Preparing for measurements of dijet azimuthal decorrelations at ATLAS

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Abstract
Dijet azimuthal decorrelations are investigated in this report. We present a study on how well the event generators PYTHIA, HERWIG and HERWIG+JIMMY describe some of the recent measurements on dijet azimuthal decorrelations made by D0. We predict the correlations in the azimuthal angle between the two largest transverse momentum jets in the central rapidity for LHC inclusive dijet event samples. Reconstructed dijet azimuthal decorrelation distributions for simulated jet events at ATLAS (Rome samples) are shown to reproduce the MC event generator predictions.

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1 Introduction

At the Large Hadron Collider (LHC) \cite{1}, the predictive power of Quantum Chromodynamics (QCD) will be probed at an energy regime never achieved in previous experiments. An accurate description of QCD radiative processes is crucial for a wide range of precision measurements as well as for discoveries of new physics such as the Higgs boson and Supersymmetry (SUSY), for example.

Most of the interesting events produced in proton-proton (pp) collisions at the LHC will contain collimated sprays of particles called jets. As recently shown by the D0 Collaboration \cite{2}, a clean and simple way to study QCD radiative processes is to examine their impact on the angular distributions of jets. Their study showed that recent next-to-leading order (NLO) calculations match the measured distributions, as well as some tuned Monte Carlo event generator models \cite{2}.

In the most simple case of high-p\textsubscript{T} jet events at the LHC, a pp collision will produce two jets with equal energies transverse to the beam direction and correlated azimuthal angles (\(\phi\)), such that the azimuthal difference \(\Delta\phi\) is equal to 180°. As additional particles or additional jets are produced in the same event \(\Delta\phi\) becomes less than 180°. The production of a small number of low energetic additional particles leads to small deviations from 180°. On the other hand, small values of \(\Delta\phi\) are an indication that additional high energy jets have been produced in the event due to hard radiative emissions or, even in some cases, multiparton interactions. The azimuthal difference therefore provides an ideal testing ground to examine the transition between soft and hard QCD processes based on a single observable.

Dijet azimuthal decorrelations are investigated in this report. In section 2, we present a study on how well the event generators PYTHIA \cite{3}, HERWIG \cite{4,5} and HERWIG+JIMMY \cite{6}

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describe some of the recent measurements on dijet azimuthal decorrelations made by D0 [2]. Predictions with different jet finder algorithms are also shown in section 2. LHC predictions of correlations in the azimuthal angle between the two largest transverse momentum jets in the central rapidity are presented in section 3. In section 4, we show that reconstructed dijet azimuthal decorrelation distributions for simulated jet events at ATLAS (“Rome” jet samples) [7–11] reproduce the MC event generator predictions. Finally, in section 5 we present our conclusions.

2 Dijet azimuthal decorrelation measured by D0

The D0 Collaboration has measured azimuthal decorrelations between jets produced at high-$p_T$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [2]. They produced the first measurement of the differential $\Delta \phi_{dijet}$ distribution in dijet production at a hadron collider, i.e. $(1/\sigma_{dijet})(d\sigma_{dijet}/d\Delta \phi_{dijet})$. Jets were defined using an iterative seed-based cone algorithm (MidPoint algorithm [12]) with radius $R=0.7$ and were required to be measured in the central rapidity sector of the detector with $|y_{jet}| < 0.5$, where $y_{jet} = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$ is the jet rapidity and $E$ and $p_z$ are the energy and longitudinal momentum of the jet [2].

D0 has defined analysis regions based on the jet with largest $p_T$ in an event ($p^{\text{max}}_T$) with the requirement of very high trigger efficiency ($\sim 100\%$) [2]. We shall use three of these regions in our study: $75 < p^{\text{max}}_T < 100$ GeV, $100 < p^{\text{max}}_T < 130$ GeV and $130 < p^{\text{max}}_T < 180$ GeV. Also, similarly to the cuts applied by D0, the second leading $p_T$ jet in each event will be required to have $p_T > 40$ GeV.

Figure 1 shows $\Delta \phi_{dijet}$ distributions measured by D0 in different $p^{\text{max}}_T$ regions. We compare the D0 data to PYTHIA6.226 (fig.1(a)) and HERWIG6.506 (fig.1(b)) predictions, both generators using CTEQ6ll PDF (LO fit with LO $\alpha_s$) [13–15]. Data and predictions are scaled by successive factors of 20 for purposes of presentation. Notice that the $\Delta \phi_{dijet}$ distributions are strongly peaked, or correlated, at $\Delta \phi_{dijet} \sim 180^\circ$. Notice also that distributions are narrower for higher $p^{\text{max}}_T$ regions.

