LHCb-2007-100

THE LHCb EXPERIMENT*

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LHCb is an experiment dedicated to the search for new phenomena in heavy flavour physics at the LHC. This review summarises the readiness of the experiment and the status of preparations for the first physics data scheduled for 2008. An overview of the expected physics highlights in the first few years of data-taking are presented and the prospects for a further programme of heavy flavour physics in the LHC era with a ten-fold increase in statistics is discussed.

1. Introduction

In recent years the Standard Model description of quark flavour physics has surpassed all expectations. The first generation B factory experiments, BABAR at PEP-II and BELLE at KEKB, together with CDF and D0 at the TEVATRON, have provided a plethora of measurements¹ that substantially constrain the CKM picture of the Standard Model². It is now apparent that the role of LHCb is to search for New Physics beyond the Standard Model through precision measurements of CP-violating observables and the study of very rare decays of charm and beauty flavoured hadrons.

This review presents an overview of the Standard Model picture of quark flavour physics, discusses the role of the LHCb experiment in the search for New Physics, summarises the current status of the experiment and its preparations for first physics, and introduces the concept of a future upgrade to the experiment to provide a heavy flavour physics programme at the LHC for many years to come.

*On behalf of the LHCb collaboration.

[†]Work partially supported by the Royal Society.

1.1. The CKM picture

We start with a gentle reminder of the Standard Model phenomenology describing the interactions between quarks. In the Standard Model with three fermion families, the weak charged current can be written as

$$J_\mu = (\bar{u}, \bar{c}, \bar{t})_L \gamma_\mu V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \quad (1)$$

where V_{CKM} is the unitary 3×3 Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix³ which describes the rotation between the weak eigenstates (d', s', b') and the mass eigenstates (d, s, b),

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (2)$$

The CKM matrix can be written explicitly as

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (3)$$

where V_{ij} is the matrix element coupling the i^{th} up-type quark to the j^{th} down-type quark. For the equivalent transitions between anti-quarks, the matrix elements are replaced by their complex conjugates (see Fig. 1). The CKM matrix has 4 independent parameters, 3 real and 1 complex phase, which are fundamental constants of nature and must be determined from experiment. It is the presence of the complex phase in the CKM matrix that introduces CP-violation into the Standard Model.

Figure 1. The Standard Model first order (tree-level) diagrams for a) a transition between a b and a u quark and b) the equivalent transition between anti-quarks.

A very popular parameterization of the CKM matrix is the perturbative form suggested by Wolfenstein⁴ which reflects the hierarchy of the

strengths of the quark transitions. The parameters of the Wolfenstein parameterization are $A = 0.818^{+0.007}_{-0.017}$, $\lambda = 0.2272 \pm 0.0010$ ⁵ (the sinus of the Cabibbo angle), ρ and η ; η represents the complex part of the matrix and, if non-zero, implies that CP-violation is present in the Standard Model. The CKM matrix can be expanded in terms of λ and is often approximated to $\mathcal{O}(\lambda^3)$,

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \quad (4)$$

In the LHC era, next-to-leading order corrections will play an important role and we need to consider the CKM matrix to $\mathcal{O}(\lambda^5)$,

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 + \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5(\frac{1}{2} - \rho - i\eta) & 1 - \frac{1}{2}\lambda^2 + \frac{1}{8}\lambda^4(1 - 4A^2) & A\lambda^2 \\ A\lambda^3(1 - \tilde{\rho} - i\tilde{\eta}) & -A\lambda^2 + A\lambda^4(\frac{1}{2} - \rho - i\eta) & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}, \quad (5)$$

where $\tilde{\rho}$ and $\tilde{\eta}$ are given by $\tilde{\rho} = \rho(1 - \lambda^2/2)$ and $\tilde{\eta} = \eta(1 - \lambda^2/2)$.

The unitarity of the CKM matrix implies that there are six orthogonality conditions, each requiring the sum of three complex numbers to vanish. These can be represented geometrically in the complex plane as triangles and are known as the *unitarity triangles*. All six triangles have the same area which is a measure of the amount of CP-violation in the Standard Model. Two of the unitarity triangles, corresponding to the conditions

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (db)$$

$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0, \quad (ut)$$

have all 3 sides of comparable magnitude, $\mathcal{O}(\lambda^3)$. These two triangles are shown in Fig. 2 by choosing a phase convention such that $V_{cd}V_{cb}^*$ is real and dividing the lengths of all the sides by $|V_{cd}V_{cb}^*| = A\lambda^3$. The two triangles are identical to $\mathcal{O}(\lambda^3)$ and differ only by $\mathcal{O}(\lambda^5)$ corrections. The unitarity triangle *db* is commonly referred to as *the* unitarity triangle.

