THE LHCb PHYSICS PROGRAMME

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A brief overview of the LHCb experiment is given, with an emphasis on the features important for heavy-flavour physics distinguishing it from the larger LHC experiments, ATLAS and CMS. The observables constraining the important unitarity triangles are discussed, and the expected LHCb performance for each of them is presented. Where appropriate this performance is compared with the expected performance of other experiments.

1 Introduction

The main goal of the LHCb experiment is to search for new physics through a precise test of the heavy-flavour sector of the Standard Model. The most stringent test is expected to be provided by a combination of precise measurements of CP violation in the B system. The unitarity of the CKM matrix implies relations between matrix elements that can be graphically represented as so-called unitarity triangles. The two triangles relevant for the B-meson system are shown in Fig. 1. Since the $\delta\gamma$ angle is relevant to the $\mathrm{B_s^0}$ system and is expected to be very small, it is likely to become accessible only after LHC starts up. The LHCb experiment intends to measure it, as well as all three angles α, β, and γ pertaining to the first unitarity triangle.

2 The LHCb Experiment

To fully exploit the high forward $\mathrm{b\bar{b}}$ production cross section at LHC energies, the LHCb experiment has been designed as a single-arm, forward spectrometer running in collider mode, as shown schematically in Fig. 2. Its acceptance ($1.6 < \eta < 5.3$) is comparable to that of the large LHC experiments. Important characteristics of the experiment are:

- The luminosity at the LHCb interaction point will be tuned to $\sim 2 \cdot 10^{32} \mathrm{cm}^2\mathrm{s}^{-1}$, well below the expected initial LHC luminosity of $10^{33}\mathrm{cm}^2\mathrm{s}^{-1}$. At this luminosity, bunch crossings with a single pp interaction, needed for a clean event reconstruction, are dominant. The lower luminosity will ensure physics output during all of LHC operation. When LHC will provide its nominal luminosity, the high multiplicities will preclude study by the large experiments;

- In addition to high-p_t lepton triggers, there will be a high-p_t hadron trigger. This trigger, as well as the lower thresholds for the lepton triggers, ensure a high trigger efficiency also for purely hadronic B decays. At the second trigger level, a secondary vertex trigger will be used to select B decays. This requires an extensive vertex detector, which will at the same time provide a very good B hadron proper time resolution (~ 40 fs);

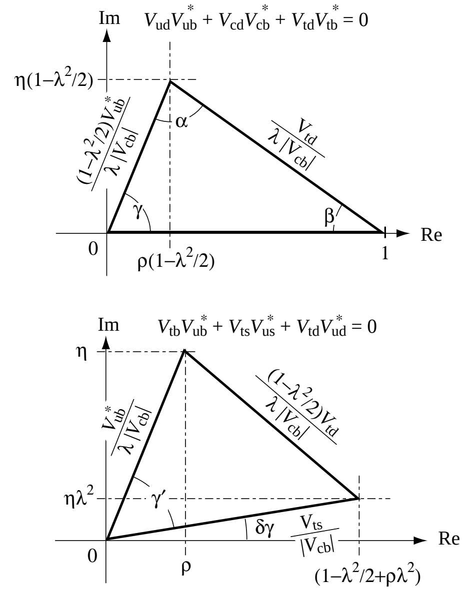

Figure 1: Unitarity triangles and their relation to the angles accessible through CP-violation measurements

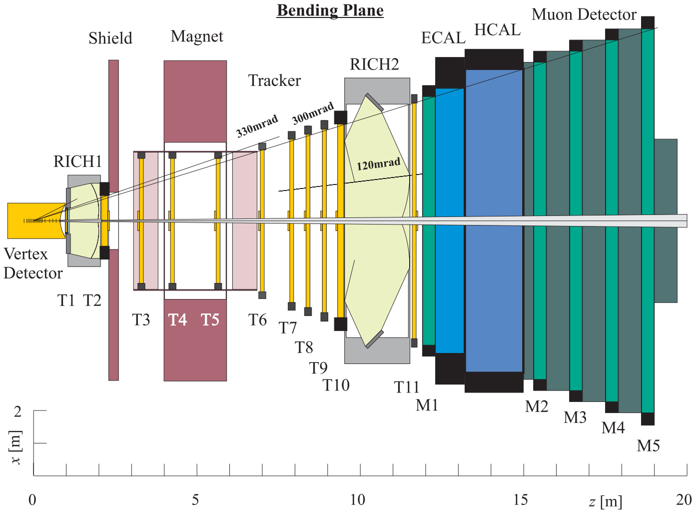

Figure 2: Top view of the LHCb spectrometer.

