RECONSTRUCTION AND CALIBRATION STRATEGIES FOR THE LHCb RICH DETECTOR

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Abstract

The LHCb experiment will make high precision studies of CP violation and rare phenomena in B hadron decays. Particle identification in the momentum range from 2-100 GeV/c is essential for this physics programme and will be provided by two Ring Imaging Cherenkov (RICH) detectors. This paper describes the performance of the different RICH reconstruction algorithms, evaluated using Monte Carlo simulations, and reports on the strategy for RICH calibration in LHCb.

INTRODUCTION

The LHCb physics programme will focus on high precision studies of CP violation and rare phenomena in B hadron decays. The ability to distinguish between pions and kaons over a large range of momenta (2 - 100 GeV/c) is essential. Particle identification (PID) will be provided by two Ring Imaging Cherenkov (RICH) detectors. Three types of radiators are used in the RICH detectors: silica aerogel and C_4F_{10} to identify particles in the range 2-50 GeV/c (RICH1); CF_4 for particles up to $\sim$ 100 GeV/c (RICH2) [1, 2]. These give rise to rings of different radii and varying number of hits per ring. The rings are detected by reflecting and focusing the cones of Cherenkov light onto arrays of hybrid photon detectors (HPDs).

The experiment will use several levels of trigger to reduce the 10 MHz rate of visible interactions to the 2 kHz that will be stored. The final level of the trigger, which runs in a processor farm, has access to the information from all sub-detectors. The standard offline RICH reconstruction is efficient [3] but is reliant on the availability of good tracking information. In addition, the algorithm is not fast enough to be used in the trigger. Alternative RICH reconstruction algorithms, that complement the standard procedure, are being investigated. Firstly, algorithms of greater robustness, less reliant on the tracking information, are being developed, using techniques such as Hough transforms and Metropolis-Hastings Markov chains. Secondly, simplified algorithms with shorter execution times, suitable for use in the trigger are being evaluated. Finally, optimal performance requires a calibration procedure that will enable the performance of the pattern recognition to be measured from the experimental data.

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LIKELIHOOD METHOD

An LHCb ring reconstruction algorithm must be able to find distorted, incomplete rings with variable radius and a variable number of hits per ring. It must be robust in the presence of background, capable of processing a large amount of information ($\sim$ 500 hits in RICH1, $\sim$300 in RICH2) and fast enough not to exceed the time limits for the event reconstruction. In particular, the ring reconstruction is very difficult in RICH1 where two different radiators are used, giving rise to overlapping rings with different characteristics. An example event can be seen in Figure 1.

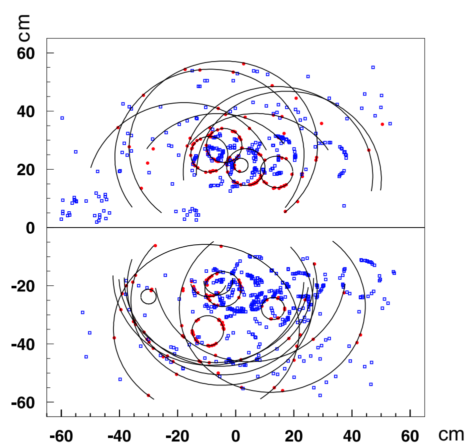

Figure 1: Event display with the photodetector planes of RICH1 drawn side by side. The Cherenkov rings predicted by the likelihood method are superimposed. A number of hits have not been assigned to a ring. These come from particles whose tracks have not been reconstructed.

The standard offline RICH reconstruction calculates for each track and photodetector hit combination a Cherenkov angle, based on the hit coordinates, the assumed track direction and emission point and the knowledge of the RICH optics. This calculation involves solving a quartic equation. As the correct association of hits and tracks is not apriori known, a pattern recognition is required. The reconstructed Cherenkov angles are compared with those expected for a given track particle hypothesis (e, μ, π, K or p). A likelihood function is calculated for the entire RICH system, and this likelihood maximised to find the best particle hypotheses.

This method has been shown to be efficient (84% efficiency for kaons and 5% efficiency for pions if identified as heavy particles, see Figure 5) [3], but it is limited by the CPU time required to solve the equation that describes the optics (~ 100 ms)[1]. This time should be compared with the order 10 ms available to run the entire final level trigger.

TRACKING-INDEPENDENT RING RECONSTRUCTION METHODS

Cherenkov rings arising from particles without associated tracks ("trackless rings") provide a dangerous correlated background to the likelihood method. The trackless ring reconstruction methods presented here, Hough transform and Markov chain, perform ring finding offline using the information from the photodetectors alone, and hence provide robustness against background which does not have associated track information.

A Hough transform [4] reconstructs a given family of shapes from discrete data points, assuming all the members of the family can be described by the same kind of equation. To find the best fitting members of the family of shapes, the data points are mapped back to the parameter space.

