W^+W^- differential cross-section
Measurement with the CMS detector at $\sqrt{s} = 8\text{ TeV}$

Daniel Meister
based on the publication in arXiv:1507.03268

08/27/2015
1 Introduction
   Motivation
   History & Current Status

2 Analysis Details
   Differential Distributions
   Inclusive Analysis

3 Conclusion
Introduction
**Introduction**

- measuring the WW production cross section
  - using the $WW \rightarrow 2\ell 2\nu$ decay channel (clean selection)
  - Signature: two leptons and large missing $E_T$
  - important irreducible background for $H \rightarrow WW$

- this process is testing EWK and QCD and Higgs sector
  - sensitive to soft gluons in initial state, triple gauge coupling
The CMS Experiment

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- Weight: 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm): ~16 m², ~66 M channels
- Microstrips (80x180 μm): ~200 m², ~9.6 M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16 m², ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
History & Current Status

• WW cross-section measurements received attention
  → inclusive measurements by ATLAS and CMS a bit above the theory prediction
  → important background for the H→WW channel + testing the gauge structure of the SM

• Also, there is a recent CDF paper on WW production
  → arXiv:1505.00801v1: $\sigma_{WW}^{\text{meas}} = 14.0^{+1.6}_{-1.4}$ pb, with an NLO SM prediction of $11.3/11.7 \pm \sim 1$ pb
• recent advancements in theory calculations

Source: arXiv:1408.5243

<table>
<thead>
<tr>
<th>√s [TeV]</th>
<th>NLO [pb]</th>
<th>NNLO [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>45.16$^{+3.7%}_{-2.9%}$</td>
<td>49.04$^{+2.1%}_{-1.8%}$</td>
</tr>
<tr>
<td>8</td>
<td>54.77$^{+3.7%}_{-2.9%}$</td>
<td>59.84$^{+2.2%}_{-1.9%}$</td>
</tr>
<tr>
<td>13</td>
<td>106.0$^{+4.1%}_{-3.2%}$</td>
<td>118.7$^{+2.5%}_{-2.5%}$</td>
</tr>
<tr>
<td>14</td>
<td>116.7$^{+4.1%}_{-3.3%}$</td>
<td>131.3$^{+2.6%}_{-2.2%}$</td>
</tr>
</tbody>
</table>
## Results from CMS

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>$\int L$ [fb$^{-1}$]</th>
<th>$\sigma_{\text{meas}}^{WW}$ [pb]</th>
<th>$\sigma_{\text{NNLO}}^{WW}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4.9</td>
<td>$52.4 \pm 2.0$ (stat.) $\pm 4.5$ (syst.) $\pm 1.2$ (lumi.) pb</td>
<td>$49.04^{+2.1%}_{-1.8%}$</td>
</tr>
<tr>
<td>8</td>
<td>3.5</td>
<td>$69.9 \pm 2.8$ (stat.) $\pm 5.6$ (syst.) $\pm 3.1$ (lumi.) pb</td>
<td>$59.84^{+2.2%}_{-1.9%}$</td>
</tr>
<tr>
<td>8</td>
<td>19.365</td>
<td>$60.2 \pm 0.9$ (stat.) $\pm 4.5$ (syst.) $\pm 1.6$ (lumi.) pb</td>
<td>$59.84^{+2.2%}_{-1.9%}$</td>
</tr>
</tbody>
</table>

### Differences to previous CMS analysis

- also measuring/publishing the fiducial cross-section
- checking differential distributions
- using the full luminosity
- multiple other improvements

→ e.g. recomputation of PDF and QCD scale uncertainties, making use of embedded data samples, etc.
Analysis Details
Signal
Looking at the fully leptonic final state we require two leptons (within acceptance cuts) and missing \( E_T \) as we have real MET coming from the neutrinos.

