Overview of the LHCb experiment

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Abstract

LHCb is a hadron collider experiment in preparation at CERN, which plans to start taking data as soon as the LHC machine becomes operational. It is dedicated to the study of CP violation and rare decays in the B-meson systems. A general overview of LHCb is given, including the physics motivations, the design of the experiment, and the expected detector, trigger, and physics performance.

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1 Physics motivations

Quark mixing in the Standard Model (SM) is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix which depends on four parameters, including a complex phase which is responsible for CP violation. Using the Wolfenstein parametrization [1], this matrix can be expanded in powers of λ , the sine of the Cabibbo angle, and approximated as

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong V_{\text{CKM}}^{(3)} + \delta V_{\text{CKM}},$$

where

$$V_{\text{CKM}}^{(3)} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(1 - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

is the expansion up to third order in λ and

$$\delta V_{\text{CKM}} = \begin{pmatrix} 0 & 0 & 0 \\ -iA^2\lambda^5\eta & 0 & 0 \\ A\lambda^5(\rho + i\eta)/2 & A\lambda^4(1/2 - \rho - i\eta) & 0 \end{pmatrix}$$

is a correction up to fifth order in λ . Two of the unitarity conditions of the CKM matrix are usually represented as triangles in the complex plane, as shown in Figure 1, with $\gamma = -\arg V_{ub}$, $\beta = -\arg V_{td}$, $\alpha = \pi - \beta - \gamma$, $\delta\gamma = \arg V_{ts} - \pi$. When δV_{CKM} is ignored, these two triangles become identical to the well-known “unitarity triangle”, with angles γ , β , α and sides joining the points $(0,0)$, $(1,0)$ and (ρ, η) . Note that $\eta \neq 0$ is required to generate Standard Model CP violation.

Before 2005, the planned date for the start of the Large Hadron Collider (LHC), many different experiments, both at e^+e^- B-factories and at hadron machines, will perform measurements in the B-meson systems which can be related to CKM matrix elements, more precisely to the angles and sides of the unitarity triangle. The length of the side opposite to the angle β , proportional to $|V_{ub}|$, will be known from $b \rightarrow u + W$ measurements, and the length of the side opposite to the angle γ , proportional to $|V_{td}|$, will be known from B-mixing measurements, although both with some non-negligible hadronic uncertainty. The knowledge of these two sides determines the triangle (the

third side having a unit length), allowing for an indirect measurement of the angles. In addition, the angle β will also be very well (and directly) measured from the CP asymmetry in $B^0 \rightarrow J/\psi K_S^0$ decays, with a combined uncertainty on $\sin(2\beta)$ most likely below 0.05. However, this will not be the case for the other angles. The low statistics measurements with decays like $B^0 \rightarrow \pi^+\pi^-$ or $B^0 \rightarrow \pi^+\pi^-\pi^0$, together with the theoretical uncertainty associated with these decays, will probably only yield a determination of α with very limited precision, and no good and direct measurement of γ will be possible either.

Although an interesting test of the SM will be performed before 2005 by comparing the direct and indirect measurements of β , more effort will be needed to fully investigate CP violation, and possibly reveal new physics beyond the Standard Model. Let us illustrate this statement with an example where new physics is present in the B^0 mixing (in the form of some new Flavour Changing Neutral Current, predicted by most SM extensions) that would compete with the usual box diagrams, and affect both the modulus and the phase of the mixing amplitude, which is proportional to $V_{tb}^{*2}V_{td}^2 \cong [(1-\rho)^2 + \eta^2] \exp(-2i\beta)$ in the SM. In other words, both the $B^0 - \bar{B}^0$ oscillation frequency and the $B^0 \rightarrow J/\psi K_S^0$ asymmetry would be affected, and therefore both the indirect and the direct measurements of β described above would be biased and no longer be measurements of the true β angle of the CKM matrix. They could however still agree with each other, within uncertainties, and in this case the new physics would not be noticed.

