Multiboson production with $W$ and $Z$ bosons at the ATLAS and CMS detectors

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on behalf of the ATLAS and CMS Collaborations

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Institut de recherche en mathématique et physique

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Outline

WZ production
  Inclusive cross section (also charge-dependent)
  Differential cross section
  Polarization
  aTGCs

WW production
  Inclusive cross section
  Evidence of DPS production
  NEW! Anomalous couplings in semileptonic decays

ZZ production: full Run-II dataset
  Inclusive cross section
  Differential cross section
  Anomalous couplings

Triboson production
  Evidence of VVV production
  aQGCs

Discussion
  Datasets and production details, publication strategy
  Analysis methods and reporting

Summary
Sensitive to the trilinear vector boson coupling
- The only process with a Z in the final state
- Probed in both EWK and VBS production
  - See talk by Kenneth for VBS results

ATLAS 36 fb$^{-1}$ (cross sections), 13 fb$^{-1}$ (couplings)
- arXiv:1902.05759 (submitted to EPJC)
- ATLAS-CONF-2016-043 (conf-note)

CMS 36 fb$^{-1}$ (cross sections and couplings)

Triggers: ~ 100% efficiency
- ATLAS: 1L triggers, $p_T \sim 20–24$ GeV, recover efficiency with additional high-$p_T$ triggers
- CMS: soup of 1L+2L+3L triggers, $p_T \sim 8–24$ GeV

Lepton reconstruction
- ATLAS: cut-based ID
- CMS: MVA ID tuned against nonprompt leptons

Similar selection
- 3L, Z boson assignment
- ATLAS: tighter ID on $\ell_W$
- CMS: b tagging veto
WZ production: fiducial cross section

- NNLO predictions favoured by the data

<table>
<thead>
<tr>
<th>Category</th>
<th>Fiducial cross section [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>eee</td>
<td>$63.7^{+3.8}<em>{-3.7}$ (stat)$^{+0.6}</em>{-0.6}$ (theo)$^{+5.3}_{-4.7}$ (syst) ± 1.9 (lumi)</td>
</tr>
<tr>
<td>eeμ</td>
<td>$61.6^{+3.0}<em>{-2.9}$ (stat)$^{+0.6}</em>{-0.5}$ (theo)$^{+3.7}_{-3.3}$ (syst) ± 1.9 (lumi)</td>
</tr>
<tr>
<td>eμμ</td>
<td>$63.4^{+2.6}<em>{-2.6}$ (stat)$^{+0.6}</em>{-0.5}$ (theo)$^{+3.5}_{-3.2}$ (syst) ± 1.9 (lumi)</td>
</tr>
<tr>
<td>μμμ</td>
<td>$67.1^{+2.1}<em>{-2.0}$ (stat)$^{+0.6}</em>{-0.5}$ (theo)$^{+3.3}_{-3.0}$ (syst) ± 1.9 (lumi)</td>
</tr>
<tr>
<td>Combined</td>
<td>$257.5^{+5.3}<em>{-5.0}$ (stat)$^{+2.3}</em>{-2.0}$ (theo)$^{+12.8}_{-11.6}$ (syst) ± 7.4 (lumi)</td>
</tr>
</tbody>
</table>

$\sigma_{\text{POWHEG+PYTHIA}}^{\text{fid, NLO}} = 227.6^{+8.8}_{-7.3}$ (scale) ± 3.2(PDF) fb

Lepton dressing
- ATLAS: scale factor scales $\sigma_{\text{Born}}$ to $\sigma_{\text{dressed}}$
- CMS: dresses each lepton before fiducial cuts

Xsec calculation and averaging
- ATLAS: basic formula, HERA-era averaging
- CMS: likelihood fit both in the four regions and simultaneous

Reporting uncertainties
- ATLAS: symmetric, propagating from

$$\sigma_{\text{W}^\pm Z\to \ell^+ \ell^-}^{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot C_{WZ}} \times \left(1 - \frac{N_{\ell}}{N_{\text{all}}}\right)$$

- CMS: asymmetric intervals from $\ln L$
WZ production: uncertainties, and extrapolation to total cross section

- Dominant uncertainties in the fiducial cross section reflect ID and strategy choices

\[ \sigma_{\text{MATRIX}}^{\text{NLO}}(pp \to WZ) = 45.09^{+4.99}_{-3.99} \text{ pb} \]
\[ \sigma_{\text{MATRIX}}^{\text{NNLO}}(pp \to WZ) = 49.98^{+2.22}_{-2.00} \text{ pb} \]

**ATLAS:** nonprompt leptons

**CMS:** b tagging (veto)

<table>
<thead>
<tr>
<th>Source</th>
<th>Combined</th>
<th>eee</th>
<th>eµµ</th>
<th>µµµ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron efficiency</td>
<td>1.9</td>
<td>5.9</td>
<td>3.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.3</td>
<td>0.9</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>1.9</td>
<td>-</td>
<td>0.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.5</td>
<td>-</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.9</td>
<td>2.0</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.9</td>
<td>1.6</td>
<td>1.0</td>
<td>1.7</td>
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<tr>
<td>b-tagging (id.)</td>
<td>2.6</td>
<td>2.7</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>b-tagging (mis-id.)</td>
<td>0.9</td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.8</td>
<td>0.9</td>
<td>0.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**ZZ**

