The LHCb experiment

C. H. Shepherd-Themistocleous [1]
Cavendish Laboratory
Cambridge University
U.K.

Abstract

LHCb is an experiment that will run at the LHC collider at CERN and is designed to explore CP violation in the B sector. A general overview of the physics motivation and the design of the detector is given.

1 Introduction

CP violation is an important and not well understood aspect of the Standard Model. To date it has only been observed in the kaon system and can be accommodated by a single phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. The origin of CP violation is closely related to the origin of mass and the reason for a least three generations of quarks and leptons. CP violation is also required to explain the baryon anti-baryon asymmetry necessary for the existence of the universe. The most promising area in which to explore this phenomenon is the B meson system where such effects are predicted to be large within the Standard Model.

The prospect of 10^{12} $b\overline{b}$ events a year at the Large Hadron Collider (LHC) at CERN affords great scope for understanding CP violation and the LHCb experiment is specifically designed to exploit this copious production. By the start of LHC operation, CP violation may have already been observed in discovery experiments such as BaBar. LHCb is a "next generation" type of experiment which will take the study of CP violation much further than will have been previously possible. The high precision and complete set of measurements possible at LHCb will allow a full exploration of CP violation both within and beyond the Standard Model. The greatest challenges of this detector are the trigger system and the Ring Imaging Cherenkov (RICH) detectors, the latter being used for particle identification, which is critical for the clean reconstruction of hadronic final states. These are also the aspects of LHCb that distinguish it most from the general purpose LHC detectors (ATLAS and CMS) and that will enable it to make more precise measurements of parameters relevant to CP violation.

2 CP violation

In the standard model CP violation is manifest as a phase in the CKM quark mixing matrix. This mixing matrix arises from the requirement to produce physical mass eigenstates which is the function of the higgs mechanism. Further a non trivial phase can only exist in the CKM matrix if it is at least a 3x3 matrix i.e. there must be at least 3 generations for CP violation to exist. This source of CP violation though does not produce an effect

[1] email: Claire.Shepherd@cern.ch

large enough to account for the observed matter in the universe. This implies that the study of CP violation is a promising place to look for effects of new physics. Since CP violation is due to interference effects will be sensitive to small "new physics" effects.

CP violation has so far only been conclusively observed in the Kaon system [2] however effects here are small and theoretical predictions hard because of hadronic uncertainties. In the B sector effects are expected to be large. This can intuitively be understood as follows: In K decays to first order only 2 generations of quarks are involved. A 2x2 "CKM" matrix does not have a non-trivial phase and hence no CP violation. To first order then kaon decays do not manifest CP violation. B decays however can involve the 3rd and 1st or even all the generations of quarks and hence CP violation can be expected to be large. Further because of the large b quark mass hadronic uncertainties can be negligible leading to much more reliable theoretical predications.

3 LHC

The LHCb detector will be at the LHC p-p collider at CERN. The luminosity at the various interaction points in tunable and LHCb have chosen to optimize the single interaction rate and to run at a luminosity of $2\text{x}10^{32}\text{cm}^{-2}\text{s}^{-1}$. The $\mathrm{b\overline{b}}$ cross-section is 500μb giving 10^{12} $\mathrm{b\overline{b}}$ pairs a year. B decay length of a few mm are obtained, but the price that has to be paid is the large background rate that will exist. This necessitates a sophisticated trigger which is described below.

A further feature of $\mathrm{b\overline{b}}$ production at the LHC is illustrated in figure 1. The $\mathrm{b\overline{b}}$ production is peaked in the forward and backward directions. This means that a detector placed to cover only the forward direction will nevertheless have a large acceptance for B events and importantly will usually contain products from the decay of both B hadrons produced. This is important for the flavour tagging described below.

4 LHCb

The principle aim of the LHCb experiment is to over constrain the CKM triangle and hence look for new physics. To do this a large number of different B decay final states must be detected. These range from low and high multiplicity hadronic final states to final states including leptons. Examples of the channels required for the different CKM angles are shown figure **??**.

Principle physics aims

- Measure the CKM angles $\alpha, \beta, \gamma, \delta\gamma$
- Determine x_s for B_s oscillations
- Look for rare decays.

To achieve these physics goals the detector must have the following properties:

[2] CDF has published [1] a measurement of β from the decay $\mathrm{B^0 \to J/\psi K_s}$

- Be able to efficiently select decays with small branching ratios ($10^{-5} - 10^{-9}$). The large cross section for $b\overline{b}$ production means interesting events are produced at the rate of one a second, but these have to be extracted from the large background. To do this a specialized trigger system is necessary.

- Detect decays in both hadronic and leptonic final states. This again influences the trigger design. Both leptonic and hadronic triggers are incorporated in the design. The use of hadronic channels means that particle identification must be available.