- A Ring Imaging CHerenkov (RICH) detector will be used to provide an excellent hadronic particle identification over a large momentum range (from 1 to 150 GeV/c). This is essential both for the exclusive reconstruction of hadronic B decay modes and to tag the neutral B hadrons' initial flavour.

3 Measurements in the Pre-LHC Era

Many 'first-generation' experiments will provide measurements of CP violation in the B system in the near future (BaBar at SLAC, Belle at KEK, CDF and D0 at Tevatron-2, HERA-B at DESY). Under reasonable assumptions (about 200 fb^{-1} collected by the asymmetric B-factories, running at the Υ(4S) only, thereby providing no access to the $\mathrm{B_s^0}$ system; about 2 fb^{-1} collected at the Tevatron) their expected measurements by 2005 can be summarised as follows [2,3]:

- $\sin 2\beta$ will have been measured to about 0.02 by combining the results from the first-generation experiments;

- $\sin 2\alpha$ will have been measured by BaBar and Belle, but with low statistics and significant theoretical uncertainties;

- $\sin(2\beta+\gamma)$ will have been measured to about 0.10 by the B-factory experiments;

- mixing in the $\mathrm{B_s^0}$ system will have been observed (and a consequent measurement of the mass difference $x_\mathrm{s} \equiv \Delta m_\mathrm{s}/\Gamma_\mathrm{s}$ made) at the Tevatron, provided $x_\mathrm{s} \lesssim 40$. Current Standard Model predictions indicate $x_\mathrm{s} \approx 20$, so it is not unreasonable to assume that it will be known. Similarly, the lifetime difference $\Delta\Gamma_\mathrm{s}/\Gamma_\mathrm{s}$ will be measured to ~ 0.02.

From this list it is evident that the ability to test the unitarity of the CKM matrix will be rather limited, with most of the emphasis put on the measurement of $\sin 2\beta$. The physics studies of the LHCb experiment are thus focused rather on the channels that allow to constrain the other angles: α, γ, and $\delta\gamma$.

4 Measurements in the B_d^0 System

4.1 Measurement of β

A time-dependent analysis of the 'gold-plated' channel $\mathrm{B}_\mathrm{d}^0 \to \mathrm{J}/\psi\mathrm{K}_\mathrm{S}^0$,

$$A(t) \equiv \frac{\mathrm{B}_\mathrm{d}^0(t) \to \mathrm{J}/\psi\mathrm{K}_\mathrm{S}^0 - \bar{\mathrm{B}}_\mathrm{d}^0(t) \to \mathrm{J}/\psi\mathrm{K}_\mathrm{S}^0}{\mathrm{B}_\mathrm{d}^0(t) \to \mathrm{J}/\psi\mathrm{K}_\mathrm{S}^0 + \bar{\mathrm{B}}_\mathrm{d}^0(t) \to \mathrm{J}/\psi\mathrm{K}_\mathrm{S}^0} = -\sin 2\beta \sin \Delta m_\mathrm{d} t \tag{1}$$

will be used, by LHCb as well as the large LHC experiments, to obtain the most accurate measurement of $\sin 2\beta$. Table 1 shows a comparison of their projected performances, for an assumed branching ratio $\mathcal{B}(\mathrm{B}_\mathrm{d}^0 \to \mathrm{J}/\psi\mathrm{K}_\mathrm{S}^0) = 4.4 \cdot 10^{-4}$ and an assumed $\sin 2\beta$ value of 0.6. An asymmetry in the production rates of B_d^0 and $\bar{\mathrm{B}}_\mathrm{d}^0$ mesons could affect the observed asymmetry. However, this asymmetry could be measured using $\mathrm{B}_\mathrm{d}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0}$, $\mathrm{K}^{*0} \to \mathrm{K}^-\pi^+$ and $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$ decays; the event samples for these channels will be an order of magnitude larger than those of the signal, so an accurate correction can be applied.

Table 1: Expected $\mathrm{B}_\mathrm{d}^0 \to \mathrm{J}/\psi\mathrm{K}_\mathrm{S}^0$ performances for one year's LHC running.