- 0.6
- 0.7
- 0.4
- 0.8
- 0.5
- 2.0
- 1.5
- 2.0
- 1.3
- 0.5
- 0.5
- 0.5
- 0.5
- 0.1
- 0.1
- 0.1
- 0.3
- 0.8
- 0.1
- 0.7
- 0.1

**Nonprompt norm.**

- 1.2
- 2.0
- 1.2
- 1.5
- 1.0
- 1.3
- 0.8
- 0.8

**Nonprompt (EWk subtr.)**

- 1.0
- 1.5
- 1.0
- 1.3

**VVV norm.**

- 0.5
- 0.6
- 0.6
- 0.6

**V H norm.**

- 0.2
- 0.2
- 0.3
- 0.2

**t t V norm.**

- 0.5
- 0.5
- 0.5
- 0.5

**tZq norm.**

- 0.1
- 0.1
- 0.1
- 0.1

**X+γ norm.**

- 0.3
- 0.8
- < 0.1
- 0.7
- < 0.1

**Total systematic**

- 4.7
- 2.8
- 5.8
- 5.4

**Integrated luminosity**

- 2.8
- 2.8
- 2.8

**Statistical**

- 2.1
- 6.0
- 4.8

**Total experimental**

- 6.0
- 10.8
- 8.0
- 7.5

**Theoretical**

- 0.9
- 0.9
- 0.9

**Total cross section compared with MATRIX results (arXiv:1604.08576)**
Charge-dependent cross sections

\[ \sigma_{\text{tot}}(\text{pp} \to W^+Z) = 28.91^{+0.63}_{-0.60} \text{ (stat)}^{+0.28}_{-0.25} \text{ (theo)}^{+1.43}_{-1.31} \text{ (syst)} \pm 0.80 \text{ (lumi)} \text{ pb}, \]
\[ \sigma_{\text{tot}}(\text{pp} \to W^-Z) = 19.55^{+0.45}_{-0.41} \text{ (stat)}^{+0.17}_{-0.15} \text{ (theo)}^{+0.97}_{-0.88} \text{ (syst)} \pm 0.55 \text{ (lumi)} \text{ pb}. \]

### ATLAS

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \sigma_{\text{fid.}}^{W^\pm Z \to \ell' \ell \ell} ) [fb]</th>
<th>( \delta_{\text{stat.}} ) [%]</th>
<th>( \delta_{\text{exp. syst.}} ) [%]</th>
<th>( \delta_{\text{mod. syst.}} ) [%]</th>
<th>( \delta_{\text{lumi}} ) [%]</th>
<th>( \delta_{\text{tot.}} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^+ ee )</td>
<td>40.8</td>
<td>4.6</td>
<td>5.4</td>
<td>0.5</td>
<td>2.2</td>
<td>7.4</td>
</tr>
<tr>
<td>( \mu^+ ee )</td>
<td>36.5</td>
<td>4.3</td>
<td>3.3</td>
<td>0.5</td>
<td>2.2</td>
<td>5.8</td>
</tr>
<tr>
<td>( e^+ \mu \mu )</td>
<td>36.7</td>
<td>4.1</td>
<td>5.0</td>
<td>0.5</td>
<td>2.2</td>
<td>6.8</td>
</tr>
<tr>
<td>( \mu^+ \mu )</td>
<td>38.2</td>
<td>3.5</td>
<td>4.0</td>
<td>0.5</td>
<td>2.2</td>
<td>5.7</td>
</tr>
<tr>
<td>Combined</td>
<td>37.9</td>
<td>2.0</td>
<td>3.4</td>
<td>0.5</td>
<td>2.2</td>
<td>4.5</td>
</tr>
<tr>
<td>SM prediction</td>
<td>36.3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.2</td>
</tr>
</tbody>
</table>

### CMS

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \sigma_{\text{fid.}}^{W^\pm Z \to \ell' \ell \ell} ) [fb]</th>
<th>( \delta_{\text{stat.}} ) [%]</th>
<th>( \delta_{\text{exp. syst.}} ) [%]</th>
<th>( \delta_{\text{mod. syst.}} ) [%]</th>
<th>( \delta_{\text{lumi}} ) [%]</th>
<th>( \delta_{\text{tot.}} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^- ee )</td>
<td>24.9</td>
<td>6.1</td>
<td>7.1</td>
<td>0.5</td>
<td>2.2</td>
<td>9.6</td>
</tr>
<tr>
<td>( \mu^- ee )</td>
<td>24.8</td>
<td>5.3</td>
<td>4.0</td>
<td>0.5</td>
<td>2.2</td>
<td>7.0</td>
</tr>
<tr>
<td>( e^- \mu \mu )</td>
<td>25.7</td>
<td>5.1</td>
<td>6.2</td>
<td>0.5</td>
<td>2.2</td>
<td>8.3</td>
</tr>
<tr>
<td>( \mu^- \mu )</td>
<td>27.1</td>
<td>4.3</td>
<td>4.3</td>
<td>0.5</td>
<td>2.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Combined</td>
<td>25.9</td>
<td>8.1</td>
<td>4.0</td>
<td>0.5</td>
<td>2.2</td>
<td>5.2</td>
</tr>
<tr>
<td>SM prediction</td>
<td>25.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Asymmetry as ratio of cross sections

\[ A_{W^\pm Z}^+ = \frac{\sigma_{\text{tot}}(\text{pp} \to W^+Z)}{\sigma_{\text{tot}}(\text{pp} \to W^-Z)} = 1.48 \pm 0.06 \text{ (stat)} \pm 0.02 \text{ (syst)} \pm 0.01 \text{ (theo)} \]

