Jets produced in association with W and Z bosons in CMS

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On behalf of the CMS Collaboration
A study of W/Z production in association with jets in proton-proton collisions at $\sqrt{s} = 7$ TeV is presented. The results are obtained with data collected by the CMS experiment over the 2010 LHC run, corresponding to an integrated luminosity of about 36 pb$^{-1}$, and have been published in [1].

**Outline of the talk:**

- Event selection and jet reconstruction.
- Signal yields extraction.
- Efficiencies measurement.
- Main results: jet multiplicity exclusive cross sections, W/Z ratio.

The reason for $W/Z + \text{Jets}$...

Processes involving QCD + EWK physics with jets, leptons and missing $E_T$ in final states.

Calculations are very difficult:

- NLO calculations: available up to 3 (Z) and 4 (W) jets.
- Matrix element + parton shower (common used tool): tree level only.

High theoretical uncertainties: cross-check with data is an important test for Standard Model!

Major background to many searches for new physics!
The CMS detector

ECAL (EB+EE):
- \( \sim 75000 \) PbWO\(_4\) crystals
- energy resolution \( \sim 0.5\% \) at 100 GeV

Superconducting solenoid generating 3.8 T magnetic field

HCAL (HB+HE+HO):
- lead and plastic scintillator sampling calorimeter
- energy resolution \( \sim 5\% \) at 100 GeV

Muon detector:
- consisting of drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC).

Tracker:
- made of pixel and micro-strip detectors.
- spatial resolution ranging from 10\( \mu \)m to 30\( \mu \)m.
- Acceptance: \( |\eta| < 2.4 \).
Event selection: $Z \rightarrow \text{ee}$

Events selected in 2010 dataset ($\sim 36 \, \text{pb}^{-1}$) using the lowest unprescaled single electron trigger: $p_T$ threshold varying from 10 to 17 GeV depending on instantaneous luminosity.

**Leading electron:**
- transverse momentum: $p_T > 20$ GeV.
- acceptance: $|\eta| < 1.44$ (barrel), or $1.56 < |\eta| < 2.5$ (endcaps).
- matched to trigger candidate.
- **tight** cuts ($\sim 80\%$ efficiency) on lepton isolation, identification and conversion rejection variables.

**Sub-leading electron:**
- transverse momentum: $p_T > 10$ GeV.
- Acceptance: $|\eta| < 1.44$ (barrel), or $1.56 < |\eta| < 2.5$ (endcaps).
- **loose** cuts ($\sim 95\%$ efficiency) on lepton isolation, identification and conversion rejection variables.

$60 \, \text{GeV} < m_{\text{ee}} < 120 \, \text{GeV}$

The event is classified as $Z \rightarrow \text{ee}$
Event selection: $W \rightarrow ev$

Events selected in 2010 dataset (~36 pb$^{-1}$) using the lowest unprescaled single electron trigger: $p_T$ threshold varying from 10 to 17 GeV depending on instantaneous luminosity.

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$\slashed{m}_T > 20$ GeV and no additional muons (top veto)

The event is classified as $W \rightarrow ev$
Event selection: $Z \rightarrow \mu\mu$

Events selected in 2010 dataset (~36 pb$^{-1}$) using the lowest unprescaled single muon trigger: $p_T$ threshold varying from 9 to 15 GeV depending on instantaneous luminosity.

**Leading muon:**
- transverse momentum: $p_T > 20$ GeV.
- acceptance: $|\eta| < 2.1$.
- matched to trigger candidate.
- well isolated and satisfying quality criteria to avoid muons from secondary decays.

**Sub-leading muon:**
- transverse momentum: $p_T > 10$ GeV.
- acceptance: $|\eta| < 2.4$ (barrel).
- well isolated and satisfying quality criteria to avoid muons from secondary decays.

$60$ GeV $< m_{\mu\mu} < 120$ GeV

The event is classified as $Z \rightarrow \mu\mu$
Event selection: $W \rightarrow \mu \nu$

Events selected in 2010 dataset (~36 pb$^{-1}$) using the lowest unprescaled single muon trigger: $p_T$ threshold varying from 9 to 15 GeV depending on instantaneous luminosity.