- Good decay time resolution is required. This is useful in a number of ways. Resolving rapid oscillations to extract x_s for B_s decays imposes stringent criteria. Time dependent analyses provide the greatest sensitivity to the CKM angles and the good vertex resolution help to reject fake vertices that lead to background contamination.

- Finally a tag of the b flavour is required in the majority of analyses.

4.1 Flavour tag

A flavour tag identifies whether the B particle in question is a B or a $\overline{B}$. The best performance is obtained from tags that make use of the fact that b quarks are produced in pairs so that by identifying the flavour of the B particle that is NOT the one that has decayed in to the signal channel of interest it is possible to deduce the flavour of the signal B in a probabilistic way. These types of tags consist of looking for leptons and kaons from the accompanying B. Other types of tags, such as a pion where this could come from a B^{**} or one produced in association with a B, are also useful for tags. These and other tags are currently under investigation.

There are a number of possible sources of wrong tags. For lepton and kaon tags an irreducible background source is B oscillations. Wrong sources such a a lepton from a charm decay instead of a B decay also produce wrong sign tags. Finally particle misidentification is also a source of wrong tags.

The requirement of a flavour tag has had number of influences on the overall design of LHCb. The first is described in the LHC section and relates to the angular distribution of $b\overline{b}$ production. Kaon tags are very important at LHCb and are made possible by the particle identification capability of the RICH detectors. The tagging kaons have relatively low momenta. This feature is the principle reason for the inclusion of aerogel in RICH1 to extend the momentum coverage to as low as 2 GeV. Finally a performance indicator derived from the performance of the tags in different triggers has also been used for optimizing the trigger design.

4.2 The LHCb detector

The LHCb detector [3] is a single arm forward spectrometer and is illustrated in figure 3. The most important features of the detector are the RICH detector which provide very good particle identification. The Si vertex detector with give excellent vertex resolution and the specialized trigger.

[3] The LHCb detector is described in detail in reference [2].

A warm dipole magnet will be used which will enable easy and frequent field reversal to remove apparent CP asymmetries induced by possible asymmetries in the overall detector efficiency. The tracking chambers will use two different technologies in the high and low occupancy regions. The final technologies to be used have yet to be decided. The design $\delta p/p$ is bout 0.3% over a momentum range of 1-200GeV. This results in good B mass resolutions of the order of 10-20 MeV depending on the channel in question.

The principle importance of the calorimeters is in the trigger (see section below). The calorimeters consist of a preshower detector followed by a Shashlik electromagnetic calorimeter and a scintillating tile hadron calorimeter. The energy resolutions are $\sigma(E)/E = 0.10/\sqrt{E} \oplus 0.015$ and $\sigma(E)/E = 0.80/\sqrt{E} \oplus 0.05$ for the electromagnetic and hadron calorimeters respectively.

The RICH detectors are illustrated in figure 4. The momentum range over which K-π separation is required is 1-150GeV. The lower end of the range is dictated by the kaon tag and the upper by two body decays of B mesons such as B$\rightarrow \pi\pi$. To cover this range there are two separate RICH detectors and the detector closest to the interaction point (RICH1) contains two different radiators, aerogel and C_4F_{10} gas. The image planes, which consist of arrays of photodetectors, are in both cases removed from the volume of the detector using tilted spherical mirrors. This means that the rings formed in the detector planes are not quite perfect circles, but are eclipses. In RICH1 two different sizes of rings are formed the the detector plane and the complexity of the task of reconstructing the rings is illustrated in figure 5. Nevertheless this task has been achieved and the effect of having particle identification available is illustrated in figure 6. The K-π separation achievable is illustrated in figure 7. From 1-150 GeV a separation of more than about 5σ is possible.

5 LHCb Trigger

The LHCb trigger is designed to extract B events of interest from the large backgrounds at the LHC. At the optimal luminosity for LHCb operation the $b\overline{b}$ production rate is very large sim100kHz however the overall interaction rate is about 16MHz. A very selective trigger is therefore required. The bunch crossing rate of 40MHz imposes two basic requirements. To run with in a deadtimeless mode detectors must be read out in less than 25ns. It is obviously impossible to also complete a complicated trigger decision is this time and so use is made of a pipelined trigger.

The are 4 levels of triggering at LHCb. The basic flow is illustrated in figure 8. The total rate reduction at any one stage is modest, between a factor of 8 and 25. Having several stages in the trigger makes it more flexible and able to adapt to adverse background conditions.

The first level, L0, makes use of the fact that the transverse momentum, with respect to the beam direction, of the B decay products is on average higher than that of other particle. The muon and calorimeter systems are used for this trigger level. The dipole magnet in LHCb means that track bending is confined largely to one plane and the muon trigger makes use of this. Tracks are reconstructed in the muon system alone and by finding the track slopes in the bending and non-bending planes an estimate of the p_t is made. The calorimeter systems determine the E_t for electrons and hadrons to provide 2 triggers.