**Selection optimized to enhance S/B ratio**

- tight lepton ID/isolation
  \[ \rightarrow \text{to reject } W+\text{jets background (where the jet fakes a lepton)} \]

- Z-mass window cut and MVA for off-peak contributions
  \[ \rightarrow \text{to reject } DY\rightarrow \ell\ell \text{ background (fake missing } E_T) \]

- top veto based on b-tagging, soft-muon-tagging
  \[ \rightarrow \text{to reject } tt\bar{t} \text{ and } tW \text{ contributions (very important in 1-jet bin)} \]

- third lepton veto
  \[ \rightarrow \text{to reject } WZ \text{ events} \]
• analysis performed in 4 exclusive categories
  → splitted in DF/SF and 0/1 jet (jet $|\eta| < 4.7$ and jet $p_T \geq 30$ GeV)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Different Flavour</th>
<th>Same Flavour</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{\ell_1} \cdot q_{\ell_2}$</td>
<td>$&lt; 0$</td>
<td>$&lt; 0$</td>
</tr>
<tr>
<td>$p_T$ [GeV]</td>
<td>$&gt; 20$</td>
<td>$&gt; 20$</td>
</tr>
<tr>
<td>min proj. $E_T^{\text{miss}}$</td>
<td>$&gt; 20$</td>
<td>$&gt; 20$</td>
</tr>
<tr>
<td>DYMVA</td>
<td>$-$</td>
<td>$&gt; 0.88$ (0jet), $&gt; 0.84$ (1jet)</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$ [GeV]</td>
</tr>
<tr>
<td>$p_{T,\ell\ell}$ [GeV]</td>
<td>$&gt; 30$</td>
<td>$&gt; 45$</td>
</tr>
<tr>
<td>$m_{\ell\ell}$ [GeV]</td>
<td>$&gt; 12$</td>
<td>$&gt; 12$</td>
</tr>
<tr>
<td>add. leptons ($p_T &gt; 10$ GeV)</td>
<td>veto</td>
<td>veto</td>
</tr>
<tr>
<td>top-quark veto</td>
<td>applied</td>
<td>applied</td>
</tr>
</tbody>
</table>
Kinematic Distributions

Leading lepton transverse momentum – $p_T^{\text{leading}}$

**DF, 0-jet**

- Data
- Z+jets
- W+jets
- WW
- VV
- top
- Higgs

**DF, 1-jet**

- Data
- Z+jets
- W+jets
- WW
- VV
- top
- Higgs

CMS (preliminary)

$\sqrt{s} = 8 \text{ TeV}, \ L = 19.365 \text{ fb}^{-1}$

DF/SF 0/1 jets

08/27/2015 — $W^+W^-$ differential cross-section — report for the 2015 PhD seminar by Daniel Meister
• measurement is dominated by the 0-jet DF category
• the main source of systematic uncertainty is the modelling of the signal efficiency
  → especially in connection with the jet veto efficiency
• reporting the production cross section in fiducial regions
  → chosen to be very close to the event selection (including the jet veto)
  → fiducial volume definitions should be reproducible by theorists
  → report values for different jet veto thresholds to communicate modeling of the jet veto efficiency
• lower systematic uncertainties compared to extrapolating to the full phase space
  → systematic uncertainty on the lepton efficiencies is very small
Fiducial Volume Definition

- jets at particle level clustered with the anti-$k_T$ algorithm
- two $e$ ($\mu$) with $|\eta| < 2.5$ (2.4) and $p_T > 20$ GeV

Results for different jet vetos in the 0 jet bin

<table>
<thead>
<tr>
<th>$p_T^{\text{jet}}$ threshold [GeV]</th>
<th>$\sigma_{\text{fiducial}}$ measured [pb]</th>
<th>$\sigma_{\text{NLO}}^{\text{fiducial}}$ predicted [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>$0.223 \pm 0.004$ (stat.) $\pm 0.013$ (exp.) $\pm 0.007$ (th.) $\pm 0.006$ (lum.)</td>
<td>$0.228 \pm 0.001$ (stat.)</td>
</tr>
<tr>
<td>25</td>
<td>$0.253 \pm 0.005$ (stat.) $\pm 0.014$ (exp.) $\pm 0.008$ (th.) $\pm 0.007$ (lum.)</td>
<td>$0.254 \pm 0.001$ (stat.)</td>
</tr>
<tr>
<td>30 (*)</td>
<td>$0.273 \pm 0.005$ (stat.) $\pm 0.015$ (exp.) $\pm 0.009$ (th.) $\pm 0.007$ (lum.)</td>
<td>$0.274 \pm 0.001$ (stat.)</td>
</tr>
</tbody>
</table>

