Multiboson Measurements in CMS and ATLAS

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Northwestern University
LHCP, 2020
Multiboson Measurements

May 2020

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

7 TeV CMS measurement (L \leq 5.0 fb$^{-1}$)
8 TeV CMS measurement (L \leq 19.6 fb$^{-1}$)
13 TeV CMS measurement (L \leq 137 fb$^{-1}$)
Theory prediction
CMS 95%CL limits at 7, 8, and 13 TeV

Spans several orders of magnitude!
dibosons (~300 pb) to tribosons (0.004 pb)

All results at: http://cern.ch/go/pNj7
# Multiboson Measurements

## Standard Model Total Production Cross Section Measurements

### ATLAS Preliminary

Run 1,2 \( \sqrt{s} = 7,8,13 \text{ TeV} \)

### Status:
May 2020

### Reference

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<th>[ pb ]</th>
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</table>

### Production Probability

- Production probability lower by factors of 2 - 100 (WZ - WWW) wrt to Higgs production

### Rare and Difficult to Isolate

- Rare and difficult to isolate from background processes

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Multiboson Measurements, LHCP

Saptaparna Bhattacharya
Multiboson Measurements

Multiboson physics is

- discovery physics (tribosons)
- precision physics ($W^+W^-$, $Z\gamma$)

Focused on newest results from ATLAS and CMS Collaborations

All results at: http://cern.ch/go/pNJ7
Observation of Heavy Tribosons with Run II data

Major milestone in Standard Model physics!

TRIPLE TREAT! CMS OBSERVES PRODUCTION OF THREE MASSIVE VECTOR BOSONS


CMS Physics Analysis Summaries

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<th>Report number</th>
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<tr>
<td>Title</td>
<td>Observation of heavy triboson production in leptonic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV</td>
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<td>Accelerator/Facility, Experiment</td>
<td>CERN LHC ; CMS</td>
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http://cds.cern.ch/record/2714899

Observation of Heavy Tribosons with Run II data

- Rich physics content in triboson final states
- Access to various couplings
- Evidence announced last year by ATLAS: arXiv:1903.10415, WWW + WWZ 4.0 (3.1) $\sigma$
- Search for WWW performed in CMS: arXiv:1905:04246, 0.6 (1.78) $\sigma$
- New from CMS: Explore leptonic final states, primarily geared toward:
  - WWW: same-signed dilepton and trilepton
  - WWZ: four leptons
  - WZZ: five leptons
  - ZZZ: six or more leptons

Combined observed significance at 5.7 $\sigma$
Observed significance for WWW and WWZ at 3.3 $\sigma$ and 3.4 $\sigma$

Search for WWW, WWZ, WZZ and ZZZ
Cross sections X Branching fractions

### WWW ~ 0.51 pb
- 0 lepton
- 1 lepton
- 2 OS leptons
- 2 SS leptons
- trileptons

### WWZ ~ 0.35 pb
- 0 lepton
- 1 lepton
- 2 leptons
- 3 leptons
- 4 leptons

### WZZ ~ 0.10 pb
- 0 lepton
- 1 lepton
- 2 leptons
- 3 leptons
- 4 leptons
- 5 leptons

### ZZZ ~ 0.04 pb
- 0 lepton
- 2 leptons
- 4 leptons
- 6 leptons

Explore leptonic final states; backgrounds reduced with a BDT based approach and complementary cut based analysis.

Background reduction:

\[ \sigma_{\text{background}} \approx \sigma_{\text{signal}} \]
WWW → 2 same-signed leptons and 2 jets and WWW → 3 leptons

- Search for WWW in:
  - 2 same-signed leptons + 2 jets
    - further categorized based on $|M_{jj} - M_W| \leq 15$ GeV
  - 2 same-signed leptons + 1 jet
  - trileptons
    - subcategories based on number of opposite-sign same-flavor (OSSF) leptons
- Two BDTs trained to mitigate prompt and nonprompt backgrounds

