Electroweak production of $Zjj$ and hadronic activity in $Zjj$ events at CMS

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for the CMS collaboration
Electroweak production of $Z+2$ jets

Features of vector boson fusion $WW \rightarrow Z$ are:

▶ Central $Z$ decay associated with **energetic forward-backward quark jets**
▶ A large $\eta$ separation between the jets
▶ A **large invariant dijet** mass
▶ Pure electroweak process: **suppressed color exchange** between the tagging quarks
Electroweak production of $Z+2$ jets

bremsstrahlung

vector boson fusion

multiperipheral

- Not only VBF, but also other pure electroweak processes lead to the same $lljj$ final state
- Large negative interference effects between these diagrams
Analysis strategy

Signal is covered by large Drell-Yan background

- Use Boosted Decision Tree technique to extract signal
- Signal and background strengths fitted from discriminator output with a CLs method
- Systematics included as nuisances
- Confirm signal in both $ee$ and $\mu\mu$ modes
- Use both Monte Carlo based and data-driven background models
Monte Carlo based analysis

$Z \rightarrow ee$ channel

Signal: \( \frac{\sigma}{\sigma_{SM}} = 0.84 \pm 0.07 \pm 0.19 \)

$Z \rightarrow \mu\mu$ channel

Information about the input variables and systematics in the back-up slides
Signal: $\frac{\sigma}{\sigma_{SM}} = 0.88 \pm 0.16 \pm 0.18$

⇒ DY $Zjj$ background model was built from $\gamma jj$ data, with $p_T(\gamma)$ reweighted to $p_T(Z)$
Use of a relative pure signal region ($M_{jj} > 1250$ GeV)

Count jets with $p_T > 15$ GeV which fall between the two tagging jets
3rd jet kinematics

- $p_T$ of 3rd jet is in good agreement with MC prediction
- Small disagreement for Zeppenfeld variable of the 3rd jet:
  
  $$y_j^* = y_j - \frac{y_{j1} + y_{j2}}{2}$$
Gap fraction: hadronic veto efficiencies

Fraction of events which do not pass a given threshold:

▶ Nice agreement between data and simulation for central jet vetoes!
Conclusions

▶ Confirmed observation of electroweak $Zjj$ production at 8 TeV

Electroweak $pp \rightarrow lljj$ cross section defined for $p_{Tj} > 25$ GeV, $|\eta_j| < 5$, $M_{jj} > 120$ GeV, $m_{ll} > 50$ GeV:

$\sigma = 174 \pm 15$ (stat) $\pm 40$ (syst) fb

in good agreement with $\sigma_{th} = 208 \pm 11$ fb prediction

▶ Produced results on the hadronic activity in the central region between the two tagging jets

arXiv:1410.3153

Back-up slides
Interference with DY background

Interference between the electroweak and DY production of $Zjj$

Representative diagrams for DY background:
Selection and BDT variables

\[ R(p_T^{\text{hard}}) = \frac{|\vec{p}_{Tj1} + \vec{p}_{Tj2} + \vec{p}_{TZ}|}{p_{Tj1} + p_{Tj2} + p_{TZ}} \]

\[ y^* = y_Z - \frac{y_{j1} + y_{j2}}{2} \]

\[ z^* = \frac{y^*}{\Delta y_{jj}} \]

<table>
<thead>
<tr>
<th>Analysis</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channels</td>
<td>ee, ( \mu \mu )</td>
<td>( \mu \mu )</td>
<td>ee, ( \mu \mu ) binned in ( M_{jj} )</td>
</tr>
<tr>
<td>Selection</td>
<td>( R p_T^{\text{hard}} &lt; 0.14 )</td>
<td>( p_{TZ} &gt; 50 \text{ GeV} )</td>
<td>(</td>
</tr>
<tr>
<td>( M_{jj} &gt; 200 \text{ GeV} )</td>
<td>( M_{jj} &gt; 450 \text{ GeV} )</td>
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<tr>
<td>Jets</td>
<td>PF</td>
<td>JPT</td>
<td>PF</td>
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<tr>
<td>Variables used</td>
<td>( M_{jj} )</td>
<td>( p_{Tj1}, p_{Tj2} )</td>
<td>( \eta_{j1}, \eta_{j2} )</td>
</tr>
<tr>
<td>DY ( Z_{jj} ) model</td>
<td>MC-based</td>
<td>MC-based</td>
<td>From data</td>
</tr>
</tbody>
</table>
\[ R(p_T^{\text{hard}}) = \frac{\vert \vec{p}_{T1} + \vec{p}_{Tj2} + \vec{p}_{TZ} \vert}{p_{Tj1} + p_{Tj2} + p_{TZ}} \]
\[ |z^*| < 0.5 \Rightarrow y_{j1} < y_z < y_{j2} \]

\[ |z^*| > 0.5 \Rightarrow Z \text{ not between tagging jets} \]

\[ z^* = 0.5 \Rightarrow y_z = y_{j1} \]

\[ z^* = -0.5 \Rightarrow y_z = y_{j2} \]
Dijet invariant mass

**Control region**

**Signal region**

**Data**

- EW Zjj (only)
- EW Zjj
- DY Zjj
- Top
- VV

CMS events

$$\mu \mu$$
Analysis A: electron channel, particle flow jets, simulation-based background

Control region

Signal region

Signal: $\mu = 0.82 \pm 0.11 \pm 0.19$
Analysis A: muon channel, particle flow jets, simulation-based background

Control region:

Signal region:

Signal: $\mu = 0.86 \pm 0.10 \pm 0.18$
BDT’s and fit results

_analysis b: muon channel, jet-plus-track jets, simulation-based background_

control region

signal region

Signal: \( \mu = 0.89 \pm 0.09 \pm 0.17 \)
**Analysis C: electron + muon channel, particle flow jets, data-driven background**

**Signal:** $\mu = 0.88 \pm 0.16 \pm 0.18$
### Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Analysis A</th>
<th>Analysis B</th>
<th>Analysis C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ee</td>
<td>$\mu\mu$</td>
<td>$ee + \mu\mu$</td>
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<tr>
<td>Luminosity</td>
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<tr>
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<tr>
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<tr>
<td>Top, dibosons</td>
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<tr>
<td>Signal acceptance</td>
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<td>DY/EW $Z\bar{Z}$ interference</td>
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<tr>
<td>Systematic uncertainty</td>
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<tr>
<td>Statistical uncertainty</td>
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<tr>
<td>$\mu = \sigma/\sigma_{th}$</td>
<td>0.82</td>
<td>0.86</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Excellent agreement between the different analyse methods!
The distributions for γjj events are in good agreement with the DY simulation.
Central hadronic activity with track-jets

- Use of high-purity tracks associated with the primary vertex, and not associated with the 2 leptons or the 2 jets
- Clustering of these tracks into soft track-jets with anti-$k_T$ algorithm
- $H_T(3)$: Scalar sum of 3 leading ($p_T$-ordered) soft track jets in the central region between the 2 tagging jets

Note: contribution of electroweak $Zjj$ is $\sim 20\%$ for $M_{jj} > 1$ TeV, and $\sim 5\%$ for $|\Delta\eta_{jj}| > 4$
Radiation patterns in Z+jets events

Average jet multiplicity vs. total $H_T$ of jets

Average jet multiplicity vs. $\Delta \eta$ of two leading jets

Selection: jets with $p_{Tj} > 40$ GeV and $|\eta_j| < 4.7$ in Z+jet events
Radiation patterns in $Z+$jets events

Selection: jets with $p_T > 40$ GeV and $|\eta_j| < 4.7$ in $Z+$jet events