A clean and direct measurement of the angle γ , independent of new physics in B mixing, would clearly reveal this kind of new physics if it turned out to be inconsistent with the indirect (and biased) determination from the measured sides of the triangle. Such a measurement can be obtained from the CP asymmetries of the decays $B^0 \rightarrow D^{*\mp}\pi^\pm$ (or similar modes with more than one pion). In this case one can extract the phase $-2\beta - \gamma$, where the term -2β comes from B^0 mixing and the term $-\gamma$ from the tree decay diagrams. A measurement of γ independent of new physics in the mixing can then be extracted by subtracting this phase from the possibly biased value of -2β measured from $B^0 \rightarrow J/\psi K_S^0$ decays.

Similarly, the phase of B_s^0 mixing, $\arg(V_{tb}^{*2}V_{ts}^2) = 2\delta\gamma$, can be extracted from the CP asymmetry in $B_s^0 \rightarrow J/\psi\phi$ decays. When combined with a measurement of $2\delta\gamma - \gamma$ obtained from the CP asymmetries in $B_s^0 \rightarrow D_s^\mp K^\pm$ decays, this yields another clean determination of γ , independent of possible new physics in B_s^0 mixing.

These examples show the importance of next generation experiments dedicated to precision studies of CP violation after 2005. The LHCb experiment [2] will take advantage of the huge b-quark production in the 14 TeV proton-proton collisions provided by the LHC machine. It is designed to perform high statistics measurements of many different B^0 and B_s^0 decays, aiming in particular for channels where the extraction of CKM observables can be performed with little theoretical uncertainty. Its main goal is to measure all angles of the unitarity triangles in many different ways, over-constraining the CKM matrix including higher order terms beyond $\mathcal{O}(\lambda^3)$, and thereby searching for an inconsistency in the CKM picture that would reveal new physics.

2 Detector design and performance

The design of the LHCb detector is driven by several requirements. First, a good acceptance is needed for both b-hadrons in a $b\bar{b}$ event, providing the ability to tag the production flavour of the decaying B of interest using the other b-hadron. Since the two b-hadrons are produced predominantly at low polar angle, either both forward or both backward, a forward geometry with a single-arm spectrometer is chosen, as shown in Figure 2 and described in detail in the Technical Proposal [2]. Polar angles from 300 mrad down to 15 mrad are covered, corresponding to a pseudo-rapidity range from 1.9 to 4.9 and representing a $b\bar{b}$ acceptance of the same order as the one of a large central detector like ATLAS or CMS. The overall length of the LHCb apparatus (consisting of a vertex detector, a tracking system with a dipole magnet, RICH counters, calorimeters and a muon system) is determined by the size of the already existing experimental hall on the LHC ring assigned to LHCb; in this hall, the interaction point will have to be displaced by ~ 11 m with respect to the center.

Secondly, an efficient trigger is needed for the fully-hadronic final states of interest like $B^0 \rightarrow \pi^+\pi^-$ or $B_s^0 \rightarrow D_s^\mp K^\pm$. In addition to the traditional lepton triggers, a hadron trigger is therefore foreseen at the first level based on calorimeter information, as well as a displaced vertex trigger at the second level based on vertex detector information. The trigger scheme is discussed in Section 3.

High rates of backgrounds will have to be rejected, even after the lower

level triggers. This can be done very effectively by identifying charged particles. Two Ring Imaging Cherenkov (RICH) detectors have been designed. The first one, located just in front of the magnet, will cover polar angles up to 330 mrad and contain two radiators: C_4F_{10} gas and aerogel. The latter has a high refractive index ($n = 1.03$), ensuring a good $\text{K} - \pi$ separation down to 1 GeV/ c , and thereby efficient flavour tagging with charged kaons from $\text{b} \rightarrow \text{c} \rightarrow \text{s}$ decays of the other b-hadron. High momentum tracks, which tend to be emitted at low angles, will be identified in front of the calorimeter by a second RICH detector with CF_4 gas. This will extend the $\text{K} - \pi$ separation capability up to 150 GeV/ c , fairly close to the high end of the momentum spectrum of tracks from two-body decays like $\text{B}^0 \rightarrow \pi^+\pi^-$.