Better coordination on display is desirable

- ATLAS: fiducial, ratio of xsecs
- CMS: total, ratio of ratios (as ATLAS previously)
WZ production: differential cross section

- Using available (NLO) MC
  - Constrain normalization to NNLO
- Different sets of observables
  - Somehow a failure of meetings done to agree on observables and such
  - ATLAS: , only for $W^\pm Z$
  - CMS: $p_T^Z, p_T^{\text{jet}}, M_{WZ}$, also split by $W^+Z, W^-Z$
- Different definitions of observables, e.g. $M_T(WZ)$
  - ATLAS: $\sim M(E_T^{\text{miss}}, \ell_1, \ell_2, \ell_3)$
  - CMS: $\sim M(E_T^{\text{miss}}, \ell\ell\ell)$
- Headache for theoreticians (true story)
- Uncertainty on response matrix
  - ATLAS: data-driven (reweighting to data)
  - CMS: physics-driven (alternative MC sample)
- Statistical uncertainties dominate the measurement

- Unfolding
  - ATLAS: no detail on technique, response matrix not public
  - CMS: public response matrix, details on $\chi^2$ fit (TUnfold) procedure, tabulated results
WZ production: accessory measurements

- ATLAS: polarization measurement
  - Measured polarization of both W and Z

\[
\frac{1}{\sigma_{W^+Z}} \frac{d\sigma_{W^+Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8} f_L[(1 + \cos\theta_{\ell,W})^2] + \frac{3}{8} f_R[(1 - \cos\theta_{\ell,W})^2] + \frac{3}{4} f_0 \sin^2\theta_{\ell,W}.
\]

- CMS: differential measurement split by charge
  - W^+

CMS

- ATLAS: polarization measurement
  - Measured polarization of both W and Z

\[
\frac{1}{\sigma_{W^+Z}} \frac{d\sigma_{W^+Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8} f_L[(1 + \cos\theta_{\ell,W})^2] + \frac{3}{8} f_R[(1 - \cos\theta_{\ell,W})^2] + \frac{3}{4} f_0 \sin^2\theta_{\ell,W}.
\]
WZ production: anomalous couplings

- EFT framework, constraining dimension-6 operators
  - $c_{WWW}, c_W, c_b$ are 0 in the SM

\[ \delta L_{AC} = \frac{c_{WWW}}{\Lambda^2} \text{Tr}[W_{\mu\nu} W^{\mu\nu} W_{\rho\sigma}] + \frac{c_W}{\Lambda^2} (D_\mu H)^\dagger W^{\mu\nu} (D_\nu H) + \frac{c_b}{\Lambda^2} (D_\mu H)^\dagger B^{\mu\nu} (D_\nu H) \]

- ATLAS: 1D intervals, 13 fb$^{-1}$

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Coupling</th>
<th>Expected [TeV$^{-2}$]</th>
<th>Observed [TeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS 8 and 13 TeV</td>
<td>$c_W/\Lambda^2_{NP}$</td>
<td>[-3.4; 6.9]</td>
<td>[-3.6; 7.3]</td>
</tr>
<tr>
<td></td>
<td>$c_B/\Lambda^2_{NP}$</td>
<td>[-221; 166]</td>
<td>[-253; 136]</td>
</tr>
<tr>
<td></td>
<td>$c_{WWW}/\Lambda^2_{NP}$</td>
<td>[-3.2; 3.0]</td>
<td>[-3.3; 3.2]</td>
</tr>
</tbody>
</table>

- CMS: 2D and 1D intervals, 36 fb$^{-1}$
  - 30–50% gain in 1D intervals, even more for 2D regions

<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>
  - VBS WW result with 35 fb$^{-1}$ in Kenneth's talk
- CMS: inclusive result, and a brand new result on anomalous couplings!
  - CMS-SMP-18-015 inclusive cross section (PAS, paper in preparation), 77 fb$^{-1}$
  - NEW!!! CMS-SMP-18-008 anomalous couplings in semileptonic channels (PAS, paper in preparation), 36 fb$^{-1}$
  - VBS same-sign WW and semileptonic WW results in Kenneth's talk

![Diagram from ATLAS 7 TeV paper](image)
1L+2L triggers, $p_T \sim 20$–$24$ GeV (99% efficiency)
Exclude same-flavours events (high DY contamination)
$b$ tagging: $\sim 3.5\%$ mistag rate
Estimate $\bar{t}t$, DY, and $W$+jets in data
Larger source of uncertainty: jet selection and calibration
Exemplary section describing details of fiducial region

