Measurement of Differential Cross Sections of W+jets and Z+jets Processes with the CMS Detector at the LHC

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For the CMS Collaboration

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Outline

The Experimental Apparatus
- The CMS detector

Motivations

Measurement Distributions
- What is measured?
- Selections and objects

Signal Extraction
- Signal and background modeling

Background subtraction and unfolding

Uncertainties

Results
- Overview of theory predictions
- Differential cross section measurements

Conclusions / looking forward

BackUp
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The CMS detector

The Compact Muon Solenoid (CMS) detector

- Inner silicon tracker to determine the tracks and vertices.
- PbWO$_4$ ECAL and brass-scintillator HCAL to measure the energies of photons, electrons, and hadrons.
- Muon subsystem with DTs, RPCs, and CSCs to measure muons with $p_T$ up to 1 TeV in $p_T$ with resolution of 1-5%.
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Motivation

- Fundamental test of perturbative QCD.
- Test performance of MC generators and calculations, and provide measurement spectra to test performance and parameters of MC generators and theoretical calculations.

\[ W \rightarrow \mu \nu + n \text{jets} \quad n=1-6 \quad Z \rightarrow l^+l^- + n \text{jets} \quad n=1-6 \quad l=e,\mu \]

CMS SMP-12-023

CMS SMP-12-017
V+jets as a background

- V+jets is an important background to searches (SUSY, exotics) and measurements (Other SM and Higgs)

![Graph showing data, signal, and background contributions](image)

**Graph Description:**
- The graph displays the production cross section for W+jets and Z+jets processes with the CMS Detector at the LHC.
- The data points are categorized by different channels and backgrounds.
- The CMS Preliminary measurement is shown for the LHC running at 8 TeV, with data points indicating the production cross sections.

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### Measurement of Differential Cross Sections of W+jets and Z+jets Processes with the CMS Detector at the LHC

- **Graph Details:**
  - The measurements are for different production channels such as tW, s-channel, and t-channel.
  - The CMS Preliminary data is shown for 5.0 fb⁻¹ at 8 TeV, with a clear distinction between signal and background contributions.

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### Results

- The experimental apparatus motivations include measurement distributions, signal extraction, and uncertainties.
- The conclusions look forward to future enhancements and improvements in background suppression.

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**Textual Notes:***
- V+jets as a background is crucial for SUSY and exotic searches.
- Measurements are essential for understanding the Standard Model and Higgs interactions.
- The CMS detector provides precise measurements at the LHC for these processes.
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What is measured?

Variables and Motivation

Jet Multiplicities

- How well-modeled are multiplicities by ME+PS MC?
- How does this compare to NLO predictions?

Kinematics

- Jet transverse momenta ($p_T$) is often cut on for final states in many CMS analyses.
- Jet $p_T$ is sensitive to higher order corrections.
- Scalar sum of jet momenta ($H_T$) is also used as a component of factorization and renormalization scale choices.
- Angular variables, like $\eta$, are sensitive to modeling of parton emission.
### Particle-level phase space

- Due to trigger limitations, measurements are fiducial.
- The particle-level is defined similar to the cuts on reconstructed events.

<table>
<thead>
<tr>
<th>Z+Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ $\ell^+\ell^-$ with $\ell = e$ or $\mu$</td>
</tr>
<tr>
<td>▶ $p_T(\ell) &gt; 20$ GeV, $</td>
</tr>
<tr>
<td>▶ $71 &lt; M(\ell,\ell) &lt; 111$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W+Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ Muon with $p_T &gt; 25$ GeV, $</td>
</tr>
<tr>
<td>▶ $M_T(\mu,\not!E_T) &gt; 50$ GeV</td>
</tr>
</tbody>
</table>

### Object properties

- Jets are anti-kT jets with $R = 0.5$. $p_T > 30$ GeV, $|\eta| < 2.4$.
  - Considering all generated particles except neutrinos
  - Separated from leptons with $\Delta R > 0.5$
- Leptons are “dressed” to account for FSR
  - Adding to lepton $\vec{p}$ all photon $\vec{p}$ within $\Delta R < 0.1$
Reconstructed event selection

- Same overall kinematic requirements as the particle-level.
- Only trigger, identification, and signal-purity conditions are added.

Z+Jets Selection

- Dilepton trigger (17 GeV, 8 GeV)
- $71 < M(\ell^+, \ell^-) < 111$ GeV
- PU-corrected lepton isolation

W+Jets Selection

- Isolated $\mu$ trigger $p_T > 24$ GeV, $|\eta| < 2.1$
- Muon relative isolation
  - $(\text{Ecal} + \text{Hcal} + \text{Trk})/p_T < 0.15$
- Suppress $t\bar{t}$ contamination
  - Veto events with $\geq 1$ bjet
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Background and Signal Simulation

- \( W \) and \( Z/\gamma^* \) events (\( N_{\text{partons}} \leq 4 \)), with \textit{MadGraph 5.1.1}
  - Normalized to NNLO calculation from \textit{FEWZ}
  - Using CTEQ6L1 PDF
- \( t\bar{t} \) events, generated with \textit{Madgraph 5.1.1}
- DiBoson \( WW, WZ, ZZ \) generated with \textit{Pythia 6.424}
- Single-top quark events, generated with \textit{Powheg}
- Pileup modeled in the MC