The excellent performance of the RICH system is illustrated in Figure 3 with the $\text{B}^0 \rightarrow \pi^+\pi^-$ analysis where abundant physics backgrounds with the same topology as the signal ($\text{B}_s^0 \rightarrow \text{K}^+\text{K}^-$, $\text{B}^0, \text{B}_s^0 \rightarrow \text{K}^\pm\pi^\mp$) can be rejected with a small loss in signal efficiency. This study has been performed with a complete simulation of the RICH detectors (including pattern recognition from the hits in the photodetectors) and confirms the results obtained at the time of the Technical Proposal with a fast parametrization of the response. More information on the RICH system, including the R&D progress on the photodetectors and the pattern recognition algorithms, can be found elsewhere [3, 2].

Other means of reducing the background include a good mass resolution. Because of the high particle density close to the beam axis, the tracking system is split into outer and inner subsystems at a radius of approximately 0.5 m. The baseline technologies being investigated are drift chambers with straw-tube geometry for the outer tracker and Micro-Strip Gas Chambers with Gaseous Electron Multipliers (MSGC+GEM) for the inner tracker. For the latter subsystem, silicon detectors can be used as a fall-back solution. A warm dipole magnet is now considered, instead of a superconducting one as proposed initially [2], with a modified shape but with unchanged bending power of 4 Tm. A momentum resolution of 0.3% is expected for tracks between 5 and 200 GeV/ c , and average mass resolutions of 4, 11 and 17 MeV/ c^2 for reconstructed $\text{D}_s^- \rightarrow \text{K}^+\text{K}^-\pi^-$, $\text{B}_s^0 \rightarrow \text{D}_s^-\pi^+$ and $\text{B}^0 \rightarrow \pi^+\pi^-$ decays respectively. The warm option will ease the regular reversal of the magnetic field, needed to reduce a possible systematic bias in the CP asymmetries due to non-uniformities in the detection efficiency.

A good proper time resolution is also necessary to resolve the fast $\text{B}_s^0 - \bar{\text{B}}_s^0$

oscillations, as needed for the observation of time-dependent asymmetries in B_s^0 decays. This is provided by the vertex detector, described in more detail elsewhere [4, 2]. It consists of 17 silicon stations (disks) spread on the beam axis around the interaction point; they will be mounted perpendicular to that axis on Roman pots inside the vacuum tank and can be retracted from the beams during injection. The 150 μm thick single-sided silicon detectors will have r and ϕ strips with an active radius from 1 to 6 cm, and an analogue readout. This device will provide a 40 μm resolution on the interaction point along the beam axis. The proper time resolution for $B_s^0 \rightarrow D_s^- \pi^+$ is estimated to be 43 fs, which is, with one year of data (34,500 reconstructed and tagged signal events), enough to measure B_s^0 oscillations up to $x_s = 75$, well beyond the current Standard Model prediction.

Finally one would like to have the ability to detect neutral pions. The calorimeter systems, the π^0 reconstruction and the physics reach with B decays to final states with π^0 are discussed in another contribution [5].

3 Trigger design and performance

The 25 ns bunch spacing at LHC implies that the pipeline of the front-end electronics will have to be clocked at 40 MHz. However, some of the bunch crossings in LHCb will involve empty bunches, reducing the bunch crossing rate to an effective average value of 30 MHz.

At high luminosities, several proton-proton interactions are expected in a single bunch crossing. However, LHCb is planning to reach its physics goal using only events with single interactions. This is motivated by radiation damage, detector occupancy, pattern recognition, flavour tagging and trigger issues. The detector will therefore be operated at a modest luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ for its entire lifetime (the beams will be defocused at the LHCb interaction point as the LHC machine gradually delivers its design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ to ATLAS and CMS). Under these conditions, and assuming an inelastic cross section of 80 mb, 30% (10%) of the bunch crossings will have one (more than one) proton-proton interaction.