(*) used in later analysis steps
• differential cross section as function of leading lepton $p_T$, dilepton $p_T$, invariant mass $m_{\ell\ell}$, and opening angle between leptons $\Delta\varphi_{\ell\ell}$

• same fiducial region as before (jet veto at 30 Gev)
  → again including lepton acceptance: two $e$ ($\mu$) with $|\eta| < 2.5$ ($2.4$) and $p_T > 20$ GeV

• unfolding of “data – background” distributions
  → top and W+jets backgrounds estimated from data, other background from MC
  → jet smearing on signal applied

• response matrix is determined from POWHEG after reweighting the $p_{T,WW}$
  → tested to be independent of the Monte Carlo used to derive the response matrix

• SVD unfolding is used as a default method
leading lepton $p_T$

CMS

$19.4 \text{ fb}^{-1}$ (8 TeV)

$\frac{1}{\sigma} \frac{d\sigma}{dp_{T,\text{max}}} (WW + 0 \text{ jets})$

Data
Madgraph
MC@NLO
Powheg

Theory / Data

Madgraph+Pythia normalized to $\sigma_{\text{NLO}}$
MC@NLO+Herwig normalized to $\sigma_{\text{NLO}}$
Powheg+Pythia normalized to $\sigma_{\text{NLO}}$

$dilepton p_{T,\ell\ell}$

CMS

$19.4 \text{ fb}^{-1}$ (8 TeV)

$\frac{1}{\sigma} \frac{d\sigma}{dp_{T}} (WW + 0 \text{ jets})$

Data
Madgraph
MC@NLO
Powheg

Theory / Data

Madgraph+Pythia normalized to $\sigma_{\text{NLO}}$
MC@NLO+Herwig normalized to $\sigma_{\text{NLO}}$
Powheg+Pythia normalized to $\sigma_{\text{NLO}}$

08/27/2015 — $W^+W^-$ differential cross-section — report for the 2015 PhD seminar by Daniel Meister
The inclusive cross section is determined as

$$\sigma_{WW} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot \varepsilon \cdot (3 \cdot B(W \rightarrow \ell\nu))^2}$$

where $\varepsilon$ is the signal efficiency, including

- detector geometrical acceptance
- selection and trigger efficiencies

### Signal Efficiencies per Category

<table>
<thead>
<tr>
<th>Event category</th>
<th>Signal efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet category</td>
<td></td>
</tr>
<tr>
<td>Different-flavor</td>
<td>3.01 ± 0.22 (syst.) ± 0.02 (stat.)</td>
</tr>
<tr>
<td>Same-flavor</td>
<td>1.21 ± 0.09 (syst.) ± 0.01 (stat.)</td>
</tr>
<tr>
<td>1-jet category</td>
<td></td>
</tr>
<tr>
<td>Different-flavor</td>
<td>0.96 ± 0.11 (syst.) ± 0.01 (stat.)</td>
</tr>
<tr>
<td>Same-flavor</td>
<td>0.34 ± 0.04 (syst.) ± 0.01 (stat.)</td>
</tr>
</tbody>
</table>
Inclusive Analysis