At the operating luminosity events at the LHCb interaction point are principly single interactions. Double interaction rejection is performed at the L0 level. This is done by looking for double primary vertices using dedicated planes in the vertex detector. The total time for the L0 decision is 4μs and the accepted rate of triggers is 1MHz.

The next trigger uses the Silicon vertex detector shown in figure 9. The detector consists of double planes of Si disks. One plane has strips such that the r coordinate is measured and the other such that the phi coordinate can be measured. Track finding is done with 3 planes of r-strip detectors. A primary vertex is reconstructed by looking at tracks in opposite ϕ sectors. Having found a primary vertex the impact parameters of all the tracks are found. ϕ information is added to track with large impact parameters and then a search is made of 2 track secondary vertices. A cut is made on the probability of there being good secondary vertices for the trigger. The main backgrounds are due to low momentum tracks that suffer from large scattering and V^0s.

The L1 trigger is followed by L2. At this level various detector elements are brought together. The si only tracks are matched to tracks found in the first few tracking stations. Using the stations through the magnet. Using this information to estimate detector resolution and multiple scattering the errors on the impact parameters are estimated. A new primary vertex is estimated by minimizing the impact parameter significances. Events are retained if a least 3 tracks are found to have impact parameter significances greater than 3. This procedure reduces the contamination due to low momentum tracks that suffer large multiple scattering. This algorithm with be run on a large processor farm.

The last level of the trigger, L3, often referred to as a filter will take the information from all the subdetectors and reconstruct the events. At the start of this level of trigger almost 50% of the events are $b\overline{b}$ events and the trigger rate is about 5 kHz. All $b\overline{b}$ events cannot therefore be recorded. Events of interest are selected using loose cuts. The baseline design does not use information from the RICH detectors however this would be useful and may be implemented later.

The overall performance of the trigger in a number of channels that have widely differing final state characteristics is shown in figure 10.

6 Physics

The basic aim of the LHCb experiment is to be able to over constrain the CKM triangle so as to be able to look for new physics effects. To do this principle measurements that will be made and are the main influence on the design of the detector are to measure B_s oscillations and measure α, β, γ and $\delta\gamma$ is as many different channels as possible. [4]

The following subsections describe a few channels that will be used. They have been selected to illustrate different requirements on the detector and different physics sources of CP violation.

[4] The angle α is not directly measured. When a measurement of α is referred to it is generally meant that some combination of $\beta + \gamma$ is measured that allows α to be extracted by assuming a closed CKM triangle.

6.1 $\mathrm{B} \to \mathrm{J}/\psi \mathrm{K}_{\mathrm{s}}^{0}$

This is the standard so called "gold plated" channel used to measure the angle β. The initial state is a CP eigenstate and the CP violation is due to interference between decays with and without mixing. This is a clean channel and does not suffer greatly from the effects of contributions from penguin decays with different phases. The important penguin decay has the same weak phase as the tree diagrams. To a good approximation there are no hadronic uncertainties.

The important detector features for this channel are the ability to trigger on final states containing leptons and good tagging efficiency. The make this measurement the differences in the decay rates of the B^0 and $\overline{\mathrm{B}}^0$ decays must be measured. The best sensitivity is obtained if a time dependent measurement is performed.

No expected sensitivities are given in the following paragraphs. This is because these values are to updated very soon (early 2000) and an LHC report including the expected performance of all LHC detectors capable of studying B physics.

6.2 $\mathrm{B}^0 \to \pi\pi$

As for the $B \to J/\psi K_s^0$ decay the final state here is also a CP eigenstate however in this case there are large penguin contributions with a different weak phase and so hadronic uncertainties exist. The analysis method is the same in this channels as for $B \to J/\psi K_s^0$. It may be possible to combat the penguin problem by utilizing the isospin relation

$$A(B^0 \to \pi^+\pi^-) + \sqrt{2}A(B \to \pi^0\pi^0) = \sqrt{2}A(B^+ \to \pi^+\pi^0)$$

Reconstructing such final states as $\pi^0\pi^0$ will however be very hard if not impossible at LHCb.

An alternative method that is being investigated is the use of the $\rho\pi$ final state. This involves the analysis of time dependent Daltiz plots.

6.3 $\mathrm{B}^0 \to \mathrm{D}^*\pi$

This decay allows the extraction of the phase $2\beta+\gamma$. The final state is not a CP eigenstate but both $\mathrm{B}^0$and $\overline{\mathrm{B}}^0$decay to the same state. The CP violation here arises from interference between mixing and decay and is theoretically clean however the CP violation effect is very small. The branching ratio for the decay is large, of the order of 10^{-3} which makes use of this channel possible. The small CP violation means that very large statistics are required and hence use is make of an analysis which reconstructs D^* decays inclusively. The features of LHCb which are important for this channels are the hadron trigger and the particle identification made possible by the RICH detectors.