<table>
<thead>
<tr>
<th>Fiducial selection requirement</th>
<th>Cut value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt; 25$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$m_{\mu\mu}$</td>
<td>$&gt; 10$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}, \text{rel}}$</td>
<td>$&gt; 15$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt; 20$ GeV</td>
</tr>
</tbody>
</table>

Sources of uncertainty | Relative uncertainty for $\sigma^{\text{fid}}_{WW\rightarrow e\mu}$
Jet selection and energy scale & resolution | 7.3%
b-tagging | 1.3%
$E_T^{\text{miss}}$ and $p_T^{\text{miss}}$ | 1.7%
Electron | 1.0%
Muon | 0.4%
Pile-up | 0.9%
Luminosity | 2.1%
Top-quark background theory | 2.4%
Drell–Yan background theory | 1.5%
$W$+jet and multi-jet background | 3.8%
Other diboson backgrounds | 1.1%
Parton shower | 3.1%
PDF | 0.2%
QCD scale | 0.2%
MC statistics | 1.2%
Data statistics | 3.7%
Total uncertainty | 11%
**WW production: inclusive cross section**

- Fiducial measurement dominated by systematic uncertainties (mostly jet selection and calibration)

\[ \sigma_{\text{fid}}^{\text{WW} \rightarrow e\mu} = 529 \pm 20 \,(\text{stat.}) \pm 50 \,(\text{syst.}) \pm 11 \,(\text{lumi.}) \,\text{fb} \]

- Ratio to 8 TeV is compatible with predictions (both fiducial and total)

\[ \frac{\sigma_{13 \text{ TeV}, \text{WW} \rightarrow e\mu}^{\text{fid}}}{\sigma_{8 \text{ TeV}, \text{WW} \rightarrow e\mu}^{\text{fid}}} = 1.41 \pm 0.06 \,(\text{stat.}) \pm 0.16 \,(\text{syst.}) \pm 0.04 \,(\text{lumi.}) \]

---

**ATLAS**

- nNNLO+H calculation (fixed-order acceptance)
- nNNLO+H calculation (MC acceptance)

Data:
- 529 ± 20 ± 50 ± 11 fb

**Cross-section ratio (13 TeV / 8 TeV)**

- Data
- stat.
- stat.+syst.
- nNNLO+H Prediction

**Total cross-section ratio (13 TeV / 8 TeV)**

**Fiducial cross-section ratio (13 TeV / 8 TeV)**

\( \sqrt{s} = 13 \text{ TeV}, 3.16 \text{ fb}^{-1} \)
**CMS evidence:** CMS-SMP-18-015 (PAS, paper in preparation)

- **Two main mechanisms at LO**
  - **DPS:** both hard scatterings give rise to a \( W \) boson
  - **SHS:** two additional high-\( p_T \) partons suppressed at matrix-element level
  - Discriminate DPS from SHS: DPS with same charge has no jets from hard process
  - \( \sigma_{\text{DPS}}^{\text{AB}} = \frac{n}{2} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \); \( A, B \) SHS processes (\( n = 1 \): indistinguishable A,B; \( n = 2 \) otherwise)

- **Probe for the validity of the factorization approach used in MC**
- **Background to searches (e.g. SUSY ewkino searches)**

\[
\begin{align*}
q(p^1) & \rightarrow W^\pm \\
\bar{q}(p^1) & \rightarrow \ell^\pm \\
q'(p^2) & \rightarrow W^\pm \\
\bar{q}'(p^2) & \rightarrow \nu \\
W^\pm & \rightarrow \ell^\pm
\end{align*}
\]
**WW double-parton-scattering evidence**

- 1L+2L triggers soup, $p_T \sim 8–35$ GeV
- Lepton MVA ID against nonprompt leptons
- Selection: 2 same-charge leptons, $E^\text{miss}_T$
  - At most 1 jet
  - Veto b jets
- DPS prediction affected by large uncertainties
  - Imprecise knowledge of $\sigma_{\text{eff}}$ (different final states yield different results)
  - Cross section predicted from simulation depends on the UE tuning
- Observed cross sections depend only on generator kinematics
  - Comparable with different predictions
  - $\sigma_{\text{eff}}^{\text{obs}}$ computable using predictions for inclusive W boson production

### CMS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Obtained Value</th>
<th>Significance (standard deviations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{DPSWW,exp}}^{\text{PYTHIA8}}$</td>
<td>1.92 pb</td>
<td>5.4</td>
</tr>
<tr>
<td>$\sigma_{\text{DPSWW,exp}}^{\text{factorized}}$</td>
<td>0.87 pb</td>
<td>2.5</td>
</tr>
<tr>
<td>$\sigma_{\text{DPSWW,obs}}$</td>
<td>$1.41 \pm 0.28 \text{ (stat)} \pm 0.28 \text{ (syst)}$ pb</td>
<td>3.9</td>
</tr>
<tr>
<td>$\sigma_{\text{eff}}$</td>
<td>$12.7^{+50}_{-29} \text{ mb}$</td>
<td>–</td>
</tr>
</tbody>
</table>

---

**Extrapolated to total WW xsec** 77 fb$^{-1}$ (13 TeV)

- **Observed**
- **Predictions:**
  - stat
  - PYTHIA 8 (CP5)
  - Factorization approach