In fig. 1(a), we compare PYTHIA6.226 with the initial state radiation (ISR) parameter for the maximum parton virtuality allowed PARP(67)=1 (“low ISR”) and a model with the ISR maximum parton virtuality parameter increased four-fold, i.e. PARP(67)=4 (“increased ISR”) [3]. Both PYTHIA6.226 with low ISR and increased ISR parameters, are too narrowly peaked at $\Delta \phi_{dijet} \sim 180^\circ$. However, the two models show significant changes in the low $\Delta \phi_{dijet}$ region, where the model with increased ISR shows higher levels of azimuthal decorrelation. As suggested by D0, this measurement is sensitive to the modelling of radiation associated to ISR and, thus, provides an useful reference to tune associated event generator parameters [2]. The corresponding plot in fig. 1(b) shows that HERWIG6.506, with default parameters, describes the data reasonably well over the entire $\Delta \phi_{dijet}$ range.

2.1 Multiparton interaction models

Dijet azimuthal decorrelation distributions generated with different multiparton interaction models are shown in fig. 2. We compare D0 data to PYTHIA6.226 (fig.2(a)) and HERWIG6.506 (fig.2(b)) predictions with different multiparton interaction models.

For PYTHIA6.226 we investigate the effect of changing the parameter MSTP(82) from 1 to 4. The option MSTP(82)=1, also known as “simple scenario” [16], generates multiparton interactions in the event distributed according to Poissonian statistics. A more sophisticated
scenario is obtained by switching MSTP(82)=4 (“complex scenario”) [16], where hadrons are described as extended objects and multiple interactions are no longer distributed as a Poissonian but rather will depend on the assumed matter distribution inside the colliding hadron. Predictions generated with the two PYTHIA models are presented in fig. 2(a). There is little difference between the two predictions, and the existing difference is particularly seen for higher \( p_T \) dijet systems in the region of lower \( \Delta \phi_{dijet} \). Dijet azimuthal decorrelation with \( \Delta \phi_{dijet} \sim 100^\circ \) is caused in part by multiparton interactions, thus it is not too surprising that the use of the different scenarios for multiparton interactions in PYTHIA leads to slightly different predictions in this \( \Delta \phi_{dijet} \) region.

HERWIG does not have a multiparton interaction model as part of its main HERWIG code [4,5]. Multiple scattering events in hadron-hadron collisions are simulated by linking it to JIMMY [6]. In fig. 2(b) we compare \( \Delta \phi_{dijet} \) distributions generated with HERWIG6.506 with its default parameters and HERWIG6.506 with JIMMY4.1 with JMUEO=0, JMRAD(73)=2.13 and PRSOF=0 [17]. Decorrelation predictions remain virtually unchanged by adding the multiple interaction model JIMMY to HERWIG. As in fig. 2(a), small changes appear for higher \( p_T \) dijet systems in the region of lower \( \Delta \phi_{dijet} \).

2.2 Jet finder algorithms
We now investigate the effect of different jet finder algorithms to \( \Delta \phi_{dijet} \) distributions. Three jet algorithms were used in our study: MidPoint, JetClu and kT cluster [12]. MidPoint and JetClu
are cone based algorithms, both of them set to use R=0.7. The other class of jet algorithms, kT cluster, merges pairs of particles in order of increasing relative transverse momentum [12]. Based on past experiments, cone jet algorithms have been the jet algorithm of choice for hadron collider experiments. The kT algorithm, on the other hand, was successfully used at LEP and continue to be used by HERA experiments. Both classes of jet algorithms are planned to be used at the LHC.

Figure 3 shows Tevatron $\Delta\phi_{dijet}$ distributions for different jet algorithms. In fig. 3(a) we compare kT cluster (R=1) to MidPoint and in 3(b) JetClu is compared to MidPoint. These distributions were generated with PYTHIA6.226 - low ISR.

For most of the $\Delta\phi_{dijet}$ range shown in fig. 3, the azimuthal decorrelation is not affected by the choice of jet algorithm. At low $\Delta\phi_{dijet}$ ($\Delta\phi_{dijet} \sim 100^\circ$) some differences can be seen,
even though the results in this region are dominated by statistical uncertainty, especially for the higher \( p_T^{\text{max}} \) regions. This seems to indicate that dijet systems in which additional high energy jets have been produced due to hard radiative emissions or, in addition to that, multiparton interactions have occurred, the jet definition will impact on the \( \Delta \phi_{\text{dijet}} \) distribution.

