Probing underlying event in Z-boson events using event shape observables

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Abstract

Experimental measurement of observables sensitive to underlying event (UE) in Z-boson events have been performed by both ATLAS and CMS experiments at the LHC. However, in the busy LHC environment, these observables receive substantial contribution from extra jets. We probe if using event shape observables in conjunction with UE observables can help us to disentangle the effect of UE from extra jets.

1 Introduction

The underlying event (UE) is defined as the activity accompanying the hard-scattering in a hadronic collision event. This includes hadronised decay products from partons not participating in a hard-scattering process (beam remnants), and additional scatters in the same proton-proton collision, termed multiple parton interactions (MPI). Initial and final state gluon radiation (ISR, FSR) also contribute to the UE activity. The soft interactions contributing to the UE
cannot be calculated reliably using perturbative quantum chromodynamics (pQCD) methods, and are generally described using different phenomenological models, usually implemented in Monte Carlo (MC) event generators. It is impossible to unambiguously separate the UE from the hard scattering process on an event-by-event basis. However, distributions have been measured that are sensitive to the properties of the UE. These measurements are critical inputs to tuning of MC event generators, especially of parameters controlling different aspects of soft-QCD.

Measurement of such distributions have been performed in Tevatron and at the LHC in several different final states, including that in Z-boson events [1–4]. Since there is no final-state gluon radiation associated with a Z-boson, lepton-pair production consistent with Z-boson decays provides a cleaner final-state environment than jet production for measuring the characteristics of the underlying event in certain regions of phase space. The direction of the Z-boson candidate is used to define regions in the azimuthal plane that have different sensitivity to the UE, a concept first used in [5]. As illustrated in Figure 1, the azimuthal angular difference between charged tracks and the Z-boson, \(|\Delta \phi| = |\phi - \phi_{Z\text{-boson}}|\), is used to define the following three azimuthal UE regions:

- \(|\Delta \phi| < 60^\circ\), the toward region,
- \(60^\circ < |\Delta \phi| < 120^\circ\), the transverse region, and
- \(|\Delta \phi| > 120^\circ\), the away region.

The away region is dominated by particles balancing the momentum of the Z-boson except at low values of \(p_T^Z\). The transverse region has been considered as sensitive to the underlying event, since it is by construction perpendicular to the direction of the Z-boson and hence it is expected to have a lower level of activity from the hard scattering process compared to the away region.

In the busy LHC environment, production of additional jets from hard radiation is seen to contaminate the transverse regions, as result they are no longer sensitive to UE only. In order to mitigate that, The two opposite transverse regions may be distinguished on an event-by-event basis through their amount of activity, as measured by the sum of the charged-particle transverse momenta in each of them. The more or less-active transverse regions are then referred to as trans-max and trans-min, respectively [6,7]. Then the trans-max region is expected to get the extra jets contribution, whereas the trans-min region is expected to be more sensitive to UE. The activity in the toward region is similarly expected to be unaffected by additional activity from the hard scatter.

However, even that approach has its limitations, as can be demonstrated by the the distribution of the transverse momentum, \(p_T\) of charged particles in the toward region in Z-boson
Figure 1: Definition of UE regions as a function of the azimuthal angle with respect to the Z-boson.
events, shown in Figure 2 from [2]. If there were no extra jets contributing to the toward region, the activity would have been same in all the $p_T^Z$ ranges, which is clearly not the case. A similar result was obtained in trans-min region as well.

In this paper, we propose that by using event topology, we can identify a region of phase space for $Z$-boson events, where the contamination from extra jets is minimal, and hence can be used to measure the UE activity more cleanly. Transverse event shape observables [8,9] are used to describe the event topology. The event shape observables in $Z$-boson events have been measured as well at the LHC [10,11].

![Figure 2: Distributions of the scalar $p_T$ sum density of charged particles, in three different $Z$-boson transverse momentum, $p_T^Z$, intervals, in the toward region [2]](image)

**2 Definition of the observables**

The UE observables measured in this analysis are derived from the number, $N_{ch}$, and transverse momenta, $p_T$, of stable charged particles in each event. These are defined for each azimuthal region under consideration. They are normalised to per unit $\eta$–$\phi$.

The event shape observables considered are the transverse thrust and transverse spherocity.
The Transverse Thrust for a given event is defined as:

\[
T_\perp = \max_{\hat{n}} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i |\vec{p}_{\perp,i}|}
\]  

(1)

where the sum is performed over all the particles in an event and \(\vec{p}_{\perp,i}\) are the transverse momenta of these particles. The unit vector \(\hat{n}\) that maximizes the sum ratio is called the Thrust axis, \(\hat{n}_T\). Transverse thrust ranges from \(T_\perp = 1\) for a back-to-back and to \(T_\perp = 2/\pi \langle |\cos \theta| \rangle\) for a circularly symmetric distribution of particles in transverse plane, respectively.