### WWW → 2 lepton + 2 jet event

-Muon (µ₁⁺) 2
  - $p_T = 37$ GeV
-Muon (µ₂⁺) 1
  - $p_T = 34$ GeV
-Jet 1
  - $p_T = 70$ GeV
-Jet 2
  - $p_T = 36$ GeV

### Events

- VVV: Data
- Lost/three leptons
- Nonprompt leptons
- Irreducible
- Charge missasignment

### Preliminary

- CMS
- 137 fb⁻¹ (13 TeV)

### BDT trained with lepton prs, jet prs, $p_T$ (miss), $m_{jj}$ plus other kinematic variables

### Data/Pred.

- 0SFOS channel

### prompt BDT score

- Data
- VVV
- Lost/three leptons
- Nonprompt leptons
- $\gamma \rightarrow$lepton
- Charge missasignment
**WWZ → 4 leptons**

- Search for WWZ in four lepton final state:
  - Require one Z candidate
  - Further splitting based on the flavor of the W candidates (eμ or ee/μμ)
- Major backgrounds from ZZ (dominant) and ttZ
- Two BDTs trained to mitigate ZZ and ttZ backgrounds: used 2D plane of BDT scores to define signal region

Main discriminant in the opposite-flavor channel

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**Multiboson Measurements, LHCP**
WZZ → 5 leptons and ZZZ → 6 leptons

- **Search for** WZZ and ZZZ in 5 and 6 lepton final states
- **Low event yields**, backgrounds dominated by nonprompt leptons: cut based analysis pursued
- **In 5 lepton channel**: Require 2 Z boson candidates and associate remaining lepton with a W (require $M_T > 50$ GeV if electron)
- **In 6 lepton channel**: Require $\sum p_T$ of all leptons > 250 GeV, powerful against backgrounds, contribute at percent level
Results

**CMS Preliminary**

137 fb⁻¹ (13 TeV)

### Events

**Same-charge/3 lepton**

- Events: 0, 20, 40, 60, 80, 100
- Same-charge/3 lepton
- 4/5/6 lepton
- Bin scaled down by 3x

### Preliminary CMS

(Data and prediction)

- Data ± stat. uncertainty
- Background ± systematics

**Triboson signals**

- WWW (μ_{WW} = 1.15^{+0.45}_{-0.40})
- WWZ (μ_{WWZ} = 0.86^{+0.35}_{-0.31})
- WZZ (μ_{WZZ} = 2.24^{+1.92}_{-1.25})
- ZZZ (μ_{ZZZ} = 0.0^{+1.30}_{-0.00})

**Bkg. in same-charge / 3 lep.**

- Lost / three leptons
- Charge misassignment
- Irreducible
- Nonprompt leptons
- γ → lepton

**Backgrounds in 4/5/6 lep.**

- ZZ
- tW
- Others

In the most sensitive signal regions (★) non-VH signal dominates with a 66% probability (33% VH)
Results

- Triboson (VVV) production observed for the first time!
- Observed significance for WWW and WWZ at 3.3 $\sigma$ and 3.4 $\sigma$

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed (expected) significance</th>
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<tbody>
<tr>
<td>WWW</td>
<td>3.3 (3.1)</td>
</tr>
<tr>
<td>WWZ</td>
<td>3.4 (4.1)</td>
</tr>
<tr>
<td>WZZ</td>
<td>1.7 (0.7)</td>
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<tr>
<td>ZZZ</td>
<td>0.0 (0.9)</td>
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<tr>
<td>Combined</td>
<td>5.7 (5.9)</td>
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CMS Preliminary

137 fb$^{-1}$ (13 TeV)
Precision Physics with dibosons: \((W^+W^-)\)

CMS: https://cds.cern.ch/record/2714766
ATLAS: https://arxiv.org/abs/1905.04242
**Diboson production, \( W^+W^- \), occurs at the LHC via s-channel, t-channel (dominant), sub-dominant \( gg \rightarrow W^+W^- \)**

