Search for New Physics in CP-violating Phenomena at LHCb

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LHCb is an experiment optimised to search for New Physics through measurements of the decays of B and D hadrons, in particular those which allow access to CP-violating observables. The principal goals are studies of B_s mixing-induced CP violation in channels such as $B_s \rightarrow J/\Psi\phi$, a precise measurement of the unitary triangle angle γ, and the search for CP violation in the charm sector. Early results will be shown from the 2010 run illustrating the performance of the LHCb detector. These will be used to predict the expected physics sensitivity in the above topics with the integrated luminosity of 37.7 pb^{-1} that has been recorded by LHCb this year.

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1. Introduction

The abundance of matter over anti-matter in the universe [1] is a continous puzzle in the Standard Model (SM), since it predicts insufficient CP violation to explain this abundance. Nevertheless, Standard Model predictions of CP-violating observables are consistent with all measurements so far, therefore suggesting a clear need for physics beyond the SM to explain that abundance [2, 3].

In the Standard Model, CP violation in flavour changing currents is caused by one single phase in the mixing matrix. This matrix describes the charged current weak interactions of quarks [4]. This so-called Cabbibo-Kobayashi-Maskawa (CKM) matrix is a complex, unitary, 3×3 matrix which relates the electroweak eigenstates of the quarks with their mass eigenstates. From the unitarity requirement of the CKM matrix 6 orthogonality relations can be derived, which are usually displayed as unitarity triangles in a complex plane.

An example is the unitarity relation

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0. \tag{1.1}$$

which can be studied using $b \to c\bar{c}s$ quark-level transitions. The elements V_{xy} describe the complex coupling strengths of the up-type quarks $(x = u, c, t)$ to the down-type quarks, $(y = d, s, b)$. The angle between the two larger sides $(V_{cb}^* V_{cs})$ and $(V_{tb}^* V_{ts})$ is small:

$$\beta_s = \arg\left[-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}\right] \approx \lambda^2 \eta \approx \arg(V_{ts}) - \pi \approx 0.02 \tag{1.2}$$

The neutral B_s meson undergoes mixing which can be described by an effective Hamiltonian consisting of two 2×2 matrices: the mass matrix M, and decay matrix Γ. The mass difference between the mass eigenstates is defined as $\Delta m_s = m_H - m_L$, and the corresponding decay-time difference by $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, where (L, H) indicate the heavy and light mass state. Since the mass eigenstates are not equal to the weak eigenstates, these matrices contain off-diagonal elements, M_{12} and Γ_{12}. The phase difference between M_{12} and Γ_{12} leads to an observable CP-violating phase. In the SM it is related to β_s through $\phi_s \approx -2\arg(V_{tb}^* V_{ts})$.

Experimentally, the angle ϕ_s is measured by evaluating the time-dependent CP asymmetry of the $B_s \to J/\Psi\phi$ decay which is constructed from the time-dependent decay rates Γ for initial $\bar{B}_s$ mesons and B_s mesons to the same final state f, where f is a CP eigenstate. It is usually parameterised as

$$A_{CP}(t) = \frac{-\eta_f \sin\phi_s \sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s \frac{t}{2}) - \eta_f \cos\phi_s \sinh(\Delta\Gamma_s \frac{t}{2})}, \tag{1.3}$$

where $\eta_f = +1, -1$ for the CP-even, CP-odd sub sample respectively. The mass-difference between the mass eigenstates of the B_s^0 meson determines the oscillation frequency of this asymmetry.