The angles of the triangle *db* are denoted by α , β and γ ;

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right). \quad (6)$$

In addition, higher order terms in the CKM matrix introduce a phase in the matrix element V_{ts} such that the relationship between the angles β and

Figure 2. The unitarity triangles a) db and b) ut . The phase convention of *the* unitarity triangle, db , is chosen such that $V_{cd}V_{cb}^*$ is real and all sides are normalized to $|V_{cd}V_{cb}^*|$.

γ and the equivalent angles in the ut triangle are modified by an angle χ . The angles β , γ and χ , are related to the Wolfenstein parameters through

$$\beta = -\arg\{V_{td}\} = \tan^{-1} \left[\frac{\tilde{\eta}}{1 - \tilde{\rho}} \right], \quad \gamma = -\arg\{V_{ub}\} = \tan^{-1} \frac{\eta}{\rho}, \quad \text{and} \quad \chi = \arg\{V_{ts}\} - \pi = \eta\lambda^2. \quad (7)$$

Allowance for the possibility of New Physics beyond the Standard Model description of B^0 mixing is made by defining

- the B_d^0 mixing phase, $\phi_d = \arg\{M_{12}^d\} = 2\beta + \phi_d^{NP}$ and
- the B_s^0 mixing phase, $\phi_s = \arg\{M_{12}^s\} = -2\chi + \phi_s^{NP}$

where M_{12} is the dispersive part of the $B^0 - \overline{B}^0$ mixing amplitude in the

Standard Model and $\phi_{d,s}^{NP}$ is the phase of any New Physics entering into the box diagrams. We also refer to γ as the *weak decay phase* which can be measured using $b \rightarrow u$ transitions but can also be affected by New Physics in loop diagrams.

1.2. *Current status*

The current status of all the measurements that constrain the unitarity triangle is shown in Fig. 3 and 4². A first observation is that the constraint on the apex of the unitarity triangle using measurements of $|V_{ub}/V_{cb}|$ and γ from pure tree-level processes, $\tilde{\rho} = 0.00 \pm 0.15$ and $\tilde{\eta} = 0.41 \pm 0.04$ (Fig. 4a)) gives categorical evidence for the presence of CP-violation in the CKM matrix, since $\eta \neq 0$. The above constraint also provides a benchmark by which New Physics must abide since it is expected that tree-level processes are unaffected by New Physics. It is therefore very important that an accurate measurement of γ is performed to pin-down this benchmark. A second observation is that the agreement between the constraint on the unitarity triangle from CP-conserving quantities ($|V_{ub}/V_{cb}|$, Δm_d and Δm_s) and CP-violating quantities (α , β , γ and ϵ_K), shown in Fig. 4b), implies that the CKM phase is dominant and that any New Physics can only appear as a small correction to the Standard Model.

1.3. *The quest for New Physics*

The arguments for searching for New Physics beyond the Standard Model are compelling⁶. In particular, New Physics is required to cancel radiative corrections to the Higgs mass whilst leaving the Standard Model electroweak predictions unaffected (the so-called *hierarchy problem*). It is also widely believed that the Standard Model cannot be the ultimate theory and is simply a low-energy effective theory of something more fundamental at a higher energy scale, $\mathcal{O}(1)$ TeV.

So how will New Physics be discovered at the LHC ? It is expected that any New Physics model will introduce new particles which could be produced and discovered directly as real particles by ATLAS/CMS^{7,8}. In addition, the new particles could appear indirectly as virtual particles in loop processes, such as those shown in Fig. 5. This would provide observable deviations from the Standard Model expectations and is a priority goal of LHCb. The direct and indirect approaches to the discovery of New Physics are very complementary and it will become increasingly important that, once New Physics has been discovered, to measure its flavour structure to

Figure 3. The current status of measurements constraining the apex of the unitarity triangle. The 68% and 95% c.l. probability contours are shown.

