Single and Diboson at CMS

ICNFP 2014

Maiko Takahashi (ETH Zürich) on behalf of CMS Collaboration
Introduction

Precision measurements to test the electroweak theory

CMS Preliminary

7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit

Feb 2014

Production Cross Section, σ [pb]

W/Z

Wγ/Zγ/γγ

WW, WZ/ZZ

Rare processes
Precision measurements to test the electroweak theory

In this talk:
- single and double W/Z/γ production
- inclusive and differential cross section
- aTGC & aQGC limits

See talk from G. D'Imperio for boson + jets
W and Z Production

Signatures from W and Z

isolated lepton(s) with high transverse momentum \((p_T > 15-25 \text{ GeV})\)

\[ W \rightarrow \ell \nu : \text{dilepton mass resonance} \]

\[ Z \rightarrow \ell \ell : \text{large missing } E_T \text{ from neutrino} \]
Inclusive W and Z Production

Measurements consistent with theory prediction (NNLO FEWZ + MSTW08 PDF)

Dominant sources of systematic uncertainty

- electron identification efficiency
- luminosity
Differential Cross Section

Drell-Yan cross section as a function of dilepton mass

\[ \frac{d\sigma}{dm} \]

Uncertainties
- lepton resolution
- background at high mass

\( \gamma^*/Z \rightarrow ll \)

Data
- FEWZ, NNLO CT10

CMS Preliminary
Double differential cross section in mass and rapidity

$$\frac{d\sigma^2}{dmdy}$$

Sensitive to parton distribution function (PDF)

CMS Preliminary

19.7 fb$^{-1}$ ee, 19.7 fb$^{-1}$ $\mu\mu$, (8 TeV)

$\gamma^*/Z \rightarrow ll$

Single and Diboson at CMS
**Z Transverse Momentum**

$Z \ p_T = p_T$ of additional parton emission

- higher order correction
- gluon PDF

**Measurement not very well represented**

- Madgraph (up to 4 partons) + PYTHIA → LO scaled to NNLO total $\sigma$ by FEWZ
- RESBOS (NNLO)

Double differential in $p_T$ and rapidity

$$\frac{d^2\sigma}{dp_T\,dy}$$

show similar discrepancy to MC in all rapidity regions

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01/08/2014 Single and Diboson at CMS
W carries the charge of valence quarks

Charge asymmetry vs rapidity is sensitive to PDF

\[
A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \rightarrow \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \rightarrow \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \rightarrow \ell^-\bar{\nu})}
\]
Diboson Production

Measurements mostly consistent with theory → need higher order calculation

Many are used to probe self coupling of the gauge bosons

Experimental challenges

- large background → data-driven estimate
- small signal acceptance → validate MC modelling

<table>
<thead>
<tr>
<th>Production Cross Section Ratio: $\sigma_{\text{exp}} / \sigma_{\text{theo}}$</th>
<th>CMS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS measurements vs. NLO theory</td>
<td>7 TeV CMS measurement (exp+th)</td>
</tr>
<tr>
<td>$\gamma\gamma$, (NNLO th.)</td>
<td>$1.04 \pm 0.11 \pm 0.09$</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>$1.16 \pm 0.13 \pm 0.06$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$0.98 \pm 0.05 \pm 0.05$</td>
</tr>
<tr>
<td>$WW+WZ$</td>
<td>$1.05 \pm 0.20 \pm 0.03$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$1.11 \pm 0.11 \pm 0.04$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$1.22 \pm 0.12 \pm 0.04$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.17 \pm 0.10 \pm 0.03$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.12 \pm 0.08 \pm 0.05$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.99 \pm 0.15 \pm 0.06$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$1.00 \pm 0.10 \pm 0.08$</td>
</tr>
</tbody>
</table>

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

01/08/2014 Single and Diboson at CMS
Template fit to photon isolation variable to estimate background NNLO (and Sherpa) prediction model the data well (esp. at low $m_{\gamma\gamma}$ & $\Delta\phi_{\gamma\gamma}$)
Photons in signal originate from:
- ISR and FSR
- triple gauge vertex (results covered later)

Template fit to photon shower shape and isolation variables

Measured in different $p_T$ thresholds
ZZ : Leptonic Final States
ZZ → 4 charged leptons ($\ell = e/\mu/\tau$)

- background free (up to > 98% purity)
- statistic limited
- hints of deviation from NLO prediction
**ZZ : Leptonic Final States**

**ZZ → 4 charged leptons (ℓ = e/μ/τ)**
- background free (up to > 98% purity)
- statistic limited
- hints of deviation from NLO prediction

**ZZ → 2ℓ + 2ν**
- several background components
  - “fake” missing $E_T$ in $Z \rightarrow ll$
- template fit to missing $E_T$ distribution

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**Data/MC**

- CMS
- $\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$
- $1/c_{ll}$ d$\sigma_{ll}$/d$M_{ll}$ (1/GeV)
- $m_{ZZ}$ (GeV)
- Unfolded data
- Total uncertainty
- ZZ
- MCFM NLO

**Entries**

- CMS Preliminary 2012, $\sqrt{s} = 8$ TeV
- Entries: ZZ → 2ℓ2ν, WZ → 3ℓν, Z → 2ℓ (data), top, WW, W+jets (data)
- Data

**Reduced MET [GeV]**

- obs/pred

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01/08/2014  Single and Diboson at CMS  12
WW/WZ : Leptonic Final States
**WW/WZ : Leptonic Final States**

\[ WW \rightarrow 2\ell + 2\nu \]

- high statistics with \( \sim 70\% \) purity
- large extrapolation to the full phase space
- \( \rightarrow \) largest uncertainty from jet veto against top quark background

![Graph showing events vs. \( p_T^{\text{max}} \) in GeV]

