Hadronically decaying massive particles, jet substructure, and measurement of the transverse momentum of the Z boson at LHC

Francesco De Lorenzi
(Iowa State University)

on behalf of the ATLAS and CMS collaborations
Introduction

- LHC experiments provided several measurements testing QCD
  - At low $p_T$: multiple soft-gluon radiation
  - At high $p_T$: hard-gluon emission
- The data are used to tune next-to-leading order plus parton shower Monte Carlo simulations
- Very high $p_T$ hadronically decaying W/Z
  - provide a direct test of QCD calculations of gluon and quark radiation
  - validate novel techniques of jet shapes and jet substructure for boson tagging and reducing the sensitivity to soft QCD and pileup
Outline

- $Z \, p_T$ distribution at 7 and 8 TeV and MC tuning
- Boosted $Z \rightarrow bb$ and $W/Z \rightarrow qq'$
- Jet substructure for high $p_T$ W
Z $p_T$: 7 TeV Results

- $Z \rightarrow \text{ee}$ and $Z \rightarrow \mu\mu$
- Low $p_T$:
  - Good agreement with ResBos, Pythia, Sherpa, Alpgen
  - Sensitivity to tunes
- High $p_T$: quite good modeling by FEWZ, ResBos
High $p_T$: good description by RESBOS (less good by POWHEG) as well as by FEWZ (but low stat. for $p_T > 100$ GeV).

Low $p_T$: sensitivity to the PS tune. Best description by PYTHIA Z2star; POWHEG+PYTHIA Z2star provide only marginal description of the low $p_T$ data.
ATLAS Z $\phi^*$ 7 TeV result

Measurements at low $p_T(Z)$ are limited by experimental resolution and uncertainties on $p_T(l)$ scale. Use new observable $\phi^*$:

$$\phi^*_\eta = \tan\left(\phi_{\text{acop}}/2\right) \times \sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) = \tanh\left[(\eta^+ - \eta^-)/2\right]$$

$$\phi_{\text{acop}} = \pi - \Delta \phi(l,l)$$

$\phi^*$ is an angular variable. Angular resolution for leptons: $\sim 0.5$ mrad on $\phi$ and $\sim 0.001$ on $\eta$

• Correlated with $p_T$ and it probes the same physics
ATLAS Parton Shower Tune

- New tunes to improve the Monte Carlo (MC) description of kinematics of vector boson production:
  - improved modeling of low \( p_T \) vector boson => reliable acceptance of \( p_T(l) \) cuts in \( W/Z \) measurements;
  - crucial for \( W \) mass measurement (and \( W/Z, \) DY for constraining PDFs).

- Use both \( Z p_T \) and \( Z \phi^* \) data
- Independent tunes
- MC generators studied:
  - **PYTHIA8, POWHEG+PYTHIA8**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation Range</th>
<th>Variation Range</th>
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<tbody>
<tr>
<td>Primordial ( k_T ) [GeV]</td>
<td>1.0–2.5</td>
<td>0.5–2.5</td>
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<tr>
<td>ISR ( \alpha_S^{ISR}(m_Z) )</td>
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<td>ISR cut-off [GeV]</td>
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<td>ISR ( \alpha_S ) order</td>
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<td>NLO</td>
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<td>PYTHIA8 base tune</td>
<td>tune 4C</td>
<td>tune 4C</td>
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<tr>
<td>POWHEG cut-off [GeV^2]</td>
<td>-</td>
<td>4.0</td>
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</tbody>
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arXiv:1406.3660
High $p_T Z \rightarrow bb$

- **Phase space:** 2 anti-$k_T$ b-jets with $R=0.4$,
  - $p_T$ (jet)$>40$ GeV,
  - $|\eta(\text{jet})|<2.5$,
  - $\Delta R<1.2$,
  - $p_T(\text{dijet})>200$ GeV,
  - $60 < M(\text{dijet}) < 160$ GeV
- Separate Signal and control regions with a NN $S_{NN}$ based on $\Delta \eta(\text{dijet}, \text{balancing jet})$ and $|\eta(\text{dijet})|
- Very small correlation between NN and dijet mass
- Constrain the background shape from data in background enriched control region
High $p_T$ $Z \rightarrow bb$

- Background: Simultaneous fit in signal and control region
- Signal model: allow peak position and yield as free parameters, other parameters from MC
- Other small backgrounds from MC
- Acceptance from MC
  \[ \sigma_{Z \rightarrow bb}(p_T^{\text{dijet}} > 200 \text{ GeV}) = 2.02 \pm 0.2 \text{(stat.)} \pm 0.25 \text{(syst.)} \pm 0.06 \text{(lumi.)} \text{pb} \]

NLO ME+PS predictions:
  \[ \sigma_{\text{POWHEG}} = 2.02^{+0.25}_{-0.19} \text{(scales)}^{+0.03}_{-0.04} \text{(PDF)} \text{pb} \]
  \[ \sigma_{\text{aMC@NLO}} = 1.98^{+0.16}_{-0.08} \text{(scales)} \pm 0.03 \text{(PDF)} \text{pb} \]