Sphericity is defined to describe isotropy of energy flow. It is based on the quadratic momentum tensor

\[
S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2} .
\]

(2)

The sphericity of the event is defined in terms of the two largest eigenvalues of this tensor, \(\lambda_2\) and \(\lambda_3\):

\[
S = \frac{3}{2}(\lambda_2 + \lambda_3)
\]

(3)

Similar to transverse thrust, the transverse sphericity is defined in terms of the transverse components only:

\[
S_{xy} = \sum_i \begin{bmatrix}
p_{x,i}^2 & p_{x,i}p_{y,i} \\
p_{x,i}p_{y,i} & p_{y,i}^2
\end{bmatrix}
\]

(4)

and

\[
S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}} ,
\]

(5)

where again \(\lambda_2^{xy} > \lambda_1^{xy}\) are the two eigenvalues of \(S_{xy}\).

Sphericity is essentially a measure of the summed \(p_T^2\) with respect to the event axis. Sphericity lies between \(0 < S < 1\), where a 2-jet event corresponds \(S = 0\) and an isotropic event to \(S = 1\).

### 3 Analysis setup

Z-bosons are reconstructed from oppositely charged muon pairs with invariant mass between 66 – 116 GeV. Muon are required to have \(p_T > 25\) GeV and \(|\eta| < 2.5\). Charged particles with \(p_T > 0.5\) GeV and \(|\eta| < 2.5\) are used to construct underlying event and event shape
observables, and muons from Z-boson decay are excluded. Jets are reconstructed using anti-$k_T$ algorithm \cite{12} with a radius parameter of $R = 0.4$, and are required to have $p_T > 25$ GeV and $|\eta| < 4.5$. A center-of-mass energy of 13 TeV is assumed.

The PYTHIA 8 \cite{13} generator were used to generate events at leading order (LO), while Madgraph \cite{14} generator was used to generate events with up to three extra jets (multileg). Events generated with Madgraph was showered with PYTHIA 8 using MLM \cite{15} matching scheme. In both cases, Monash tune \cite{16} with NNPDF2.3LO PDF \cite{17} was used. Each of these samples were generated again with turning MPI off. One million events were generated in each case.

Rivet analysis toolkit \cite{18} has been used.

4 Results

The toward region is one of the most important from the the point of view of UE. Comparing the charged particle sum $p_T$ and multiplicity density as a function of Z-boson $p_T$ obtained from PYTHIA 8 and Madgraph +PYTHIA 8 generators show that extra hard jets indeed result in much higher activity. The effect of turning off MPI is roughly a constant decrease in the activity. So the target is to find events where difference due to extra hard jets will be negligible.

![Figure 3](image)

Figure 3: Charged particle scalar sum $p_T$ (left) and multiplicity density (right) as functions of $Z$ $p_T$ in toward region, both with MPI on and off for LO and multileg setups

Looking at Figure 4, depicting inclusive distribution of transverse thrust and sphericity, it is clear that MPI results in making events more spherical.
Now combining the two sets of observables, Figure 5 shows charged particle sum $p_T$ and multiplicity density as a function of transverse thrust. A number of interesting observations can be made from these plots:

- The Madgraph +PYTHIA 8 activity slowly decreases with increase of thrust values, indicating spherical events have more activity. In fact, the activity is almost the same for Madgraph +PYTHIA 8 and PYTHIA 8 for most isotropic events. That must mean events with more activity are more spherical, while events with less activity are more dijet-like. For Madgraph this is true for multiplicity, but not true for sum $p_T$. So that will imply that in toward region Madgraph gives more soft particles compared to PYTHIA 8, causing events to be more spherical, but the spherical events have lower sum $p_T$.

- This decrease is much sharper for PYTHIA 8, resulting from the absence of extra jets. In other words, less extra jets in PYTHIA 8 causes much more isotropic events.

- Without MPI, both the distributions are mostly flat, showing that the effect of extra jets is independent of topology. The activity without MPI is non zero for PYTHIA 8, indicating presence of softer extra jets.

- For the multiplicity distribution, there is a noticeable difference from sum $p_T$ distribution. The activity falls even with extra jets, indicating MPI gives softer particles than extra jets.
Figure 5: Charged particle scalar sum $p_T$ (left) and multiplicity density (right) as functions of transverse thrust in toward region, both with MPI on and off for LO and multileg setups.

These features were seen to come almost exclusively from events with more than one jets. Transverse region profiles show same trend as toward, but are more affected by extra jets.

In Figure 6, same distributions for UE observables as a function of transverse sphericity is looked at. The features are qualitatively similar, but slightly less prominent.

Figure 6: Charged particle scalar sum $p_T$ (left) and multiplicity density (right) as functions of transverse sphericity in toward region, both with MPI on and off for LO and multileg setups.
5 Conclusions

From these results, it can be inferred that a measurement of UE observables for transverse thrust $< 0.75$, or transverse spherocity $> 0.65$ would select a class of events where the effect of extra jets is minimal. These can then help to constrain MPI in a much cleaner way in Z-boson events.

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