Abstract

The region $\eta > 3$ is a kinematic range of interest for Higgs searches, QCD physics and beyond the Standard Model studies in $pp$ interactions at TeV energies. We explore the feasibility of measuring jets in the LHCb experiment, mainly devoted to precision measurements in the $b$-physics domain, but covering the very forward region $2 < \eta < 4.5$. The jets reconstruction capabilities of LHCb are presented, together with some preliminary results on inclusive jets and dijets that show the potential interest of LHCb results for low-$x$/high-$Q^2$ perturbative QCD tests. The data have been taken at LHC during the 2010 runs at $\sqrt{s} = 7$ TeV.
1 Introduction

The LHCb detector [1] is a single arm spectrometer for the $2 \leq \eta \leq 5$ region, with excellent particle identification and charged particle tracking from vertex detector to calorimeters. Neutral pions are reconstructed using calorimeter clusters not associated to charged tracks. The detector is optimized for the reconstruction of the $b$ hadrons.

Jets are fundamental tools for the study of any process that involves final state partons, either in the Standard Model (SM) or beyond it [2, 3]. Beside the expected discovery of new particles and/or processes, jet physics in the forward region $\eta > 3$ at LHC (not covered by experiments at Tevatron) could open new opportunity for testing some specific aspects of perturbative QCD, as for example the Parton Distribution Functions (PDF) and their dynamical evolution in the proton [4, 5, 6].

Figure 1 (adapted from Ref. [7]) shows the region accessible to LHCb in the Bjorken invariants $(x, Q^2)$ plane, where $x$ is the fraction of the beam momentum carried by the colliding parton and $Q^2$ the squared momentum transfer in the partonic collision. Inclusive jet events $pp \rightarrow jet + X$ and dijet events $pp \rightarrow jet_1 + jet_2 + X$ in LHCb can provide valuable information on the PDF in a regime of $x < 10^{-3}$. This region has been already explored by H1 and ZEUS at HERA [8, 9] at $Q^2 < 10$ GeV$^2$. Figure 1 shows that new data in the region $x < 10^{-3}$ and $Q^2 > 100$ GeV$^2$ can test effectively the evolution of the PDF with $Q^2$ [7].

This preliminary analysis investigates the performance of jet detection at LHCb and establishes a benchmark for future more quantitative analysis. To do this we have exploited the low luminosity runs of the LHC commissioning phase (May–August 2010).

2 Data, event selection and jet reconstruction

Different LHCb sub-detectors are used in this analysis. The tracking system placed along the beam line of the LHC, starting with the Vertex Locator (VELO), that provides precise locations for primary $pp$ interaction vertices and contributes to the measurement of tracks momentum. The Electromagnetic Calorimeter (ECAL) used for $\pi^0$ detection and the Hadron Calorimeter (HCAL) which essentially provides the hardware trigger for jet events. These last two detectors, in combination with the 4 Tm dipole magnet, are used to measure the momentum of charged particles.

LHCb at present does not have a dedicated jet trigger. The jet reconstruction has been applied to hardware triggered events, eventually prescaled when required by the event production rate [1, 10]. Two periods of data taking in the year 2010 are included in this analysis: i) from May 10 to July 5 $(0.05 \text{ pb}^{-1})$ with a trigger requiring at least one hadron with $E_T > 0.24 \text{ GeV}$; ii) from July 12 to August 24 $(0.97 \text{ pb}^{-1})$ with a slightly harder trigger requiring $E_T > 2.26 \text{ GeV}$ for the hadron.

Events included in the analysis are required to have only one reconstructed primary vertex and a minimum of five charged tracks with $p_T \geq 0.2 \text{ GeV}/c$. Events with more than one reconstructed primary vertex have been excluded in order to get a pure sample
of jets coming from a single \( pp \) interaction. This requirement reduces the statistics by a factor \( \sim 2 \).