6.4 $\mathrm{B}^0 \to \mathrm{D}^0\mathrm{K}^*$

This channels provides a theoretically clean measurement of the angle γ. The CP violation in this channels arises from the interferences of the two amplitudes contributing to the decay $B^0 \to D_1^0 K^*$ where $D_1^0 = \frac{1}{2}(|D^0\rangle + |\overline{D^0}\rangle$ This analysis therefore requires the measurement of branching ratios in 6 channels $B^0 \to D^0 K^*$, $B^0 \to \overline{D^0} K^*$, $B^0 \to D_1^0 K^*$ and the complex conjugates. The challenge in this channel is the very small branching ratios, of the order of 10^{-7} to 10^{-8}. Fortunately in this channel no flavour tagging is required as the charged K from the K* decays give the flavour of the B^0. The LHCb features which are important for this channel are the hadron trigger and the RICH particle identification information. Figure 11 shows the effect of using the RICH information on the purity of the signal.

6.5 $\mathrm{B_s}$ oscillations

All the decay channels where a time dependent analysis is performed benefit from the excellent secondary vertex resolution achievable by the Si vertex detector. This feature of LHCb is vital to the determination of x_s for B$_s$ decays. The final state used is $D_s^- \pi^+$. LHCb will be able to reconstruct 120,000 events in this channels per year and will be able to determine Δm_s up to 48ps-1 with a significance of greater than 5%. The decay time resolution that allows this is less than 50fs.

6.6 $\mathrm{B_s \to D_s K}$

This is the final example that will be mentioned. The phase determined in this case is $\gamma - 2\delta\gamma$ and allows the angle $\delta\gamma$ to be extracted. This channel is the analogue of the B$^0 \to D^* \pi$ decay used to measure $2\beta + \gamma$. This is a theoretically clean channel where the CP violation arises in interference between mixing and decay. In this case the interferences effects are much larger than in the B$^0 \to D^* \pi$ case because there is no relative Cabibbo suppression in one of the paths to the final state. The important LHCb features are the hadron trigger, the RICH particle identification and the decay vertex resolution.

7 Conclusion

CP violation is an important and not well understood phenomenon. It is a necessary condition for the existence of the universe, but standard model sources are of insufficient magnitude to account for the matter dominated universe observed. This implies that the study of CP is a promising place to look for new physics effects. Within the standard model the effects are likely to be largest in the B system and many decays have theoretically clean predictions of the expected effects of CP violation.

The LHCb experiment has been specifically designed to study the effects of CP violation in the B system. The particle identification capabilities the precise vertexing and the specialized trigger are the principle features of the detector that will make it an ideal tool for the study of CP violation in the B system.

The ability to overconstrain the CKM triangle will, hopefully, lead to uncovering indications of physics beyond the standard model.

References

[1] FERMILAB-Pub-99/225-E , Phys.Rev.Lett. 81, 5513 (1998)

[2] S. Amato et al. (LHCb Collaboration), LHCb TEchnical Proposal CERNN/LHCC 98-4, February 20, 1998.

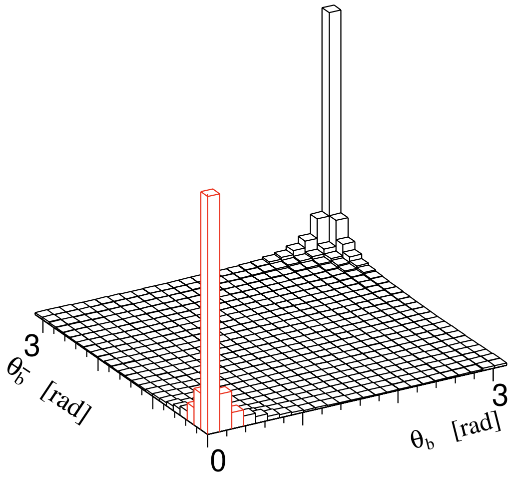

Figure 1: The angular distribution of b quarks and antiquarks at the LHC colllider.

