WW, WZ, and ZZ Production

Masahiro Morii, Harvard University

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Diboson production

LO diagrams for WW, WZ, and ZZ production are

- Cross sections are calculated to NLO
- Gluon-gluon enters at NLO. Less than 10% of the cross section

Allows access to triple gauge couplings (TGCs)

- New physics may show up as anomalous (= non-SM) TGCs

Important background to Higgs and beyond-SM searches

- Precise knowledge of cross sections and kinematical distributions are important
Leptonic final states ($\ell = e, \mu$ and $\nu = \nu_e, \nu_\mu, \nu_\tau$)

- High-$p_T$ isolated leptons + missing $E_T$ gives good S/B ratios
- Price: $\text{Br}(W \to \ell \nu) = 22\%$, $\text{Br}(Z \to \ell\ell') = 7\%$, $\text{Br}(Z \to \nu\nu) = 20\%$

Semi-leptonic final states

- $\text{Br}(W \to qq) = 68\%$, $\text{Br}(Z \to qq) = 70\%$ → More signal, but huge background
- $b$-jet identification can enhance $Z \to bb$ signal
References

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Note/Conference</th>
<th>Process</th>
<th>Luminosity [fb⁻¹]</th>
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<td>CDF note 10957</td>
<td>ZZ → ℓℓℓℓ, ℓℓνν</td>
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<td>CDF note 10973</td>
<td>WW + WZ → ℓνjj</td>
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<td>CDF note 10864</td>
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<td>PRD 86 (2012) 031104</td>
<td>WW → ℓℓνν</td>
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<td>PRL 104 (2010) 201801</td>
<td>WW → ℓℓνν</td>
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<td>PLB 718 (2012) 451</td>
<td>TGC limits based on the following three analyses</td>
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<td>PRD 85 (2012) 112005</td>
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<td>EPJC 72 (2012) 2173</td>
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<td>CMS</td>
<td>CMS-PAS-FSQ-12-010</td>
<td>γγ → WW → ℓνμν</td>
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<td>4.9</td>
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</table>

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**ZZ → ℓℓℓℓ** is the cleanest of all channels

- Two $e^+e^-$ or $μ^+μ^-$ pairs in loose $Z$ mass windows
- Very small background from $WZ$ and $Z + jets$
- CMS allows $Z → τ^+τ^-$ for one $Z$

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**Figure 1:** Comparison of the MC simulation prediction and observed events in data for $Z → ℓℓ$.

**Figure 2:** Distribution of the invariant mass of the leading lepton pair. Events are required to contain two $ℓℓ$ candidates versus the invariant mass of the subleading lepton pair. Events with one or both leptons outside the mass window are excluded. The signal region is indicated by the red box.

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**Figure 3:** Distribution of the leading lepton pair mass and $p_T$ in the signal region ($66 < m_{ll} < 120$ GeV, $p_T^{ll} < 116$ GeV) for data and simulation.

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**Figure 4:** Distribution of the transverse mass of the leading lepton pair in the signal region ($66 < m_{ll} < 120$ GeV, $p_T^{ll} < 116$ GeV) for data and simulation.
**ZZ → ℓℓνν**

ZZ → ℓℓνν looks for missing $E_T$ recoiling against a $Z \rightarrow ℓℓ$

- Define “axial missing $E_T$” = $-\vec{E}_T \cdot \vec{p}_T / |p_T|$.

- CDF and DØ use neural-net discriminators to separate signal from background.

**Table III:** Table of predicted signal and background yields

<table>
<thead>
<tr>
<th>Channel</th>
<th>Predicted Signal</th>
<th>Predicted Background</th>
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<tbody>
<tr>
<td>ℓℓ</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>ττ</td>
<td>3.4</td>
<td>2.2</td>
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**Entries**

<table>
<thead>
<tr>
<th>ℓℓ</th>
<th>1.2</th>
<th>0.8</th>
</tr>
</thead>
</table>

**Figures:**

- **Fig. 2:** Histograms showing the distribution of $E_T$ recoiling against a $Z$.

- **Fig. 2a:** Neural network output distributions for ZZ signal and background.