<table>
<thead>
<tr>
<th>Process</th>
<th>Total</th>
<th>Stat</th>
<th>Syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\mu^-\mu^+\mu^-$</td>
<td>$1.96 \pm 0.74 \pm 0.54, \pm 0.51$ pb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^-\mu^+\mu^-$</td>
<td>$1.36 \pm 0.46 \pm 0.33, \pm 0.32$ pb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^-\mu^+\mu^-$</td>
<td>$1.41 \pm 0.40 \pm 0.28, \pm 0.28$ pb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NEW!!! Anomalous couplings in $\ell + jets$ $WW$ and $WZ$ decays

- Semileptonic decays: larger branching fraction, but also larger backgrounds (QCD multijet)
- Triggers: 1L, $p_T = 45(50)$ GeV, $|\eta| < 2.5(2.4)$ for electrons (muons)
- Full reconstruction of diboson system ($65 < M_{WW} < 85 < M_{WZ} < 105$ GeV)
  - $W$: $p_T > 200$ GeV from lepton+$E_T^{miss}$ ($p_T^\nu$ from $W$ mass constraint)
  - Smallest of the two real solutions, or $Re()$ of the complex one
- $W$+jets and $t\bar{t}$ backgrounds in sidebands of diboson mass
- Anti-$k_T$ jets: cone 0.4 (bkg rejection) and 0.8 (hadronic boson decay)
  - Boson candidate: $p_T$-leading AK8 jet (soft drop and $\tau_{21}$ to reject quarks and gluons)
  - Reject AK4 b-tagged jets to reject $t\bar{t}$...
  - ...but only if $\Delta R > 0.8$ w/ hadronic $W$ (to not reject $WZ$, $Z \rightarrow b\bar{b}$)
  - Mass after soft-drop and pileup-per-particle subtraction (PUPPI) used as $M_{WW}$
- Back-to-back topology, avoid modelling turn-on in bkg description by $M_{WW} > 900$ GeV
  - $\Delta R$(AK8 jet, $\ell) > \pi/2$
  - $\Delta \phi$(AK8 jet, $E_T^{miss}) > 2$
  - $\Delta \phi$(AK8 jet, $W_{lep}) > 2$

![Graph](image-url)
Anomalous couplings in semileptonic $WW$ and $WZ$ decays

Signal modelling:
$M_{W^V} \sim$ exponentially falling

- SM shape and normalization from aTGC simulated samples (MG5@NLO)
- SM-aTGC interference from comparison with aTGC with opposite sign
- Pure aTGC from simultaneous fit
- aTGC-aTGC from comparison of samples with suitable pairs of couplings on/off
- Erf models turn-on of the aTGC
- Small $c_{WWW}$-SM, $c_{WWW}$-$c_b$, and erf on $c_b$ neglected

Largest prefit normalization uncertainty: V-tagging, scale, and JES (no postfit quoted)

Results at the level of the WZ multilepton ones

<table>
<thead>
<tr>
<th>Parametrization</th>
<th>aTGC</th>
<th>Expected limit</th>
<th>Observed limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFT $c_{WW}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>[-1.44, 1.47]</td>
<td>[-1.58, 1.59]</td>
<td></td>
</tr>
<tr>
<td>$c_{W}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>[-2.45, 2.08]</td>
<td>[-2.00, 2.65]</td>
<td></td>
</tr>
<tr>
<td>$c_{B}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>[-8.38, 8.06]</td>
<td>[-8.78, 8.54]</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\lambda_Z$</th>
<th>$\Delta\lambda_Z$</th>
<th>$\Delta\kappa_Z$</th>
<th>$\kappa_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>[4.6 fb]</td>
<td>35.9 fb</td>
<td>33.6 fb</td>
<td>19.6 fb</td>
<td>19 fb</td>
</tr>
<tr>
<td>WZ</td>
<td>[20.3 fb]</td>
<td>13 TeV</td>
<td>13 TeV</td>
<td>13 TeV</td>
<td>13 TeV</td>
</tr>
<tr>
<td>WV</td>
<td>[5.0 fb]</td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>7 TeV</td>
</tr>
</tbody>
</table>

March 2019

Pietro Vischia

Multiboson production at ATLAS and CMS — SM@LHC 2019, Zürich

April 24th, 2019

17 / 30
ATLAS: four-lepton result with 36 fb$^{-1}$ (2016)

CMS: four-lepton result with full Run-II data!
- $ZZ \rightarrow 4\ell$: CMS-PAS-SMP-19-001, 137 fb$^{-1}$!!!
- $ZZ+\text{jets}$:
  - VBS ZZ+2jets in Kenneth's talk

Pietro Vischia
Multiboson production at ATLAS and CMS — SM@LHC 2019, Zürich
**ZZ production: object and event selection**

- Different generators for signal
  - ATLAS: SHERPA (POWHEG as alternative prediction)
  - CMS: POWHEG

- Trigger strategies
  - ATLAS: 1L+2L+3L soup, $\sim 100\%$ efficiency
  - CMS: 2L triggers, $p_T \sim 8$–17 GeV, $>98\%$ efficiency