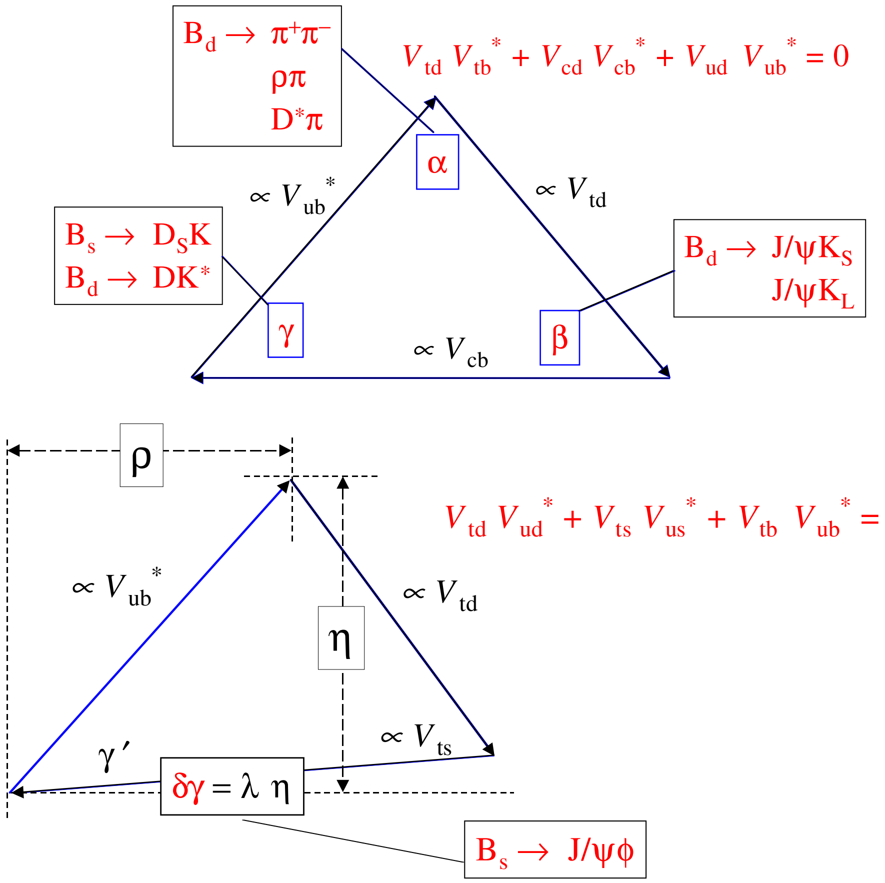

Figure 2: Triangles obtained from unitarity condition for the CKM matrix. Examples of the channels required to determine given angles are shown.

