Measurement of electroweak production of a W boson in association with two jets in proton-proton collisions at 13 TeV

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on January 24, 2022
» **Introduction**

**What?**

* pure electroweak (EW) production
* $\ell\nu jj$ in the final state
* $\ell\nu jj = \text{lepton-neutrino pair (}\ell\nu\text{) + 2 jets (}\ jj\text{)}$

**How?**

* through Vector Boson Fusion (VBF) processes

**Why?**

* distinctive signature of two jets with large energy
* good separation in pseudorapidity

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**Diagram:**

- Production of $W^+$, $Z$, $d$, $u$, $d$, $d$
- $W^+$ decays into $Z$, $d$, $d$
- $Z$ decays into $\ell\nu jj$

**Text:**

- Physics processes of interest

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[1/15]
Goals and a bit of history

Previous measurements agree with the expectations of SM within a precision of $10 - 20\%$

- $\text{EW } W_{jj}$
  - at $\sqrt{s} = 7 \text{ TeV}$ by ATLAS [1]
  - at $\sqrt{s} = 8 \text{ TeV}$ by CMS [2] and ATLAS [1]
- $\text{EW } Z_{jj}$
  - at $\sqrt{s} = 7 \text{ TeV}$ by CMS [3]
  - at $\sqrt{s} = 8 \text{ TeV}$ by CMS [4] and ATLAS [5]

Goals of this paper:

1. measurement of the EW $W_{jj}$ by CMS using pp collisions at $\sqrt{s} = 13 \text{ TeV}$ in 2016,
   - cross sections at higher energies in muon and electron channels,
   - possibility to reduce the uncertainties from the previous measurements,
   - probing additional hadronic activity in selected events can shed light on the modeling of the additional parton radiation,

2. perform a search for anomalous trilinear gauge couplings (ATGCs)
   - limits on ATGCs associated with dimension-six operators are given in the framework of an effective field theory,
   - measurement of the coupling strengths provides an indirect search for the BSM physics
» Signal and background events

1. EW $W_{jj}$ processes
   * Vector Boson Fusion (VBF)
   * bremsstrahlung-like (most of the interference)
   * multiperipheral (only when lepton-neutrino mass is close to the masss of the W boson)

2. some DY $W_{jj}$ (Drell-Yan) processes (much smaller interference than in $W_{jj}$ processes)
» Strategy in the offline analysis

* particle-flow (PF) algorithm is used to determine stable particle candidates,
* offline muons are reconstructed by fitting trajectories based on hits in the silicon tracker and in the muon system,
* offline electrons are reconstructed from clusters of energy deposits in ECAL that match tracks extrapolated from the silicon tracker,
* missing transverse momentum $\vec{p}_T^{\text{miss}}$ is calculated offline as the negative of the vector sum of transverse momenta of all PF objects,
* jets are reconstructed by clustering PF candidates with the anti-$k_T$ algorithm
» Selections

Trigger selections:

* at least 2 high-$p_T$ jets
* exactly 1, isolated high-$p_T$ lepton:
  * $p_T > 27$ GeV for electron trigger,
  * $p_T > 24$ GeV for muon trigger,

Offline selections:

* electrons:
  * $p_T > 20$ GeV within $|\eta| \leq 2.4$ excluding transitional region $1.444 < |\eta| < 1.566$ of ECAL,
  * events with more than one electron with $p_T > 30$ GeV are rejected,
* muons:
  * $p_T > 20$ GeV within $|\eta| \leq 2.4$,
  * events with more than one muon with $p_T > 25$ GeV are rejected,
* jets:
  * $p_T > 15$ GeV and $|\eta| \leq 4.7$
  * the 2 highest with $p_T > 50$ GeV and $p_T > 30$ GeV are defined as tagging jets,
  * the invariant mass $m_{jj} > 200$ GeV,
  * event balance $R(p_T) < 0.2$, 

$$ R(p_T) = \frac{|\vec{p}_{Tj_1} + \vec{p}_{Tj_2} + \vec{p}_{TW}|}{|\vec{p}_{Tj_1}| + |\vec{p}_{Tj_2}| + |\vec{p}_{TW}|} $$
Discriminating signal from background

1. General
   - missing transverse momentum $p_T^{\text{miss}}$
   - lepton-$p_T^{\text{miss}}$ system transverse mass $m_T(W)$

