The LHCb EM calorimeter and $\pi^0$ detection

Agnieszka Jacholkowska$^{a,b,*}$

for the LHCb collaboration

$^a$CERN, EP division, CH-1211 Genève 23, Switzerland
$^b$LAL, CNRS-IN2P3, 91405 Orsay, France

Abstract

The LHCb calorimeter system comprises a preshower detector, an electromagnetic and a hadronic calorimeter. The purpose of the calorimeters is to identify and provide an energy and position measurement of photons, electrons and hadrons. The calorimeters are an essential part of the LHCb trigger, and are used in offline analysis. Good photon identification is important for the study of B decays with $\pi^0$s in the final state, an example of which is the $B_0 \rightarrow \pi^+\pi^-\pi^0$ decay. This provides an alternative channel to $B_0 \rightarrow \pi^+\pi^-$ for the measurement of the angle $\alpha$ of the unitarity triangle.

1. Introduction

The main purpose of the LHCb electromagnetic calorimeter is to trigger on electrons and photons at Level-0, and to reconstruct $\gamma$s and $\pi^0$s for physics analysis [2]. The LHCb collaboration has studied the following channels containing a $\pi^0$ or $\gamma$ from $B^0_d$ decays:

- $B^0_d \rightarrow \pi^+\pi^-\pi^0$, which produces a high-energy $\pi^0$ (up to 100 GeV). The theoretically predicted branching ratios vary between a few times $10^{-5}$ (for the $\rho^+\pi^-$ state) and a few times $10^{-6}$ (for the $\rho^0\pi^0$ state) [1].

- $B^0_d \rightarrow D^0K^*$, where the $D^0$ decays to $K^-\pi^+\pi^0$. In this channel $\pi^0$s of average energy 10 GeV are produced. The predicted branching ratios vary between $10^{-7}$ and $10^{-8}$ [2]. This $B$ decay mode allows the extraction of the angle $\gamma$ of the unitarity triangle.

- Radiative $B^0_d$ decays such as $B^0_d \rightarrow K^*\gamma$, which produce high-energy photons. The expected branching ratio from the Standard Model is a few times $10^{-5}$ [2] and any deviation from this prediction would be a signature of new physics. A special photon trigger with transverse energy ($E_t$) threshold above 4 GeV is planned.

The study of this channel allows extraction of the angle $\alpha$ of the unitarity triangle.

In the following sections the LHCb calorimeter system is described, together with its use in triggering and $\pi^0$ reconstruction. An evaluation
of the $B_d^0 \rightarrow \pi^+\pi^-\pi^0$ channel is then briefly discussed.

2. The LHCb calorimeters

The LHCb calorimeter system [2] is composed of three components: preshower detector, electromagnetic and hadronic calorimeters.

2.1. The preshower detector and pad chamber

The preshower detector plays an important role in electron and photon identification and pion rejection. Studies show that the preshower detector should provide a pion rejection factor $\sim 10$ for $E_p > 5$ GeV. Immediately upstream of the preshower detector is a pad chamber (at present the first muon chamber) which provides a space-point position measurement for electron/photon discrimination. The size of the pads in this chamber is $2 \times 4$ cm$^2$, about half of the preshower detector cell size.

The preshower detector is constructed from lead and scintillator cells of 14 and 10 mm thickness, respectively. The total depth of the preshower detector is 2.5 radiation lengths ($X_0$). The preshower detector matches the granularity of the electromagnetic calorimeter, described below. Its readout is achieved with fast photomultipliers (PMs).

2.2. The electromagnetic calorimeter

The electromagnetic calorimeter plays a major role in electron and photon identification at each LHCb trigger level. The energy and position measurements of the EM clusters allow efficient $\pi^0$ reconstruction.

The electromagnetic calorimeter has a “Shashlik”-type sampling structure. Lead and scintillators are coupled to wavelength shifting fibers (WLS) which are read out by fast PMs. There are 70 longitudinal layers with inner and outer transverse regions. These regions have granularities which are chosen to keep particle occupancy everywhere below 5–10%. The total calorimeter depth is 25$X_0$. The inner section is composed of 2620 $\times$ 4.1 cm$^2$ cells and the outer section has 3008 $\times$ 12.4 cm$^2$ cells (the Moliere radius being equal to 3.6 cm). The geometrical acceptance of the electromagnetic calorimeter is $300 \times 250$ mrad$^2$ with an inner beam hole of $30 \times 30$ mrad$^2$. The dynamic range is adapted to the different kinematical zones, and is between 50 MeV and 200 GeV in the central region. The calorimeter signals are digitized by 12 bit ADCs with a sampling time of 25 ns. The expected energy resolution is $10% / \sqrt{E}$ with a 1.5% constant term.

2.4. The level-0 trigger

The aim of the LHCb Level-0 trigger is to select B decay events with electron, hadron or muon candidates. Events are selected with measured $E_t$ or transverse momenta, $p_t$, above predefined thresholds. The requirement for this trigger level is to reduce the rate from 40 (the beam crossing rate) to 1 MHz (the maximum Level-0 rate).