- Allows for **precise tests of the SM**
- Important **background** in many **New Physics (NP) searches**
- Pursued in both CMS and ATLAS
- **ATLAS**: Cut based analysis in 0 jet bin
- **CMS**: Two different complementary search strategies designed to reduce top and Drell-Yan backgrounds explored:
  - **sequential cut based analysis** (in 0 and 1 jet bins)
  - **Random forest classifier** trained on simulated events (incl. \( n_{\text{jet}} \geq 2 \))

Analysis performed in oppositely charged leptonic final state

**Higgs \( \rightarrow W^+W^- \) considered:**
- background (CMS)
- signal (ATLAS)
Using the Random Forest Discriminator

- Background contributions reduced by using novel method:
  - Random Forest discriminator
  - Independently trained collection of binary decision trees
  - Score defined as combination of decisions of each tree
  - Uses all jet categories

![Graphs showing event distributions and cross sections](image)

**Multiboson Measurements, LHCP**

Saptaparna Bhattacharya
Systematic Uncertainties

### Theoretical Uncertainties

- Event selection in jet binned category (**cut based analysis**): sensitive to higher order QCD corrections
- Ascertained by varying factorization and renormalization scales (in some cases pT- resummation technique used)
- Additional theoretical uncertainties arise from $\alpha_s$, PDFs

#### Total cross section:

$$\sigma = 117.6 \pm 1.4 \text{ (stat)} \pm 5.5 \text{ (syst)} \pm 1.9 \text{ (theo)} \pm 3.2 \text{ (lumi)} \text{ pb}$$

$$\sigma_{\text{NNLO}} = 118.7 + 3.0 - 2.6 \text{ pb}$$

<table>
<thead>
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<th>Uncertainty source</th>
<th>(%)</th>
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<td>Drell-Yan normalization</td>
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<td>$W\gamma^*$ normalization</td>
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<td>PDFs</td>
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<td>Total theoretical systematic uncertainty</td>
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<td>Luminosity</td>
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<td><strong>Total uncertainty</strong></td>
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Precision Physics with Multibosons ($W^+W^-$)

- $W^\pm W^\mp \rightarrow e^\pm \nu e^\mp \nu$ decay studied, with jet vet, includes b-veto
- Fiducial cross section computed (definition on slide 19)

Sensitive to spin structure of $e\mu$ pairs
Systematic uncertainties associated with fiducial cross section:

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<th>Uncertainty source</th>
<th>Uncertainty [%]</th>
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<tr>
<td>Total uncertainty</td>
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Total cross section:

$\sigma_{\text{fid}} = 379.1 \pm 5.0 \text{ (stat)} \pm 25.4 \text{ (syst)} \pm 8.0 \text{ (lumi)} \text{ fb}$
Differential cross sections

Fiducial selection requirements

\[ p_T^e > 27 \text{ GeV} \]
\[ |\eta^e| < 2.5 \]
\[ m_{e\mu} > 55 \text{ GeV} \]
\[ p_T^{e\mu} > 30 \text{ GeV} \]
\[ E_T^{\text{miss}} > 20 \text{ GeV} \]
No jets with \( p_T > 35 \text{ GeV}, |\eta| < 4.5 \)

Fiducial cross section computed in:

\( m(ll) > 20 \text{ GeV}, \ p_T(ll) > 30 \text{ GeV} \) and
\( p_T(\text{miss}) > 20 \text{ GeV} \)

High \( m(ll) \) sensitive to contributions from higher order operators

[Graphs and diagrams showing data and calculations]
EFT Interpretation

- Limits set on Wilson coefficients associated with CP conserving operators:
  \[ \mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\mu\rho}] \]
  \[ \mathcal{O}_{W} = (\mathcal{D}_\mu \Phi) \dagger W^{\mu\nu} (\mathcal{D}_\nu \Phi) \]
  \[ \mathcal{O}_{B} = (\mathcal{D}_\mu \Phi) \dagger B^{\mu\nu} (\mathcal{D}_\nu \Phi) \]

<table>
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<th>Observed 95% CL [TeV^2]</th>
<th>Expected 95% CL [TeV^2]</th>
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<td>[−3.0, 3.0]</td>
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<td>( c_{W}/\Lambda^2 )</td>
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<td>( c_{\tilde{W}}/\Lambda^2 )</td>
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<td>[−91, 91]</td>
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Multiboson Measurements, LHCP
EFT Interpretation

