Outline

1 Physics Motivation

2 Cross section measurements
   - WW cross-section measurements
   - WW+WZ cross-section measurements
   - WZ cross-section measurements
     - UPDATED 7 TeV with $\mathcal{L}_{\text{int}} = 4.9\,fb^{-1}$
     - NEW CMS 8 TeV with $\mathcal{L}_{\text{int}} = 19.6\,fb^{-1}$
     - FIRST measurement of $\sigma_{W+Z}/\sigma_{W-Z}$ at 7 TeV and 8 TeV
   - ZZ cross-section measurements
     - UPDATED 8 TeV with $\mathcal{L}_{\text{int}} = 19.6\,fb^{-1}$

3 Anomalous couplings
Physics Motivation

- Precision test of QCD/EW dynamics of the Standard Model
- Allow test of anomalous Triple Gauge Couplings (aTGC)

Background to several Higgs production and other new physics channels (Exotica, SUSY, ...)

![Diagram showing TGC vertex and Higgs production channels](image)
Overview of WW, WZ and ZZ measurements at CMS

- Updated 7 TeV measurement for WZ
- First results at 8 TeV for WZ at CMS
- Updated results at 8 TeV for ZZ
- First measurement $\sigma_{W^+Z}/\sigma_{W^-Z}$

### Production Cross Section, $\sigma_{tot}$

**WW, WZ and ZZ Production**

- **WW**
  - $W \rightarrow 2\ell 2\nu$
  - $WW \rightarrow \ell \nu jj$
- **WZ**
  - $WZ \rightarrow 2\ell \ell' \nu$
  - $ZZ \rightarrow 4\ell$

### Integrated Luminosity at 7 TeV and 8 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>7 TeV</th>
<th>8 TeV</th>
<th>Limits on TGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW \rightarrow 2\ell 2\nu$</td>
<td>5.0 fb$^{-1}$</td>
<td>3.5 fb$^{-1}$</td>
<td>$\gamma W, WZW$</td>
</tr>
<tr>
<td>$WW + WZ \rightarrow \ell \nu jj$</td>
<td>5.0 fb$^{-1}$</td>
<td>-</td>
<td>$W\gamma W, WWZ$</td>
</tr>
<tr>
<td>$WZ \rightarrow 2\ell \ell' \nu$</td>
<td>4.9 fb$^{-1}$</td>
<td>19.6 fb$^{-1}$</td>
<td>-</td>
</tr>
<tr>
<td>$ZZ \rightarrow 4\ell$</td>
<td>4.9 fb$^{-1}$</td>
<td>19.6 fb$^{-1}$</td>
<td>$ZZZ, Z\gamma Z$</td>
</tr>
</tbody>
</table>
$WW \rightarrow 2\ell 2\nu$ ($\ell = e, \mu$)

$\mathcal{L}_{\text{int}} = 4.9 \, fb^{-1}$ @ 7 TeV, \hspace{1cm} $\mathcal{L}_{\text{int}} = 3.5 \, fb^{-1}$ @ 8 TeV

See also Jonathan Hollar’s talk: $gg \rightarrow WW$ and aQCG at CMS

**Signature**

- 2 isolated leptons ($ee, e\mu, \mu\mu$) with opposite sign
- Large missing $E_T$

**Background rejection**

- **QCD/W+jets:** Tight isolation and ID
- **top:**
  - Jet Veto (0 jets with $E_T > 30$ GeV)
  - Top Veto (b-tag + soft muon events vetoed)
- **Drell-Yan:**
  - $Z$ Veto, $|m_{\ell\ell} - m_Z| < 15$ GeV
  - $E_T^{\text{miss}} > 20/45$ GeV ($e\mu/\mu\mu, ee$)
  - $\Delta\phi(\ell\ell, jet) > 165^0$ (jet $E_t > 15$ GeV)
- **WZ, ZZ:** Veto events with third (good id,iso)lepton

- Main source of systematic uncertainty from background estimation (20 %)
- Measured cross sections slightly above the NLO prediction
- Expected contribution from SM $H \rightarrow WW$ about $\approx 4 \%$ (not included in the theoretical prediction)