Jet clustering has been performed with the \( k_T \) algorithm [11, 12], as implemented in the FastJet package [13] using as inputs the four-momenta of the particles, assumed to be massless. This is similar to the “particle flow jets” (PFJ) type of reconstruction applied by the CMS experiment [14]. The uncorrected four-momentum \( \{ E^{RAW}, \vec{p}^{RAW} \} \) of the jet is calculated in the E-recombination scheme, namely as the sum of the four-momenta of its constituents. In this preliminary analysis no corrections for jet energy scale, acceptance and smearing have been applied.

Figure 2 shows examples of jet events detected in the very early runs of LHCb at \( \sqrt{s} = 7 \) TeV, with a leading jet with \( p_T^{RAW} \geq 10 \) GeV/c. There is a clear observation of dijets in the LHCb acceptance.

## 3 Results

Figure 3 shows the normalized differential raw transverse energy distribution of inclusive jet events. The raw transverse energy in the E-recombination scheme is defined\(^2\) as

\[
E_T^{RAW} = \frac{\sum E_j}{\cosh \eta_{jet}}
\]

where \( E_j \) are the energies of the constituent particles of the jet and \( \eta_{jet} \) the reconstructed pseudorapidity of the jet in the laboratory system \( \eta = -\log(\tan\theta/2) \). In this figure the experimental distribution is compared with that obtained applying the \( k_T \) algorithm to particles simulated with the LHCb MonteCarlo (LHCb-MC) program [15] based upon PYTHIA 6.4 [16] with CTEQ6-LO parton distribution functions [17], tracked through the detector with the GEANT4 package [18], taking into account the details of the geometry and material composition of the LHCb detector.

Figure 4 shows the azimuthal angle difference \( \Delta \phi = \phi_{jet_1} - \phi_{jet_2} \) between the two jets with the highest \( p_T^{RAW} \) in all the events that have at least two jets with \( p_T^{RAW} > 20 \) GeV/c. It clearly illustrates that a large number of jet pairs with \( \Delta \phi \approx \pi \) is present in the sample. The distribution of Fig. 4 is reasonably well fitted by a Gaussian peak plus a polynomial background, likely originated by the accidental pairing of a partonic jet with a jet from the underlying event.

The asymmetry parameter is defined as

\[
A = \frac{|p_T^{RAW}_{jet_1} - p_T^{RAW}_{jet_2}|}{p_T^{RAW}_{jet_1} + p_T^{RAW}_{jet_2}}.
\]

\(^2\)It is worth noticing that the transverse energy differs from the transverse momentum of the jet even if the constituent particles are assumed to be massless. In fact the transverse momentum of the jet is defined as the modulus of the vectorial sum of the projection on the x-y plane of the momenta of the constituent particles. The transverse energy is usually preferred as kinematical variable to plot because it is, at least in principle, less affected by tracking inefficiencies and uncertainties.
It is worth noting that this parameter is not changed by the jet energy scale correction if \( p_{T1}^{RAW} \approx p_{T2}^{RAW} \).

The differential distribution of the asymmetry is shown in Fig. 5 for the events in which the two leading jets have \( p_{T1}^{RAW} \) and \( p_{T2}^{RAW} > 20 \text{ GeV/c} \) and \( |\Delta \phi - \pi| < 0.7 \text{ rad.} \)

The salient features of Figs. 4 and 5 are indicative of the presence of long range QCD effects, such as the initial and final state radiation and the multiple partonic interactions.

The invariant mass of the dijet system, not corrected for jet energy scale, is defined as

\[
\tilde{M}_{jj} = \sqrt{(E_{1}^{RAW} + E_{2}^{RAW})^2 - (\vec{p}_{1}^{RAW} + \vec{p}_{2}^{RAW})^2},
\]

where \( \{E_{1}^{RAW}, \vec{p}_{1}^{RAW}\} \) and \( \{E_{2}^{RAW}, \vec{p}_{2}^{RAW}\} \) are respectively the uncorrected four-momenta of the two jets. Figure 6 shows the invariant mass distribution for the jet pairs satisfying the criteria

\[
p_{T1}^{RAW}, p_{T2}^{RAW} \geq 20 \text{ GeV/c}, \quad |\Delta \phi - \pi| \leq 40^\circ, \quad A \leq 0.2.
\]

The distribution is well described by the LHCb Monte Carlo.