For electrons and hadrons, trigger processors independently search for energy deposits in the electromagnetic and hadronic calorimeters. To reduce the number of connections in hardware, a search for the highest $E_t$ in $2 \times 2$ blocks in a region of $8 \times 8$ calorimeter cells is performed. This procedure yields approximately 100 maxima in $\sim 6000$ channels of the electromagnetic
calorimeter and approximately 25 maxima in \(\sim 1500\) channels of the hadronic calorimeter. These clusters are processed by a validation unit, where information from the pad chamber and the preshower detector is incorporated to allow shower localisation and electron–hadron discrimination. The highest \(E_i\) electron and photon candidates are selected and sent to a decision unit. For the hadron trigger, the two highest \(E_i\) candidates and the total energy are sent.

The overall efficiency of the electron trigger for reconstructable \(B^0\) events is 16\%, and for \(J/\Psi \rightarrow e^+e^-\) it is 50\%. These values correspond to an \(E_i\) cut of 2.4 GeV, giving a minimum bias event suppression factor of 100.

2.5. \(\pi^0\) reconstruction

The electromagnetic calorimeter is designed to give adequate granularity and energy resolution for \(\pi^0\) reconstruction. The LHCb spectrometer offers a 12 m lever arm.

As a first step in offline analysis, a photon candidate corresponding to an isolated electromagnetic cluster is found. This cluster results from a search for a maximum in a 3 \(\times\) 3 cell aggregation, with no pointing charged track. A gap of at least one cell is required to separate two overlapping photons. The position of the photon candidate is determined with the so-called “s-wave” algorithm [2].

Only \(\pi^0\)'s constructed from two resolved photons are used in the analysis. Fig. 1(a) shows the two photon invariant mass in \(B^0 \rightarrow \pi^+\pi^-\pi^0\) events, for photons with energy above 2 GeV. The resolution of the \(\pi^0\) mass varies between 5 and 7 MeV, dependent on the \(\pi^0\) production angle. The overall efficiency for \(\pi^0\) reconstruction is 25\%, with a signal-to-combinatorial-background ratio of approximately 1. The measured \(\pi^0\) mass is used in further \(B^0\) mass reconstruction.

3. \(B^0_d \rightarrow \pi^+\pi^-\pi^0\) analysis

The analysis of \(B^0_d\) decays to three pions can lead to an alternative measurement of \(\alpha\). This was proposed by Snyder and Quinn [3], and subsequent studies by the BaBar collaboration [1] have identified this decay mode as a most promising one. The interesting decays with \(\rho\) mesons in the intermediate state are

\[
B^0_d \rightarrow \rho^+\pi^- \rightarrow \pi^+\pi^-\pi^0,
\]

\[
\rho^0\pi^0
\]
A time-dependent analysis of the Dalitz plot allows the extraction of $\alpha$ as well as the tree and penguin terms separately. The interference between the $\rho^+ \rho^-$, $\rho^+ \rho^0$ and $\rho^- \rho^0$ amplitudes allows the determination of $\cos 2\alpha$ and $\sin 2\alpha$, and this removes some ambiguities in the determination of $\alpha$. The information about penguin amplitudes may also be interesting for other decay channels (although the penguin amplitudes for $\rho \pi$, $\pi \pi$ and $K \pi$ final states are expected to differ).

The LHCb collaboration has performed full simulation studies of the $B^0 \to \pi^+ \pi^- \pi^0$ channel. The background comes from combinatorics and from inclusive $b\bar{b}$ events. In order to suppress background the following qualitative selection cuts have been applied:

- preselection based on $p_t$ or $E_t$ cuts for charged pions and photons, respectively;
- selection of signal-like events based on a discriminant variable built from kinematic variables of the $\pi$, $\rho$ and $B^0$;
- selection based on the reconstructed secondary vertex for a $\pi^+ \pi^-$ combination;
- dalitz plot cuts to eliminate low energy $\pi^0$ combinatorial background due to particles from the primary vertex.

These selection criteria result in a combinatorial background suppression factor of the order of $10^7$ and give an acceptance for triggered and tagged events of 1%. Fig. 1(b) shows the expected $\pi^+ \pi^- \pi^0$ invariant mass distribution after one year of data taking. The measured $B^0 \to \pi^+ \pi^- \pi^0$ width is 50 MeV/$c^2$. The annual event yields for triggered, fully reconstructed and tagged events and using the theoretically predicted branching ratios [1] are

$$\rho^+ \pi^- \sim 1000 \ (BR = 44 \times 10^{-6})$$
$$\rho^- \pi^+ \sim 200 \ (BR = 10 \times 10^{-6})$$
$$\rho^0 \pi^0 \sim 50 \ (BR = 1 \times 10^{-6}).$$

The $\rho^0 \pi^0$ channel contains an energetic $\pi^0$ which allows better discrimination, resulting in a factor two increase in efficiency compared with the other decay modes. These rates are to be compared with the $B^0 \to \pi^+ \pi^-$ channel which yields $\sim 7000$ events ($BR = 7 \times 10^{-6}$) per year.

4. Conclusions

The calorimeters constitute an essential part of the LHCb spectrometer. They will be used to make
electron and photon energy and position measurements, and to trigger on electron, photon and hadron candidates at Level-0. Full event reconstruction is achieved for analyses of $B_d^0$ decays with $\pi^0$s in the final state.

The $B_d^0 \to \pi^+\pi^-\pi^0$ decay mode is considered a benchmark channel for $\pi^0$ reconstruction in the LHCb detector. The channel will be used for the determination of the angle $\alpha$ of the unitarity triangle from a time dependent Dalitz plot analysis. The expected precision after two years of running will be a few degrees.

References