**WW inclusive cross section**

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\sigma_{\text{meas.}}$ [pb]</th>
<th>$\sigma_{\text{theo.}}$ [pb] (MCFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$52.5 \pm 2.0(\text{stat.}) \pm 4.5(\text{syst.}) \pm 1.2(\text{lumi.})$</td>
<td>$47.0 \pm 2.0$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$69.9 \pm 2.8(\text{stat.}) \pm 5.6(\text{syst.}) \pm 3.1(\text{lumi.})$</td>
<td>$57.3^{+2.4}_{-1.8}$</td>
</tr>
</tbody>
</table>

Jordi Duarte Campderros (IFCA)
**Signature and signal selection**

- Exactly 1 isolated lepton: \( p_T > 20/30 \text{ GeV} \) (\( \mu/e \)) + trigger
- Exactly 2 jets: \( p_T > 35 \text{ GeV} \)
- Large missing \( E_T \): \( E_T > 25/30 \text{ GeV} \) (\( \mu/e \))
- \( W \) transverse mass:
  \[ M_T(\ell, E_T) > 30/35 \text{ GeV} \) (\( \mu/e \))

**Main backgrounds**

- \( W + \text{jets} \)
- \( \text{top} (t\bar{t}, tW) \)
- \( \text{DY+jets} \)
- \( \text{Multijets (QCD)} \)

**CMS cross section measurement**

\[
\sigma(pp \to WW + WZ) = 68.89 \pm 8.71(\text{stat.}) \pm 9.70(\text{syst.}) \pm 1.52(\text{lumi.}) \text{ pb}
\]

\[
\sigma_{\text{NLO theo.}} = 65.6 \pm 2.2 \text{ pb} \text{ (MCFM)}
\]
$WZ \rightarrow 2\ell\ell'\nu$ ($\ell = e, \mu$)

$L_{int} = 4.9 \text{ fb}^{-1}$ @ 7 TeV,  \quad L_{int} = 19.6 \text{ fb}^{-1}$ @ 8 TeV

**Signature**

- 3 isolated leptons (3$e$, 2$e1\mu$, 2$\mu1e$, 3$\mu$)
  - Z candidate: 2 same flavor, opposite charge; $p_t > 20, 10$ GeV and $|m_{\ell\ell} - m_Z| < 20$ GeV
  - W candidate: $p_t > 20$ GeV + $E_T^{\text{miss}} > 30$ GeV

- Large missing $E_T$

**Background rejection**

- **ZZ** (irreducible background)
  - vetoed events with $> 3$ good id. and iso. leptons
  - $E_T^{\text{miss}} > 30$ GeV

- Fakes leptons Instrumental background due to mis-identified particles or leptons not decaying from W/Z: Z+jets, top ($t\bar{t}$, $tW$, $\bar{t}W$), WW, W+jets, QCD, ...
  - Tight isolation, Z mass, Large $E_T^{\text{miss}}$, ...

- Analysis signal dominated

- Main background coming from instrumental background: Z+jets, $t\bar{t}$

CMS Preliminary $\sqrt{s} = 7$ TeV

---

Jordi Duarte Campderros (IFCA)  
WW, WZ and WZ Production  
EPS2013, July 18th 2013 7 / 16
\[ WZ \rightarrow 2\ell\ell'\nu (\ell = e, \mu) \]

\[ \mathcal{L}_{\text{int}} = 4.9 \text{ fb}^{-1} \text{ @ 7 TeV}, \quad \mathcal{L}_{\text{int}} = 19.6 \text{ fb}^{-1} \text{ @ 8 TeV} \]

### Cross section measurements

<table>
<thead>
<tr>
<th></th>
<th>(\sigma_{\text{CMS}}^{\text{meas.}}) [pb]</th>
<th>(\sigma_{\text{NLO}}^{\text{theo.}}) [pb] (MCFM, MSTW08 pdf sets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>(20.8 \pm 1.3) (stat.) (\pm 1.1) (syst.) (\pm 0.5) (lumi.)</td>
<td>(17.8^{+0.7}_{-0.5})</td>
</tr>
<tr>
<td>8 TeV</td>
<td>(24.7 \pm 0.8) (stat.) (\pm 1.1) (syst.) (\pm 1.1) (lumi.)</td>
<td>(22.0^{+1.2}_{-0.8})</td>
</tr>
</tbody>
</table>