The kinematics of the scattering of light partons are determined by the fraction of momentum carried by the two incoming partons \( x_1 \) and \( x_2 \) and the \( Q^2 \). The quantities

\[
\tilde{x}_{1,2} = \frac{2 p_{T1,2}^{RAW}}{\sqrt{s}} e^{\pm \eta} \cosh \frac{\Delta \eta}{2}, \quad \tilde{Q}^2 = p_{T1}^{RAW} p_{T2}^{RAW}
\]

are computed, where \( p_{T1}^{RAW} \) and \( p_{T2}^{RAW} \) are respectively the uncorrected transverse momenta of the two jets, \( \tilde{\eta} = \frac{1}{2} (\eta_1 + \eta_2) \) is the pseudo-rapidity of the centre-of-mass system of the colliding partons, \( \Delta \eta = \eta_1 - \eta_2 \) the rapidity gap, and \( \sqrt{s} = 7 \text{ TeV} \) the centre-of-mass energy of the \( pp \) collision.

The two quantities \( (\tilde{x}, \tilde{Q}^2) \) are lower estimates of the Bjorken invariants \( (x, Q^2) \). Figure 7 is indicative of the range in \( (x, Q^2) \) experimentally accessible to LHCb through the measurement of dijets. Finally Fig. 8 shows the uncorrected \( \tilde{x} \) distribution for \( \tilde{Q}^2 \) bins. Ultimately the calibrated data could be used to constrain the PDF at \( x < 10^{-3} \) and \( Q^2 > 100 \text{ GeV}^2 \).

4 Conclusion

This preliminary analysis of \( \sim 1 \text{ pb}^{-1} \) of LHCb data shows that the inclusive jet distribution and dijet characteristics can be measured by the LHCb experiment in the range \( 2 \leq \eta \leq 4.5 \). Interesting results on perturbative QCD at \( x < 10^{-3} \) are expected from the \( \sim 36 \text{ pb}^{-1} \) data obtained in the 2010 runs of LHC.

References


Figure 1: Region in the \((x, Q^2)\) plane accessible to LHCb (adapted from Ref. [7]).
Figure 2: Some illustrative events reconstructed in LHCb where the leading jet has $p_T > 10$ GeV/c from very early runs at 7 TeV. One of the runs on which we have tested the selection criteria. Jets reconstruction has been done with the $k_T$ algorithm in the E-recombination scheme with $R = 1$ and $p_T^{cut} = 1$ GeV/c. As “Underlying Event” (yellow) we classify any particle non clustered in the two jets with higher momentum, while “noise” is any track with $\chi^2/dof \geq 10$. 
Figure 3: Normalized differential raw transverse energy distribution compared with that obtained applying the $k_T$ algorithm to particles simulated with the LHCb Monte Carlo program (see text).
Figure 4: Distribution of the azimuthal angle difference $\Delta \phi = \phi_{\text{jet}1} - \phi_{\text{jet}2}$ for the two leading jets in all events that have at least two jets with $p_T > 20 \text{ GeV}/c$. The peak at $\Delta \phi \approx \pi$ is evident. The full line is the result of the fit of the data with the sum of a polynomial background (dashed line) and a Gaussian function.
Figure 5: Differential distribution of the asymmetry parameter $A$, defined by Eq. (2), for the events in which the two jets have $|\Delta \phi - \pi| < 40^\circ$. 
Figure 6: Invariant mass distribution for jet pairs with $p_T^1$ and $p_T^2 \geq 20$ GeV/c, $|\Delta\phi - \pi| \leq 40^\circ$ and $A \leq 0.2$. The dashed histogram shows the LHCb-MC (see text) simulated distribution.
Figure 7: Range in $(\tilde{x}, \tilde{Q}^2)$, defined in the text, that could be experimentally accessible to LHCb through the measurement of dijets at $\sqrt{s} = 7$ TeV.
Figure 8: Dijet $\tilde{x}$ distribution for various $\tilde{Q}^2$ ranges.