Figure 4. a) The constraint on $\bar{\rho}$ and $\bar{\eta}$ from tree-level processes through measurements of γ using $B \rightarrow D^{(*)}K$ decays and $|V_{ub}/V_{cb}|$ and b) a comparison of the constraint on $\bar{\rho}$ and $\bar{\eta}$ from CP-conserving quantities compared to the measurements of CP-violating quantities.

distinguish between the various New Physics models ⁹.

Figure 5. Examples of Standard Model loop processes; a) the $B^0 - \bar{B}^0$ box diagram and b) the penguin decay diagram, in which new particles could appear.

The search for new phenomena in heavy flavour physics with LHCb will be approached from two directions. The first will be the measurement of processes which are very suppressed in the Standard Model, such as

- CP-violation in B_s^0 mixing;
- radiative and very rare B decays;
- rare D decays and D^0 mixing; and
- lepton flavour violating decays.

The second approach, which requires clean and improved theoretical predictions, will be the precision measurements of the CKM angles and matrix elements, using

- B_s^0 oscillations;
- the comparison of pure tree-level processes with processes that include loop diagrams; and
- the search for inconsistencies in measurements of the angles and sides of the unitarity triangles.

2. The LHCb Experiment

The LHCb experiment ¹⁰, shown in Fig. 6, is a single-arm forward spectrometer with a polar angle coverage of 15-300 mrad and a pseudo-rapidity range of $1.9 < \eta < 4.9$. The pp interaction point is displaced by ~ 11 m and, together with low-beta insertions in the final focussing magnets, enables LHCb to run at a lower luminosity, $2 - 5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, compared to the nominal LHC luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$). The lower luminosity maximises the probability of a single interaction per beam crossing (see Fig. 7),

thereby simplifying the event reconstruction and reducing radiation levels. Even with the lower luminosity, the $b\bar{b}$ cross-section is large, $\sim 230 \mu\text{b}$, and corresponds to $\sim 10^{12}$ $b\bar{b}$ produced per year (10^7 s).

Figure 6. A schematic of the LHCb experiment.

Figure 7. Probabilities for having 0, 1, 2, 3, 4 pp interactions per bunch crossing as a function of luminosity at LHCb.

Other significant physics advantages of studying B physics at the LHC and, in particular, in the forward region are:

- all species of B hadrons ($B^\pm$, B_d^0 , B_s^0 , $B_c^\pm$ and b-baryons) are produced;
- the average momentum of the B hadrons is about 80 GeV, corresponding to a mean decay length of ~ 7 mm, thereby allowing a good decay time resolution to be achieved;
- a large number of primary particles determine the B production vertex; and
- both the b - and $\bar{b}$ -hadrons in a single event are predominantly produced in the same direction; the detection of both at the same time is essential for tagging the flavour of B mesons at production.

The LHCb detector is comprised of a silicon strip vertex locator (VELO), a 4 Tm warm dipole magnet, a tracking system, two Ring Imaging Cherenkov detectors, a calorimeter system and a muon system. The VELO consists of 21 stations separated by 3 cm located around the interaction region. Each station provides a measurement of the azimuthal and radial track coordinates and consists of two semi-circular silicon sensors which can be moved to within 8 mm of the beam in stable running conditions. The other tracking detectors consist of a silicon strip tracker situated upstream of the magnet which provides p_T information for use in the trigger, and three tracking stations downstream of the magnet. These are constructed from kapton-aluminium straw tubes in the outer region and silicon strips in the inner region. The measurement of the impact parameter of tracks relative to the primary vertex is crucial for the identification of secondary vertices and is made with a precision of $(14 + 35/p_T) \mu\text{m}$. The overall performance of the tracking system provides a proper time resolution of ~ 40 fs and a B mass resolution of ~ 15 MeV for most B decays of interest.

The particle identification for the experiment is provided by two RICH detectors. RICH1, upstream of the magnet, utilizes two radiators (aerogel and C_4F_{10}) and covers a momentum range of 2 – 60 GeV. RICH2, downstream of the magnet, utilizes a CF_4 gas radiator and provides a momentum coverage of 16 – 100 GeV. In both RICH detectors, the Cherenkov light is focussed by a system of mirrors on to planes of Hybrid Photo-Diodes (HPDs). Each HPD contains an array of 1024 silicon pixels (pixel size $0.5 \text{ mm} \times 0.5 \text{ mm}$) and an overall granularity of $2.5 \text{ mm} \times 2.5 \text{ mm}$ for the determination of the position of photons on the photodetector plane. This measurement, combined with the measurement of track momenta (better

than 0.5%), provides an expected kaon efficiency and misidentification probability as shown in Fig. 8 ¹¹.