- $4\ell$ Selection
  - ATLAS: relaxed ID on at most 1 muon, $66 < M(Z_i) < 166$ GeV
  - CMS: no relaxed ID, $M(Z_i) > 60$ GeV

- Background estimation: Z, VV, $t\bar{t}$ from sidebands
  - ATLAS+CMS: transfer factors accounting for nonprompt estimates
ZZ production: fiducial cross section

- Different reporting of uncertainties
- Dominant uncertainties
  - ATLAS: PDF/QCD scales
  - CMS: lepton ID
- Good agreement with NNLO predictions
  - Including NLO EW and QCD corrections

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measurement [fb]</th>
<th>Prediction [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e</td>
<td>13.7$^{+1.1}_{-1.0}$ [± 0.9 (stat.) ±0.4 (syst.) ]</td>
<td>10.9$^{+0.5}_{-0.4}$</td>
</tr>
<tr>
<td>2e2μ</td>
<td>20.9$^{+1.4}_{-1.3}$ [± 1.0 (stat.) ±0.6 (syst.) ]</td>
<td>21.2$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>4μ</td>
<td>11.5$^{+0.9}_{-0.9}$ [± 0.7 (stat.) ±0.4 (syst.) ]</td>
<td>10.9$^{+0.5}_{-0.4}$</td>
</tr>
<tr>
<td>Combined</td>
<td>46.2$^{+2.5}_{-2.3}$ [± 1.5 (stat.) ±1.2 (syst.) ±1.0 (lumi.) ]</td>
<td>42.9$^{+1.9}_{-1.5}$</td>
</tr>
</tbody>
</table>

CMS pred: $\sigma_\text{fid}^{\text{POWHEG+MCFM}} = 34.4^{+0.7}_{-0.6}$ (PDF) ± 0.5(scale) fb

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

<table>
<thead>
<tr>
<th>Effect on total predicted yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC statistical uncertainty</td>
</tr>
<tr>
<td>Electron efficiency</td>
</tr>
<tr>
<td>Electron energy scale &amp; resolution</td>
</tr>
<tr>
<td>Muon efficiency</td>
</tr>
<tr>
<td>Muon momentum scale &amp; resolution</td>
</tr>
<tr>
<td>Pileup modeling</td>
</tr>
<tr>
<td>Luminosity</td>
</tr>
<tr>
<td>QCD scales</td>
</tr>
<tr>
<td>PDFs</td>
</tr>
<tr>
<td>Background prediction</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range of values</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–8%</td>
<td>Lepton efficiency</td>
</tr>
<tr>
<td>1–2%</td>
<td>Trigger efficiency</td>
</tr>
<tr>
<td>0.6–1.3%</td>
<td>Background</td>
</tr>
<tr>
<td>1%</td>
<td>Pileup</td>
</tr>
<tr>
<td>1%</td>
<td>PDF</td>
</tr>
<tr>
<td>1%</td>
<td>$\mu_R$, $\mu_F$</td>
</tr>
<tr>
<td>2.3% (2017) 2.5% (2018)</td>
<td>Integrated luminosity</td>
</tr>
</tbody>
</table>
**ZZ production: extrapolation to total cross section**

- **Extrapolation to full phase space**
  - **ATLAS**: $66 < M(Z) < 116$ GeV, any SM decay
  - **CMS**: $60 < M(Z) < 120$ GeV, any SM decay

<table>
<thead>
<tr>
<th>Year</th>
<th>CMS Total cross section, pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 [5]</td>
<td>$17.5^{+0.6}_{-0.5}$ (stat) ± 0.6 (syst) ± 0.4 (theo) ± 0.4 (lumi)</td>
</tr>
<tr>
<td>2017</td>
<td>$16.8$ ± 0.5 (stat) ± 0.5 (syst) ± 0.4 (theo) ± 0.4 (lumi)</td>
</tr>
<tr>
<td>2018</td>
<td>$16.8$ ± 0.4 (stat) ± 0.6 (syst) ± 0.4 (theo) ± 0.4 (lumi)</td>
</tr>
<tr>
<td>Combined</td>
<td>$17.1$ ± 0.3 (stat) ± 0.4 (syst) ± 0.4 (theo) ± 0.3 (lumi)</td>
</tr>
</tbody>
</table>

- $\sigma_{\text{POWHEG} + \text{MCFM}}^{\text{tot}} = 14.5^{+0.5}_{-0.4}$ (PDF) ± 0.2 (scale) pb
- $\sigma_{\text{MATRIX} 1.0 \text{ NNLO}}^{\text{tot}} = 16.2^{+0.6}_{-0.4}$ pb
- $\sigma_{\text{MCFM NLO-QCD}}^{\text{tot, } +\text{LO } gg \rightarrow ZZ} = 16.2^{+0.6}_{-0.4}$ pb

---

**Pietro Vischia**

Multiboson production at ATLAS and CMS — SM@LHC 2019, Zürich

April 24th, 2019 21 / 30
ZZ production: differential cross section

- D’Agostini unfolding: minimize overall uncertainty
  - Results in 2–3 iterations
  - More iterations: higher statistical uncertainty
  - Fewer iterations: higher unfolding method uncertainty (stronger dependence on theoretical prediction)