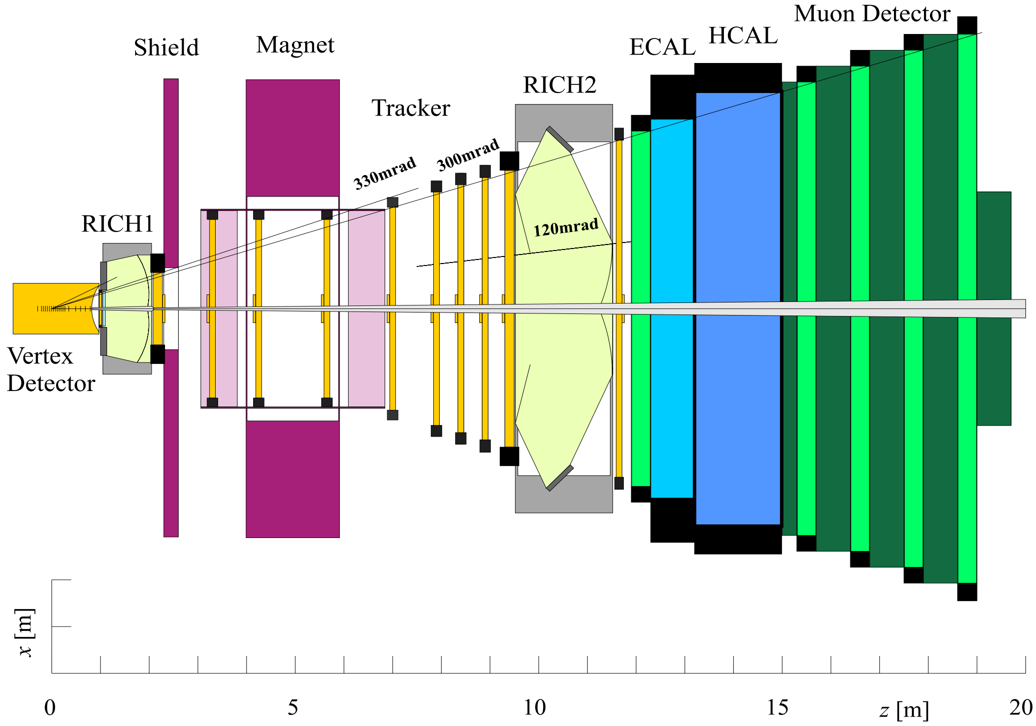

Figure 3: The layout of the LHCb detector

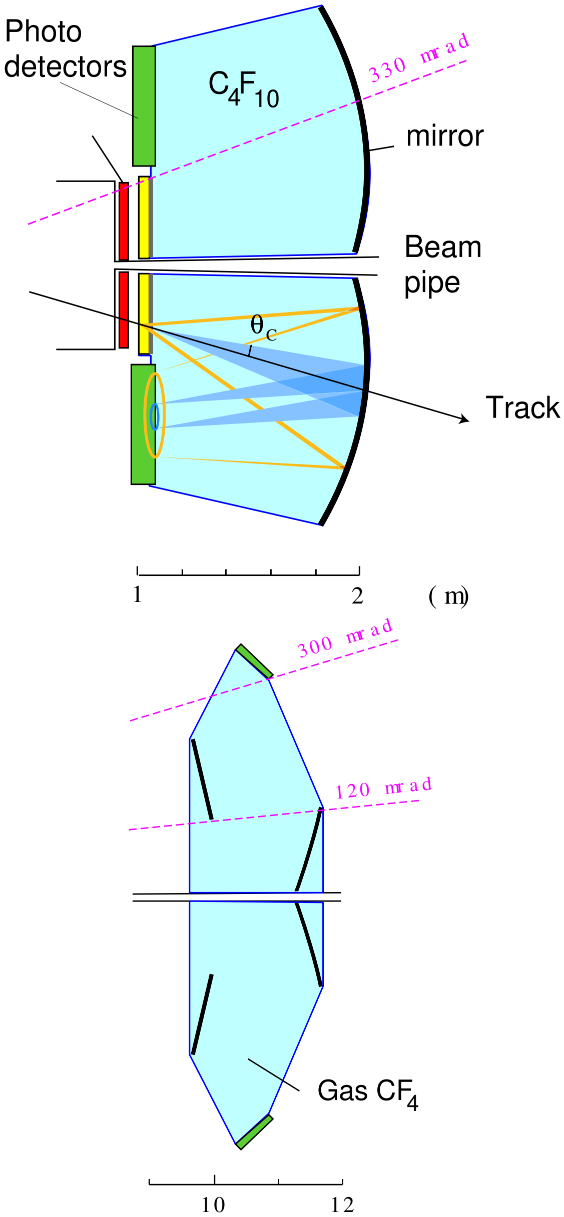

Figure 4: The two RICH detectors in LHCb. The upper figure is for RICH1 closest to the interaction point. This detector contain two radiators aerogel and C_4F_{10}. The lower is for RICH2, farthest from the interaction point and containing a single gas radiator.

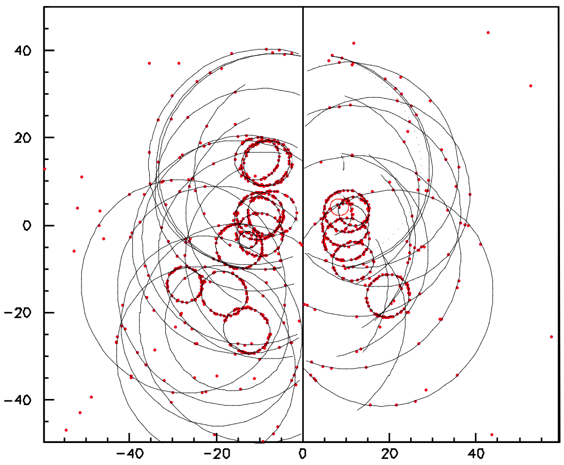

Figure 5: The distribution of photon hits in the photodetector plane of RICH1 for a simulated $B \to \pi\pi$ event. The circles are the reconstructed rings.

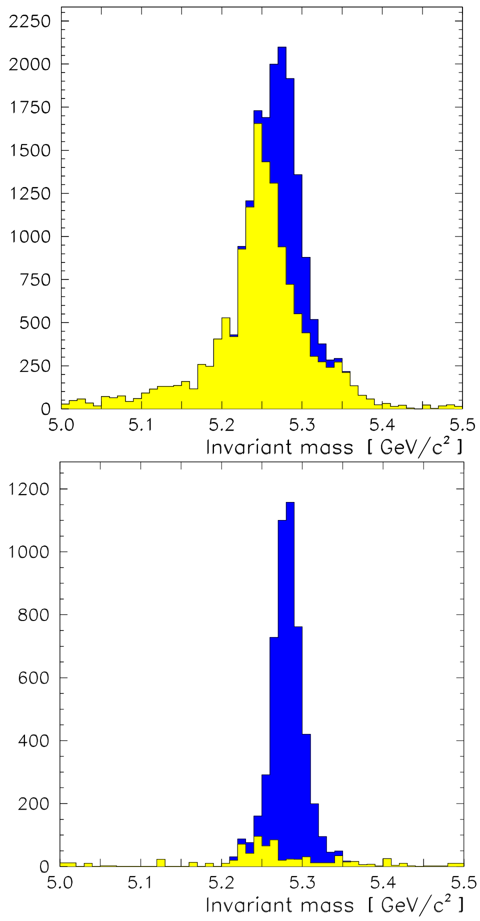

Figure 6: Plots of $\pi\pi$ invariant mass peaks in $B \to \pi\pi$ events with (bottom) and without (top) using RICH information. It can clearly be seen that the serious background from B to $K\pi$ and KK events is reduced to a negligible level by using RICH information.