In addition, a pile-up veto system is foreseen at the earliest trigger level: two dedicated silicon disks located upstream of the vertex detector will be used to reconstruct the longitudinal position of the interaction vertices and reject events with two or more such vertices. After this cut, the event rate

is approximately 10 MHz, with more than 90% single interactions; assuming a $b\bar{b}$ production cross-section of $500 \mu\text{b}$, this represents 5.6×10^{11} $b\bar{b}$ pairs per year (10^7 s) available in single interactions.

To extract the B decays of interest, some of them with visible branching ratios down to 10^{-7} or lower, an efficient and highly selective triggering scheme is necessary. The lower level triggers (Levels 0 and 1), will aim at rejecting non-b events. They will merely rely on the two main features of the b-hadron decays: long lifetime and significant transverse momentum release due to the high b-quark mass. The higher level triggers (Levels 2 and 3) will consist of software algorithms running on farms of commercial computers, and reject uninteresting $b\bar{b}$ events as well.

The first level of triggering (Level 0), based on calorimeter and muon chamber information only, will reduce the event rate to 1 MHz by requiring a muon, an electron or a hadron with a transverse momentum (p_T) or energy (E_T) above some threshold, typically 1, 2.1 and 2.4 GeV respectively: tracks from b-hadron decays have indeed a harder p_T spectrum than tracks from non-b events. The fractions of the bandwidth attributed to the muon, electron and hadron triggers have been chosen to maximize the overall CP reach and will approximately be 20%, 10% and 60% respectively, the rest being allocated to other triggers (high E_T photon, dimuon, ...). The Level-0 decision will take $4 \mu\text{s}$ during which the data will be kept in the pipeline of the front-end electronics. All data will be digitized after a Level-0 accept.

The Level-1 trigger achieves a further reduction in rate by a factor of 25. It uses vertex detector information to identify secondary vertices produced by the b decays [4]. Tracks are found from the hits in the silicon and a primary vertex is reconstructed; secondary vertices are then formed with large impact parameter tracks. The Level-1 buffer will reside on off-detector electronics; its depth will determine the maximum latency, which will be at least $256 \mu\text{s}$ and could be as large as 1024 or 2048. After a Level-1 accept, the zero-suppressed data are transferred to the DAQ system and the full event buffer made available to the software triggers.

Some secondary vertices found at Level 1 are fake, due to low momentum tracks undergoing multiple scattering. The aim of the Level-2 trigger is to reconstruct large impact parameter tracks in the silicon and the first tracking chambers, and use the momentum information to refine the secondary vertex requirement. At Level 3, specific b-hadron decay modes will be reconstructed and selected with loose cuts, using all available information. Approximately

200 events per second will be written to tape at a rate of 20 Mbytes/s.

The triggering scheme is summarized in Table 1. Is it robust, flexible and well balanced between the various levels. The exact operating point can be adjusted to running conditions without significant loss in physics. As an example, Figure 4 shows that, for a fixed output rate, the Level-0 thresholds can be varied in a reasonably wide range without degrading substantially the CP asymmetry measurement in the $B^0 \rightarrow \pi^+\pi^-$ channel.

The hadron trigger is essential for the fully-hadronic decay modes. As can be seen from Table 2, the overall trigger efficiencies for useful events in such modes is comparable to the ones obtained for other b-decay channels involving leptons, i.e. around 30%. It should be noted that the Level-0 trigger can not only be fired by a track from a decaying B of interest, but also by a track from the other b-hadron; in this case, the sign of the track can be used for tagging if it is identified as a lepton or a kaon. The trigger therefore ensures a respectable tagging efficiency of 40%, using these simple tags alone. The average tagging purity has been estimated to be approximately 30%.