Quantity	ATLAS	CMS	LHCb
# signal events ($\times 10^3$)	17	28	56
# background events ($\times 10^3$)	0.8	4.2	22
$\sigma(m_{\mathrm{B}_\mathrm{d}^0})(\mu^+\mu^-)$ (GeV)	20	16	7
$\sigma(m_{\mathrm{B}_\mathrm{d}^0})(\mathrm{e}^+\mathrm{e}^-)$ (GeV)	26	22	20
$\delta \sin 2\beta$	0.017	0.018	0.014

4.2 Measurement of α

The measurement of α is substantially more complicated. The two-body hadronic decay $\mathrm{B}_\mathrm{d}^0 \to \pi^+\pi^-$, which has long been considered as the benchmark channel for this quantity, suffers from a low branching ratio (assumed to be $7 \cdot 10^{-6}$) [4] and a lack of submass constraints. This leads to large backgrounds: notably the $\mathrm{B}_\mathrm{d}^0 \to \pi^\pm\mathrm{K}^\mp$ decays have a branching ratio about twice as large ($1.5 \cdot 10^{-5}$) [4] as the signal one, and have a different expected CP asymmetry. To suppress these backgrounds, the use of the RICH detectors is essential.

The interpretation of the measurement is made difficult by penguin contributions, which due to their different weak phase could change the measured value of $\sin 2\alpha$ by as much as 0.25 [2]. An accurate measurement of $\sin 2\alpha$ is still possible povided the ratio of penguin to tree contributions, $|P/T|$, is known to 10%. This would require a substantial improvement in the theoretical understanding.

A possible alternative to measure α is through the decay $\mathrm{B}_\mathrm{d}^0 \to \rho\pi \to \pi^+\pi^0\pi^-$; in particular, a decay-time dependent Dalitz-plot analysis of the 3-pion final state would allow to determine the penguin contributions at the same time as $\sin 2\alpha$, fitting up to 9 parameters [5]. To control the combinatorial background severe cuts are needed: after kinematic and quality cuts, also a cut in Dalitz space is applied, rejecting the soft π^0. Preliminary studies have been made, indicating that an accuracy of $\sim 10^\circ$ can be reached using one year's data.

Another good alternative is to analyze the decay $\mathrm{B}_\mathrm{d}^0 \to \mathrm{D}^{*\pm}\pi^\mp$, which is sensitive to the angle $2\beta+\gamma = \pi+\beta-\alpha$. These are not a CP-eigenstates, but combination with the measurement of their CP-conjugate decays allows to determine $\sin(\beta-\alpha)$ up to a twofold ambiguity. The absence of penguin contributions ensures a clean measurement. The CP asymmetries are small, requiring large statistics. These can be obtained performing a partial reconstruction of the D^0 from the $\mathrm{D}^{*-} \to \mathrm{D}^0\pi^-$ decay. Depending on the actual value of the quantity $\beta-\alpha$, the projected uncertainty for one year's running ranges between 12° and 25°. In addition, first studies indicate that the decay $\mathrm{B_d^0} \to \mathrm{D}^{*\pm}3\pi$ can be reconstructed with similar efficiency, and with a three times higher branching ratio should yield better CP sensitivity.

4.3 Measurement of γ

An untagged method can be used to measure γ, through the decays $\mathrm{B_d^0} \to \mathrm{D^0K^{*0}}$, $\mathrm{\overline{D}^0K^{*0}}$, and $\mathrm{D^0_+K^{*0}}$, as well as their CP-conjugate decays. The analysis assumes the absence of CP violation in $\mathrm{D^0-\overline{D}^0}$ mixing, yielding for the CP-even eigenstate $|\mathrm{D^0_+}\rangle = (|\mathrm{D^0}\rangle + |\mathrm{\overline{D}^0}\rangle)/\sqrt{2}$. The consequent amplitude relations can be used to derive the weak phase γ. The $\mathrm{K^{*0}}$ or $\overline{\mathrm{K^{*0}}}$ tags the decay as that of either a $\mathrm{B_d^0}$ or a $\mathrm{\bar{B}_d^0}$.

This analysis requires the observation of the $\mathrm{D^0_+}$, through its decay to CP-eigenstates ($\mathrm{K^+K^-}$ or $\pi^+\pi^-$), as well as that of the $\mathrm{D^0}$ ($\mathrm{\overline{D}^0}$), through their decay to the flavour-specific states $\mathrm{K^-}\pi^+$ ($\mathrm{K^+}\pi^-$). With assumed branching ratios $\mathcal{B}(\mathrm{B_d^0} \to \mathrm{\overline{D}^0K^{*0}}) \approx 1.3 \cdot 10^{-5}$, $\mathcal{B}(\mathrm{B_d^0} \to \mathrm{D^0K^{*0}}) \approx 1.7 \cdot 10^{-6}$, one expects several hundreds of reconstructed events per year, with a signal/background ratio of 1 and a determination of γ up to 10° (with a twofold ambiguity). The use of particle identification is again crucial in order to distinguish the various final states.