Contrary to the B_s case, CP violation in the D^0 system is expected to be negligibly small. This is related to the fact that in this case the mixing proceeds via intermediate states with down-type quarks. In contrast to the case of B_s-mixing, here the heaviest participating quark, the b-quark, is strongly suppressed by the CKM-factor $\left|V_{ub}V_{cb}^*\right|^2 / \left|V_{us}V_{cs}^*\right|^2 \sim \lambda^8$, and the GIM mechanism. With this factor, its contribution to D-mixing is only at the percent level, and therefore negligible. In the case of mixing, the mass eigen states $|D1\rangle, |D2\rangle$ are composed of linear combinations of the two flavour eigen states D^0 and $\bar{D}^0$, $|D1\rangle = p\left|D^0\right\rangle + q\left|\bar{D}^0\right\rangle$ and $|D2\rangle = p\left|D^0\right\rangle - q\left|\bar{D}^0\right\rangle$.
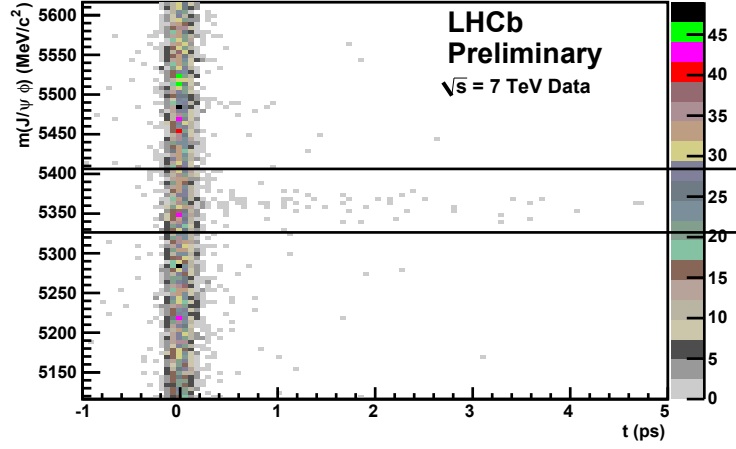
Figure 1: Reconstructed $B_s \to J/\Psi\phi$ signal *vs.* proper time in $\mathscr{L} \approx 2$ pb^{-1} of data.

This leads to the following relations for the mass difference (ΔM), decay width (Γ) and width difference ($\Delta\Gamma$): $x = \frac{\Delta M}{\Gamma}$ and $y = \frac{\Delta\Gamma}{2\Gamma}$. The two decay rates are defined as $A_f = \langle f|\mathscr{H}|D^0\rangle$ and $\bar{A}_f = \langle f|\mathscr{H}|\bar{D}^0\rangle$. Using $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$, the decay rate for $D^0 \to f$ can be expressed as

$$\Gamma(D^0(t) \to f) = \frac{1}{4}e^{-\Gamma t}\left|\bar{A}_f\right|^2\left|\frac{q}{p}\right|^2\left[4|\lambda|^2 + (\Delta M^2 + \frac{\Delta\Gamma^2}{4})t^2 + (2\Re(\lambda)\Delta\Gamma + 4\Im(\lambda)\Delta M)t\right]. \quad (1.4)$$

In order to measure possible CP violation in the D-meson system, the flavour of the meson at the time of its decay has to be determined. For this purpose, the case of the fully reconstructed $D^* \to \pi_s D^0(\bar{D}^0)$ chain is considered. Here, the charge of the slow pion ($\pi_s^\pm$) is used to tag the flavour of the D_s meson at production time. The doubly-Cabibbo-suppressed decay of the $\bar{D}^0$ into $f = K^+\pi^-$ is a flavour-eigen state, and hence can be used to determine CP violation from $D^0 - \bar{D}^0$ mixing.

Using Nir's parameterisation [5] of the effects of indirect CP violation, $\lambda = \sqrt{R_D}e^{-i(\delta+\phi)}$, and rotating the mass and life-time differences due to the presence of a strong phase (δ) and a weak phase (ϕ): $x' = x\cos\delta + y\sin\delta$ and $y' = y\cos\delta - x\sin\delta$, the time-dependent decay rate can be expressed as

$$\Gamma(D^0(t) \to K^+\pi^-) = \left|\bar{A}\right|^2\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[R_D + \sqrt{R_D}(y'\cos\phi - x'\sin\phi)\Gamma t + \frac{x'^2 + y'^2}{4}\Gamma^2 t^2\right]. \quad (1.5)$$

Here, R_D is the ratio of amplitude of the Cabibbo-Favoured (CF) decay over the doubly Cabibbo suppressed (DCS) decay. The three terms in expression 1.5 describe the effects of the DCS amplitudes (constant with time), effects from the interference between mixing and DCS amplitudes (linearly with time), and effects from mixing (quadratic with time).

Theoretically, CP-violating effects in the Standard Model are expected to be on the order of $\mathscr{O}(10^{-3})$, hence any measurement of CP violation larger than this value is a clear signature of physics beyond the standard model.