4 Physics performance

Like any other experiment pursuing a CP violation programme, LHCb will measure the phase of B^0 mixing, i.e. the angle β , using the $B^0 \rightarrow J/\psi K_S^0$ mode. Since the dominant penguin contribution has the same weak phase as the $b \rightarrow c + W$ tree diagram, the time-dependent decay rate asymmetry of B^0 and $\bar{B}^0$ to this pure CP-odd final state is predicted, with very little theoretical uncertainty, to be $-\sin(2\beta)\sin(\Delta m t)$, where Δm is the mass difference between the two mass eigenstates of the B^0 system. With just its first year of data, LHCb will be able to reconstruct and tag 56,000 signal events: from the oscillation amplitude observed in their CP asymmetry, $\sin(2\beta)$ can be extracted with a precision of 0.017, 0.014 or 0.011 for $\beta = 0^\circ$, 20° or 30° respectively. New physics in B^0 mixing could affect β ; however, as explained in Section 1, this might not be noticed until a clean measurement of γ is performed.

The phase of B_s^0 mixing, i.e. the angle $\delta\gamma$, is best measured using the $B_s^0 \rightarrow J/\psi\phi$ mode, which is similar to $B^0 \rightarrow J/\psi K_S^0$, except that the spectator d-quark is replaced with a strange quark. However, in this case, due to the non-zero spin of the ϕ meson, the $J/\psi\phi$ final state is a CP-odd or CP-

even eigenstate, depending on the relative orbital angular momentum. An angular analysis is needed to separate the two contributions, resulting in a new dilution on the CP asymmetry, in addition to the ones due to flavour tagging and proper time resolution. Assuming no strong-phase difference between the CP-even and CP-odd eigenstates, $\delta\gamma$ can be extracted with an accuracy of 0.01 using the 44,000 reconstructed and tagged signal events expected in one year. Since the Standard Model prediction for $\delta\gamma \cong \lambda^2\eta$ is of order 10^{-2} , such experimental precision is adequate to look for new physics in B_s^0 mixing.

Several methods are investigated to measure the angle γ . The most promising ones involve the decays $B^0 \rightarrow D^{*\mp}\pi^\pm$ to extract $\gamma + 2\beta$ and $B_s^0 \rightarrow D_s^\mp K^\pm$ to extract $\gamma - 2\delta\gamma$. In each case, the absence of penguin diagrams allows a clean determination of γ , after the mixing phase (as measured from $B^0 \rightarrow J/\psi K_S^0$ or $B_s^0 \rightarrow J/\psi\phi$) has been subtracted out. Four different time-dependent decay rates can be measured, corresponding to the two B flavours at production and the two CP-conjugated final states (i.e. $B^0 \rightarrow D^{*-}\pi^+$, $B^0 \rightarrow D^{*+}\pi^-$, $\bar{B}^0 \rightarrow D^{*-}\pi^+$ and $\bar{B}^0 \rightarrow D^{*+}\pi^-$ in the first case). From these, two CP asymmetries can be formed, one for each final state, allowing the extraction of both the weak phase ($\gamma + 2\beta$ or $\gamma - 2\delta\gamma$) and the strong-phase difference between the two tree diagrams involved.

In the non-strange case, $\text{BR}(B^0 \rightarrow D^{*+}\pi^-) \ll \text{BR}(B^0 \rightarrow D^{*-}\pi^+)$ because of double Cabibbo-suppression, and the resulting CP asymmetries are very small: therefore very large statistics are required. Recent studies show that 270k signal events/year can be selected and tagged, based on a partial reconstruction of the D^0 from $D^{*-} \rightarrow D^0\pi^-$, with a reasonable signal-to-noise ratio of ~ 7 . Furthermore, the $B^0 \rightarrow D^{*\mp}a_1^\pm$ channels can be added and provide another 320k events/year, although with somewhat worse purity. If no strong-phase difference is assumed, this may yield, depending on the value of $\gamma + 2\beta$, a combined statistical precision as low as $\sim 4^\circ$ on $\gamma + 2\beta$ after 5 years of running (see Figure 5).

In the $D_s^\mp K^\pm$ case, the CP asymmetries are expected to be much larger because the two branching ratios are of the same order of magnitude. The powerful $K - \pi$ separation provided by the RICH system is here essential to eliminate the abundant background from the Cabibbo-allowed $B_s^0 \rightarrow D_s^-\pi^+$ decay. The 2400 reconstructed and tagged signal events expected with one year of data are sufficient to reach a statistical precision on $\gamma - 2\delta\gamma$ between 6° and 13° , depending on $\gamma - 2\delta\gamma$, Δm_s and the strong-phase difference.