### Z+Jets Backgrounds
- All background estimated with MC
- QCD is found to be negligible

### W+Jets Backgrounds
- Most backgrounds estimated with MC
- QCD estimated with data in inverted isolation control region.
Background subtraction and unfolding

**Unfolding**

- Deconvolution is performed with regularized SVD unfolding using **ROOUNFOLD**
  - Arxiv 1105.1160
- Background is subtracted from data
- Response is trained on the **MADGRAPH** signal MC
- The unfolding procedure uses the response matrix to invert the effects of reconstruction, and estimate the deconvoluted distribution.
- **ROOUNFOLD** allows for treatment of misreconstructed and fake objects
  - i.e. differences between the Gen and Reco level

**Response Matrix**

- A response matrix defines the probability of migration from a true quantity to a reconstructed quantity
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Measurement of Differential Cross Sections, of W+jets and Z+jets Processes, with the CMS Detector at the LHC
Systematic uncertainties

- Systematic uncertainties are propagated through the unfolding
  - Including jet energy and lepton momentum scale and resolution
  - Corrections for reconstruction, ID, isolation efficiencies
  - The statistics of the data-background and of the response matrix

Z+jets

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>( \frac{d\sigma}{dN} )</th>
<th>( \frac{d\sigma}{dp_T} ) 1st jet</th>
<th>( \frac{d\sigma}{dp_T} ) 2nd jet</th>
<th>( \frac{d\sigma}{dp_T} ) 3rd jet</th>
<th>( \frac{d\sigma}{dp_T} ) 4th jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>JEC+JER</td>
<td>2.0-17.7</td>
<td>4.9-8.7</td>
<td>6.3-16.2</td>
<td>8.8-15.1</td>
<td>15.2-21.5</td>
</tr>
<tr>
<td>Unfolding</td>
<td>1.7-8.1</td>
<td>1.3-22.0</td>
<td>0.5-21.4</td>
<td>0.8-13.2</td>
<td>0.3-11.8</td>
</tr>
<tr>
<td>PU</td>
<td>0.3-0.8</td>
<td>0.2-2.7</td>
<td>0.3-1.1</td>
<td>0.2-0.7</td>
<td>0.5-1.1</td>
</tr>
<tr>
<td>Bkg XSec</td>
<td>0.8-25.3</td>
<td>0.1-1.1</td>
<td>0.6-1.8</td>
<td>1.6-3.3</td>
<td>2.7-4.7</td>
</tr>
<tr>
<td>Total Systematics</td>
<td>2.8-31.9</td>
<td>5.1-23.5</td>
<td>9.0-26.8</td>
<td>10.2-20.0</td>
<td>16.9-24.8</td>
</tr>
<tr>
<td>Statistics</td>
<td>0.7-6.3</td>
<td>0.1-7.5</td>
<td>1.5-12.8</td>
<td>3.0-13.1</td>
<td>6.2-19.6</td>
</tr>
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Conclusions / looking forward

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### Overview of theory predictions

- Several comparisons to MC generators and calculations are performed
- Including an NLO calculation from Sherpa2 or Blackhat+Sherpa
- Intended as comparisons with common tools, not complete picture.

#### Z+Jets Predictions

- **NLO from Sherpa2 (beta2)**
  - CT10 PDF
  - NLO virtual corrections with Blackhat library
  - NLO for 0+1 jet, merged with LO for up to four real emissions matched to PS
  - PS with Pythia6

- **Powheg + Pythia6**

- **Madgraph 5.1.1 + Pythia 6.424**
  - Same as for unfolding

#### W+Jets Predictions

- **NLO from Blackhat+Sherpa**
  - CT10 PDF
  - Parton-level predictions corrected for showering using MadGraph+Pythia
  - NLO up to four jets, fixed order predictions

- **Sherpa 1.4**

- **Madgraph 5.1.1+Pythia 6.424**
  - Same as for unfolding
The jet multiplicity

CMS Preliminary

\( \sigma = 7 \text{ TeV} \) L_{int} = 4.9 fb

Data
Sherpa2 (0,1@NLO ≤4@LO +PS)
Powheg+Pythia6 (Z+1@NLO +PS)
MadGraph+Pythia6 (≤4@LO +PS)

- Inclusive jet multiplicity
- Agreement within uncertainties across jet multiplicity.

Measurement of Differential Cross Sections, of W+jets and Z+jets Processes, with the CMS Detector at the LHC
The jet transverse momentum

Good agreement w/ NLO, some mis-modeling with MadGraph/Sherpa
Differential cross section measurements

The sum of jet transverse momenta ($H_T$)

Some deficits in NLO due to lack of higher order contribution
**Differential cross section measurements**

**The jet pseudorapidity (|η|)**

- **Measurement of Differential Cross Sections, of W+jets and Z+jets Processes, with the CMS Detector at the LHC**

- **Good agreement in |η| with all predictions.**

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**Differential cross section measurements**

**The Experimental Apparatus**

**Motivations**

**Measurement Distributions**

**Signal Extraction**

**Uncertainties**

**Results**

**Conclusions / looking forward**

**BackUp**
The jet-muon angular separation

Some disagreement at low $\Delta \phi(\mu, \text{jet})$ for the leading jet.
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Conclusions and looking forward.