2. CP violation in the beauty sector

At the LHC, the colliding proton beams produce $b\bar{b}$ quark pairs predominantly in the forward and backward direction, hence the forward-angle design of the LHCb detector. The design and detailed description of the spectrometer is given elsewhere [6]. As of writing, the LHC has delivered $\mathscr{L} = 42.15$ pb^{-1} of colliding proton beams, out of which LHCb recorded $\mathscr{L} = 37.7$ pb^{-1} (equivalent to a 89.3 % efficiency).

The LHCb collaboration will measure the phase ϕ_s using the B$_s \to J/\Psi\phi$ channel. Here, the flavour of the B$_s$ at creation time needs to be tagged, and the proper time of the decaying B$_s$ so that asymmetry $\mathscr{A}_{\mathrm{CP}}$ can be constructed. For the determination of the flavour of the B$_s$ at decay, the propertime and its oscillation frequency Δm_s have to be known. The final state of the B$_s$ decay is composed of CP-even and CP-odd components, and will be disentangled using an analysis of the angular distribution of the final state decay products.
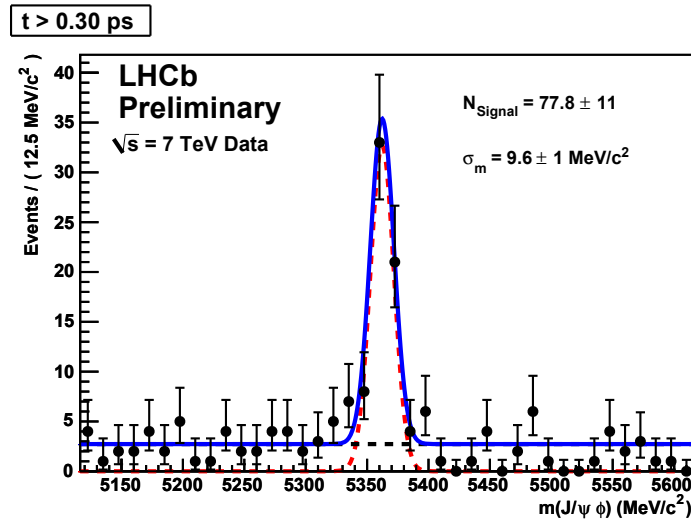

Figure 2: Reconstructed mass for B$_s \to J/\Psi\phi$ signal for $\tau > 0.3$ ps in $\mathscr{L} \approx 2$ pb^{-1} of data.

In order to study the angular acceptance of the spectrometer, the decay B$_d \to J/\Psi$K* is used; for the proper time resolution, the channels B$_d \to J/\Psi$K* and B$_u^+ \to J/\Psi$K$^+$ are useful. The channel B$_d \to J/\Psi$K$_s$ is used as a benchmark channel. A coherent set of cuts for the reconstruction of the four B $\to J/\Psi X, X \in (\phi, \mathrm{K}^*, \mathrm{K}^+, \mathrm{K}_s)$ decays has been developed, based mainly on track- and vertex-quality criteria, particle identification criteria and requirements on the transverse momentum of the two muons $P_t(\mu^\pm) > 0.5$ GeV, and the J/Ψ, $P_t(J/\Psi) > 1.0$ GeV. In addition, criteria are imposed upon the other particle/resonance (e.g. $P_t(\phi) > 1.0$ GeV, and on the reconstructed B meson (impact
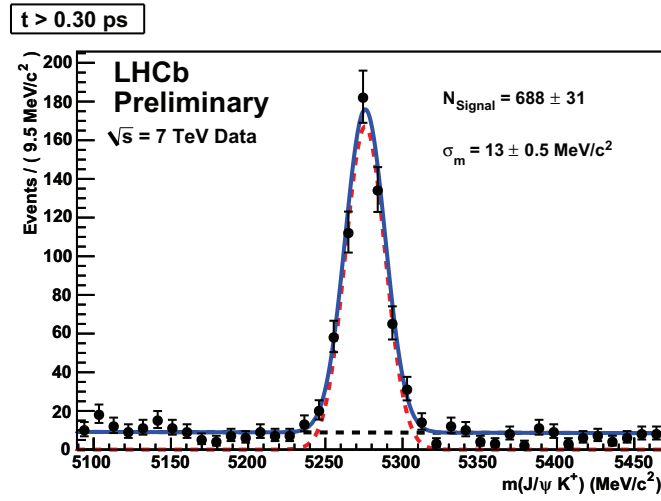
Figure 3: Reconstructed B_u^+ mass from the exclusive decay $B_u^+ \to J/\Psi K^+$ with the requirement $\tau > 0.3$ ps.

parameter significance and vertex reconstruction). In this way, a mostly lifetime-unbiased selection is achieved.