- Modelling uncertainty
  - Unfold POWHEG spectrum nominal SHERPA response matrix
  - Use difference as uncertainty

- Modelling and regularization bias: 1–22% uncertainty

- Statistical uncertainty due to fluctuations in data
  - 2000 Poisson pseudodata
ZZ+jets production: differential cross section

- Unfold at particle level (dressed leptons)
- D’Agostini unfolding: 4 iterations
  - Default number of iterations
  - Cross-checked with SVD unfolding
- Modelling uncertainty
  - Unfold nominal spectrum using different response matrices
  - Use difference as uncertainty
ZZ production: anomalous couplings

- Use $p_{T,Z_1}$ to probe aTGC
  - $M_{4\ell}$ similar sensitivity but no NLO EW correction binned in $M_{4\ell}$ available
- Model CP-violating/conserving lagrangian
  - 2 CP-violating ($f^I_4, f^Z_4Z$) and 2 CP-conserving ($f^I_5, f^Z_5Z$) couplings
  - No unitarizing form factor (sensitivity is within unitarity bounds)

\[
N \left( f^\gamma_4, f^Z_4, f^\gamma_5, f^Z_5 \right) = N_{SM} + f^\gamma_4 N_{01} + f^Z_4 N_{02} + f^\gamma_5 N_{03} + f^Z_5 N_{04} \\
\quad + \left( f^\gamma_4 \right)^2 N_{11} + f^\gamma_4 f^\gamma_5 N_{12} + f^\gamma_5 f^\gamma_5 N_{13} + f^Z_4 f^Z_5 N_{14} \\
\quad + \left( f^Z_4 \right)^2 N_{22} + f^Z_4 f^Z_5 N_{23} + f^Z_4 f^Z_5 N_{24} \\
\quad + \left( f^Z_5 \right)^2 N_{33} + f^Z_5 f^Z_5 N_{34} \\
\quad + \left( f^Z_5 \right)^2 N_{44},
\]

<table>
<thead>
<tr>
<th>Coupling strength</th>
<th>Expected 95% CL $[$x $10^{-3}$]</th>
<th>Observed 95% CL $[$x $10^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f^\gamma_4$</td>
<td>$-2.4, 2.4$</td>
<td>$-1.8, 1.8$</td>
</tr>
<tr>
<td>$f^\gamma_5$</td>
<td>$-2.1, 2.1$</td>
<td>$-1.5, 1.5$</td>
</tr>
<tr>
<td>$f^Z_4$</td>
<td>$-2.4, 2.4$</td>
<td>$-1.8, 1.8$</td>
</tr>
<tr>
<td>$f^Z_5$</td>
<td>$-2.0, 2.0$</td>
<td>$-1.5, 1.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EFT parameter</th>
<th>Expected 95% CL $[$TeV$^{-4}$]</th>
<th>Observed 95% CL $[$TeV$^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{BW}/\Lambda^4$</td>
<td>$-8.1, 8.1$</td>
<td>$-5.9, 5.9$</td>
</tr>
<tr>
<td>$C_{WW}/\Lambda^4$</td>
<td>$-4.0, 4.0$</td>
<td>$-3.0, 3.0$</td>
</tr>
<tr>
<td>$C_{BW}/\Lambda^4$</td>
<td>$-4.4, 4.4$</td>
<td>$-3.3, 3.3$</td>
</tr>
<tr>
<td>$C_{BB}/\Lambda^4$</td>
<td>$-3.7, 3.7$</td>
<td>$-2.7, 2.8$</td>
</tr>
</tbody>
</table>
Triboson production

- ATLAS: evidence for VVV production 1903.10415, 80 fb$^{-1}$
- CMS: WWW search CMS-PAS-SMP-17-013, 36 fb$^{-1}$
Triboson production: object and event selection

- **Trigger strategy**
  - ATLAS: 1L triggers, $p_T \sim 20–60$ GeV
  - CMS: 2L triggers, $p_T \sim 8–23$ GeV

- **Selection: BDT vs manual classification**
  - ATLAS: BDT classifier, no detail on training
  - CMS: exploit ID, $M(jj)$, $M_T$

- **Background**
  - ATLAS: WZ and ttZ estimated and validated in sidebands
  - CMS: lost (below threshold) and nonprompt leptons from sidebands

---

**Diagrams**

- **Graphs** showing event distributions and signal regions with BDT response and data vs prediction.

---

**Table**

<table>
<thead>
<tr>
<th>Signal Regions</th>
<th>Data / Pred.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-\mu^+\mu^-$</td>
<td>0.5 – 1.5</td>
</tr>
<tr>
<td>$\mu^+\mu^+\mu^-$</td>
<td>0.75 – 1.25</td>
</tr>
<tr>
<td>$\mu^+\mu^-\mu^-$</td>
<td>1.25 – 1.75</td>
</tr>
<tr>
<td>Signal regions 1/2/3</td>
<td>1.75 – 2.25</td>
</tr>
</tbody>
</table>

---

**Signal**

- ATLAS: $13$ TeV, $79.8$ fb$^{-1}$
- CMS: Preliminary

---

**Results**

- **Events**
  - ATLAS: $13$ TeV, $79.8$ fb$^{-1}$
  - CMS: $35.9$ fb$^{-1}$ (13 TeV)