Production Cross Section per Category

<table>
<thead>
<tr>
<th>Event category</th>
<th>WW production cross section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet category</td>
<td></td>
</tr>
<tr>
<td>Different-flavor</td>
<td>$59.9 \pm 1.1\text{ (stat.)} \pm 4.9\text{ (syst.)} \pm 1.6\text{ (lum.)}$</td>
</tr>
<tr>
<td>Same-flavor</td>
<td>$64.6 \pm 2.1\text{ (stat.)} \pm 6.4\text{ (syst.)} \pm 1.7\text{ (lum.)}$</td>
</tr>
<tr>
<td>1-jet category</td>
<td></td>
</tr>
<tr>
<td>Different-flavor</td>
<td>$59.8 \pm 2.8\text{ (stat.)} \pm 8.8\text{ (syst.)} \pm 1.6\text{ (lum.)}$</td>
</tr>
<tr>
<td>Same-flavor</td>
<td>$65.8 \pm 5.5\text{ (stat.)} \pm 11.4\text{ (syst.)} \pm 1.7\text{ (lum.)}$</td>
</tr>
</tbody>
</table>

Combination

The categories are then combined using a profile likelihood fit; this yields (theory: $\sigma_{WW}^{\text{NNLO}} = 59.8^{+1.3}_{-1.1}$ pb)

$$\sigma_{WW} = 60.1 \pm 0.9\text{ (stat.)} \pm 4.5\text{ (syst.)} \pm 1.6\text{ (lumi.)} \text{ pb}$$
Inclusive Analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.6</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td>3.8</td>
</tr>
<tr>
<td>Lepton momentum scale</td>
<td>0.5</td>
</tr>
<tr>
<td>missing $E_T$ resolution</td>
<td>0.7</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1.7</td>
</tr>
<tr>
<td>$tt+tW$ normalization</td>
<td>2.2</td>
</tr>
<tr>
<td>$W+\text{jets}$ normalization</td>
<td>1.3</td>
</tr>
<tr>
<td>$DY \rightarrow \ell\ell$ normalization</td>
<td>0.6</td>
</tr>
<tr>
<td>$DY \rightarrow \tau\tau$ normalization</td>
<td>0.2</td>
</tr>
<tr>
<td>$W\gamma$ normalization</td>
<td>0.3</td>
</tr>
<tr>
<td>$W\gamma^*$ normalization</td>
<td>0.4</td>
</tr>
<tr>
<td>VV normalization</td>
<td>3.0</td>
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<tr>
<td>$H \rightarrow WW$ normalization</td>
<td>0.8</td>
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<tr>
<td>Jet counting theory model</td>
<td>4.3</td>
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<tr>
<td>PDFs</td>
<td>1.2</td>
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<tr>
<td>MC statistics</td>
<td>0.9</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>7.9</td>
</tr>
</tbody>
</table>

- **Total uncertainty around 8%**
- **Result limited by systematics**
  - $\rightarrow$ jet counting: $\sim 4.3\%$
  - $\rightarrow$ lepton efficiencies $\sim 3.8\%$
  - $\rightarrow$ background normalization
  - $\rightarrow$ luminosity $\sim 2.6\%$
Conclusion
Conclusion

• presented an updated measurement of the $WW$ cross-section at $\sqrt{s} = 8$ TeV with the CMS detector

• inclusive result compatible with latest NNLO theory predictions ($\sigma_{WW}^{\text{NNLO}} = 59.8^{+1.3}_{-1.1} \text{ pb}$)

\[
\sigma_{WW}^{\text{measured}} = 60.1 \pm 0.9 \text{ (stat.)} \pm 4.5 \text{ (syst.)} \pm 1.6 \text{ (lumi.) pb}
\]

• measurement is currently limited by systematics

• fiducial results and differential distributions agree with MC predictions within the uncertainties

• looking forward to have a measurement at 13 TeV
Kinematic Distributions

Dilepton transverse momentum – $p_T, \ell\ell$

DF, 0-jet

DF, 1-jet

08/27/2015 — $W^+W^-$ differential cross-section — report for the 2015 PhD seminar by Daniel Meister
Kinematic Distributions

Dilepton mass – $m_{\ell\ell}$

DF, 0-jet

DF, 1-jet

08/27/2015 — $W^+W^-$ differential cross-section — report for the 2015 PhD seminar by Daniel Meister
Kinematic Distributions