Figure 8. The kaon identification efficiency (top curve) and pion misidentification probability (bottom curve) provided by the LHCb RICH detectors.

The calorimeter system for the experiment comprises a preshower detector consisting of a 2.5 radiation length lead sheet sandwiched between two scintillator plates, a 25 radiation length lead-scintillator shashlik geometry electromagnetic calorimeter and a 5.6 interaction length iron-scintillator hadron calorimeter. The expected mass resolution for isolated (merged) π^0 's is $\sim 10(15)$ MeV, resulting in an overall selection efficiency of $\sim 53\%$ for $B_d^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$ decays and an estimated precision on the CKM angle α of approximately 10° for 2 fb^{-1} of data ¹². The muon system consists of 5 planes of detectors (M1-M5) which are comprised of a total of 1368 multi-wire proportional chambers and 24 triple-GEM detectors in the inner region of M1, where the occupancy is the highest.

At the time of writing, the majority of the detector has been installed and started commissioning. LHCb is confident that the complete detector will be ready to take first LHC physics data in 2008.

2.1. The trigger

The LHCb trigger ¹³ is crucial to the successful operation of the experiment. This is because the B fraction is only $\sim 1\%$ of the inelastic cross-section,

the branching ratios of the B decays of interest is small ($< 10^{-4}$) and the properties of the minimum-bias events is similar to those of the B hadrons. Hence, the LHCb trigger exploits the fact that B -hadrons are long-lived, resulting in a secondary decay vertex far from the primary vertex, and have a high mass, resulting in decay products with large p_T . In the forward region, momenta are mainly carried by the longitudinal components. Therefore, the threshold value for the p_T trigger can be set low for electrons, muons and hadrons without being constrained by the detector requirements, thereby making the p_T trigger more efficient than in the central region.

The LHCb trigger consists of two-levels. The first level trigger (L0) is designed to reduce the 40 MHz interaction rate to 1 MHz. This is achieved by employing custom electronics which selects electrons, photons, muons or hadrons above a given threshold in p_T , typically 1-4 GeV. The L0 trigger utilizes information from the muon system and calorimeters only and has a latency of $4\mu\text{s}$. The L0 selected events are then transmitted to a High Level Trigger based on a processor farm with 1800 nodes. The HLT has access to the data from all the sub-detectors and, by successive application of algorithms, selects and records a total of 2 kHz of data.

3. LHCb Start-up Physics Programme

In the current schedule for the start-up of the LHC, it is planned that physics running at $\sqrt{s} = 14$ TeV will commence during 2008. In the very early phase of running, LHCb will have a full programme of work to finalise the commissioning of all the sub-detectors and trigger, align the detectors in time and space, and perform calibration of momenta, energy and particle identification. During this period it is expected that the experiment will collect an integrated luminosity of $\sim 0.5 \text{ fb}^{-1}$ of physics data. In subsequent years, the experiment will develop its full physics programme and estimates that an integrated luminosity of 2 fb^{-1} per year will be collected in stable running conditions.

A brief overview of some of the expected physics highlights during the first phase of the experiment follows.

3.1. *Very rare B decays*

3.1.1. $B_s^0 \rightarrow \mu^+ \mu^-$

The decay $B_s^0 \rightarrow \mu^+ \mu^-$ is very sensitive to New Physics since the Standard Model branching ratio is expected to be very small, $\text{Br}(B_s^0 \rightarrow$

$\mu^+\mu^-) = (3.4 \pm 0.4) \times 10^{-9}$ ¹⁴. However, it can be greatly enhanced in certain SUSY scenarios¹⁵. Assuming the Standard Model branching ratio, a total of 70 events is expected with 2fb^{-1} of data at LHCb^{16,17}. The main backgrounds arise from two sources, a) random combinations of a μ^+ and a μ^- originating from two distinct B decays and b) from $B \rightarrow hh$, where the hadrons (h) are misidentified as muons. Both backgrounds are addressed by the very good mass resolution of LHCb; the second also by the excellent particle identification. The expected LHCb sensitivity as a function of integrated luminosity is shown in Fig. 9. A 3σ observation at the level of the Standard Model prediction should be achievable with 2fb^{-1} of data and a 5σ observation will require about 10fb^{-1} .