### 3 Predictions for the LHC

Predictions for the azimuthal decorrelations between central jets produced at high-\( p_T \) in pp collisions at \( \sqrt{s} = 14 \) TeV are presented in this section.

As in the study presented by D0 [2], we define two analysis regions based on the jet with largest \( p_T \) in a LHC event (\( p_T^{\text{max}} \)): \( 180 < p_T^{\text{max}} < 500 \) GeV and \( 500 < p_T^{\text{max}} < 1200 \) GeV. In addition, the second leading \( p_T \) jet in each event will be required to have \( p_T > 80 \) GeV, jets are
defined using the MidPoint algorithm [12] with radius R=0.7 and are required to be measured in the central rapidity sector of the detector with \(|y_{jet}| < 0.5\).

Predictions for the LHC azimuthal decorrelation in different \(p_T^{max}\) regions are shown in fig. 4. We compare predictions generated with PYTHIA6.226 for PARP(67)=1 and 4 (low and increased ISR, respectively) to HERWIG6.506 with its default settings. The two PYTHIA predictions show significant changes in the low \(\Delta \phi_{dijet}\) region, where the model with increased ISR shows higher levels of azimuthal decorrelation. Note also that distributions generated with HERWIG6.506 are fairly similar to those generated with PYTHIA6.226 - increased ISR.

We have also investigated the effect of different multiparton interaction models on LHC predictions for \(\Delta \phi_{dijet}\). Figure 5(a) shows LHC predictions for \(\Delta \phi_{dijet}\) generated with PYTHIA 6.226 - MSTP(82)=1 (“simple scenario”) and PYTHIA6.226 - MSTP(82)=4 (“complex scenario”). Any difference between the model predictions is limited to the region of lower \(\Delta \phi_{dijet}\). More accurate observations require a larger statistical dijet sample.

In fig. 5(b) we compare predictions generated with HERWIG6.506 - default to HERWIG6.506 with JIMMY4.1. Once again, the two distributions look very similar and indicate that multiparton interaction models in HERWIG have little influence in the dijet azimuthal decorrelation.

4 Reconstructed dijet azimuthal decorrelations

In this section we present dijet azimuthal decorrelation distributions using ATLAS reconstructed jet events.
Fig. 5: LHC predictions for $\Delta \phi_{dijet}$ distributions in different $p_T^{max}$ regions. Comparison of (a) PYTHIA6.226 and (b) HERWIG6.506 predictions (both using MidPoint) with different multiparton interaction models.

The ATLAS simulation and reconstruction software has been intensively tested and updated in the past few years [8, 18]. Large samples of simulated physics signals and backgrounds have recently been prepared for analysis which focused on fully simulated and reconstructed events assuming the initial ATLAS geometry (“Rome” samples) [9]. Among the produced samples, there are QCD jet samples which were produced in 8 $p_T$ bins spanning a jet $p_T$ range of $p_T^{lead. jet} > 17$ GeV.

Table 1 shows the reconstructed jet samples which were produced assuming the initial ATLAS layout. The samples used in our analysis were reconstructed using ATHENA 10.0.1 [8]. PYTHIA6.226 with the ATLAS tuning [19] was the event generator used in the production of these samples [10]. The cross sections for the generated jet samples are also shown in table 1. The simulation settings used can be found in Ref. [11].
Table 1: Reconstructed QCD jet samples assuming the initial ATLAS geometry - Rome samples.

<table>
<thead>
<tr>
<th>Reconstructed jet samples [9]</th>
<th>Leading jet p_\text{T} range</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1: rome.003034.reco.J1Pt_17-35.pool.root</td>
<td>17 &lt; p_\text{T} &lt; 35 GeV</td>
<td>1.38</td>
</tr>
<tr>
<td>J2: rome.003035.reco.J2Pt_35-70.pool.root</td>
<td>35 &lt; p_\text{T} &lt; 70 GeV</td>
<td>9.32 \times 10^{-2}</td>
</tr>
<tr>
<td>J3: rome.003036.reco.J3Pt_70-140.pool.root</td>
<td>70 &lt; p_\text{T} &lt; 140 GeV</td>
<td>5.88 \times 10^{-3}</td>
</tr>
<tr>
<td>J4: rome.003037.reco.J4Pt_140-280.pool.root</td>
<td>140 &lt; p_\text{T} &lt; 280 GeV</td>
<td>3.08 \times 10^{-4}</td>
</tr>
<tr>
<td>J5: rome.003038.reco.J5Pt_280-560.pool.root</td>
<td>280 &lt; p_\text{T} &lt; 560 GeV</td>
<td>1.25 \times 10^{-5}</td>
</tr>
<tr>
<td>J6: rome.003039.reco.J6Pt_560-1120.pool.root</td>
<td>560 &lt; p_\text{T} &lt; 1120 GeV</td>
<td>3.60 \times 10^{-7}</td>
</tr>
<tr>
<td>J7: rome.003040.reco.J7Pt_1120-2240.pool.root</td>
<td>1120 &lt; p_\text{T} &lt; 2240 GeV</td>
<td>5.71 \times 10^{-9}</td>
</tr>
<tr>
<td>J8: rome.003041.reco.J8Pt_2240.pool.root</td>
<td>p_\text{T} &gt; 2240 GeV</td>
<td>2.44 \times 10^{-11}</td>
</tr>
</tbody>
</table>