- We have measured the Z+jets and W+jets cross sections as a function of jet multiplicity up to 6 jets and differentially as a function of several kinematic variables up to 4 jets.
  - The jet transverse momentum
  - The jet pseudorapidity
  - The scalar sum of jet transverse momenta ($H_T$)
- Deconvoluted detector affects using regularized SVD unfolding
- Accounted for important systematics including energy and momentum scales and reconstruction modeling
- Compared with predictions from MC generators and NLO calculators
- Found good agreement with predictions in most generators
  - Some disagreement observed in $p_T$, $H_T$, and $\Delta\phi(\ell,\text{jet})$ distributions
- Measurements serve as a good fundamental test of perturbative QCD and improve understanding of major backgrounds in LHC searches and measurements.
BackUp Plots
Exclusive jet multiplicity

CMS Preliminary

$\frac{d^2N}{d^2p_T}$ ($p_T^* > 30$ GeV, $|\eta^*| < 2.4$

$Z/\gamma^{*} \rightarrow ll$ channel

$\frac{d^2N}{d^2p_T}$ ($p_T^* > 30$ GeV, $|\eta^*| < 2.4$

$W \rightarrow ll\nu$ channel

Theory/Data 0.5

1

1.5

2

3

$\sigma_{\text{NLO}}$ Madgraph (LO+PS), Normalized to $\sigma_{\text{NLO}}$
The sub-leading jet $p_T$

**Measurement of Differential Cross Sections, of $W+$jets and $Z+$jets Processes, with the CMS Detector at the LHC**

**Figure:**
- **CMS Preliminary:** Comparison of theoretical predictions with data for jet $p_T$ distributions.
- **Data:** Measurement of differential cross sections for $W+$jets and $Z+$jets processes.
- **Theoretical Models:**
  - Sherpa (LO+PS)
  - Powheg+Pythia6 (Z+1j@NLO+PS)
  - MadGraph+Pythia6 (Z+1j@NLO+PS)
  - BlackHat+Sherpa (NLO)

**Distributions:**
- Anti-$k_T$ ($R = 0.5$) Jets $p_T > 30$ GeV, $|\eta| < 2.4$
- $Z/\gamma^* \rightarrow \ell\ell$ channel

**Results:**
- $s = 7$ TeV, $L_{\text{int}} = 5.0$ fb$^{-1}$
- $NLO$/Data, with PDF and Ren./Fac. Scale Unc.
- MC/Data, with PDF and Ren./Fac. Scale Unc.

**Conclusions / looking forward:**
- Evaluation of theoretical predictions against experimental data.
- Further analysis and improvements in jet substructure studies.

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**Table:**
- Summary of $p_T$ distributions for jets in the $W+$jets and $Z+$jets processes.
- Cross sections in pb/GeV for different theoretical models.

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**Graphs:**
- Comparison of data with predictions for jet $p_T$ distributions.
- Different scales and binning for jet $p_T$.

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**References:**
- CMS Preliminary Report.
- Theoretical and experimental collaborations.

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**Further Reading:**
- Detailed analysis of jet substructure in high-energy physics.
- Advanced techniques for jet reconstruction and analysis.

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**Acknowledgments:**
-Contributions from various institutions and collaborations.
- Support from funding agencies and scientific communities.

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**Appendix:**
- Technical details of the experimental apparatus.
- Methodology for signal extraction and uncertainties.

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**BackUp:**
- Additional material for further analysis and discussion.
The third-leading jet $p_T$

![Graph showing the measurement of differential cross sections for W+jets and Z+jets processes with the CMS detector at the LHC.](image)

Measurement of Differential Cross Sections, of W+jets and Z+jets Processes, with the CMS Detector at the LHC
The fourth-leading jet $p_T$
The $H_T$ for $\geq 2$ jet events
The $H_T$ for $\geq 3$ jet events

Measurement of Differential Cross Sections, of W+jets and Z+jets Processes, with the CMS Detector at the LHC
The $H_T$ for $\geq 4$ jet events

Measurement of Differential Cross Sections, of $W$+jets and $Z$+jets Processes, with the CMS Detector at the LHC
The sub-leading jet pseudorapidity ($|\eta|$)

Measurement of Differential Cross Sections, of W+jets and Z+jets Processes, with the CMS Detector at the LHC
The third-leading jet pseudorapidity ($|\eta|$)

Measurement of Differential Cross Sections, of $W$+jets and $Z$+jets Processes, with the CMS Detector at the LHC
The fourth-leading jet pseudorapidity ($|\eta|$)
The jet-muon angular separation for the third and fourth leading jet