Another interesting method to extract γ independently of B mixing consists of measuring the following 6 time-integrated rates: $B^0 \rightarrow D^0 K^{*0}$, $\bar{D}^0 K^{*0}$, $D_{CP=+1}^0 K^{*0}$ and their CP-conjugates. The D^0 ($\bar{D}^0$) meson is reconstructed in the $K^-\pi^+$ ($K^+\pi^-$) mode and the CP-even eigenstate $D_{CP=+1}^0 = (D^0 + \bar{D}^0)/\sqrt{2}$ in the K^+K^- and $\pi^+\pi^-$ modes. The charge of the kaon from the $K^{*0} \rightarrow K^+\pi^-$ decay tags the flavour of the decaying B^0 . No production state tag is needed. The RICH performance again plays a crucial role, this time to reduce the combinatorial background. Only a few hundred signal events can be reconstructed with one year of data, due to the very low visible branching ratios ($10^{-7} - 10^{-8}$). This should nonetheless yield measurements of γ and the strong-phase difference between the tree diagrams generating the $B^0 \rightarrow \bar{D}^0 K^{*0}$ and $B^0 \rightarrow D^0 K^{*0}$ decays. The statistical precision on γ , of order 10° , depends on the central values of the extracted parameters. It is foreseen [5] to improve the sensitivity with the addition of the $D^0 \rightarrow K^-\pi^+\pi^0$ mode.

The time-dependent asymmetry between $B^0 \rightarrow \pi^+\pi^-$ and $\bar{B}^0 \rightarrow \pi^+\pi^-$ will also be measured, using 6900 reconstructed and tagged signal events per year² with relatively low background (see Figure 3). This would correspond to an uncertainty of 0.05 on $\sin(2\alpha)$, if penguin diagrams could be ignored. However, penguin contributions are large; this makes the interpretation of this CP asymmetry in terms of CKM parameters difficult, as long as the ratio of penguin to tree contributions is not known or predicted accurately. The study of the three-pion modes, $B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$, described in another contribution [5], is a more promising way of measuring α .

5 Status of LHCb and summary

LHCb was approved in fall 1998 following the submission of the Technical Proposal [2]. At that time, the total investment cost was estimated to be 86 MCHF. The collaboration presently consists of 49 institutes from 15 different countries, representing approximately 500 participants. It is actively preparing the Technical Design Reports (TDR) for all the subsystems, which will be submitted at different times over the next several years. Magnet installation is foreseen during the second half of 2003, and detector installation

²This assumes $BR(B^0 \rightarrow \pi^+\pi^-) = 0.7 \times 10^{-5}$, approximately 1σ above the first preliminary measurement reported by CLEO just after this conference [6].

will start early 2004. LHCb is expected to be ready to take data at its full potential and optimal luminosity in 2005, and steadily accumulate very large statistics over the years.

The mystery of CP violation will certainly not be solved before LHC starts; the available measurements may be consistent with the Standard Model and yet still hide some undiscovered physics. Precision CP violation and rare decay measurements in the B^0 and B_s^0 systems will be needed, in many different channels, including fully hadronic modes, possibly with π^0 mesons in the final state or very low visible branching ratios.

The LHCb experiment, dedicated to this kind of physics, will rely on an efficient triggering scheme, a high performance particle identification and excellent mass and proper time resolutions to fully exploit the unique $b\bar{b}$ statistics offered by LHC. As shown in Table 3, summarizing some of the measurements expected with just the first year of data, LHCb will measure all angles of the CKM triangles with unprecedented precision and redundancy. This may lead to surprises, and will certainly improve our understanding of CP violation and its origin within or beyond the Standard Model.

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Level	Location of data	Latency	Reduction factor	Output rate
0	front-end	$4 \mu\text{s}$	10	1 MHz
1	off-detector	$512 - 2048 \mu\text{s}$	25	40 kHz
2	DAQ buffer	10 ms	8	5 kHz
3	DAQ buffer	200 ms	25	200 Hz

Table 1: LHCb triggering scheme.