There are 40,000 reconstructed events for each of the samples J1, J2, J3, J4 and J5, while for the remaining samples, J6, J7 and J8, 20,000 reconstructed events are available. Assuming that LHC jet events have been triggered, reconstructed and stored on disk, or in our case, simulated and reconstructed, then selecting suitable dijet events is the first step in the study of the dijet azimuthal decorrelation.

Fig. 6: LHC predictions for \( \Delta \phi_{\text{dijet}} \) distributions. Comparison between reconstructed and MC truth: (a) J5 jet sample and (b) J6 jet sample.

We selected dijet events from samples J5 and J6 which allow us to investigate jet p_\text{T} regions in a similar range to those shown in fig. 4. For simplicity, we will use only calorimeter information for ATLAS events.
Jets, both MC truth and reconstructed, are defined using a cone jet algorithm in which the default cone jet radius R is set to R=0.7. The second leading $E_T$ jet in each event is required to have $E_T > 80$ GeV. Both jets in a dijet system are required to be measured in the central rapidity sector of the detector with $|y_{jet}| < 0.5$. From sample J5 we required leading jets with $300 < E_{T}^{max} < 600$ GeV and from sample J6, $600 < E_{T}^{max} < 1200$ GeV.

Figure 6(a) and 6(b) show $\Delta\phi_{dijet}$ distributions comparing reconstructed and MC truth distributions for jet samples J5 and J6, respectively. In both cases, the reconstructed $\Delta\phi_{dijet}$ distribution reproduces reasonably well the MC truth distributions. Although our jet samples being analysed are statistically limited to only a few thousand selected dijet events, the plots clearly suggest that the reconstructed $\Delta\phi_{dijet}$ distributions reproduce their MC truth counterparts.

In fig. 7 we compare reconstructed and MC truth $\Delta\phi_{dijet}$ distributions generated with a cone jet radius R=0.4. Figures 7(a) and 7(b) show $\Delta\phi_{dijet}$ distributions for jet samples J5 and J6, respectively. Similarly to the distributions generated with R=0.7, reconstructed $\Delta\phi_{dijet}$ distributions for R=0.4 also seem to reproduce the MC truth distributions.

Reconstructed $\Delta\phi_{dijet}$ distributions for R=0.7 and 0.4 are compared in fig. 8. Distributions for jet samples J5 and J6 are displayed in figs. 8(a) and 8(b), respectively. Although, again, these $\Delta\phi_{dijet}$ distributions are limited by statistical uncertainties, these comparisons suggest that dijet azimuthal decorrelation measurements will not depend on the size of the cone radius used to define jets. In order to understand further the implications of jet definitions for dijet azimuthal decorrelation measurements at ATLAS, it would nonetheless be necessary an enlarged reconstructed jet sample and possibly the implementation of different jet finder algorithms.
5 Conclusions

We have investigated dijet azimuthal decorrelations in this report. Our study has been motivated by recent measurements on dijet azimuthal decorrelations made by D0 [2].

Studying how well the event generators PYTHIA6.226 and HERWIG6.505 describe D0’s measurements of $\Delta \phi_{dijet}$ distributions, we verified that HERWIG6.505 reproduce the data with its default parameters, while PYTHIA6.226 needs to be tuned. In fig. 1 it is shown that a better agreement between PYTHIA6.226 and the data is obtained with tunings which have increased ISR parton virtuality. In fact, dijet azimuthal decorrelations both at Tevatron and LHC energies (see fig. 4) have shown to be sensitive to the modeling of ISR in PYTHIA and, therefore, such a measurement will contribute to the correct tuning of this feature in the PYTHIA model. Ideally, the information obtained from dijet azimuthal decorrelation will also be combined with estimates for the ISR from $\gamma$-jet and Z-jet measurements, for example, in order to provide a more complete tuning of the ISR models used to study LHC physics.