Figure 9. The integrated luminosity required to achieve a 3σ (bottom curve) or 5σ (top curve) observation of $B_s^0 \rightarrow \mu^+\mu^-$ decay as a function of its branching ratio. The Standard Model prediction, with its uncertainty, is also shown.

3.1.2. $B_d^0 \rightarrow K^* \mu^+ \mu^-$

The radiative penguin decay, $B_d^0 \rightarrow K^* \mu^+ \mu^-$, where the photon manifests itself as a $\mu^+ \mu^-$ pair, is also highly suppressed in the Standard Model, $\text{Br}(B_d^0 \rightarrow K^* \mu^+ \mu^-) = (1.22_{-0.32}^{+0.38}) \times 10^{-6}$ ⁵. The angular distribution of the $\mu^+ \mu^-$ pair is sensitive to New Physics contributions in the loop, such as gluinos, charginos or neutralinos followed by Higgs emission and decay to $\mu^+ \mu^-$ or a Higgs box diagram ¹⁸. The procedure is to measure the forward-backward asymmetry of the angular distribution of the μ^+ relative to the B direction in the $\mu^+ \mu^-$ rest frame as a function of the $\mu^+ \mu^-$ invariant mass. The number of events expected to be selected by LHCb in 2fb^{-1} of data is 7200 ± 2100 , with a $B/S < 0.5$, where the error is mostly due to the branching ratio ¹⁹. An example of the expected forward-backward asymmetry, A_{FB} , for 2fb^{-1} of data is shown in Fig. 10. The value of the $\mu^+ \mu^-$ invariant mass for which the A_{FB} is equal to zero, s_0 , is most sensitive to New Physics contributions. LHCb is expected to achieve a precision on s_0 of 0.52 GeV^2 with 2fb^{-1} of data.

Figure 10. An example of the expected forward-backward asymmetry in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays as a function of the $\mu^+ \mu^-$ invariant mass for 2fb^{-1} of data.

3.2. B_s^0 mixing phase

In the Standard Model, the B_s^0 mixing phase, $\phi_s = -2\chi = -2\lambda^2\eta$, is expected to be very small; $\phi_s = (-0.037 \pm 0.002)$ radians from the unitarity triangle fits ². However, New Physics contributions in the box diagram could introduce an additional contribution to the phase and significantly modify the measurement. The *golden* decay channel to measure ϕ_s is $B_s^0 \rightarrow J/\psi\phi$ which proceeds either directly or through B_s^0 mixing. The procedure is to measure the proper time dependence of tagged B_s^0 and $\overline{B}_s^0$ decays and form the time dependent CP-asymmetry,

$$A_{CP}(t) = \frac{\eta_f \sin \phi_s \sin(\Delta m_s t)}{\cosh(\Delta \Gamma_s t/2) - \eta_f \cos \phi_s \sinh(\Delta \Gamma_s t/2)} \quad (8)$$

where Δm_s and $\Delta \Gamma_s$ are the difference between the mass and width of the two B_s^0 CP eigenstates and η_f is ± 1 depending on the CP eigenstate. Since the final state is a mixture of CP eigenstates, the contribution of the two states is identified by performing an analysis based on the angle between the μ^+ and the normal to the ϕ decay plane. A simultaneous fit to both the angular and time distributions yields a precision on ϕ_s of 0.023 with 2fb^{-1} of data at LHCb ^{20,21}. Combining this result with the expected overall sensitivity of 0.059 from the pure CP eigenstate decay modes ($B_s^0 \rightarrow J/\psi\eta$, $\eta_c\phi$ and $D_s D_s$), results in an expected precision of 0.021 for 2fb^{-1} of data.

New Physics contributions to B_s^0 mixing can be parameterized ²² as

$$M_{12} = (1 + h_s \exp^{2i\sigma_s}) M_{12}^{SM}. \quad (9)$$

The current allowed range for h_s , σ_s is shown in Fig. 11a) and the expected improvement from LHCb with 2fb^{-1} data is shown in Fig. 11b).