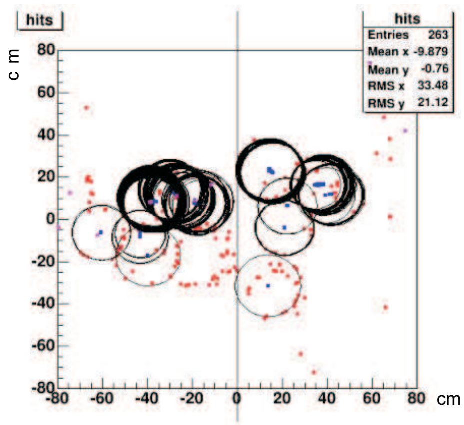

Figure 2: The Hough transform reconstructed Cherenkov rings in RICH2: hits in red, Hough centres in blue, track impact points in pink. The rings for which the Hough centres are not associated to track impact points would not have been reconstructed by the likelihood method.

A Hough transform algorithm has been implemented to find the rings in RICH2. Here the optical distortions are sufficiently small that the rings can be found using a circle search. A circular ring can be described in the data point coordinate space by:

$$f(x, y, x_0, y_0, r) = (x - x_0)^2 + (y - y_0)^2 - r^2 = 0 \quad (1)$$

where x_0, y_0 and r, being the centre and radius of the circle, are the three parameters that describe the parameter space. To find the mapping between the rings and the space of the parameters, the parameter space is quantized into a convenient number of cells. For each cell, $H(x_0, y_0, r)$, in the parameter space and for each data point, (x, y), the value associated to the content of the cell is increased by one unit if $|f(x, y, x_0, y_0, r)| < T$, where T is a tunable parameter chosen taking into account the error with which the position of the x, y points is determined and the quality requirement for the circular ring. After this procedure the cells associated with high contents indicate the possible solutions in the parameter space. The gradient direction can be used to reduce the amount of computations, since only a small number of the $H(x_0, y_0, r)$ cells, in the direction of the maximum growth of the function, need to be incremented. The preliminary results presented in Figure 2 are encouraging. Procedures to resolve the near degenerate solutions are under study.

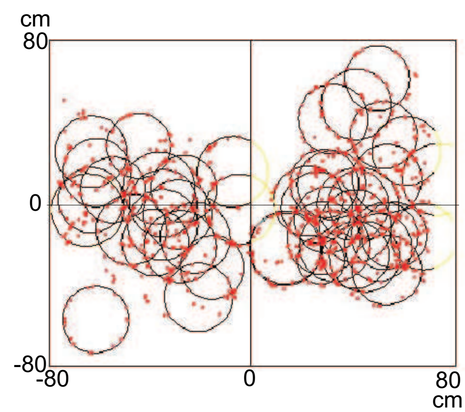

Figure 3: Rings reconstructed by the Markov chains method are visible in RICH2.

The Metropolis-Hastings Markov chains method [4] samples possible ring distributions according to how likely they would appear to have been given by the observed data points. The formalism is based on Bayes' theorem. Defining the distribution of hits as $\mathbf{H}$ and the ring distribution as $\mathbf{R}$, the probability that a certain distribution $\mathbf{R}$ is the one that gave rise to the distribution of signal hits $\mathbf{H}$, $P(\mathbf{R}|\mathbf{H})$, can be determined as:

$$P(\mathbf{R}|\mathbf{H})P(\mathbf{H}) = P_P(\mathbf{H}|\mathbf{R})P_M(\mathbf{R}) \quad (2)$$

where $P_P(\mathbf{H}|\mathbf{R})$ is the probability of obtaining a hit distribution given the process P that creates the Cherenkov rings (subject to known inefficiency, detector geometry etc), and $P_M(\mathbf{R})$ is the probability of obtaining the Cherenkov ring distribution $\mathbf{R}$ subject to the mechanism $\mathbf{M}$ that generated the Cherenkov radiation. $P(\mathbf{H})$ is the unconditional probability to obtain the hit distribution $\mathbf{H}$. Only the $\mathbf{R}$ dependence of $P(\mathbf{R}|\mathbf{H})$ is interesting, and so the factor $P(\mathbf{H})$, not depending on $\mathbf{R}$, can be set to unity. In the case of the Cherenkov ring reconstruction [5] we want to determine $P(\mathbf{R}|\mathbf{H})$. At first sight this way of redefining the problem does not appear simpler given the impossibility of defining, analytically or graphically, $P(\mathbf{R}|\mathbf{H})$, which is a function of a number of parameters equal to three times (x_0, y_0, r for each circle) the number of rings. However the Markov Chain Monte Carlo method allows values of this function

[1]This and subsequent CPU times are estimated scaling the present speed to the foreseen performance of 2007 machines.

to be sampled as a succession of elements, each of them being generated from a small number of elements preceeding it. Elements are generated based on the knowledge of the other involved probabilities. The best distribution is kept.