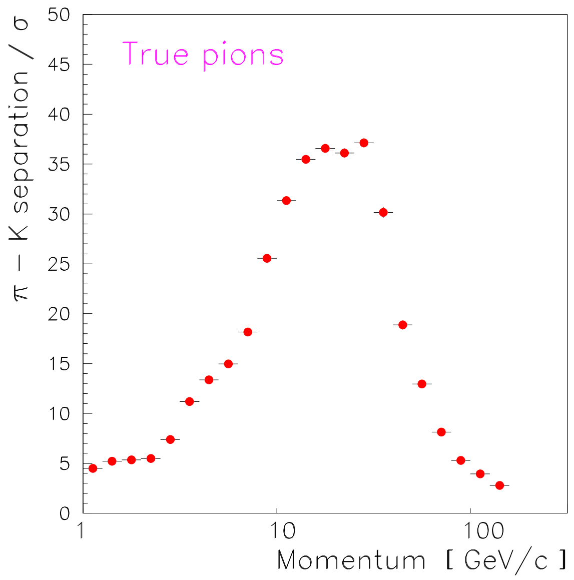

Figure 7: The number of σ for K-π separation in B $\rightarrow \pi\pi$ events.

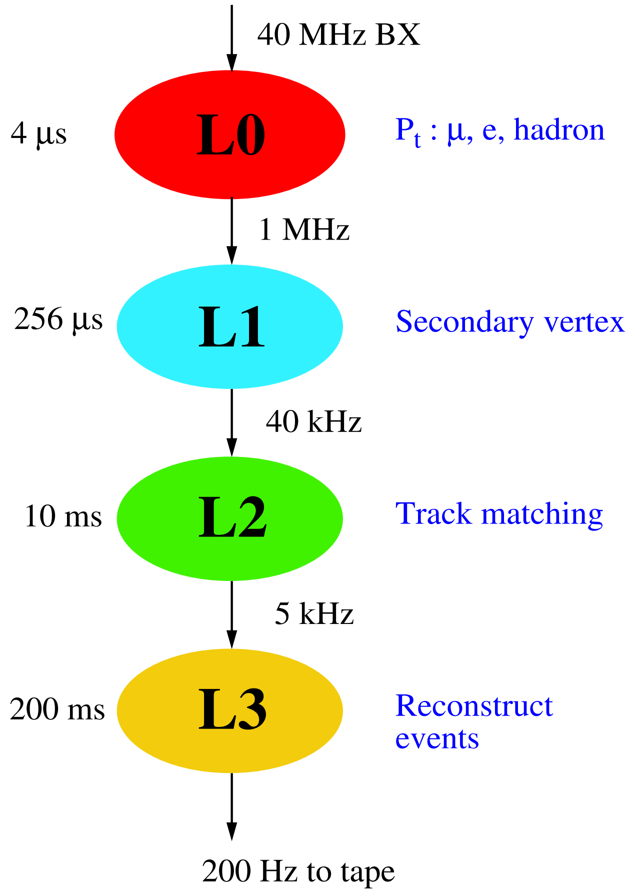

Figure 8: Outline of the flow of the LHCb trigger. The times at the left are the total time allowed for a particular trigger level. The rates are the trigger rates at the start of each trigger level.