5 Measurements in the $\mathrm{B_s^0}$ System

5.1 $\mathrm{B_s^0}$ mixing measurements

The measurement of x_s is important in its own right, providing a measurement of the CKM matrix element $|V_\mathrm{ts}|$. However, its main use for LHCb will be as a basis for time-dependent CP violation measurements in the $\mathrm{B_s^0}$ system: a good proper-time resolution is essential in order not to dilute the CP-violation signal.

A clean measurement of $\mathrm{B_s^0} - \mathrm{\bar{B}_s^0}$ oscillations can be performed through the flavour-specific decay $\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$, $\mathrm{D_s^-} \to \phi\pi^-$, $\mathrm{K^{*0}K^-}$ and its CP-conjugate decay. The submass constraints and high visible branching ratios ($\sim 1.2 \cdot 10^{-4}$) lead to large samples, $86 \cdot 10^3$ ($35 \cdot 10^3$) untagged (tagged) events per year. The large statistics, together with a good proper-time resolution of about 42 fs, allows a 3σ detection limit of $x_\mathrm{s} < 75$ for one year's running, to be compared with limits of 30 and 40 for ATLAS and CMS, respectively. At the same time, a fit to the untagged sample can be used to determine $\Delta\Gamma_\mathrm{s}/\Gamma_\mathrm{s}$ to ~ 0.05.

5.2 Measurement of $\delta\gamma$

The good proper time resolution allows to perform a time-dependent analysis of $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decays. These result from the same diagrams as the $\mathrm{B_d^0} \to \mathrm{J}/\psi\mathrm{K_S^0}$ decays, replacing the spectator d quark by an s quark. In addition, the decay products are both spin-1 particles. This leads to a mixture of angular-momentum states and, therefore, CP-even and CP-odd final states. The ratio, r, of CP-odd to CP-even decay amplitudes is *a priori* unknown, but can be determined from a time-dependent analysis of the untagged sample, making use of the lifetime difference between heavy- and light-mass meson. Also a more elaborate analysis using three decay angles could be used to determine the angular momentum amplitudes. The dilution of the asymmetry can then simply be taken into account as a correction factor in the measured oscillation amplitude in Eqn. 1.

The relatively large branching ratio ($\sim 10^{-3}$) [1] allows to measure $\sin 2\delta\gamma$ with a good precision (~ 0.03 using one year's data). The clear signature provided by the $\mathrm{J}/\psi \to \ell^+\ell^-$ decays will allow also the ATLAS and CMS experiments to analyze this channel; they expect to collect similar statistics.

5.3 Measurement of $\gamma - 2\delta\gamma$

A time-dependent measurement of the decay $\mathrm{B_s^0} \rightarrow \mathrm{D_s^{\pm}K^{\mp}}$ can be used to determine $\gamma - 2\delta\gamma$. A theoretically clean measurement is ensured by the absence of penguin diagrams. The high $\mathrm{D_s^{\pm}}\pi^{\mp}$ background is again reduced using particle identification information. For non-negligible lifetime differences between the heavy and light $\mathrm{B_s^0}$ mesons, as expected in the Standard Model, the oscillations are damped by a term containing a $\cos(\gamma - 2\delta\gamma)$ dependence; this allows to resolve the twofold ambuity that would otherwise result. About $2.5 \cdot 10^3$ reconstructed and tagged events are expected per year. These statistics allow to determine $\gamma - 2\delta\gamma$ with an accuracy of $6° - 13°$, depending on the actual values of x_s, $\gamma - 2\delta\gamma$, and the strong phases involved.

6 Conclusion

It is likely that by LHC startup, most of the angle in the unitarity trangles will still be largely unmeasured. Thanks to its particle identification capabilities, its precise vertexing and its ambitious triggering scheme, the LHCb experiment will be able to cover much of the unexplored areas. In particular, good precision can be expected for measurements of the phases β, α, $\beta - \alpha$, γ, $\delta\gamma$, and $\gamma - 2\delta\gamma$. As such, LHCb will provide crucial tests of the unitarity of the CKM matrix, which may lead to signs of new physics.

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