Preliminary results are encouraging. Fitted rings for one example event are shown in Figure 3.

ONLINE CHERENKOV RING RECONSTRUCTION

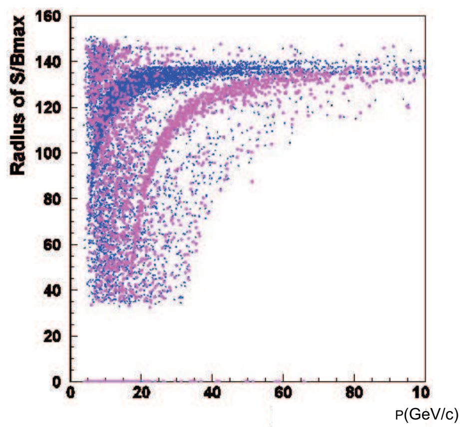

Figure 4: Radius of the rings corresponding to the most significant peak in signal/background distribution as determined by the "local" particle identification (true π in blue, true K in pink), as a function of the particle momentum.

The offline likelihood strategy of calculating the Cherenkov angle for each photon, assuming the track trajectories and knowledge of the detector optics, is unsuitable for online applications. The online ring reconstruction uses a simplified procedure for increased speed whilst maintaining acceptable performance. This makes it suitable for use in the final level trigger. To avoid solving the optics quartic equation, the Cherenkov angles are calculated directly on the photodetector plane, applying a local coordinate transformation to correct optical distortions. The algorithm reconstructs the angle for all photons relative to a particular track.

Two online particle identification methods are used:

- The "local" algorithm performs a peak search in the Cherenkov angle distribution looking for the maximum signal over background ratio. This method makes a heavy/light particle identification decision on a track-by-track basis. Having found the angle at which there is the most significant peak in the number of photons, a momentum and radiator dependent cut is made on this angle value, in order to determine whether the track came from a kaon-like or a pion-like particle. The resulting radius of the rings corresponding to the most significant peak in signal/background distribution is shown in Figure 4, as a function of the particle momentum for pions and kaons.

- The "global" algorithm is similar to the offline likelihood method but is faster since the full reconstruction is

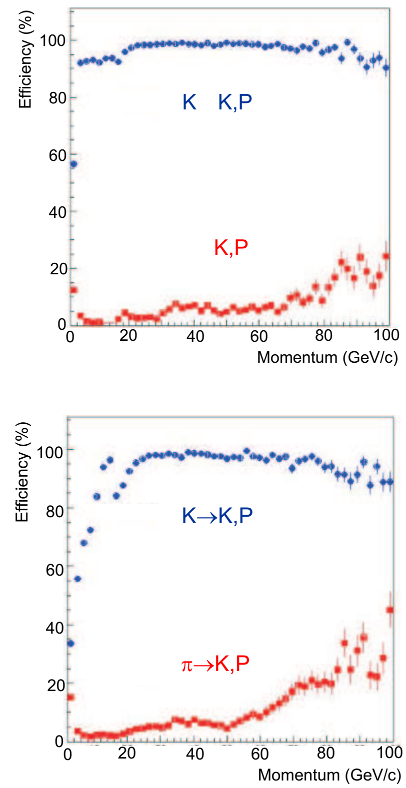

Figure 5: Offline (above) and online (below) particle identification efficiency as a function of particle momentum, for kaons identified as heavy particles and for pions misidentified as heavy particles.

not required. Rather than considering the contribution from every track to each hit, the hits within the Cherenkov angle resolution are assigned to the track with the closest predicted ring image. The event likelihood is calculated taking into account the number of hits on the rings. Only two hypotheses are considered: all tracks are initially taken to be pions, then changed in turn to kaons until the likelihood is maximised. No attempt is made to reconstruct the aerogel rings in this approach. In Figure 5 the performance of the online and offline particle identification is compared. For these plots Monte Carlo truth information is used to determine the true particle identification of the particle.

The time to perform the online reconstruction is $\sim$3 ms/event. This allows RICH particle identification to be used in the final level trigger, resulting in a substantial gain in efficiency with a comparable background rate. A 25% gain in efficiency is obtained in channels such $B_s \rightarrow \phi\phi$ and $B_s \rightarrow D_s h$ (where h is an hadron, K or π). The same algorithm can be used to reduce the background rate without any loss in efficiency, as shown in Figure 6 for $B_s \rightarrow D_s h$ decays.