**CDF 9.7 fb⁻¹**

- CDF Run II preliminary

**CDF 8.6 fb⁻¹**

- DØ Run II preliminary

**References:**

PRD 85 (2012) 112005

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WW, WZ, and ZZ
## ZZ → llll and lllνν

<table>
<thead>
<tr>
<th>√s</th>
<th>L dt</th>
<th>Measured cross section (pb)</th>
<th>Theory (pb)</th>
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<tbody>
<tr>
<td>CDF</td>
<td>1.96 TeV</td>
<td>9.7 fb⁻¹</td>
<td>1.38 ± 0.19(stat)⁺0.20⁻0.19(sys)</td>
</tr>
<tr>
<td>DØ</td>
<td>1.96 TeV</td>
<td>6.4–8.6 fb⁻¹</td>
<td>1.40⁺0.43⁻0.37(stat) ± 0.14(sys)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>7 TeV</td>
<td>4.6 fb⁻¹</td>
<td>6.7 ± 0.7(stat)⁺0.4⁻0.3(sys) ± 0.3(lumi)</td>
</tr>
<tr>
<td>CMS</td>
<td>7 TeV</td>
<td>5.0 fb⁻¹</td>
<td>6.24⁺0.86⁻0.80(stat)⁺0.41⁻0.32(sys) ± 0.14(lumi)</td>
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<tr>
<td>ATLAS</td>
<td>8 TeV</td>
<td>20 fb⁻¹</td>
<td>7.1⁺0.5⁻0.4(stat) ± 0.3(sys) ± 0.2(lumi)</td>
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<tr>
<td>CMS</td>
<td>8 TeV</td>
<td>5.3 fb⁻¹</td>
<td>8.4 ± 1.0(stat) ± 0.7(sys) ± 0.4(lumi)</td>
</tr>
</tbody>
</table>

**Measured cross sections agree with the SM prediction**

- **NB:** “total” cross section depends on the Z mass window

**Measurement precisions are statistics-limited**

- Leading systematic errors is the lepton identification efficiency

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WW, WZ, and ZZ
WZ → ℓνℓℓ is quite clean: S/B ~ 4

- e⁺e⁻ or μ⁺μ⁻ pair in a tight Z mass window, plus one isolated lepton and missing Eₜ
- Loose cut on mₜ of W candidate
- Background from Z + jets and ZZ

Enough statistics to measure kinematical distributions, e.g. pₜ(Z) and m(WZ)

- ATLAS “unfolded” (= corrected for experimental resolutions) pₜ(Z) and m(WZ) distributions with 7 TeV data
**WZ → ℓ⁺ℓ⁻ℓ⁺ℓ⁻**

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>∫Ldt (fb⁻¹)</th>
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<th>Theory (pb)</th>
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<tr>
<td>CDF</td>
<td>1.96</td>
<td>3.93±0.60(stat)±0.59(sys)</td>
<td>3.50±0.21</td>
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<tr>
<td>DØ</td>
<td>1.96</td>
<td>4.50±0.61(stat)±0.16(sys)</td>
<td>3.21±0.19</td>
</tr>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>19.0±1.4(stat)±0.9(sys)±0.4(lumi)</td>
<td>17.6±1.1</td>
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<tr>
<td>CMS</td>
<td>7</td>
<td>17.0±2.4(stat)±1.1(sys)±1.0(lumi)</td>
<td>(19.8±0.1)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>8</td>
<td>20.3±0.8(stat)±1.2(sys)±0.7(lumi)</td>
<td>20.3±0.8</td>
</tr>
</tbody>
</table>

Measured cross sections agree with the SM prediction

- NB: “total” cross section depends on the Z mass window

Measurement precisions are statistics-limited

- Exception: ATLAS 8 TeV, 13 fb⁻¹
- Leading systematic error is Z + jets background estimate

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WW, WZ, and ZZ
$WW \rightarrow \ell\nu\ell\nu$ needs a tight event selection to fight background

- Two isolated opposite-sign leptons
- Jet veto to suppress top background
  - $\text{DØ}$ uses 0-jet and 1-jet samples
- More kinematical cuts to suppress $W/Z/\gamma^* + \text{jets}$
  - ATLAS/CMS/CDF use a hard missing $E_T$ cut for $e^+e^-$ and $\mu^+\mu^-$ to suppress $Z/\gamma^* + \text{jets}$
  - $\text{DØ}$ uses a BDT for $e^+e^-$ or $\mu^+\mu^-$, $m_{T\text{min}}$ and $m_{T2}$ for $e^\pm\mu^\mp$
- ATLAS also unfolded the leading lepton $p_T$ distribution
**WW → ℓνℓν**

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\int L,dt$</th>
<th>Measured cross section (pb)</th>
<th>Theory (pb)</th>
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<tbody>
<tr>
<td>CDF</td>
<td>1.96 TeV</td>
<td>$12.1 \pm 0.9\text{(stat)}^{+1.6}_{-1.4}\text{(sys)}$</td>
<td>$11.7 \pm 0.7$</td>
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<tr>
<td>DØ</td>
<td>1.96 TeV</td>
<td>$11.6 \pm 0.4\text{(stat)} \pm 0.6\text{(sys)}$</td>
<td>$11.3 \pm 0.7$</td>
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<td>ATLAS</td>
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<td>$51.9 \pm 2.0\text{(stat)} \pm 3.9\text{(sys)} \pm 2.0\text{(lumi)}$</td>
<td>$44.7^{+2.1}_{-1.9}$</td>
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<tr>
<td>CMS</td>
<td>7 TeV</td>
<td>$52.4 \pm 2.0\text{(stat)} \pm 4.5\text{(sys)} \pm 1.2\text{(lumi)}$</td>
<td>$47.0 \pm 2.0$</td>
</tr>
<tr>
<td>CMS</td>
<td>8 TeV</td>
<td>$69.9 \pm 2.8\text{(stat)} \pm 5.6\text{(sys)} \pm 3.1\text{(lumi)}$</td>
<td>$57.3^{+2.4}_{-1.6}$</td>
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</tbody>
</table>