3.3. Hadronic penguin decays

One method for searching for New Physics beyond the Standard Model is to compare CP phases extracted from tree-level B decay modes with those which have significant penguin contributions. For example, a significant difference between the measurement of the angle β from the tree-level process $B_d^0 \rightarrow J/\psi K_s^0$ compared to the measurement from the penguin process $B_d^0 \rightarrow \phi K_s^0$ would be evidence for New Physics. Interestingly, current measurements indicate a tantalizing difference between these two measurements of $\Delta(\sin 2\beta) \approx 0.15$ ¹, a 2.6σ effect. The same gluonic penguin loop appears in the decay of $B_s^0 \rightarrow \phi\phi$. Hence, a difference in the measurement of

Figure 11. The allowed range for h_s , σ_s using a) current data and b) for 2fb^{-1} of data at LHCb, assuming the Standard Model prediction as the central value. The dark, medium and light shaded areas have c.l. $> 90\%$, 32% and 5% respectively. Note the two figures have different abscissa scales.

the angle χ using this decay compared to the same measurement using the decay $B_s^0 \rightarrow J/\psi\phi$ would once again indicate the presence of New Physics. In addition, Standard Model CP-violation effects in the decay $B_s^0 \rightarrow \phi\phi$ are expected to be less than 1% , since V_{ts} enters in both the mixing and decay amplitudes. Therefore, an observation of a significant CP-violating phase in this decay mode would indeed be due to New Physics.

In LHCb it is expected that $\sim 4\text{k}$ $B_s^0 \rightarrow \phi\phi$ signal events will be selected with a background-to-signal ratio between $0.4 - 2.1$ at the 90% c.l. with 2fb^{-1} of data ²³. Once again a time-dependent angular analysis has to be performed to extract the CP-asymmetry. This would result in a sensitivity on a possible CP-violating New Physics phase of 0.1 radians, a similar precision to the $\Delta\beta$ difference observed in the B_d^0 system after many years of data-taking. It is envisaged that with 10fb^{-1} of LHCb data a sensitivity on ϕ_s^{NP} of 0.042 radians (2°) will be achieved.

3.4. The weak decay phase γ

The raison d'être for measuring the CKM angle γ is two-fold. Firstly, a precision measurement of γ , using tree-level B decays, is necessary to pin down a significant benchmark for New Physics. Secondly, the comparison of the γ measurements using tree-level B decays with those using decays containing penguin contributions are sensitive to New Physics. LHCb intends to measure γ using a variety of methods. Some of the latest studies using tree-level $B \rightarrow D^{(*)}K$ decays ²⁴ and $B_d^0 \rightarrow \pi^+\pi^-/B_s^0 \rightarrow K^+K^-$ con-

taining penguin contributions are summarised in Table 1. It is evident from Fig. 12 that the excellent hadron particle identification of LHCb is very important, in particular for separating out the contributions of $B_d^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$.

The most sensitive decay modes offer an expected precision on γ of $5 - 10^\circ$ with 2 fb^{-1} of data. Overall, combining all the measurements, a $2 - 3^\circ$ precision on γ should be achievable with 10 fb^{-1} of data.

Table 1. A summary of the most recent LHCb γ sensitivity studies.

B mode	D mode	Method	$\sigma(\gamma)$, 2 fb^{-1}
$B_s^0 \rightarrow D_s K$	$KK\pi$	tagged, $A(t)$ ²⁵	13° ²⁶
$B^+ \rightarrow DK^+$	$K\pi + KK/\pi\pi + K3\pi$	ADS+GLW ^{27,28}	$5 - 15^\circ$ ²⁹
$B^+ \rightarrow DK^+$	$K_s^0 \pi\pi$	3-body Dalitz ³⁰	$7 - 12^\circ$ ³¹
$B^+ \rightarrow DK^+$	$KK\pi\pi$	4-body Dalitz ³²	$\sim 18^\circ$ ³³
$B^0 \rightarrow DK^{*0}$	$K\pi + KK + \pi\pi$	ADS+GLW ^{27,28}	$7 - 10^\circ$ ³⁴
$B_d^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$	—	U-spin symmetry ³⁵	$\sim 10^\circ$ ³⁶

Figure 12. The invariant mass distributions for a) $B_d^0 \rightarrow \pi^+ \pi^-$ and b) $B_s^0 \rightarrow K^+ K^-$ decays using the pion mass hypothesis and after selection and particle identification cuts.

