Jet production in association with vector bosons at LHC with the CMS detector

Jet rates in W/Z+jets
Azimuthal correlations and event shapes in Z+jets

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On behalf of the CMS collaboration
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V+jets at LHC

- Important for two broad classes of reasons
  - It is an ubiquitous source of background for virtually any signal (both SM and searches) at a hadron collider
  - It is a tool to test the predictions of perturbative QCD
    - The current understanding of our detector allows us to do **precision** QCD measurements
- 2010 and 2011 LHC data recorded by the CMS detector at 7 TeV provided high statistics for precision tests of perturbative QCD predictions and Monte Carlo techniques
Available predictions

- Accurate predictions for W/Z+jets production at the LHC are available

- Monte Carlo event generators
  - NLO + parton shower (MC@NLO, POWHEG...)
  - LO (many legs) + parton shower (Alpgen, MadGraph, Sherpa)

- Parton level codes for distributions at NLO
  - BlackHat, Rocket...

- Modern parton distribution functions
  - LHC data start to contribute to PDF fits
CMS published jet rates and related observables for W/Z+jets using 2010 36pb⁻¹ data sample and selecting the electron and muon decay channels

- Jet rates normalized to the inclusive cross section
- Ratios of events with n/n-1 jets
- Ratios of W/Z versus the number of jets
- W charge asymmetry versus the number of jets

The use of ratios allows the cancellation of several systematic uncertainties either completely...

- Luminosity in particular

...or largely

- Jet energy scale in particular

All results are quoted in the leptonic kinematic acceptance and detector effects have been unfolded
Event selection

- $p_T(l) > 20$ GeV, $|\eta| < 2.4$,
  - $Z$: $60 \text{GeV} < M(\ell\ell) < 120 \text{GeV}$
  - $W$: $M_T > 20$ GeV

- Jets definition
  - anti-kt algorithm with radius parameter 0.5 and $p_T$ threshold of 30 GeV and $|\eta| < 2.4$
  - The average energy added by pile-up interactions has been removed with the FastJet median subtraction techniques on an event by event basis
Jet rates

- Normalized to the inclusive cross section
- \( n/(n-1) \) jets
- The comparison to the predictions of multi-leg matrix element + parton shower (Madgraph) shows good agreement
  - Pure parton shower (Pythia) fails to predict multi-jet final states
- Given the pT threshold on jets the sensitivity to underlying event is negligible
Double ratio

- Defined as \[
\frac{\sigma(W+\text{jet})/\sigma(W)}{\sigma(Z+\text{jet})/\sigma(Z)}\]
- It is an observable with very small systematic uncertainty
- Jet energy scale systematic cancels almost completely
Charge asymmetry

- Charge asymmetry \[\frac{\sigma(W^+)-\sigma(W^-)}{\sigma(W^+)+\sigma(W^-)}\] as a function of jet multiplicity

- Depends on the number of associated jets due to the fraction of u (d) quarks contributing to the different multiplicities

- It was measured fitting for the two charges independently

- Good agreement with Madgraph+Pythia predictions

- Parton shower only (Pythia) departs from data already for jet multiplicity=1
Azimuthal correlation in Z+jets

- In depth characterization of the topology of Z+jets using 2011 CMS data (5 fb⁻¹)
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021
  - Full kinematic information is available for Z
- Useful as a test of QCD predictions and for searches
  - Searches with invisible Z irreducible background, searches for resonances decaying in Z+X
- We measured the azimuthal correlation between the Z and the leading jet, and between the jets
  - Both inclusively and in a boosted Z regime, pT(Z)>150 GeV
- Jet reconstruction:
  - anti-kt with radius of 0.5 and pT>50 GeV
- Event selection:
  - pT(l)>20GeV, |η|<2.4, 71GeV<M(ll)<111GeV, at least one jet with pT>50GeV, |η|<2.5
- Results unfolded at particle level
- Muon and electron lepton flavors are combined at “dressed” level
- Shows a peak for Z back to back to the jet, and a long tail for events with many jets

- Both Sherpa (version 1.3.1. with default tune) and Madgraph give a good description of data
  - Sherpa slightly undershoots at intermediate values
    - Fewer events at intermediate jet multiplicity
  - Pythia is unable to describe multi-jet configurations

Error bars on data points: statistical uncertainty after unfolding
Shaded blue band: total data systematic
\( \Delta \phi(Z, J_1) \)

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Error bars on data points: statistical uncertainty after unfolding
Shaded blue band: total data systematic
Hatched band: statistical uncertainty on Madgraph
Another way of looking at angular correlations in Z+jets is through event shapes:

- It embeds more information than angular separation.
- It holds information from momenta.