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**Sub-leading muon:**
- transverse momentum: $p_T > 10$ GeV.
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$m_T > 20$ GeV

The event is classified as $W \rightarrow \mu \nu$
Jet reconstruction

- Clusterization algorithm: $\textit{anti-}k_T$ (cone size $\Delta R = 0.5$) applied to Particle Flow candidates. Isolated leptons removed from jet collection.
- Acceptance: $|\eta| < 2.4$ (i.e. tracker acceptance).
- Transverse momentum: $p_T > 30$ GeV.
- Jet energy is calibrated to remove detector effects (JEC).
- Pile-up contribution to jet energy removed via $\text{FastJet}$ algorithm.

Data is compared to MadGraph simulation, scaled to NNLO cross section.
Signal extraction

Both signal yields estimated with un unbinned ML fit to the $M_{ll}$ distribution (Z+Jets sample) and to the $M_T$ distribution (W+Jets sample).

**Z+Jets sample:**
- background (mainly W+Jets and t-tbar) is very low and non-peaking: exponential parametrization.
- Z peak signal: asymmetric gaussian parametrization.

**W+Jets sample:**
- heavy background from t-tbar and QCD.
- 2-dimensional fit to the $M_T$ and # of b-tagged jet distributions.

more details in the poster: “Study of W and jets associated production with CMS”-S. Gonzi
Efficiencies

Efficiencies are measured as a function of \# jets, with a data-driven Tag&Probe method on a sample of Z candidates.

Contributions to the global efficiency:

- High Level Trigger (only one leg)
- Reconstruction process
- Offline selection

\[
\epsilon_{\text{tot}} = \epsilon_{\text{HLT}} \times \epsilon_{\text{RECO}} \times \epsilon_{\text{Offline}}
\]

Signal yields are extracted from the distribution of events with a passing probe and a failing probe:

Simultaneous fit, with the efficiency as a floating parameter:

\[
\epsilon = \frac{n_{\text{passing}}}{n_{\text{passing}} + n_{\text{failing}}}
\]

Left tail parameter of signal distribution is estimated from simulations. For \# jets > 2 multiplicity bins (few statistics), use parameters estimated from lower jet multiplicities.
Results: Z + Jets

Exclusive cross sections as a function of the number of associated jets: all the results are presented in terms of ratios, in order to reduce systematics.

- Yields corrected with efficiencies calculated on data and unfolded to remove detector effects.
- Results are compared with PYTHIA (PS only) and PYTHIA+MadGraph (ME+PS)
Results: $W + \text{Jets}$

- Yields corrected with **efficiencies** calculated on data and **unfolded** to remove detector effects.
- Results are compared with **PYTHIA** (PS only) and **PYTHIA**+**MadGraph** (ME+PS).

- Similar results to $Z + \text{Jets}$: worse sample purity is compensated by higher statistics.
- Matrix element calculation yields a good agreement with data: scaling between exclusive jet multiplicity cross sections is well behaved.
Jet multiplicity exclusive cross sections are used to test scaling hypothesis:

$$\frac{\sigma (V + (\geq n) \text{ Jets})}{\sigma (V + (\geq n-1) \text{ Jets})} = \alpha + \beta \times n$$

(“Berends-Giele scaling”)

both with $W + \text{Jets}$ cross sections and $Z + \text{Jets}$ ones.

$\beta$ is consistent with zero within uncertainties:

\textbf{no violation to the expected scaling.}
Results: W/Z ratio

Cross sections measured from W+Jets and Z+Jets samples are used to calculate the ratio:

\[
\frac{\sigma(W + (\geq n)\text{Jets})}{\sigma(Z + (\geq n)\text{Jets})}
\]

- Event selection needs to be consistent between the W and Z (first leg) candidates.
- W/Z ratio is independent from the jet multiplicity.

Good agreement with Standard Model predictions!
Conclusions

In this talk:

- Most relevant steps of the W/Z + Jets event selection and analysis.
- Main results with 2010 dataset (≈36 pb$^{-1}$): many other interesting measurements have been done.

(e.g. dedicated poster: “Measurements of associated production of vector bosons and heavy flavours with the CMS detector” - S. Casasso)

In the future:

- Exciting new results are expected with 2011(-2012) data: differential cross sections, angular correlations, etc. etc.
- Fascinating new challenges expected with the analysis of 2011(-2012) data (high luminosity and pile-up, complex triggers...): stay tuned!