Cross sections at the LHC are slightly larger than the SM prediction

- Significances are small (+1.4σ, +1.0σ, +1.7σ) but starting to draw attention
  - Are the NLO calculations sufficiently precise?
  - Could this be a subtle sign of new physics?

Measurement precisions are systematics-limited

- Leading source of systematics is the jet veto
  - Experimental: jet-energy scale and resolution affects jet $p_T$ threshold
  - Theoretical: number of jets in $WW + jets$

We still really want to see results from the full 8 TeV data
$WW/WZ \rightarrow \ell \nu jj$

$WW/WZ \rightarrow \ell \nu jj$ is a tour de force of SM measurements

- Reconstruct a $W$ candidate in one lepton + missing $E_T$
- Two jets with $p_T > 25$–30 GeV
- Fit the di-jet invariant mass distribution

- Background must be exquisitely modeled

Signal is established by all experiments

- Precisions limited by both statistics and background modeling
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Cross sections at the LHC

WW, WZ, and ZZ
Triple Gauge Couplings

WWV \((V = Z/\gamma)\) couplings ↔ WW and WZ (also \(W\gamma\))

\[
\frac{\mathcal{L}_{\text{WWV}}}{g_{\text{WWV}}} = ig_1^V (W_{\mu\nu}^+ W^{\mu\nu} - W_{\mu\nu}^+ V_{\mu\nu} W_{\mu\nu}^+) + i\kappa_V W_{\mu\nu}^+ V_{\mu\nu} W_{\mu\nu}^+ V_{\mu\nu}^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W_{\mu\nu}^+ W_{\mu\nu}^+ V_{\mu\nu}^{\mu\nu}
\]

- 5 parameters: \(\Delta g_1^Z (\equiv g_1^Z - 1)\), \(\Delta \kappa_Z (\equiv \kappa_Z - 1)\), \(\Delta \kappa_\gamma (\equiv \kappa_\gamma - 1)\), \(\lambda_Z\), \(\lambda_\gamma\)
- Additional constraints may be imposed

Equal coupling \(\Delta g_1^Z = 0\), \(\Delta \kappa_Z = \Delta \kappa_\gamma\), and \(\lambda_Z = \lambda_\gamma\)

LEP scenario \(\Delta g_1^Z = \Delta \kappa_Z = \Delta \kappa_\gamma \tan^2 \theta_W\) and \(\lambda_Z = \lambda_\gamma\)

HISZ scenario \(\Delta \kappa_Z = \Delta g_1^Z (\cos^2 \theta_W - \sin^2 \theta_W)\), \(\Delta \kappa_\gamma = 2\Delta g_1^Z \cos^2 \theta_W\) and \(\lambda_Z = \lambda_\gamma\)

ZZV \((V = Z/\gamma)\) couplings ↔ ZZ (also \(Z\gamma\))

\[
\mathcal{L}_{\text{ZZV}} = -\frac{e}{M_Z^2} \left[ f_4^V (\partial_\alpha^V V_{\mu\beta}) Z_{\alpha} (\partial_\alpha^Z Z_{\beta}) + f_5^V (\partial_\sigma^V V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_{\beta} \right]
\]

- 4 parameters: \(f_4^Z\), \(f_4^\gamma\), \(f_5^Z\), \(f_5^\gamma\)

Parameters in red (anomalous TGCs) are zero in the SM
Triple Gauge Couplings

Effects of anomalous TGCs increase with $\hat{S}$

- Increase sensitivity by binning in, or selecting the upper tail of $\hat{S}$
- Observables: $m_{ZZ}$ (for ZZ), $p_T$ of Z (for WZ or ZZ), $p_T$ of leading lepton (for WW)

Also used: $p_T$ of di-jet in $WW/WZ \rightarrow \ell \nu jj$

Extraction of TGC relies on NLO calculations: Powheg, MC@NLO, MCFM

- LO-to-NLO correction is substantial at large $\hat{S}$

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**TGC results**

**WWZ couplings**

- \( \Delta \kappa_Z \)
  - WW: \(-0.043 - 0.043\) 4.6 fb\(^{-1}\)
  - WV: \(-0.043 - 0.033\) 5.0 fb\(^{-1}\)
  - LEP Combination: \(-0.074 - 0.051\) 0.7 fb\(^{-1}\)