The transverse momentum of the Z and of the jets are used as input to the computation of the transverse thrust.

- The peak at $\Delta \Phi = \pi$ gets diluted in a long tail.
- Madgraph shows nice agreement with data.
- Sherpa is shifted to the left.
- Consistent with the pattern observed in the $\Delta \Phi$ distribution:
  - Fewer events with many jets.

$\tau_\perp \equiv 1 - \max \frac{\sum_i |\vec{p}_{\perp i} \cdot \vec{n}_T|}{\sum_i p_{\perp i}}$

CMS preliminary, $\sqrt{s} = 7$ TeV, L=5.0 fb$^{-1}$
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$\Delta \phi (Z, J1)$ with $p_T Z > 150$ GeV

- The request of high $p_T$ for the Z boson enhances configurations with most of the hadronic activity recoiling in the other direction.
- Distributions become flatter.
  - When the Z recoils against a hard jet an additional jet is less correlated with the Z direction than it was in the inclusive case.
- In this Z+1 jet dominated phase space, the discrepancy with Pythia is less evident.
Δϕ(Z, J1) with ptZ > 150 GeV

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Event shapes for \( p_T(Z) > 150 \) GeV

- The requirement on \( p_T(Z) \) shifts the distribution towards lower values.

- The selection enhances \( Z+1 \) jet topologies.
High hadronic activity

- We checked the azimuthal separation between the Z and the jets and between jets in events with high hadronic activity (at least 3 jets)
  - The dominant configuration is Z and a sub-leading jet balancing together the leading jet
  - The ME+PS descriptions are in good agreement with data
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High hadronic activity and Z boost

- The most extreme kinematic region we have explored is the one with at least three jets and a highly boosted Z.

- It is particularly interesting to notice that in this regime the correlation between the jets becomes flat.

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**CMS Preliminary, √s=7 TeV, L=5.0 fb⁻¹**

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**1/σ dσ/dφ**

- $\Delta φ_{ZJ_1}$
- $\Delta φ_{ZJ_2}$
- $\Delta φ_{J_1J_2}$

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**1/σ dσ/dφ**

- $\Delta φ_{J_1J_2}$

**10^2**

$\Delta φ_{ZJ}$

x300

$\Delta φ_{ZJ}$

x10

$\Delta φ_{J_1J_2}$

x100

$\Delta φ_{J_1J_2}$

x10
High hadronic activity and Z boost

- The most extreme kinematic region we have explored is the one with at least three jets and a highly boosted Z.
- It is particularly interesting to notice that in this regime the correlation between the jets becomes flat.
Conclusion

- Results from CMS in W/Z+jets have been presented
  - Jet rates and related observables in 2010 data sample at 7 TeV (36 $\text{pb}^{-1}$)
  - Azimuthal correlation and event shapes in Z+jets at 7 TeV (5 $\text{fb}^{-1}$)
- These observables probe perturbative QCD in an unprecedented energy regime
  - Excellent agreement with predictions from matched Matrix Element + Parton Shower
Backup
Systematic uncertainties

- The main systematic uncertainty on the jet counting is the jet energy scale
Selection strategy

- Online selection:
  - Single electron and single muon triggers
- Reconstructed lepton selection
  - Events with at least one electron/muon with $p_T$ above 20 GeV are selected
  - If a second, looser ($p_T > 15$ GeV), same species lepton is found, it is assigned to the Z sample, otherwise to the W sample
- Lepton identification
  - Isolation requirements for both muons and electron
- Z selection: two opposite charge lepton with invariant mass between 60 and 120 GeV
- W selection: transverse mass cut at 20 GeV
High hadronic activity and Z boost

- The most extreme kinematic region we have explored is the one with at least three jets and a highly boosted Z (pt > 150 GeV)

- It is particularly interesting to notice that in this regime the correlation between the jets becomes flat
Hard QCD at LHC

