Vector boson production in association with jets and heavy flavor quarks from CMS

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Motivation

• Vector boson + jets studies essential for the LHC physics program:
  • Probe into **perturbative QCD** calculations, testing predictions at high energies and jet multiplicities
  • Important for **tuning MC generators** and theoretical calculations
  • Probing strange and heavy content of the proton and **constraining** PDFs
  • **Background** to many interesting processes (Higgs, BSM...)

![Production Cross Section, \(\sigma \text{ [pb]}\)](image)}
Vector boson + jets
Signal selection:

- **W**: $M_T > 50 \text{ GeV}$, $|\eta| < 2.4$
- **µ**: $p_T > 25 \text{ GeV}$, $|\eta| < 2.1$, isolated
- **at least one jet**: $p_T > 30 \text{ GeV}$, $|\eta| < 2.4$

Results compared to:
- MadGraph+Pythia
- Sherpa
- NLO calculations from BlackHat+Sherpa

Differential cross section as a function of:
- jet multiplicity
- $p_T$ and $\eta$ of the four leading jets
- $\Delta \phi$ between muon and each of the jets
- scalar sum of the jet transverse momenta

- Luminosity: 5 fb$^{-1}$
- $\sqrt{s} = 7 \text{ TeV}$
**W + jets differential cross section**

- differential cross section as a function of:
  - jet multiplicity
  - $p_T$ and $\eta$ of the four leading jets
  - $\Delta\phi$ between muon and each of the jets
  - scalar sum of the jet transverse momenta

overestimated in high $p_T$ regions

OK for all 4 leading jets
W + jets differential cross section

- differential cross section as a function of:
  - jet multiplicity
  - $p_T$ and $\eta$ of the four leading jets
  - $\Delta \phi$ between muon and each of the jets
  - scalar sum of the jet transverse momenta

underestimated in low $\Delta \phi$ region
Z + jets differential cross section

Signal selection:

I: \( p_T > 20 \text{ GeV}, |\eta| < 2.4 \), isolated

at least one jet:

Z: \( 70 < M < 110 \text{ GeV} \)

\( p_T > 30 \text{ GeV}, |\eta| < 2.4 \)

Differential cross section as a function of:

- \( p_T \) and \( \eta \) up to 5 leading jets
- exclusive and inclusive jet multiplicities
- scalar sum of the jet transverse momenta

Results compared to:

- MadGraph+Pythia 6
- Sherpa 2

• Luminosity: 19.6 fb\(^{-1}\)
• \( \sqrt{s} = 8 \) TeV
Z + jets double differential cross section

- Signal selection similar to previous measurement with extended rapidity range $|y|<4.7$
- Only for muons

MadGraph overestimates xsec in almost all $\eta$ bins and $p_T>100$ GeV
Sherpa shows large disagreement in several bins

Results compared to:
- MadGraph+Pythia 6
- Sherpa 2
Z+ jets/γ+jets cross section ratio

• Differential cross sections as a function of $p_T$ of the vector boson measured

Results compared to:
• MadGraph+Pythia 6
• Sherpa 2
• Blackhat

- Luminosity: 19.7 fb$^{-1}$
- $\sqrt{s} = 8$ TeV

19.7 fb$^{-1}$ (8 TeV)
Z+ jets/γ+jets cross section ratio

- Ratio expected to become constant at high $p_T$ of the vector boson and LO in pQCD
- Test of the higher order pQCD corrections
- Used for Z+jets modelling where $Z\rightarrow vv$

- Measurement performed for different kinematic selections:

\[ \text{~ 20\% difference between data & theory} \]
W + 2 jets, EWK production

Signal selection:
- centrally produced electron or muon
- two jets with invariant mass of the dijet system $m_{jj} > 1000$ GeV

Important as test of SM predictions and background to Higgs VBF studies

<table>
<thead>
<tr>
<th>$\sigma(W\rightarrow l\nu+2j, l=e,\mu)$</th>
<th>0.42±0.04(stat)±0.09(syst)±0.01(lumi) pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madgraph + Pythia6</td>
<td>0.50±0.02(scale)±0.02(PDF) pb</td>
</tr>
</tbody>
</table>

Result in agreement with SM prediction

Luminosity: 19.3 fb⁻¹
$\sqrt{s} = 8$ TeV
Signal selection:

- Luminosity: 19.7 fb⁻¹
- √s = 8 TeV

Results

<table>
<thead>
<tr>
<th>Event</th>
<th>Cross-section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z+2 jets</td>
<td>174±15(stat)±40(syst)</td>
</tr>
<tr>
<td>Madgraph + Pythia6</td>
<td>208±9(scale)±7(PDF)</td>
</tr>
</tbody>
</table>

Result in agreement with SM prediction
Vector boson + heavy flavor
W + 2b jets

Fiducial region:

- $\mu$: $p_T > 25$ GeV, $|\eta| < 2.1$
- Two jets: $p_T > 25$ GeV, $|\eta| < 2.4$, both b-tagged
- B hadron $p_T > 5$ GeV

- Sensitive to gluon splitting
- **Background** to many interesting processes like Higgs and BSM
- In agreement with SM

- Luminosity: 5 fb$^{-1}$
- $\sqrt{s} = 7$ TeV

CMS L=5/fb $\sqrt{s} = 7$ TeV

- MCFM MSTW08
- $P_T^{\mu} > 25$ GeV/c, $|\eta^{\mu}| < 2.1$
- $P_T^{b\text{-jet}} > 25$ GeV/c, $|\eta^{b\text{-jet}}| < 2.4$
- $P_T^{b\text{-hadron}} > 5$ GeV/c
- anti-$K_T$ $R=0.5$

Data: $0.53 \pm 0.05$ (stat) $\pm 0.09$ (syst) 
$\pm 0.06$ (th) $\pm 0.01$ (lumi) pb
W + c jets

sensitive to **strange quark** content of the proton

- Luminosity: 5 fb$^{-1}$
- $\sqrt{s} = 7$ TeV

Fiducial region:
- jet $p_T > 25$ GeV, $|\eta|<2.5$
- lepton $p_T > 35$ GeV, $|\eta|<2.1$

Predictions:
NLO MCFM + NNLO PDF

CMS 2011
84.1 ± 2.0 (stat.) + 4.9 (syst.) pb

- MSTW08
  78.7 ± 11.4$_{\text{PDF}}$ pb
- CT10
  87.3 ± 5.2$_{\text{PDF}}$ pb
- NNPDF23
  78.2 ± 3.3$_{\text{PDF}}$ pb
- NNPDF23$_{\text{coll}}$
  102.7 ± 11.8$_{\text{PDF}}$ pb

CMS 2011
0.938 ± 0.019 (stat.) ± 0.006 (syst.)

- MSTW08
  0.904 ± 0.018$_{\text{PDF}}$
- CT10
  0.942 ± 0.004$_{\text{PDF}}$
- NNPDF23
  0.923 ± 0.015$_{\text{PDF}}$
- NNPDF23$_{\text{coll}}$
  0.936 ± 0.022$_{\text{PDF}}$
Z + b jets cross sections

Fiducial region:
\[ p_T > 20 \text{ GeV}, |\eta| < 2.4 \]

Z: \( 76 < M_{ll} < 106 \) GeV

at least one jet: \( p_T > 25 \) GeV

|\( |\eta| < 2.1, \) b-tagged |

- Luminosity: 5 fb\(^{-1}\)
- \( \sqrt{s} = 7 \) TeV

**Z->BB+X angular correlations:**

- Luminosity: 5 fb\(^{-1}\)
- \( \sqrt{s} = 7 \) TeV

- Underestimated in low \( \Delta R \) region

- Total uncertainties
- Statistical uncertainties
- Systematic uncertainties

**Figure 5:** Differential cross sections for all \( p_{T} \) bins.

<table>
<thead>
<tr>
<th>CMS</th>
<th>L=5/fb</th>
<th>( \sqrt{s} = 7 ) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>data: 3.52 ( \pm 0.02 ) (stat) ( \pm 0.2 ) (syst) pb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6:** Differential cross sections for all \( \Delta R \) bins.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>data: 0.36 ( \pm 0.01 ) (stat) ( \pm 0.07 ) (syst) pb</td>
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</tr>
</tbody>
</table>

**Figure 7:** Differential cross sections for all \( \eta \) bins.

<table>
<thead>
<tr>
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**Figure 8:** Differential cross sections for all \( \phi \) bins.

<table>
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Z + b jets differential cross sections

Differential cross section as a function of:
- $p_T$ and $\eta$ of the leading b jet
- Z boson $p_T$
- angular distance between Z and b jet
- scalar sum of the jet transverse momenta
- in case of Z+2b: $M_{jj}$, angular distances between jets...

Results compared to:
- MadGraph+Pythia 6 (4FS and 5FS)
- Powheg + Pythia 6

Preliminary

**Z+1b**

- $Z/\gamma^* +$ at least 1 b jet
- anti-$k_T$ (R = 0.5) jets
- $p_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$

**Z+2b**

- $Z/\gamma^* +$ at least 2 b jets
- anti-$k_T$ (R = 0.5) jets
- $p_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$

CMS Preliminary

19.8 fb$^{-1}$ (8 TeV)

Luminosity: 19.8 fb$^{-1}$

$\sqrt{s} = 8$ TeV
Conclusions

• Measurements of V+jets processes are important as a test of SM predictions and a background to BSM

• Various measurements performed by CMS using data collected during 2011 and 2012

• Measured results show good agreement with theoretical predictions

• Analyses of the Run 2 data at 13 TeV already ongoing

• Looking forward to the new results in yet unprobed phase space