Dilepton opening angle – $\Delta \varphi_{\ell\ell}$

**DF, 0-jet**

- **Data** vs. **Prediction** for various processes:
  - WW
  - VV
  - Higgs
  - Z+jets
  - W+jets
  - Top

**CDF/SF 0/1 jets**

**DF, 1-jet**

- **Data** vs. **Prediction** for various processes:
  - WW
  - VV
  - Higgs
  - Z+jets
  - W+jets
  - Top

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08/27/2015 — $W^+W^-$ differential cross-section — report for the 2015 PhD seminar by Daniel Meister
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Leading lepton transverse momentum – $p_{T,\text{leading}}$

SF, 0-jet

SF, 1-jet

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Kinematic Distributions

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Dilepton mass – $m_{\ell\ell}$

SF, 0-jet

SF, 1-jet

$08/27/2015$ — $W^+W^-$ differential cross-section — report for the 2015 PhD seminar by Daniel Meister
Kinematic Distributions

Dilepton opening angle – $\Delta \varphi_{\ell \ell}$

SF, 0-jet

SF, 1-jet

08/27/2015 — $W^+W^-$ differential cross-section — report for the 2015 PhD seminar by Daniel Meister
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\text{qq} \rightarrow \text{WW}$</th>
<th>$\text{gg} \rightarrow \text{WW}$</th>
<th>$\text{tt} + \text{tW}$</th>
<th>$\text{W} + \text{jets}$</th>
<th>$\text{WZ} + \text{ZZ} \rightarrow \ell\ell$</th>
<th>$\gamma\gamma$</th>
<th>$\gamma\gamma^*$</th>
<th>$\gamma\gamma$</th>
<th>$\text{Higgs}$</th>
</tr>
</thead>
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<tr>
<td>Luminosity</td>
<td>2.6</td>
<td>2.6</td>
<td>–</td>
<td>–</td>
<td>2.6</td>
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<td>Lepton momentum scale</td>
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<td>$\text{tt} + \text{tW}$ norm.</td>
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<td>–</td>
<td>13-3</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>$\text{W} + \text{jets}$ norm.</td>
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<td>–</td>
<td>–</td>
<td>36</td>
<td>–</td>
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<td>DYII norm.</td>
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<td>DYtt norm.</td>
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<td>–</td>
<td>–</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>10</td>
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<tr>
<td>$\gamma\gamma$ norm.</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>30</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma\gamma^*$ norm.</td>
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<td>–</td>
<td>–</td>
<td>30</td>
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<td>30</td>
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<td>PDFs</td>
<td>1.3</td>
<td>0.8</td>
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<td>4.0</td>
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<td>8.0</td>
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<td>Higher-order corrections</td>
<td>3.8-9.2</td>
<td>30</td>
<td>–</td>
<td>5.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>18-28</td>
</tr>
</tbody>
</table>
Effective Field Theory

- If scale is large, new physics can be described by an effective field theory.
- There are six different dim-6 operators; where the following three are C- and P-conserving:
  
  \[ O_{WWW} = \frac{c_{WWW}}{\Lambda^2} \text{Tr}[W_{\mu\nu}W^{\nu\rho}W^\rho_{\mu}], \]
  
  \[ O_{W} = \frac{c_{W}}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi), \]
  
  \[ O_{E} = \frac{c_{E}}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi), \]

- Only 0 jet category is considered.
- Using the \( m_{\ell\ell} \) distribution.
68% and 95% CL contours for the three 2D cases

95% CL allowing only one coupling constant to vary

- \( -5.73 < c_{WWW}/\Lambda^2 < 5.95 \) TeV\(^{-2}\)
- \( -11.38 < c_{W}/\Lambda^2 < 5.39 \) TeV\(^{-2}\)
- \( -29.17 < c_{B}/\Lambda^2 < 23.90 \) TeV\(^{-2}\)