- Hard QCD processes are important for two broad classes of reasons
  - They represent a ubiquitous source of background for virtually any signal (both SM and searches) at a hadron collider
  - They provide a tool to test the predictions of perturbative QCD
    - The current understanding of our detectors allows both ATLAS and CMS collaborations to do precision QCD measurements
- 4 T solenoid
- Pixel + SiStrip tracker
- Scintillating crystals (PbWO₄)
  electromagnetic calorimeter
- Brass/plastic hadron calorimeter (non-compensating)
- Muon spectrometer in the magnet iron return yoke
Jet reconstruction

- Jets are reconstructed with the anti-kt algorithm, with radius of 0.5 or 0.7
- 3 available algorithms for jet reconstruction
  - Calo-Jets: use only the calorimeter towers
  - Jet-Plus-Track Jets: improve the calorimeter jets using the tracks in the jet cone
  - Particle-Flow jets: uses particle flow candidates as input to the clustering algorithm

  ▪ **Particle flow reconstruction:**
    ▪ global event reconstruction
    ▪ Identifies muons, electrons, taus, photons, charged hadron, neutral hadrons
    ▪ Combines the information from all detectors
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Jet energy scale

- We use a multi-step procedure to correct the energy of our jets

\[ p^\text{cor}_\mu = C \cdot p^\text{raw}_\mu. \]

\[ C = C_{\text{offset}}(p^\text{raw}_T) \cdot C_{\text{MC}}(p^\gamma_T, \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p^\gamma_T) \]

- \( C_{\text{offset}} \) accounts for detector noise and pile-up

- The method uses correction factors extracted from the full simulation of CMS, \( C_{\text{MC}} \)

- Residual differences with respect to data are accounted for as further scaling factors
  - \( C_{\text{rel}} \) accounts for non-uniformity in eta. It is obtained applying on data and MC the di-jet balance method
  - \( C_{\text{abs}} \) accounts for residual absolute scale differences between data and MC. It is obtained applying on data and MC the \( \gamma + \text{jet} \) and \( Z + \text{jet} \) pT balancing

- In this MC + residual method effects like the presence of additional radiation spoiling dijet or \( \gamma + \text{jet} \) and \( Z + \text{jet} \) balancing enter only at second order
Jet energy scale

- Total systematic uncertainty on the energy scale for particle-flow jets
- The main sources of uncertainty are:
  - The photon energy scale, known at 1%
  - The relative response across detector regions
  - Pile-up effects
  - Extrapolations down to 0 for the additional activity in the balance methods
  - Dependency on jet flavor in the MC used
Jet energy resolution

- Determined with di-jet and γ+jet pT balance
- Plots show two example regions in η
- Resolution is of the order of 10% around 50 GeV
Signal extraction

- Main backgrounds
  - QCD dijets with fake leptons
  - Ttbar, especially for the W
  - Z+jets for the W
- For Z (W) the signal is extracted with a fit to the dilepton invariant mass (transverse mass)
  - In the W channel, due to the presence of real W from ttbar a b-tagging estimator has been added to the fit
- Background shapes
  - From inverted identification criteria for QCD
  - From data ttbar sample for ttbar
- Efficiency correction
  - Estimated with tag and probe methods
CMS measured the associated production of $Z + b$-jets

- $Z$ selection plus high purity $b$-tagging
- Main systematics: JES, $b$-tagging efficiency and mistag rate
- The ratio between the $Z + b$ jets and $Z +$ any jet has been measured for both electron and muon decay channels

| Sample       | $\mathcal{R}(Z \rightarrow ee)\%$, $p_T^e > 25$ GeV, $|\eta^e| < 2.5$ | $\mathcal{R}(Z \rightarrow \mu\mu)\%$, $p_T^\mu > 20$ GeV, $|\eta^\mu| < 2.1$ |
|--------------|---------------------------------------------------------------|---------------------------------------------------------------------------------|
| Data HE      | $4.3 \pm 0.6$ (stat) $\pm 1.1$ (syst)                        | $5.1 \pm 0.6$ (stat) $\pm 1.3$ (syst)                                          |
| Data HP      | $5.4 \pm 1.0$ (stat) $\pm 1.2$ (syst)                        | $4.6 \pm 0.8$ (stat) $\pm 1.1$ (syst)                                          |
| MADGRAPH     | $5.1 \pm 0.2$ (stat) $\pm 0.2$ (syst) $\pm 0.6$ (theory)     | $5.3 \pm 0.1$ (stat) $\pm 0.2$ (syst) $\pm 0.6$ (theory)                      |
| MCFM         | $4.3 \pm 0.5$ (theory)                                       | $4.7 \pm 0.5$ (theory)                                                        |