3.5. The impact of the LHCb measurements

Over the past few years the CKM picture of the Standard Model has improved enormously and the precision on the Wolfenstein parameters $\tilde{\rho}$ and

$\tilde{\eta}$ has reached a level of 17% and 5% respectively. Once LHCb starts producing its first results, the picture will once again change and the knowledge of the parameters will reach unprecedented precision. With 10fb^{-1} of data, LHCb expects to measure the angles α , β and γ with a precision of $\sigma(\alpha) \sim 4.5^\circ$, $\sigma(\sin 2\beta) \sim 0.01$ and $\sigma(\gamma) \sim 2.4^\circ$ respectively. These measurements, together with final measurements from BABAR, BELLE, CDF and D0 and expected theoretical improvements, are expected to result in a precision on $\tilde{\rho}$ and $\tilde{\eta}$ of 4% and 2% respectively and is illustrated in Fig.13³⁷. Also shown are two possible scenarios for the outcome of the measurement of γ from tree-level processes alone compared with the allowed region of the apex of the unitarity triangle from all other CKM measurements including those containing loop diagrams. In the second scenario, in which the allowed regions disagree, there would be clear evidence for New Physics contributions.

4. Super-LHCb

During the first phase of the experiment, LHCb aims to collect in excess of 10fb^{-1} of data and establish the presence of phenomena beyond the Standard Model in heavy flavour physics. However, it is evident that the effect of New Physics will be small and that very high precision measurements will be required to distinguish between the various New Physics models. It is therefore prudent to ask whether LHCb can exploit the full potential of flavour physics at the LHC by running at a significantly higher luminosity such as $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$, thereby collecting a ten-fold increase in statistics and a data sample of 100fb^{-1} .

LHCb is in the process of studying upgrade possibilities which could be implemented around 2015. The main issues concerning an upgrade to run at higher luminosities are: a) an increase in the number of interactions per beam crossing to ~ 4 (see Fig. 7) requiring more granularity in the tracking system, b) an increase in radiation levels requiring more radiation tolerant detectors (in particular the VELO detector) and c) the need to improve the trigger to have more selective capabilities such as the implementation of a displaced vertex trigger at L0 and a faster data-acquisition. Any upgrade to the detector does not require an upgrade to the LHC, such as the Super-LHC, but is compatible with a machine upgrade certain running scenarios.

With an upgrade in luminosity, the physics reach of LHCb will improve enormously, although systematic effects may become increasingly important. In four of the key measurements discussed in this review, the expected

Figure 13. The potential status of the unitarity triangle including a) all measurements and theoretical improvements after 10 fb^{-1} of data at LHCb; b) and c) show two possible outcome scenarios for the measurement of γ compared to the constraint on the apex of the unitarity triangle from all other measurements including loop processes.

precisions that are achievable with 100 fb^{-1} of data are:

- $B_d^0 \rightarrow K^* \mu^+ \mu^-$: the forward-backward asymmetry zero crossing point, s_0 , can be measured with a precision of 0.16 GeV^2 and the ratio of the Wilson coefficients, C_7^{eff}/C_9^{eff} with a 4% error;
- $B_s^0 \rightarrow J/\psi \phi$: the B_s^0 mixing phase, ϕ_s , can be measured with a precision of $\sigma(\phi_s) = 0.003$ giving a 10σ Standard Model measurement;
- $B_s^0 \rightarrow \phi \phi$: a difference between the B_s^0 mixing phase extracted

from $B_s^0 \rightarrow \phi\phi$ and $B_s^0 \rightarrow J/\psi\phi$ decays can be measured with a precision of $\Delta S = \sin\phi_s(\phi\phi) - \sin\phi_s(J/\psi\phi) \approx 0.04$ which could provide clear evidence for New Physics; and

- γ : the weak decay phase can be measured with a precision of $\sim 1^\circ$.

All of these measurements and many more would provide exciting physics results and measurements in heavy flavour with unprecedented precision for many years to come.

5. Summary

The LHCb experiment will be ready to collect data with a complete detector as soon as the LHC turns on during 2008. The first measurements will severely constrain the CKM picture of the Standard Model and probe for New Physics in CP-violation and very rare decays. The LHC era should be a rewarding period for flavour physics and LHCb looks forward to many years of exciting physics results and the potential of the discovery of New Physics.

Acknowledgements

I would like to thank the organisers for inviting me to the Lake Louise Winter Institute and the experience of a true winter wonderland. I would also like to thank my colleagues on LHCb for their help in preparing this lecture and manuscript.

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