- \( \lambda_Z \)
  - WW: \(-0.062 - 0.059\) 4.6 fb\(^{-1}\)
  - WV: \(-0.048 - 0.048\) 4.9 fb\(^{-1}\)
  - WZ: \(-0.046 - 0.047\) 4.6 fb\(^{-1}\)
  - WV: \(-0.038 - 0.030\) 5.0 fb\(^{-1}\)
  - D0 Combination: \(-0.036 - 0.044\) 8.6 fb\(^{-1}\)
  - LEP Combination: \(-0.059 - 0.017\) 0.7 fb\(^{-1}\)

- \( \Delta g_1^Z \)
  - WW: \(-0.039 - 0.052\) 4.6 fb\(^{-1}\)
  - WV: \(-0.095 - 0.095\) 4.9 fb\(^{-1}\)
  - WZ: \(-0.057 - 0.093\) 4.6 fb\(^{-1}\)
  - D0 Combination: \(-0.034 - 0.084\) 8.6 fb\(^{-1}\)
  - LEP Combination: \(-0.054 - 0.021\) 0.7 fb\(^{-1}\)

**ZZZ and ZZ\(\gamma\) couplings**

- \( f_4^\gamma \)
  - ZZ: \(-0.015 - 0.015\) 4.6 fb\(^{-1}\)
  - ZZ: \(-0.013 - 0.015\) 5.0 fb\(^{-1}\)

- \( f_4^Z \)
  - ZZ: \(-0.013 - 0.013\) 4.6 fb\(^{-1}\)
  - ZZ: \(-0.011 - 0.012\) 5.0 fb\(^{-1}\)

- \( f_5^\gamma \)
  - ZZ: \(-0.016 - 0.015\) 4.6 fb\(^{-1}\)
  - ZZ: \(-0.014 - 0.014\) 5.0 fb\(^{-1}\)

- \( f_5^Z \)
  - ZZ: \(-0.013 - 0.013\) 4.6 fb\(^{-1}\)
  - ZZ: \(-0.012 - 0.012\) 5.0 fb\(^{-1}\)

---

**TGCs consistent with the SM**

- Four of the WWZ and WW\(\gamma\) couplings are constrained to O(0.05)
  - Caveat: LEP scenario is used
  - \( \Delta \kappa_\gamma \) remains less precise
- ZZZ and ZZ\(\gamma\) couplings are constrained by the LHC results to O(0.01)

8 TeV data not included yet
Does it make sense?

Shouldn’t the WW “excess” show up as anomalous TGCs?

- TGC sensitivity is concentrated in the highest bins of leading lepton $p_T$
- Excesses are mostly at low $p_T$ where anomalous TGCs don’t contribute

If the excess is real, it’s not a kind of physics described with aTGCs
- i.e. not a heavy new particle in s-channel loop diagrams
Summary

WW, WZ, and ZZ measurements continue to improve
- CDF/DØ results with full Run-II data
- ATLAS/CMS results with (full or partial) 8 TeV data

Data are largely consistent with the SM prediction
- WW cross sections at the LHC slightly higher than expected
  ▶ This has spurred theoretical investigations
  ▶ Jet veto is the leading source of experimental/theoretical uncertainties
  ▶ Analyze full 8 TeV data!

TGCs show no deviation from the SM
- Four (out of 5) WWZ and WWγ couplings constrained at ~0.05 level
  ▶ $\Delta \kappa_\gamma$ remains less precise, but improving
- All ZZZ and ZZγ couplings constrained at ~0.01 level
- 8 TeV data have yet to be used ➔ Expect improvements soon
Backup Slides
Two-photon WW production

New measurement from CMS of $\gamma\gamma \rightarrow WW$

- Final state is $e^\pm\mu^\mp$ with no other tracks from the event vertex
- $p_T(e\mu) > 30$ GeV suppresses $\tau\tau$ background

<table>
<thead>
<tr>
<th>$m_W$ (GeV)</th>
<th>$m_{WW}$ (GeV)</th>
<th>Signal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>40</td>
<td>0.14</td>
</tr>
</tbody>
</table>

- 2 events observed. $2.2 \pm 0.5$ signal and $0.84 \pm 0.13$ (stat.) background expected

Limits are set on anomalous quartic gauge couplings (aQGCs)

- $-0.00017 < a^W_0 / \Lambda^2 < 0.00017$ GeV$^{-2}$ ($a^W_0 / \Lambda^2 = 0, \Lambda = 500$ GeV),
- $-0.0006 < a^W_C / \Lambda^2 < 0.0006$ GeV$^{-2}$ ($a^W_0 / \Lambda^2 = 0, \Lambda = 500$ GeV),