RICH CALIBRATION

The decay chain $D^* \rightarrow D^0(\pi K)\pi$ can be cleanly selected without the use of RICH information. This is due to

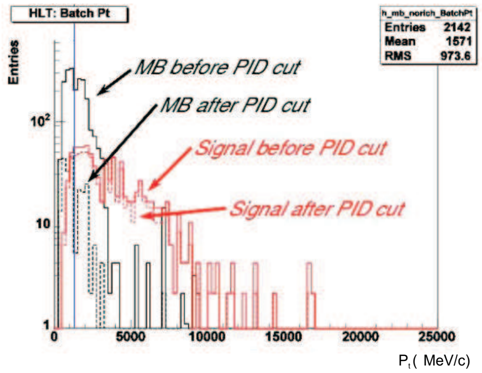

Figure 6: p_T distribution of the hadron h in $B_s \rightarrow D_s h$ candidates in the trigger. Signal and background (minimum bias = MB) events are shown before and after applying the particle identification (PID). The background falls by an order of magnitude while the signal is unaffected.

the fact that these events have a clear kinematic signature, based on the very small difference between the D^* and D^0 masses $(M_{D^*} - M_{D^0}) = 144.5$ MeV/c^2 (to be compared to the pion mass 139.5 MeV/c^2).

$D^* \rightarrow D^0(\pi K)\pi$ events are selected in the final level trigger and then offline, using kinematic information alone. These then constitute an unbiased sample which may be used to calibrate the particle identification performance for pions and kaons. The very high production cross-section of D^* events at LHC energies means that 10^8 events per year will be available with this method. Figure 7 shows a pure D^0 peak from D^*, reconstructed from 13 million minimum bias events which corresponds to only 0.8 seconds of data taking.

This sample will be used to measure the particle identification performance in real data. Figure 8 shows the performance of the kaon identification as evaluated on a sample enriched in D^* decays (92500 $B_d \rightarrow D^*\pi$ events) selected with this technique. It can be seen to closely correspond to that obtained from Monte Carlo truth information shown in Figure 5.

CONCLUSION

The performance of the LHCb RICH detectors is essential for the foreseen CP violation studies. The offline likelihood particle identification method has proved to be succesful but is reliant on good tracking performance and is futhermore too slow for online use.

Three types of methods for ring reconstruction have been investigated and their performance has been summarised. Hough transform and Markov chain methods attempt to reconstruct the rings based only on the photodetector information. An online reconstruction, fast enough to be used in the final level trigger, has been developed. Finally, a succesful calibration strategy using D^* events has been presented.

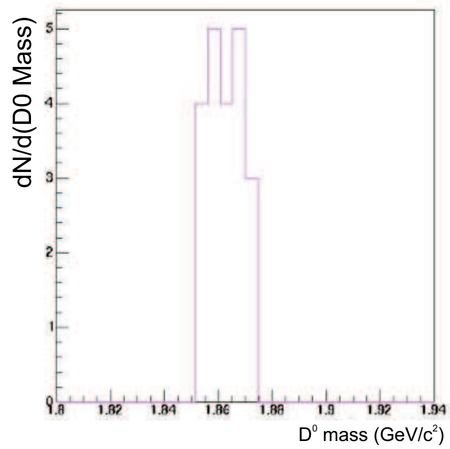

Figure 7: Distribution of the invariant mass of 21 D^0s from 13 million minimum bias events, corresponding to $\sim$0.8 seconds of data taking at $L = 2 \times 10^{32}$ cm^{-2}s^{-1}.

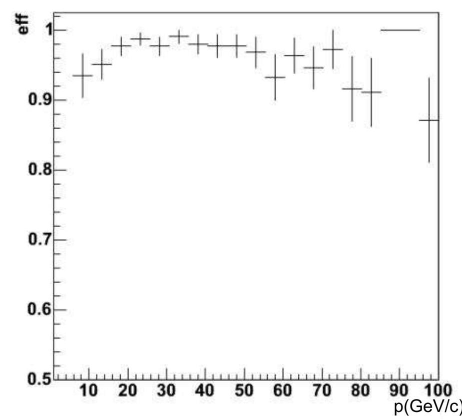

Figure 8: Efficiency of the kaon identification as evaluated with D^* events, as a function of the kaon momentum.

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REFERENCES

[1] **LHCb RICH Technical Design Report**, *CERN/LHCC/2000-0037*, LHCb TDR 3, September 2000.

[2] **LHCb Reoptimized Detector Design and Performance**, *CERN/LHCC 2003-030*, LHCb TDR 9, September 2003.

[3] R. Forty, O. Schneider, **RICH Pattern Recognition**, *LHCB/98-040*, April 1998.

[4] R.K. Bock, W. Krischer, **The Data Analysis Briefbook**, Springer 1998, ISBN:3-540-64119-X.

[5] C.G. Lester, **Trackless ring identification and pattern recognition in Ring Imaging Cherenkov (RICH) detectors**, To be published in NIM A, http://dx.doi.org/10/1016/j.nima.2006.01.073.