: 1611.02428 [hep-ex]
- PRD 93, 092004 (2016)
Conclusions

• Challenging multi-bosons measurements are possible thanks to the impressive LHC performance: now >50 fb$^{-1}$ per experiment @13 TeV

• Multi-bosons analyses are precision tests of the state of the art of the theory:
  • Cross-sections sensitive to NNLO QCD and NLO EWK
  • Probe the EWK Gauge structure of the SM: anomalous TGC and QGC

• First observations of Triboson production ($Z\gamma\gamma$), evidence for $W\gamma\gamma$
  and the first observation of VBS process ($W\pm W\pm jj$)

• 13 TeV Run 2 data are increasing sensitivity to search of BSM physics

• EFT a very attractive framework with the promise of the combination of all EWK data, in particular of the LHC Higgs and multi-bosons measurements.
  Still a challenging work in progress for both theorists and experimentalists