Using an integrated luminosity of approximately $\mathcal{L} \approx 2$ pb^{-1}, the $B_s \to J/\Psi\phi$ channel has been reconstructed . In Figure 1 the reconstructed B_s mass *vs.* proper time is shown. Figure 2 shows the background subtracted signal, for proper time $\tau(B_s) > 0.3$ ps. From this, a yield of $N_{B_s} = 38.9 \pm 5.5$ has been determined.

Another example of the result of the analysis of these four channels is the $B_u^+ \to J/\Psi K^+$ decay. The signal is shown in Figure 3, with the background removed by a requirement on the proper time, $\tau > 0.3$ ps. In $\mathcal{L} = 3$ pb^{-1}, a yield $N_{B_d} = 688 \pm 31$ events has been found.

The opposite site tagger is being calibrated using in addition to the $B_u^+ \to J/\Psi K^+$ channel, also the $B_d \to J/\Psi K^{*0}$ channel. As a test, the tagger has been used on $\mathcal{L} = 2$ pb^{-1} of data with the $B_d \to D^{*-}\mu^+\nu$ channel, where the $D^{*-} \to D^0\pi^-$ and the $D^0 \to K^+\pi^-$. Here, both the mass difference and the B proper time were fitted, to result in the first observation of B_d oscillations at LHCb, see Fig. 4. A preliminary value of $\Delta m_d = 0.530 \pm 0.076 \times 10^{12}\hbar/s$ was found, where only a statistical error was determined. Note that here, the tuning of the the tagging application had yet to be performed, and also that the proper time calibration is still under way.

3. CP violation in the charm sector

CP violation in the charm sector can be measured in two independent ways. The first method relies on the different time evolution of the components in eq. 1.5. In this case, the decay $D^{*+} \to \pi_s D^0$ is used, where the slow pion (π_s) tags the flavour of the initial D^0. For the CP measurement, the wrong-sign (WS) decay $D^0 \to \pi^- K^+$ is reconstructed. In this decay two amplitudes contribute, namely a diagram where mixing occurred followed by the subsequent Cabibbo-favoured decay to $K^-\pi^+$, and the amplitude where no mixing occurred and the D^0 decays via the doubly Cabibbo-suppressed channel directly into $K^-\pi^+$. So far, an integrated luminosity of $\mathcal{L} = 124$ nb^{-1} has
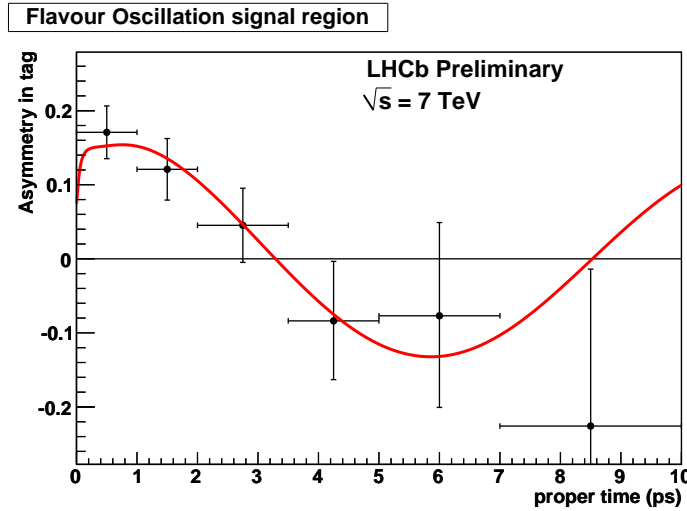
Figure 4: Oscillations of the $B_d \to D^{*-}\mu^+\nu_\mu$ channel in LHCb.

been analysed. With this small sample, a yield of $N(RS) = 17033 \pm 186$ events for the right-sign (RS) decay in the chain $D^{*+} \to \pi_s D^0 (\to K^-\pi^+)$ was found; the observation of the WS decay has yet to be released. In Figure 5(a) the reconstructed right-sign decay is shown. A two-dimensional fit in the $\delta m, m(D^0)$ plane was performed to derive the yield.