- Statistical errors dominates 7 TeV measurement
- Main systematic uncertainty source coming from background estimation (\(\sim 6\%\))
- Cross section measured slightly above the NLO predictions

### \(\sigma_{W^+Z}/\sigma_{W^-Z}\) ratio measurements

<table>
<thead>
<tr>
<th></th>
<th>(\sigma_{\text{CMS}}^{\text{meas.}}) [pb]</th>
<th>(\sigma_{\text{NLO}}^{\text{theo.}}) [pb] (MCFM, MSTW08 pdf sets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>(1.94 \pm 0.25) (stat.) (\pm 0.04) (syst.)</td>
<td>(1.776^{+0.006}_{-0.003})</td>
</tr>
<tr>
<td>8 TeV</td>
<td>(1.81 \pm 0.12) (stat.) (\pm 0.03) (syst.)</td>
<td>(1.724 \pm 0.003)</td>
</tr>
</tbody>
</table>

- Luminosity systematic uncertainty cancels
- Background systematic uncertainties highly reduced
- Added systematic uncertainty in efficiency ratio \(\varepsilon^-/\varepsilon^-\) and charge misidentification rate. Main systematic source: efficiency ratio (\(\sim 3\%\))

Good agreement with NLO predictions
**Signature**

- First Z(→ ee, μμ): 2 isolated leptons, $p_T > 20, 10$ GeV, same flavor with opposite charge and $60 < m_{\ell\ell} < 120$ GeV
- Second Z:
  - $Z_2 \rightarrow ee, \mu\mu$: 2 isolated leptons, $p_T > 7, 5$, same flavor with opp. charge and $60 < m_{\ell\ell} < 120$ GeV
  - $Z_2 \rightarrow \tau\tau (\tau \rightarrow e, \mu, \text{had})$: $p_T(\tau \rightarrow e, \mu) > 10$, $p_T(\tau \rightarrow \text{had}) > 20$, and $30 < m_{\text{visible}}^{\tau\tau} < 90$ GeV

**Main Backgrounds**

- Jets faking $\ell$ or $\tau$ (WZ+jets,Z+jets)
- Heavy flavour jets ($t\bar{t}$, Zbb)

**ZZ inclusive cross section**

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\sigma_{\text{meas.}}^{\text{CMS}}$ [pb]</th>
<th>$\sigma_{\text{NLO}}$ [pb] (MCFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$6.2^{+0.9}<em>{-0.8} (\text{stat.})^{+0.4}</em>{-0.3} (\text{sys.}) \pm 0.1 (\text{lumi.})$</td>
<td>$6.3 \pm 0.4$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$7.7 \pm 0.5 (\text{stat.}) \pm 0.6 (\text{syst.}) \pm 0.3 (\text{lumi.})$</td>
<td>$7.7 \pm 0.4$</td>
</tr>
</tbody>
</table>

Differential cross-sections are also measured. See CMS-SMP-13-005
The SM predicts exact values for vector boson couplings

the effective Lagrangian used to describe the effect of non-SM processes on TGCs depends on several parameters

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Parameters</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW\gamma$</td>
<td>$\lambda_\gamma, \Delta \kappa_\gamma$</td>
<td>WW</td>
</tr>
<tr>
<td>$WWZ$</td>
<td>$\lambda_Z, \Delta \kappa_Z, \Delta g_1^Z$</td>
<td>WW, WZ</td>
</tr>
<tr>
<td>$ZZ\gamma$</td>
<td>$f_4^Z, f_5^Z$</td>
<td>ZZ</td>
</tr>
<tr>
<td>$ZZZ$</td>
<td>$f_4^\gamma, f_5^\gamma$</td>
<td>ZZ</td>
</tr>
</tbody>
</table>

All parameters are 0 in SM

This parametrization is $SU(2) \times U(1)$ gauge symmetry respecting

- New physics is expected at high boson transverse momentum or high diboson invariant mass

- the expected number of signal events can be written as function of the SM cross section plus some aTGC parameters

- In absence of deviations from the SM expectations, upper limits on aTGC parameters can be set using the profile-likelihood formalism and CLs method
Triple Gauge Couplings