---

**Figure**

- Multiboson production at ATLAS and CMS — SM@LHC 2019, Zürich April 24th, 2019

---

**Authors**

- Pietro Vischia
Evidence and quartic gauge couplings

- **ATLAS**: evidence for VVV production
  - No detail on systematics!
- **CMS**: $\sigma(pp \rightarrow WWW) = 173^{+326}_{-173}$ fb
  - Under background-only: $782^{(599)}$ fb 95%CL obs(exp)
  - Confidence intervals for aQGC (dim-8 operators)
  - Limits on photophobic axion-like particles

### Table 8: Limits on anomalous quartic couplings at 95% CL

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

### ATLAS

<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>3.3$\sigma$</td>
</tr>
<tr>
<td>$WWW \rightarrow \ell\nu\nu\nu\nu$</td>
<td>4.3$\sigma$</td>
</tr>
<tr>
<td>$WWW \rightarrow \ell\nu\nu\nu\nu$</td>
<td>1.0$\sigma$</td>
</tr>
<tr>
<td>WVZ combined</td>
<td>2.9$\sigma$</td>
</tr>
<tr>
<td>$WVZ \rightarrow \ell\nu\nu\nu\nu$</td>
<td>–</td>
</tr>
<tr>
<td>$WVZ \rightarrow \ell\nu\nu\nu\nu/qqlll$</td>
<td>3.5$\sigma$</td>
</tr>
<tr>
<td>VVV combined</td>
<td>4.0$\sigma$</td>
</tr>
</tbody>
</table>

### Photophobic ALP parameter $1\Gamma_{te}$

- **CMS Preliminary**: 35.9 fb$^{-1}$ (13 TeV)

### ATLAS

- $\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$

__________________________________________________________________________
For discussion: datasets, samples

- We need precision measurements to improve constraints on aTGC/aQGC couplings
- Data set widely incoherent among and within collaborations
  - Soup of comparisons with 3, 13, 36, 70–80, 101 fb$^{-1}$: even a comparison of 3 vs 77 fb$^{-1}$!
  - Collaboration strategy? Personpower?
- Agree on the choice of main/alternative generators?
  - Often different generators used (POWHEG vs SHERPA; etc)
- Level of detail provided as public material should be dramatically improved
  - Sometimes the collaborations push against too much detail
- Presentation of results
  - Same formulas, same comparisons
- Not only between ATLAS and CMS: even within ATLAS and CMS individually!!!
For discussion: analysis-specific topics

- Phase space definitions: discrepancies and reporting
  - Some justified by the detector structure
  - Some perhaps could be agreed upon
  - Publish the details of the definitions (theoreticians need them for using results in global fits)

- Machine learning: don’t let it be a black box
  - Training samples and methodology should be clearly mentioned
  - The relevant hyperparameters of your classifier are interesting and deserve to be mentioned!

- Systematics: don’t be afraid of detailing them!
  - At the very minimum, table detailing the postfit uncertainties split by source
  - Even better, impact plots with pulls and constraints: particularly interesting for theory uncertainties!!!

- Differential measurements could profit from better reporting and agreements
  - Unfolding is an open topic, many discussions (ATLAS StatForum and CMS StatComm)
  - Use methods correctly (do not use defaults!)
    - Sometimes no unique “right” answer
    - Mostly we know what we should not do
  - Can we at least agree on this?
    - Publish the response matrix
    - Publish the tabulated results
    - Publish the details of the unfolding (e.g. number of iterations, choice of regularization, etc)

- Combinations: it is time, is it?
  - Cross section: wait for full Run-II?
  - Couplings: start combining current results, or wait for full Run-II?
Summary of multiboson production studies

- Large landscape of precision measurements (and check out Kenneth’s talk on VBS production modes!)
- We are now in the era of the couplings
- WZ production: data point to NNLO predictions
  - Ratios and asymmetries all consistent with SM predictions
  - Statistical uncertainties dominate differential measurement
  - Confidence regions for aTGC shrinking dramatically!
- WW production: data compatible with nNNLO
  - Systematic-dominated, but still profit from more data (currently: 3 fb$^{-1}$!)
  - Evidence for DPS WW production (and good agreement with CMS-tuned PYTHIA 8)
  - NEW!!! anomalous couplings constrained in VW production at the level of the latest multilepton result!
- ZZ production: impressive detail of 36 fb$^{-1}$ analysis, plus first look at Full Run-II w/ 101 fb$^{-1}$!
  - Data agree well with NNLO predictions with NLO EW and QCD corrections
- Triboson production: establishing evidence, and constraints on quartic couplings
  - VVV production emerging, but evidence (3$\sigma$ exp) only combining all VVV, so far: must go further
  - Sensitive to quartic couplings (dimension 8 operators!)
  - Sensitive to axion-like models
- NNLO predictions favoured everywhere, but generators kinematics still NLO
- The NNLO revolution is ongoing: when do we get NNLO MC spectra? 😊

Stay tuned on the ArXiv for a small contribution on the issues in reporting I outlined in this talk
THANKS FOR THE ATTENTION!
Backup