\( \sqrt{s} = 8 \text{ TeV}, L = 3.5 \text{ fb}^{-1} \)
**WW/WZ: Leptonic Final States**

**WW → 2ℓ + 2ν**
- high statistics with ~70% purity
- large extrapolation to the full phase space
  → largest uncertainty from jet veto against top quark background

**WZ → 3ℓ + ν**
- dominant fake lepton background estimated from data
- consistent results across different final states
WW/WZ/ZZ: Semi-Leptonic
**WW/WZ/ZZ: Semi-Leptonic**

- **WW/WZ → ℓν + qq**
  - large branching fraction of W/Z → qq
  - background from W + additional patrons → few % purity
  - fit to $m_{qq}$ to extract signal

![Graph](image)
**WW/WZ/ZZ: Semi-Leptonic**

**WW/WZ → ℓν + qq**
- large branching fraction of W/Z → qq
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**WZ/ZZ → ℓν / ℓℓ + bb**
- important background to Higgs analysis
- two methods: fit to $m_{bb}$ and MVA
- total uncertainty ~ 30–40 %
Search for anomalous TGC using **diboson final states**

Significant improvement from Run I data → no sign of aTGC

### Charged aTGC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \kappa_T$</td>
<td>W$^+$ $-0.410 - 0.460$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>W$^-$ $-0.380 - 0.280$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>WW $-0.210 - 0.220$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>WW $-0.110 - 0.140$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>DD Combination $-0.158 - 0.255$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>LEP Combination $-0.099 - 0.067$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\lambda_T$</td>
<td>W$^+$ $-0.065 - 0.061$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>W$^-$ $-0.050 - 0.037$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>WW $-0.048 - 0.048$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>WW $-0.038 - 0.039$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>DD Combination $-0.036 - 0.044$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>LEP Combination $-0.059 - 0.017$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

### Neutral aTGC

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<tr>
<td>$f_4^+$</td>
<td>ZZ $-0.015 - 0.015$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>ZZ $-0.004 - 0.004$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>ZZ (2l2v) $-0.004 - 0.003$ fb$^{-1}$</td>
</tr>
<tr>
<td>$f_4^-$</td>
<td>ZZ $-0.013 - 0.013$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>ZZ $-0.004 - 0.004$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>ZZ (2l2v) $-0.003 - 0.003$ fb$^{-1}$</td>
</tr>
<tr>
<td>$f_5^+$</td>
<td>ZZ $-0.015 - 0.015$ fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>ZZ $-0.005 - 0.005$ fb$^{-1}$</td>
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<td></td>
<td>ZZ (2l2v) $-0.004 - 0.004$ fb$^{-1}$</td>
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<td>ZZ $-0.013 - 0.013$ fb$^{-1}$</td>
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“Rare” Processes
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Exclusive $\gamma\gamma \rightarrow WW$
- look for a dilepton vertex with no additional tracks
- 2 events expected in $5\, fb^{-1}$ (7 TeV)
- Strongest constraints on aQGC
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Tribpson $WW\gamma$ / $WZ\gamma$
- semileptonic signature of 1 lepton and 2 jets + a photon
- background dominated
- aQGC should appear in the tail of photon $E_T$
“Rare” Processes

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Vector Boson Scattering $W^{\pm}W^{\pm}qq$
- leptons with same-sign charge from $W^{\pm}W^{\pm}$ and forward backward jets
- small physics background
Quartic Gauge Coupling

Strong limits on aQGC from exclusive $\gamma\gamma \rightarrow WW$, triboson $WW\gamma$ and electroweak $W^\pm W^\pm qq$ production

<table>
<thead>
<tr>
<th>July 2013</th>
<th>LEP L3 limits</th>
<th>D0 limits</th>
<th>CMS WW$\gamma$ limits</th>
<th>CMS $\gamma\gamma \rightarrow WW$ limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomalous $WW\gamma$ Quartic Coupling limits @95% C.L.</td>
<td>Channel</td>
<td>Limits</td>
<td>$L$</td>
<td>$1\sigma$</td>
</tr>
<tr>
<td>$a_q^w/\Lambda^2$ TeV$^{-2}$</td>
<td>WW$\gamma$</td>
<td>[-15000, 15000]</td>
<td>0.43fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[-430, 430]</td>
<td>9.70fb$^{-1}$</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td></td>
<td>WW$\gamma$</td>
<td>[-21, 20]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[-4, 4]</td>
<td>5.05fb$^{-1}$</td>
<td>7.0 TeV</td>
</tr>
<tr>
<td>$a_c^w/\Lambda^2$ TeV$^{-2}$</td>
<td>WW$\gamma$</td>
<td>[-48000, 26000]</td>
<td>0.43fb$^{-1}$</td>
<td>0.20 TeV</td>
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<tr>
<td></td>
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<td></td>
<td>WW$\gamma$</td>
<td>[-34, 32]</td>
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<td>7.0 TeV</td>
</tr>
<tr>
<td>$f_{T,0}/\Lambda^4$ TeV$^{-4}$</td>
<td>WW$\gamma$</td>
<td>[-25, 24]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
<tr>
<td></td>
<td>$W^\pm W^\pm qq$</td>
<td>[-4.6, 4.9]</td>
<td>19.40fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
</tbody>
</table>
Summary

Single and diboson production at the LHC

- Precision measurements mostly within 1 \( \sigma \) of the theory prediction
- Some discrepancy in certain phase space, higher order corrections needed
- Limits on aTGC and aQGC are approaching / exceeding world’s best

Outlook

- More results on Run I data expected later this year
- Run II physics programme starts in Spring 2015
  \( \rightarrow \) first measurements at 13/14 TeV by next summer

All public results from CMS SM analyses are found here: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP