EPJ Web of Conferences **49**, 13005 (2013)
DOI: 10.1051/epjconf/20134913005

CP Violation in B Mixing and Decays

Mika Vesterinen[1,a], on behalf of the LHCb Collaboration.

[1] *CERN*

Abstract. Recent LHCb results on CP violation in B mixing and decays are reported. The analyses are based on 1 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV recorded in 2011. First evidence is presented for CP violation in $B^{\pm}$ decays to the $K^{\pm}K^{+}K^{-}$, $\pi^{\pm}K^{+}K^{-}$, and $\pi^{\pm}\pi^{+}\pi^{-}$ final states. The CP violating flavour specific asymmetry, a^{s}_{sl}, is measured to be $(-0.24 \pm 0.54_{\mathrm{stat}} \pm 0.33_{\mathrm{syst}}) \times 10^{-2}$, in good agreement with Standard Model expectations. A flavour tagged and time dependent analysis of the decays, $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi^{+}\pi^{-}$, measures $\phi_s = -0.002 \pm 0.083_{\mathrm{stat}} \pm 0.027_{\mathrm{syst}}$ rad, in good agreement with Standard Model predictions.

1 Introduction

Precision studies of B mixing and decays may reveal new physics through loop corrections, even at scales that are not accessible by direct searches at the LHC. In particular, CP asymmetries may be significantly modified by amplitudes involving new particles. The large cross section for $b\bar{b}$ production at the LHC permits measurements with unprecedented precision, particularly in the B^0_s sector, which is less accessible at the e^+e^- collider based B-factories.

The time evolution of neutral B mesons is characterised by the 2×2 complex matrix,

$$\begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M^{*}_{12} - \frac{i}{2}\Gamma^{*}_{12} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}. \tag{1}$$

Key observables are the mass and decay width differences between the mass eigenstates; $\Delta M = M_H - M_L$ and $\Delta\Gamma = \Gamma_L - \Gamma_H$, respectively. These are related to the off diagonal elements of the matrix. Violation of CP in mixing, would be apparent as a flavour specific asymmetry, e.g., in semileptonic decays,

$$a_{\mathrm{sl}} \equiv \frac{\Gamma(\bar{B}(t) \to f) - \Gamma(B(t) \to \bar{f})}{\Gamma(\bar{B}(t) \to f) + \Gamma(B(t) \to \bar{f})} = \frac{\Delta\Gamma}{\Delta M}\tan\phi_{12}, \tag{2}$$

where $\phi_{12} = \arg(-M_{12}/\Gamma_{12})$. In the B^0_s sector, the Standard Model predicts a very small value for ϕ_{12} – around 0.2° [1]. The predicted value of $a^{s}_{\mathrm{sl}} = (1.9 \pm 0.3) \times 10^{-5}$ is negligible compared to current experimental precision. A measurement that is significantly different from zero would therefore be a strong indication of new physics. The D0 Collaboration reports an anomalously large asymmetry in the rate of like sign muon pairs, $A_{\mu\mu} = (-0.787 \pm 0.172_{\mathrm{stat}} \pm 0.093_{\mathrm{syst}}) \times 10^{-2}$ [2]. This observable is a linear combination of the semileptonic asymmetries of the B^0_s and B^0_d systems: $A_{\mu\mu} \approx 0.6a^{d}_{\mathrm{sl}} + 0.4a^{s}_{\mathrm{sl}}$. The B-factories are only able to measure a^{d}_{sl}. Here, an LHCb measurement of a^{s}_{sl} is presented.

Charged B mesons cannot oscillate, but their decays can still violate CP if there are competing amplitudes with different strong and weak phases. In charmless three body $B^{\pm}$ decays, one can exploit the interference pattern in the Dalitz space, to reveal weak phases via local CP violation.

A third type of CP violation can occur in the decay of a neutral B meson to a final state that is accessible by both B^0 and $\bar{B}^0$. For a B^0_s decay to a CP eigenstate f with eigenvalue η_f, the CP asymmetry is given by $A_{CP} = \eta_f \sin\phi_s \cos(\Delta M_s t)$. In the Standard Model, $\phi_s = -2\beta_s = \arg(-V_{ts}V^{*}_{tb}/V_{cs}V^{*}_{cb})$, with indirect fits giving $2\beta_s = 0.036 \pm 0.002$ rad [3]. The mixing phase is particularly sensitive to new physics contributions.

The analyses presented here are based on 1 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV, collected with the LHCb detector [4]. LHCb is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV to 0.6% at 100 GeV. Charged hadrons are identified using two ring-imaging Cherenkov (RICH) detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers. The trigger consists of a hardware stage (level-0), based on information from the calorimeter and muon systems, followed by a software stage (HLT)

[a] e-mail: mika.vesterinen@cern.ch

which applies a full event reconstruction. The magnet polarity is reversed periodically. Approximately 40% of the data were taken with the magnetic field up and the rest with the magnetic field down. We exploit the fact that certain detection asymmetries cancel if data from different magnet polarities are combined.

Section 2 reports on measurements of the CP asymmetry in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ [5, 6], with $h = \pi$ or K. Section 3 reports on a measurement of the a^{s}_{sl} with a time integrated and untagged analysis [7]. Section 4 reports on measurements of ϕ_s and $\Delta\Gamma_s$ with the $B^0_s \to J/\psi\phi$ [8] and $B^0_s \to J/\psi\pi^{+}\pi^{-}$ [9] decay modes.

2 Charmless three body B decays

Candidate $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays are constructed from three high-p_T charged tracks that form a common vertex with a significant flight distance from the primary vertex. The three tracks must satisfy requirements on impact parameter, and on PID (depending on the specific decay). The level-0 trigger looks for a high E_T hadron, while an inclusive approach is employed for triggering on B hadrons in the HLT [10]. Figure 1 shows the mass distributions for the four different $B^{-} \to h^{-}h^{+}h^{-}$ decay modes.

The raw CP asymmetries are polluted by both production and detection asymmetries. The $K^{\pm}K^{+}K^{-}$ and $K^{\pm}\pi^{+}\pi^{-}$ modes have an odd number of kaons, which is the main source of asymmetry after averaging the two magnet polarities. A sample of $B^{\pm} \to J/\psi K^{\pm}$ events is used to correct for both the production asymmetry, and the kaon detection asymmetries that arise due to the different nuclear interaction cross section for K^{+} compared to K^{-}. The $\pi^{\pm}K^{+}K^{-}$ and $\pi^{\pm}\pi^{+}\pi^{-}$ modes are corrected in a similar manner. A residual $K^{\pm}\pi^{\mp}$ detection asymmetry is corrected for using prompt charm decays [11, 12]. Table 1 lists the measured CP asymmetries for each of the decay modes. First evidence is claimed for global CP asymmetry in the $K^{\pm}K^{+}K^{-}$, $\pi^{\pm}\pi^{+}\pi^{-}$ and $\pi^{\pm}K^{+}K^{-}$ modes.

Figure 2 shows the Dalitz projections of the CP asymmetries. Large local asymmetries are observed, e.g., a negative asymmetry at low $m_{K^{+}K^{-}}$ in the $\pi^{\pm}K^{+}K^{-}$ and $K^{\pm}K^{+}K^{-}$ modes. In the $\pi^{\pm}\pi^{+}\pi^{-}$ mode, a large positive asymmetry is apparent at low (high) values of the smaller (larger) of the two pion pair masses. None of these asymmetries are clearly associated to a resonance, indicating peculiar strong interaction dynamics. In the $K^{\pm}\pi^{+}\pi^{-}$ mode, a large positive asymmetry is seen at low $m_{\pi^{+}\pi^{-}}$, close to the $\rho(770)$ and $f_0(980)$ resonances.

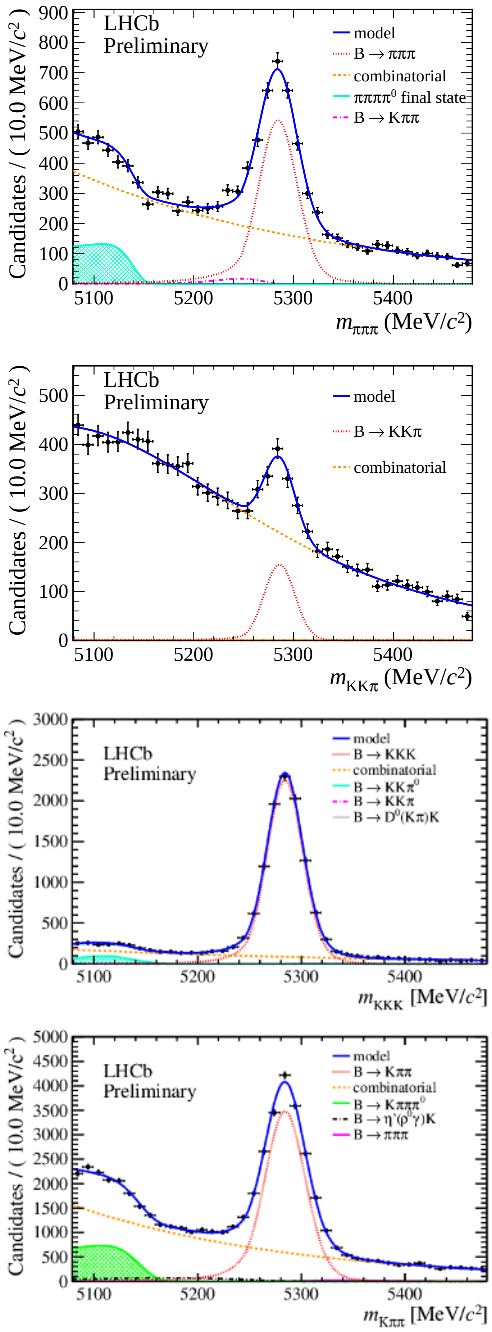

Figure 1. Mass distributions for the $B^{-} \to h^{-}h^{+}h^{-}$ decay modes.

Decay mode	A_{CP}	Significance
$K^{\pm}\pi^{+}\pi^{-}$	0.034 ± 0.009 ± 0.004 ± 0.007	2.8σ
$K^{\pm}K^{+}K^{-}$	-0.046 ± 0.009 ± 0.005 ± 0.007	3.7σ
$\pi^{\pm}\pi^{+}\pi^{-}$	0.120 ± 0.020 ± 0.019 ± 0.007	4.2σ
$\pi^{\pm}K^{+}K^{-}$	-0.153 ± 0.046 ± 0.019 ± 0.007	3.0σ

Table 1. Measured CP asymmetries in the four different $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decay modes. The first uncertainty is statistical, the second systematic, and the third is from the uncertainty on $A_{\mathrm{CP}}(B^{\pm} \to J/\psi K^{\pm})$.

3 Semileptonic asymmetry

The measurement of a^{s}_{sl} with equation 2 requires flavour tagging to select wrong-sign decays. Without flavour tagging, the time integrated asymmetry is

$$A_{\mathrm{raw}} \equiv \frac{N(B^0_s) - N(\bar{B}^0_s)}{N(B^0_s) + N(\bar{B}^0_s)} = \frac{a^{s}_{\mathrm{sl}}}{2} + \mathcal{K}\left[a_p - \frac{a^{s}_{\mathrm{sl}}}{2}\right], \quad (3)$$

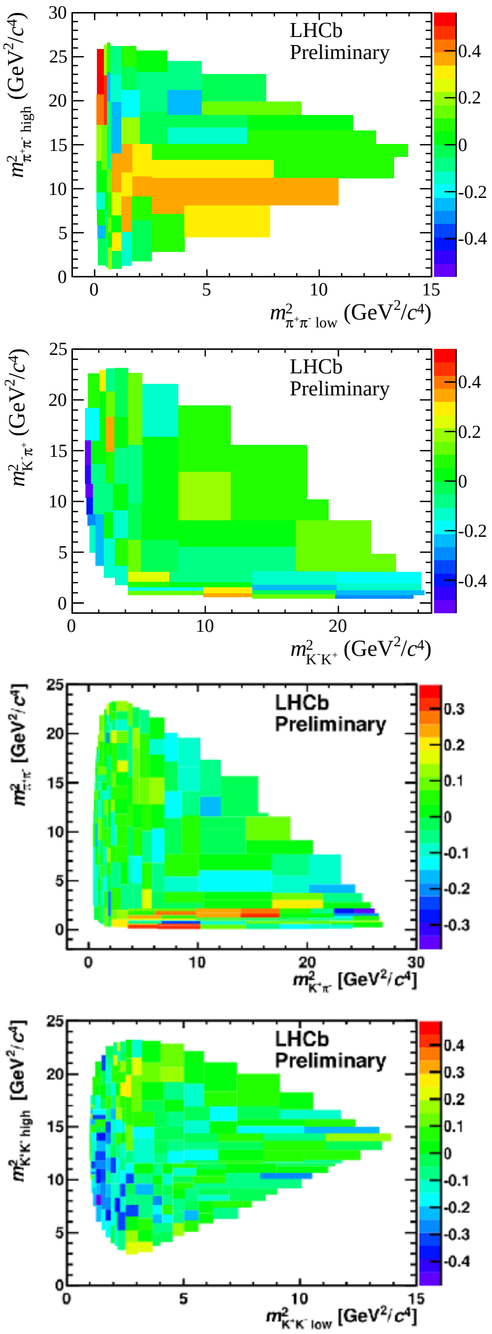

Figure 2. Dalitz projections of the CP asymmetries in the four $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decay modes.

where a_p is the production asymmetry, and

$$\mathcal{K} = \frac{\int e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int e^{-\Gamma_s t}\cosh(\Delta\Gamma_s t/2)\epsilon(t)dt}. \quad (4)$$

Inserting the LHCb efficiency as a function of decay time, $\epsilon(t)$, and the mixing parameters for the B^0_s, one obtains a value of $\mathcal{K} \approx 2 \times 10^{-3}$. A production asymmetry of even a few percent is thus washed out by the fast oscillations, to a level that is negligible compared to the statistical precision on A_{raw}.

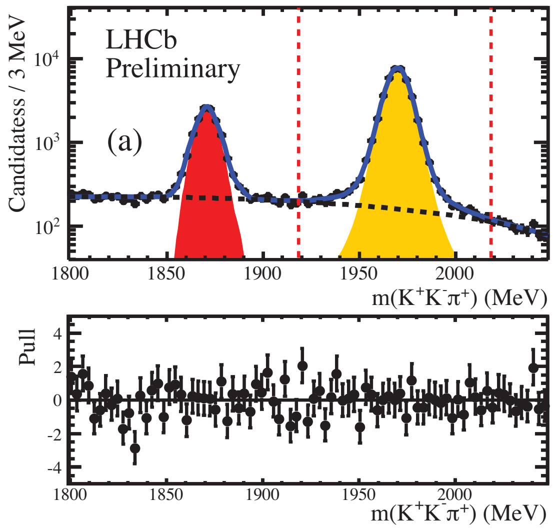

Figure 3. Mass distribution of the $B^0_s \to D^-_s\mu^+$ candidates in the magnet-up data.

The decay mode $B^0_s \to D^-_s\mu^+\nu_\mu X$ is used, with the D^-_s decaying to $\phi\pi^-$ and $\phi \to K^+K^-$. Candidates are triggered by the muon at level-0 and at the first stage of the HLT. The final stage of the HLT uses a similar approach to that used in the $B^{\pm} \to h^{\pm}h^{+}h^{-}$ analysis.

Random combinatoric background is subtracted by fitting the $D^-_s\mu^+$ mass distributions. Figure 3 shows a fit to roughly half of the dataset, that was collected with the magnet polarity in the up configuration.

Detection asymmetries are mostly cancelled by averaging the data collected with the two magnet polarities. Residual asymmetries are estimated with the help of dedicated control samples. Muon asymmetries are measured with a sample of $J/\psi \to \mu^+\mu^-$ events. Tracking asymmetries are studied using a sample of prompt charm decays as detailed in [11]. Additional trigger asymmetries are studied with the help of a larger sample of $B^0_d \to D^-\mu^+\nu_\mu X$ events. Background processes are estimated to have a small effect and are accounted for in the systematic uncertainties.

The measured asymmetry is $a^s_{\mathrm{sl}} = (-0.24 \pm 0.54_{\mathrm{stat}} \pm 0.33_{\mathrm{syst}}) \times 10^{-2}$, which agrees with the Standard Model prediction. Figure 4 compares this result to other measurements of a^s_{sl} and a^d_{sl}, plus the D0 measurement of $A_{\mu\mu}$.

4 Measurement of ϕ_s and $\Delta\Gamma_s$

A sample of $B^0_s \to J/\psi\phi$ decays is triggered by the J/ψ at level-0. Figure 5 shows the B^0_s mass distribution of the selected candidates. In order to determine the flavour of the B^0_s at production, an "opposite side" tagger is used [13]. This looks for electrons, muons and kaons from the decay of the B hadron produced in association with the signal B^0_s. In addition, inclusively reconstructed secondary vertices are included. A multivariate combination of this information gives an effective tagging power of $\epsilon_{\mathrm{tag}}(1-\omega_{\mathrm{tag}})^2 = (2.29 \pm 0.07 \pm 0.26)\%$, as determined using control sam-

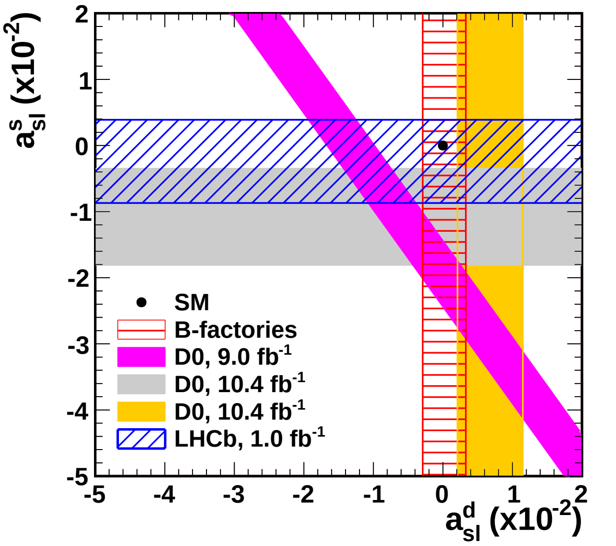

Figure 4. Comparison of the different measurements of $a^s_{\rm sl}$ and $a^d_{\rm sl}$.

ples, where ϵ and ω denote the efficiency and mis-tag rates, respectively.

The $B^0_s \to J/\psi\phi$ decay, being a $P \to VV$ transition (with P and V representing pseudoscalar and vector particles, respectively), contains both CP-even and -odd amplitudes. These need to be disentangled statistically, by means of an angular analysis. In addition, there is a possible S-wave K^+K^- contribution. A signal PDF is constructed, that captures the decay time and angular of the different amplitudes and their interference terms. This PDF also takes into account experimental resolution and acceptance effects, as well as the flavour mis-tag rate. A maximum likelihood fit of this PDF to the data allows ϕ_s and $\Delta\Gamma_s$ to be extracted. In addition, the amplitudes and strong phases of the polarisation amplitudes are determined. The fit obtains $\phi_s = -0.001 \pm 0.101_{\rm stat} \pm 0.027_{\rm syst}$rad, and $\Delta\Gamma_s = 0.116 \pm 0.018_{\rm stat} \pm 0.006_{\rm syst}$ ps^{-1}. This is the first ($> 5\sigma$) observation of $\Delta\Gamma_s \neq 0$.

The two-fold ambiguity in the ϕ_s and $\Delta\Gamma_s$ fit was recently resolved by an LHCb analysis of the $J/\psi K^+K^-$ final state [14]. The variation of the strong phase difference between the S- and P-wave amplitudes around the $\phi(1020)$ resonance allowed $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H > 0$ to be identified as the physical solution.

An alternative mode with which to measure ϕ_s, is $B^0_s \to J/\psi\pi^+\pi^-$ [15]. A detailed study of this mode by the LHCb Collaboration showed that this decay is at least 97.7% CP-odd, at the 95% confidence level [16]. An angular analysis is therefore not needed. Figure 8 shows the mass distribution of the selected $B^0_s \to J/\psi\pi^+\pi^-$ candidates. The signal purity is enhanced with the use of a multivariate selection. A simultaneous fit with the $J/\psi\phi$ mode gives $\phi_s = -0.002 \pm 0.083_{\rm stat} \pm 0.027_{\rm syst}$ rad.

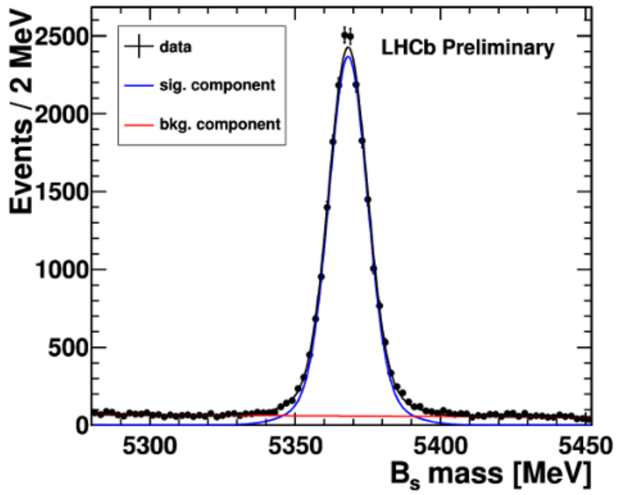

Figure 5. Mass distribution of the selected $J/\psi\phi$ candidates.

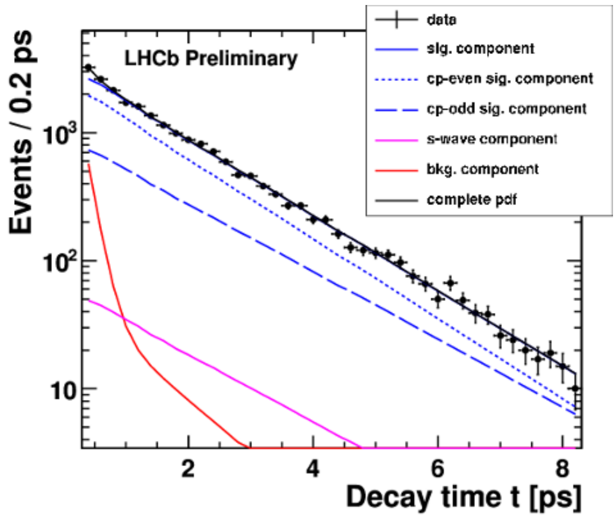

Figure 6. Projection of the $J/\psi\phi$ data and the signal fit fit in decay time.

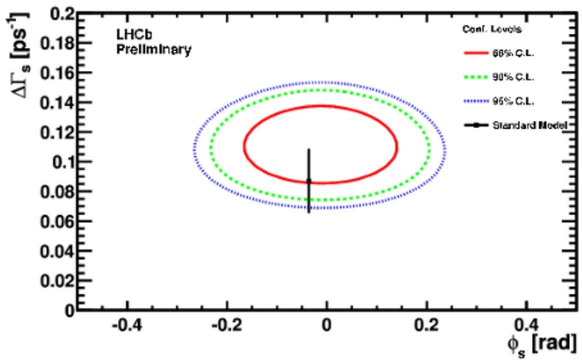

Figure 7. Measured ϕ_s and $\Delta\Gamma_s$ from the analysis of the $B^0_s \to J/\psi\phi$ decay mode, compared to the Standard Model.

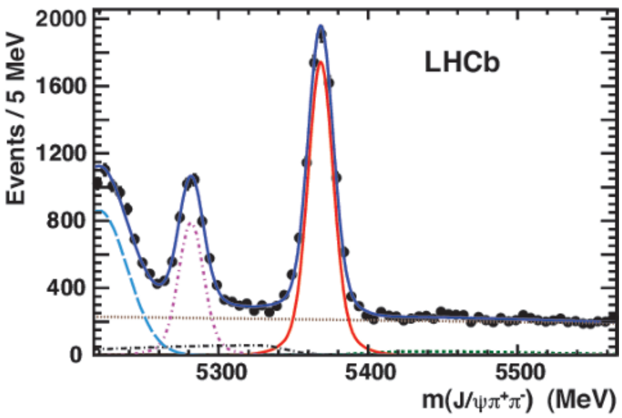

Figure 8. Mass distribution of the $J/\psi\pi^+\pi^-$ candidates. The signal component is represented by the red line.

5 Conclusions

Decays and mixing of B hadrons are excellent places to search for the effects of new physics. Here, a selection of recent LHCb results on CP violation in mixing and decays is reported. These analyses are based on the full 2011 dataset of 1 fb^{-1} of pp collisions at $\sqrt{s}$ = 7 TeV. First evidence is presented for CP violation in the $B^{\pm}$ decays to the $K^{\pm}K^{+}K^{-}$, $\pi^{\pm}K^{+}K^{-}$, and $\pi^{\pm}\pi^{+}\pi^{-}$ final states. The CP-violating flavour-specific asymmetry, $a^s_{\rm sl}$, is measured to be $(-0.24 \pm 0.54_{\rm stat} \pm 0.33_{\rm syst}) \times 10^{-2}$, in good agreement with Standard Model expectations. A flavour-tagged and time-dependent analysis of the decays, $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi^+\pi^-$, measures $\phi_s = -0.002 \pm 0.083_{\rm stat} \pm 0.027_{\rm syst}$ rad, in good agreement with predictions of the Standard Model. This measurement places tight constraints on the parameter space for new physics models.

References

[1] A. Lenz and U. Nierste, JHEP **0706**, 072 (2007).
[2] D0 Collaboration, V. M. Abazov *et al.*, Phys. Rev. D **84**, 052007 (2011).
[3] J. Charles *et al.*, Phys.Rev. D**84** 033005 (2011).
[4] LHCb collaboration, A. A. Alves Jr. *et al.*, JINST **3** S08005 (2008).
[5] LHCb Collaboration, R. Aaij *et al.*, LHCb-CONF-2012-018.
[6] LHCb Collaboration, R. Aaij *et al.*, LHCb-CONF-2012-028.
[7] LHCb Collaboration, R. Aaij *et al.*, LHCb-CONF-2012-022.
[8] LHCb Collaboration, R. Aaij *et al.*, LHCb-CONF-2012-002.
[9] LHCb Collaboration, R. Aaij *et al.*, Phys. Lett. B **713** 378-386 (2012).
[10] V. Gligorov, C. Thomas, and M. Williams, The HLT inclusive B triggers, LHCb-PUB-2011-016.
[11] LHCb Collaboration, R. Aaij *et al.*, Phys. Lett. B **713** 186-195 (2012).
[12] LHCb Collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **108** 201601 (2012).
[13] LHCb Collaboration, R. Aaij *et al.*, LHCb-CONF-2012-026.
[14] LHCb Collaboration, R. Aaij *et al.*, Phys. Rev. Lett. **108** 241801 (2012).
[15] S. Stone and L. Zhang, S-waves and the measurement of CP violating phases in B_s decays, Phys. Rev. D**79** 074024 (2009).
[16] LHCb Collaboration, R. Aaij *et al.*, Phys. Rev. D**86** 052006 (2012).
[17] LHCb Collaboration, R. Aaij *et al.*, Phys. Rev. D**86** 052006 (2012).