- Limits set on Wilson coefficients associated with CP conserving operators:

\[ O_{WW} = \langle D_\mu \Phi \rangle^\dagger W^{\mu\nu} (D_\nu \Phi) \]

\[ O_B = \langle D_\mu \Phi \rangle^\dagger B^{\mu\nu} (D_\nu \Phi) \]

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ATLAS}
Precision Physics with dibosons: ($Z\gamma$)

ATLAS: https://arxiv.org/abs/1911.04813
Precision Physics with Multibosons: Zγ

- Production of Z in association with a photon (γ) offers important probe of the electroweak sector of the SM
- Major background in Higgs → Zγ channel
- Previous exploration focused on large photon ET: Zγ → ννγ (ET > 150 GeV) and Zγ → bbg (ET > 175 GeV), designed to be sensitive to higher dimensional operators
- This analysis explored an ET range of 30-1200 GeV
- Photons arising from final state radiation (FSR) suppressed by requiring m(ll) + m(llγ) > 182 GeV
- Highly precise measurement of fiducial cross section achieved
- **Z+jets** where a jet is misidentified as a photon constitutes the largest background: estimated from sidebands

- Background arising from pileup: photon and lepton pair from different pp collisions in one LHC bunch crossing

  - **Novel** method used to determine this background by correlating z-coordinates of the Z and the γ

- All other backgrounds determined from simulations
Relative precision of the cross section is 2.9%.

Fiducial cross section defined by:
- $m(ll) > 40$ GeV
- $m(ll) + m(ll\gamma) > 182$ GeV

Computed in bins of $\gamma E_T$, $m(ll\gamma)$, $|\eta_{\gamma}|$, $p_T(ll\gamma)$, $p_T(ll\gamma)/m(ll\gamma)$, $\Delta \Phi(ll, \gamma)$

Low systematic uncertainty, major contributors associated with:
- Photon identification (1%)
- Electron identification (1.4%)
- Z+jets background (1.3%)
- Luminosity (1.7%)

Total statistical uncertainty lower by a factor of ~6

$\sigma_{\text{fiducial}} = 533.7 \pm 2.1 \text{ (stat)} \pm 12.4 \text{ (syst)} \pm 9.1 \text{ (lumi)}$ fb
Conclusion

- **Three different analysis presented** that highlight the myriad possibilities of exploration in multiboson final states

- While, **new processes being discovered, precision physics is being concurrently carried out**:
  - New processes:
    - VVV
  - Precision analysis:
    - \(W^+W^-\)
    - \(Z\gamma\)
- I’ll be in the zoom room after the talk: [https://cern.zoom.us/j/95764014445](https://cern.zoom.us/j/95764014445) (session password)

Full list of Standard Model analyses performed by ATLAS and CMS Collaborations can be found here:
- **ATLAS**: [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults)
- **CMS**: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP)
Additional Material
Analysis Strategy

Probe WWW, WWZ, WZZ, ZZZ processes by counting number of leptons

21 bins in total

2 same-sign leptons (9 bins)

3 leptons (3 bins)

4 leptons (7 bins)

5 leptons (1 bin)

6 leptons (1 bin)

- $N_j = 1$
- $N_j \geq 2$

**SS1J**
- $|M_{jj} - 80| < 15$
- $|M_{jj} - 80| \geq 15$

**SS2J**

# of Same-flavor Opposite Sign (SFOS) pair

Flavor based splitting of the W-candidates

- $W^{\pm}(l\nu)W^{\pm}(l\nu)W^{\mp}(q\bar{q})$
- $W^{\pm}(l\nu)W^{\pm}(l\nu)W^{\mp}(l\nu)$

- For cut-based, further split into 4 $M_{T2}$-MT (ee/μμ) bins
- For BDT, further split into 5 bins in ee and 2 in ee/μμ

Multiboson Measurements, LHCP