Very good agreement with predictions
Boosted $W/Z \rightarrow qq'$

- Reconstruct hadronic decay product in a single jet
- $\text{anti-}k_T \text{ R}=0.6$
- $p_T > 320 \text{ GeV}$
- Boosted back the constituents in the jet center of mass frame
- QCD jets isotropic distribution while $W/Z$ jets back-to-back topology
- Build a discriminating likelihood variable using jet shape variables in the jet CoM frame (thrust, sphericity and aplanarity)
Boosted $W/Z \rightarrow qq'$

- Signal extracted with fit to the jet mass distribution
- Background model extensively studied in control regions, in different kinematic ranges and with different MC
- Signal Model from MC
- Other small background from MC
- Signal acceptance from MC

\[ \sigma_{W+Z}(W^\pm/Z \rightarrow qq; p_T > 320 \text{ GeV}, |\eta| < 1.9) = 8.5 \pm 0.8 \text{ (stat.)} \pm 1.5 \text{ (syst.) \, pb}. \]

\[ \sigma_{W+Z}^{\text{MC} \text{F M}} = 5.1 \pm 0.5 \text{ pb}. \]

Consistent with MCFM prediction within $2\sigma$
Jet substructure: Boosted W

- Exploit jet substructure and jet shapes techniques for W tagging in searches and measurement

- Studies performance of different jet algorithm (anti-kt, CA)
- grooming combinations (trimming, pruning, split-filter, BDRS)
- Jet R (0.8, 1.0, 1.2)
- $p_T$ bins
- Data/MC comparison in QCD/Signal enriched samples
W-tagging variables

- Several tagging variables studied
  - splitting scales, width n-subjettines, mass drop, Q-jets, planar flow, subjet balance, energy correlation functions (and MVA combinations)
- Tagging performance optimized in $p_T$ bins and for different jet algorithm, grooming and size
Conclusion

• Many measurements that probe kinematics of W/Z production at LHC.

• $p_T(Z)$: low $p_T$ gives sensitivity to the parton-shower model and to resummation effects; high $p_T$ – test of higher-order calculations.

• $Z \phi^*$: probes same physics as $p_T$, but doesn't depend on momentum scale; test of resummation and parton-shower models.

• **MC tunes to $p_T/\phi^*$ data**: improved modeling of the low-$p_T$ region (crucial for W-mass measurement.)

• Hadronically decaying boosted boson:
  • Important check for searches using boosted system
  • measurement in agreement with prediction (fixed order or ME +PS)
Backup
MC Generators/Calculation

- **Low pT: (multiple soft-gluon radiation):**
  - resummation up to NNLL (RESBOS) with 2 different non-perturbative parameterization used to perform the resummation
  - parton shower (PS) techniques (PYTHIA, HERWIG),
  - ME+PS with ME $\mathcal{O}(\alpha_S)$ (MC@NLO, POWHEG);

- **High pT: (hard-gluon emission):**
  - fixed-order calculations up to $\mathcal{O}(\alpha_S^2)$ (FEWZ, DYNNLO) V+jet @NLO: MCFM, Blackhat+Sherpa)
  - multi-leg tree-level ME+PS (SHERPA, ALPGEN).
Grooming

**Clustering**

**De-clustering**

\[ \sqrt{y_f} = p_{T(p2)} \times \Delta R_{12} / M_{(j1)} \]

\[ \mu = \max(m_{(p1)}, m_{(p2)}) / M_{(j1)} \]

- **Keep**
- **Discard**

*At each step:*

- If \( \sqrt{y_f} < \sqrt{y_{\text{min}}} \), continue to next step.
- If \( \mu > \mu_{\text{max}} \), continue to next step.
- Else, keep the constituents of j1 and stop.
**Filtering**

Type 1 (Trimming): If $p_T^i / p_T^j < f_{\text{cut}}$ then discard subject.

Type 2: If $N_{\text{subjets}} \leq N_{\text{min}}$ then discard jet.

Resulting jet is sum of subjets.

**Pruning**

For each step in clustering:

\[ z = \frac{p_T^i}{p_T^{i+j}} \]
\[ p_T^i < p_T^j \]

At each step:

If $\Delta R_{ij} < d_{\text{cut}}$ OR $z > z_{\text{cut}}$

continue to next step.

Otherwise, discard object $i$. 
Z → bb

Dominant trigger

Other triggers

p_T > 250 GeV

Different kinematic regions and triggers provide consistent measurements
$W/Z \rightarrow qq'$

$\alpha = p_{\text{bal}}/M_{\text{dijet}},$ where $p_{\text{bal}}$ is the transverse momentum of the best balancing jet and $M_{\text{dijet}}$ is the invariant mass of the candidate jet - balancing jet system.
W/Z → qq'
Data/MC comparison

- Compare data and MC in background and signal enriched samples
- Background: dijet sample
- Signal: Semileptonic ttbar events (high pT lepton/MET OR HepTopTagged events)
b-jet shapes in ttbar events

- Ttbar event selection
- Jet shapes comparison: b-jet and light (W->qq)
- Sensitive to underlying event, soft gluon radiation, non-perturbative effects.
- $p_T$ bins up to 150 GeV

\[ \Psi(r): \text{Integrated energy density} \]
\[ < \Psi(r) > = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{p_T(0, r)}{p_T(0, R)} \]

\[ \rho(r): \text{Fractional energy density} \]
\[ < \rho(r) > = \frac{1}{\Delta R \cdot N_{\text{jets}}} \sum_{\text{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)} \]