Charged aTGCs

- WV (V=W,Z) production used to probe vertex WWV (V=Z,γ)
- Set limits on parameters (applying gauge constrains: 3 independent parameters),
  1. $Δg_z^1$
  2. $λ = λ_γ = λ_Z$
  3. $Δκ_z = Δg_z^1 - Δκ_γ tan^2(θ_W)$
- 95 % CL limits sets using leading lepton $p_t$ (WW) or $p_t^{jj}$ (WW+WZ)

No deviations from SM observed

Equal or World Leading Sensitivity

From WV (V=Z, W → jj)

Jordi Duarte Campderros (IFCA)
ZZ production used to probe vertex ZVZ ($V=Z,\gamma$)

Set limits on parameters $f_4^V$, $f_5^V$ ($V=Z,\gamma$)

95% CL limits sets using $4\ell$ invariant mass

No deviations from SM observed

NEW IMPROVED LIMITS
World Leading Sensitivity

Jordi Duarte Campderros (IFCA)
Summary and Conclusions

- Presented cross sections measurements for WW, WZ and ZZ production at CMS at 7 TeV and 8 TeV
  - Updated WZ cross section measurement at 7 TeV
  - First CMS measurement of WZ at 8 TeV
  - First measurement of $\sigma_{W^+Z}/\sigma_{W^-Z}$ at 7 TeV and 8 TeV
  - Updated ZZ cross section measurement at 8 TeV
- Cross sections measured compatible with NLO SM predictions
  - WZ and WW slightly above SM prediction
- aTGC searches using the WW, WZ and ZZ channels showed no deviation from SM
  - Improved limits from $f_V^4$, $f_V^5$ parameters (a factor $\simeq 3-4$ since last measurement)
Summary of cross section measurements

<table>
<thead>
<tr>
<th>$\sigma_{\text{meas}}^{\text{CMS}}$ [pb]</th>
<th>Channel</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$L_{\text{int}}$ [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(pp \to WW + WZ)$</td>
<td>$\ell \nu jj, (\ell = e, \mu)$</td>
<td>7</td>
<td>5.0</td>
</tr>
<tr>
<td>$\sigma(pp \to WW)$</td>
<td>$2\ell, (\ell = e, \mu)$</td>
<td>7</td>
<td>4.9</td>
</tr>
<tr>
<td>$\sigma(pp \to WW)$</td>
<td>$2\ell, (\ell = e, \mu)$</td>
<td>8</td>
<td>3.5</td>
</tr>
<tr>
<td>$\sigma(pp \to WZ)$</td>
<td>$2\ell' \nu, (\ell' = e, \mu)$</td>
<td>7</td>
<td>4.9</td>
</tr>
<tr>
<td>$\sigma(pp \to WZ)$</td>
<td>$2\ell' \nu, (\ell' = e, \mu)$</td>
<td>8</td>
<td>19.6</td>
</tr>
<tr>
<td>$\sigma(pp \to ZZ)$</td>
<td>$2\ell 2\ell', (\ell = e, \mu, \ell' = e, \mu, \tau)$</td>
<td>7</td>
<td>4.9</td>
</tr>
<tr>
<td>$\sigma(pp \to ZZ)$</td>
<td>$2\ell 2\ell', (\ell = e, \mu, \ell' = e, \mu, \tau)$</td>
<td>8</td>
<td>19.6</td>
</tr>
<tr>
<td>$\sigma(pp \to W^+Z)/\sigma(pp \to W^-Z)$</td>
<td>$2\ell' \nu, (\ell' = e, \mu)$</td>
<td>7</td>
<td>4.9</td>
</tr>
<tr>
<td>$\sigma(pp \to W^+Z)/\sigma(pp \to W^-Z)$</td>
<td>$2\ell' \nu, (\ell' = e, \mu)$</td>
<td>8</td>
<td>19.6</td>
</tr>
</tbody>
</table>

Jordi Duarte Campderros (IFCA)
Selection cuts and count analysis yields observed events

Background estimation with data-driven and MC methods

Measured the cross section within the fiducial region:

- Fiducial region is defined by the limited coverage of the detector and selection cuts

\[ \sigma_{\text{fiducial}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \cdot L_{\text{int}}} \]

Correct the fiducial cross section by the acceptance and branching ratio of measured channel to measure the total cross section

\[ \sigma_{\text{total}} = \frac{\sigma_{\text{fiducial}}}{A \cdot BR} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{A \cdot \varepsilon \cdot BR \cdot L_{\text{int}}} \]