The lifetime difference between CP-even and CP-mixed states can be studied using the decays $D^0 \to K\pi$ and $D^0 \to KK$ by means of the quantity known as 'y_{CP}':

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi+)}{\tau(K^-K^+)} - 1. \tag{3.1}$$

In addition, a measurement of the lifetime asymmetry

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)} \tag{3.2}$$

can be performed using the $D^0 \to KK$ and $\bar{D}^0 \to KK$ channels. An example of the reconstructed D^0 mass is given in Fig. 5(b).

In a completely independent method, a Dalitz-ratio analysis will be performed using the three-body decay in the channel $D^+ \to K^+K^-\pi^+$ and its charged conjugate. Here, Dalitz-plot analyses are made for the two decays, after which a Miranda [7] statistic

$$D_{ps_{CP}} = \frac{N(i) - \bar{N}(i)}{\sqrt{N(i) + \bar{N}(i)}} \tag{3.3}$$

is used to probe for CP violation. Although this method is very sensitive, and rather robust against e.g. detector-induced asymmetries, it suffers from the fact that it can only establish CP violation, but one can not derive the source. In this analysis, two control channels can be used, namely $D_s^+ \to K^+K^-\pi^+$ and $D^+ \to K^+\pi^+\pi^-$ channels. For an integrated luminosity of $\mathcal{L} = 580$ nb^{-1} approximately 5000 D events were found.

(a)   (b)
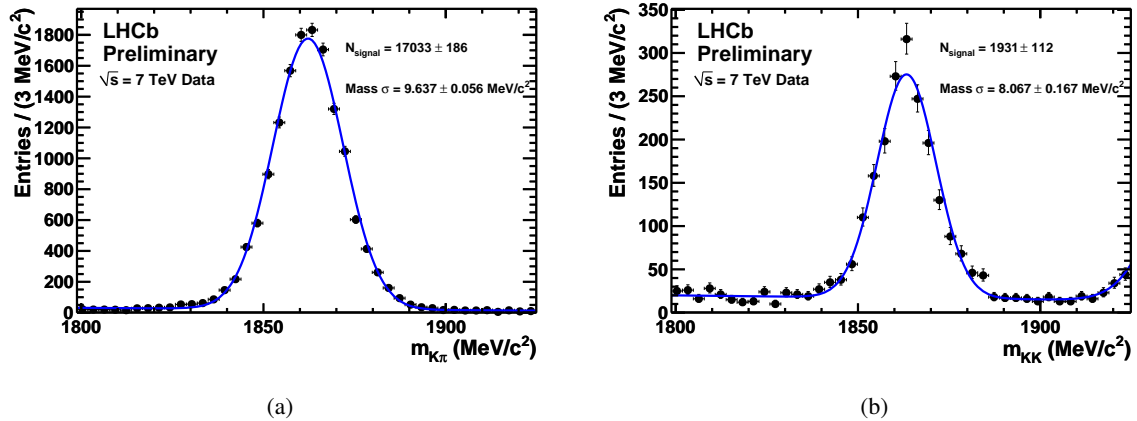
Figure 5: a) Reconstructed invariant mass of the right-sign decay $D^{*+} \rightarrow D^0 (\rightarrow K^+ \pi^-) \pi_s$, a mass width of $\sigma = 9.6$ MeV is found. b) Reconstructed D^0 mass using the chain $D^{*+} \rightarrow D^0 (D^0 \rightarrow KK)$. The fit resulted in a mass width of $\sigma = 8.067$ MeV.

4. Conclusions

Thanks to the successful commencement and operation of the Large Hadron Collider, a total of $\mathscr{L} = 37.7$ pb^{-1} was recorded this year by the LHCb experiment, with an efficiency close to 90%. In many new physics models, new, heavy particles may contribute to processes which proceed through Feynman diagrams of the box- and penguin type. In this way, also possible new CP-violating phases may become visible. In particular, since the Standard Model predicts only small CP violation in the B_s meson sector and negligible CP violation in the D-meson sector, here measurements of these quantities may be sensitive to new physics. With these data, a yield of $N(B_s) \approx 1 \times 10^3$ in the $B_s \rightarrow J/\Psi \phi$ channel is expected with a proper time resolution of $\sigma(t) \approx 50 - 60$ fs, yielding an error on ϕ_s of $\sigma(\phi_s) \approx 0.30 - 0.80$ rad. With this dataset, LHCb are expecting $\mathscr{O}(10^6)$ events for the CP violation searches in the charm sector.

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