On the other hand, the multiparton interaction model does not produce any significant change in the prediction of $\Delta \phi_{dijet}$ distributions, as can be seen in fig. 2. Here we used two multiparton interaction scenarios (MSTP(81)=1 or 4) for PYTHIA and HERWIG with and without
its multiparton scattering generator, JIMMY. There is little difference between predictions of both PYTHIA and HERWIG with their enhanced models for multiparton interactions switched on or off. The existing difference is particularly seen for higher $p_T$ dijet systems in the region of lower $\Delta \phi_{dijet}$. However, one should also note that in this region statistical uncertainties are considerably high. This indicates that dijet azimuthal decorrelation in central rapidities is not a good indicator of multiparton interactions in the event. This is confirmed by looking at LHC predictions (fig. 5) with different multiparton models which, again, do not show any significant differences due to the models employed in the event generation.

We have also investigated predictions generated with different jet finder algorithms. In fig. 3 we compared distributions generated by PYTHIA6.226 with MidPoint, kT cluster and JetClu to the D0 data. The comparison shows that for most of the $\Delta \phi_{dijet}$ range, the azimuthal decorrelation is not affected by the choice of jet algorithm. At low $\Delta \phi_{dijet}$ ($\Delta \phi_{dijet} \sim 100^{\circ}$) some differences can be seen, even though the results in this region are, again, dominated by statistical uncertainty, especially for the higher $p_T^{max}$ regions. This suggests that dijet systems in which additional high energy jets have been produced due to hard radiative emissions or systems which have been affected by multiparton interactions, the jet definition will impact on the $\Delta \phi_{dijet}$ distribution.

In section 4 we investigated $\Delta \phi_{dijet}$ distributions generated from ATLAS reconstructed jet events (Rome samples). Reconstructed dijet azimuthal decorrelation distributions for simulated jet events at ATLAS have been shown to reproduce the MC event generator predictions (figs. 6 and 7).

The results shown in fig. 8 suggest that the reconstructed $\Delta \phi_{dijet}$ distributions are independent of the cone radius size used in the cone-jet algorithm. However, due to the current large statistical uncertainty, this needs to be re-assessed with a larger number of selected dijet events.

The relatively small number of selected dijet events (few thousands for J5 and J6) in the central rapidity, which lead to large statistical uncertainties clearly noticeable in figs. 6, 7 and 8, is the main limiting factor in this study. A more detailed quantitative study based on larger statistical jet samples would, therefore, be needed in order to verify further the potential of ATLAS measurements of dijet azimuthal decorrelation.

Uncertainties in the detection of the two leading calorimeter jets have not been included in this study and should also be the subject of further investigations. However, by limiting our jet selection to the ATLAS central region ($|y_{jet}| < 0.5$) [7] and by selecting jets with relatively high $E_T$, we hope that any uncertainty contributions coming from systematic uncertainties related to jet selection will be minimized. Based on the comparisons shown here, the effects from variations of the ISR model, which can get to factors of $\sim 4$ for low $\Delta \phi_{dijet}$, are expected to be much larger than uncertainties arising from jet reconstruction. We also estimate that uncertainties due to the effect of multiparton interactions will be even less relevant to the overall systematic uncertainty than those coming from jet reconstruction.

<table>
<thead>
<tr>
<th>Integrated luminosity / Number of events</th>
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<tr>
<td>Sample J5 0.5 fb$^{-1}$ / 6.25 \times 10^6 events</td>
</tr>
<tr>
<td>Sample J6 0.5 fb$^{-1}$ / 1.8 \times 10^5 events</td>
</tr>
</tbody>
</table>

Table 2: Estimated number of events per integrated luminosity for J5 and J6 jet samples
5.1 Low luminosity measurement

The expected amount of data on tape by the end of 2008 varies between the official 10 fb\(^{-1}\) and a more conservative value of \(\sim 500\) pb\(^{-1}\) [20]. Considering that we used approximately 1.6 pb\(^{-1}\) of integrated luminosity for the analysis done with J5 events and \(\sim 56\) pb\(^{-1}\) of integrated luminosity for J6, the measurement of dijet azimuthal decorrelation can be done with considerably good statistics during the first year of data taking at ATLAS. Based on the expected rate of data taking, we estimate that the J5 jet sample will be increased by a factor ranging from 300 to 6000 compared to the sample available to us in this study. For J6, we expect the recorded sample to be increased by a factor between 9 to 180. Table 2 summarises the estimated number of events per integrated luminosity for J5 and J6 jet samples.

References


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