2. separation of DY $Wjj$ from EW $Wjj$
   - dijet invariant mass $m_{jj}$,
   - pseudorapidity separation $\Delta \eta_{jj}$,
   - $y^* = y_W - \frac{1}{2} (y_{j1} + y_{j2})$ Zeppenfeld variable,
   - $z^* = \frac{y^*}{\Delta y_{jj}}$ Zeppenfeld variable,

3. discriminating quarks from gluons
   - quark-gluon likelihood discriminant QGL evaluated for the 2 tagging jets,
Results

1. muon channel

\[ \sigma(\text{EW } \ell \nu jj) = 6.22 \pm 0.75 \text{ pb} \]

2. electron channel

\[ \sigma(\text{EW } \ell \nu jj) = 6.27 \pm 0.82 \text{ pb} \]

The results obtained for the different channels are compatible with each other, and in agreement with the SM predictions.

Data compared with simulation for the BDT’ output distribution for the muon channel.
## Results

<table>
<thead>
<tr>
<th>Coupling constant</th>
<th>Expected 95% CL interval (TeV(^{-2}))</th>
<th>Observed 95% CL interval (TeV(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_{WWW}/\Lambda^2)</td>
<td>[-2.5, 2.5]</td>
<td>[-2.3, 2.5]</td>
</tr>
<tr>
<td>(c_W/\Lambda^2)</td>
<td>[-16, 19]</td>
<td>[-8.8, 16]</td>
</tr>
<tr>
<td>(c_B/\Lambda^2)</td>
<td>[-62, 61]</td>
<td>[-45, 46]</td>
</tr>
</tbody>
</table>

No significant deviation from the SM is observed.

Data compared with simulation for the BDT' output distribution for the muon channel.
Conclusions

1. The cross section of the EW $W jj$ was measured in the kinematic region $m_{jj} > 120$ GeV and $p_{Tj} > 25$ GeV for the data collected in 2016 with 35.9 fb$^{-1}$ at $\sqrt{s} = 13$ TeV.

2. The measured cross-sections agree with the LO SM prediction.

3. In addition, a search for anomalous trilinear gauge couplings associated with dimension-six operators was performed.

4. No evidence for ATGCs is found.

5. (in backup) The additional hadronic activity was studied in a signal-enriched region and compared with simulation.
THANK YOU!
BACKUP SLIDES
» Results

Probing additional hadronic activity in selected events can shed light on the modeling of the additional parton radiation.

* production of additional jets in the rapidity gap,
* hadronic activity using track-only observables,
* hadronic activity vetoes.

The activity agrees with the quantum chromodynamics predictions with HERWIG++ parton shower and hadronization model. A bit lower agreement was found with the PYTHIA model predictions.

Leading additional jet $p_T(j_3)$ in the muon channel including the prediction from MADGRAPH interfaced with HERWIG++ parton showering.
Additional correction of $m_{jj}$ in simulation

- a systematic overestimation of the simulation is caused by a partial mistiming of the signals in the forward region of the ECAL endcaps ($2.5 < |\eta| < 3.0$),
- the higher the $m_{jj}$, the bigger the effect,
- solution: a third-order polynomial fit to the ratio of data to the overall prediction from simulation for signal and background.

Data provided by simulation as a function of $\ln(m_{jj}/\text{GeV})$.
### Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>(\Delta\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
<td>+0.02 -0.02</td>
</tr>
<tr>
<td><strong>Size of simulated samples</strong></td>
<td>+0.05 -0.05</td>
</tr>
<tr>
<td><strong>Experimental</strong></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.03 -0.01</td>
</tr>
<tr>
<td>QCD multijet estimation</td>
<td>+0.03 -0.03</td>
</tr>
<tr>
<td>(m_{jj}) correction</td>
<td>+0.05 -0.05</td>
</tr>
<tr>
<td>Background normalization</td>
<td>+0.02 -0.02</td>
</tr>
<tr>
<td>Other experimental uncertainties</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td><strong>Theory</strong></td>
<td></td>
</tr>
<tr>
<td>QCD scale and PDF</td>
<td>+0.05 -0.05</td>
</tr>
<tr>
<td>Interference</td>
<td>+0.02 -0.02</td>
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<tr>
<td>Signal acceptance</td>
<td>+0.05 -0.05</td>
</tr>
<tr>
<td>Other theory uncertainties</td>
<td>+0.01 -0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+0.10 -0.10</td>
</tr>
</tbody>
</table>

Major sources of uncertainty in the measurement of the signal strength.
References to the previous measurements