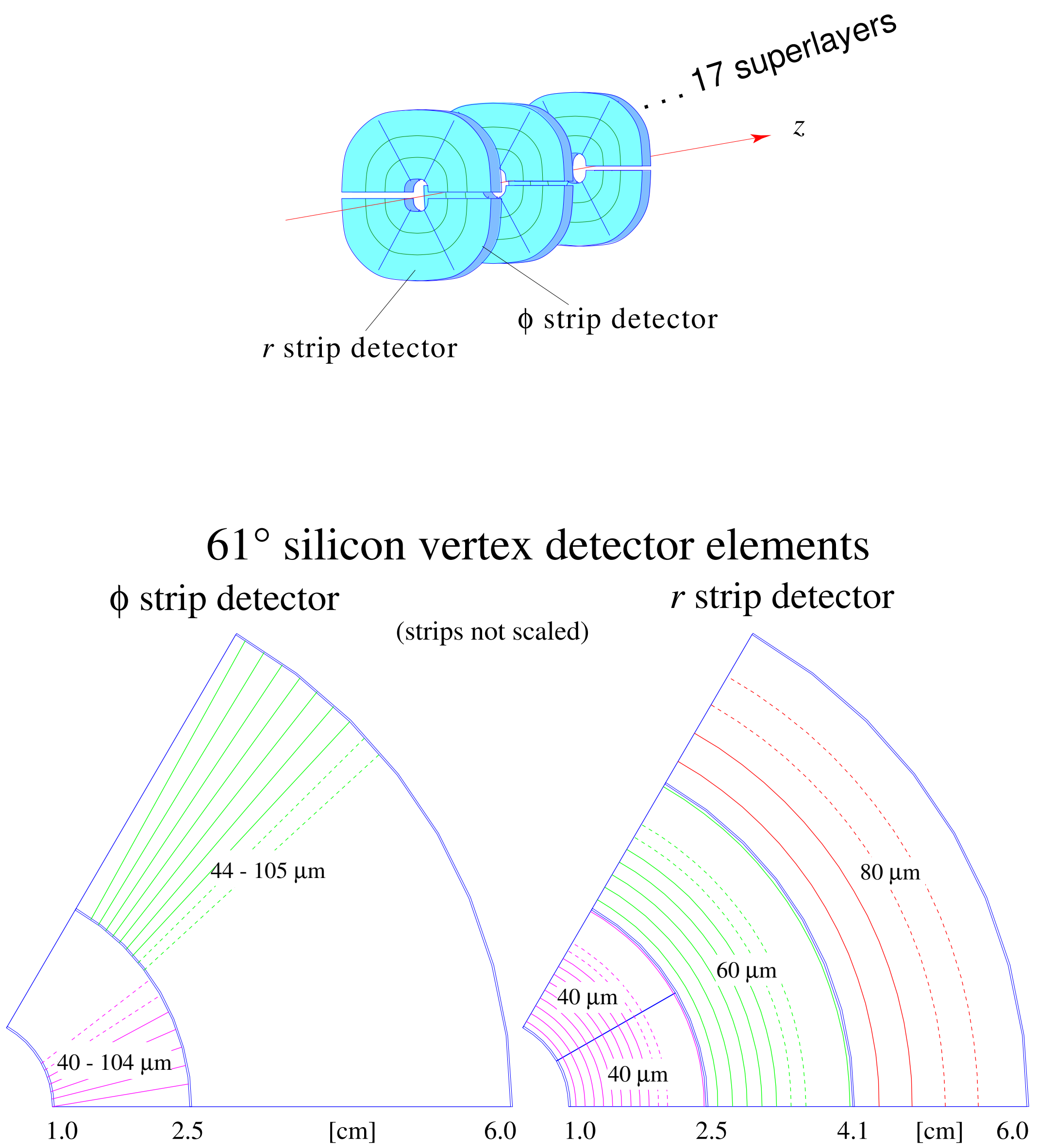

Figure 9: Si vertex detector. The layout of the detector planes and details of the r- and ϕ- detectors. The beam direction is the z direction.
N.B. Despite appearences in the top figure the disks are circular.

	L0 % μ	e	h	all	L1 %	L2 %	Total %
$B_d \to J/\psi(ee)\ K_S$ + tag	17	63	17	72	42	81	24
$B_d \to J/\psi(\mu\mu)\ K_S$ + tag	87	6	16	88	50	81	36
$B_s \to D_s K$ + tag	15	9	45	54	56	92	28
$B_d \to D K^*$	8	3	31	37	59	95	21
$B_d \to \pi\pi$ + tag	14	8	70	76	48	83	30

Figure 10: Table showing the performance of the various levels of the LHCb trigger in a number of "benchmark" channels.

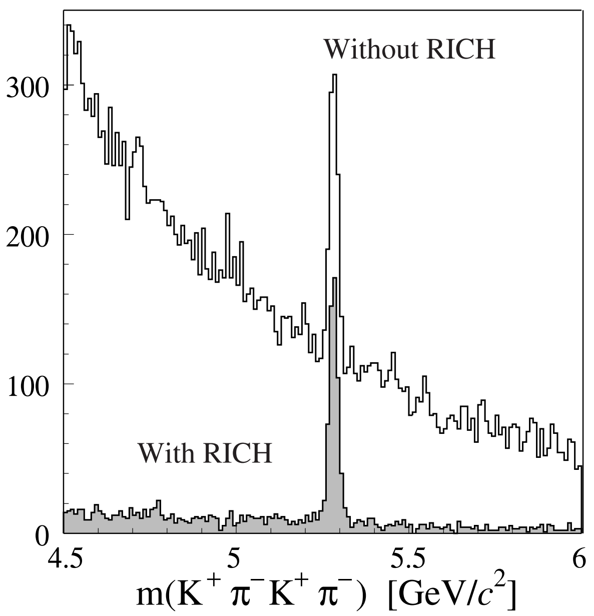

Figure 11: The plot shows the importance of the RICH particle identification information for the channel that uses D^0K^* final states. The resolution of the mass peak is about 13MeV/c^2.