Channel	Level 0				Level 1	Level 2	Levels 0–2 combined
	μ	e	h	all			
$B^0 \rightarrow J/\psi(ee)K_S^0 + \text{tag}$	17	63	17	72	42	81	24
$B^0 \rightarrow J/\psi(\mu\mu)K_S^0 + \text{tag}$	87	6	16	88	50	81	36
$B_s^0 \rightarrow D_s^\mp K^\pm + \text{tag}$	15	9	45	54	56	92	28
$B^0 \rightarrow D^0 K^{*0}$	8	3	31	37	59	95	21
$B^0 \rightarrow \pi^+ \pi^- + \text{tag}$	14	8	70	76	48	83	30

Table 2: Trigger efficiencies (in %), as determined from simulated events which can be reconstructed and correctly tagged (if needed) in the offline analysis. For Level 0, the muon (μ), electron (e) and hadron (h) triggers are listed separately as well as combined (all).

Decay modes (+cc)	Parameter	σ_{stat}
$B^0 \rightarrow J/\psi K_S^0$ ($\beta = 0^\circ, 30^\circ$)	$\sin(2\beta)$	0.017, 0.011
$B_s^0 \rightarrow J/\psi \phi$	$\delta\gamma$	0.01
$B^0 \rightarrow D^{*\mp} \pi^\pm, D^{*\mp} a_1^\pm$	$\gamma + 2\beta$	$\sim 9^\circ$
$B_s^0 \rightarrow D_s^\mp K^\pm$	$\gamma - 2\delta\gamma$	$6^\circ - 13^\circ$
$B^0 \rightarrow D^0 K^{*0}, \bar{D}^0 K^{*0}, D_{\text{CP}=+1}^0 K^{*0}$	γ	$\sim 10^\circ$
$B^0 \rightarrow \pi^+ \pi^-$ (no penguin)	$\sin(2\alpha)$	0.05

Table 3: Expected statistical precision on the angles of the CKM unitarity triangles from a few LHCb analyses with one year (10^7 s) of data taken at a luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

Figure 1: Two unitarity conditions of the CKM matrix, represented as triangles in the Wolfenstein parametrization with an approximation valid up to $\mathcal{O}(\lambda^5)$.

Figure 2: Layout of the LHCb detector in the bending (horizontal) plane, as proposed in 1998 [2].

Figure 3: Reconstructed $\pi^+\pi^-$ mass before and after cuts based on RICH information, for simulated $B^0 \rightarrow \pi^+\pi^-$ signal (light histograms) and background from other two-body B decays (dark histograms). The background consists here of $B^0 \rightarrow K^\pm\pi^\mp$, $B_s^0 \rightarrow K^+K^-$, and $B_s^0 \rightarrow K^\pm\pi^\mp$ decays, with respective branching ratios of 2, 2, and 1, in units of the $B^0 \rightarrow \pi^+\pi^-$ branching ratio.

Figure 4: This plot shows how the expected significance of the CP asymmetry measured with $B^0 \rightarrow \pi^+ \pi^-$ decays, proportional to $\sqrt{\epsilon}(1 - 2\omega)$ where ϵ is the efficiency and ω the mistag probability, varies as a function of the fractions of events accepted at Level 0 by the muon and the hadron triggers, for a fixed total fraction of 9% (including the electron trigger). In the two shaded areas, the significance exceeds 90% or 95% of its maximal value. The cross indicates the optimal operating point that maximizes the overall CP sensitivity of the experiment.

Figure 5: Statistical uncertainty on $2\beta + \gamma$, as a function of $2\beta + \gamma$, expected with 1 year or 5 years of data recorded at a luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ using the decays $B^0, \bar{B}^0 \rightarrow D^{*\mp}\pi^\pm, D^{*\mp}a_1^\pm$. The ratio between the Cabibbo-allowed and doubly Cabibbo-suppressed decay amplitudes is assumed to be known at the 5% level, and no strong-phase difference is assumed between these two amplitudes.