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Measurement of the *CP* violating phase ϕ_s in $\overline{B}{}^0_s \to J/\psi f_0(980)$ ☆

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Measurement of mixing-induced *CP* violation in $\overline{B}{}^0_s$ decays is of prime importance in probing new physics. So far only the channel $\overline{B}{}^0_s \to J/\psi\phi$ has been used. Here we report on a measurement using an LHCb data sample of 0.41 fb^{-1}, in the *CP* odd eigenstate $J/\psi f_0(980)$, where $f_0(980) \to \pi^+\pi^-$. A time-dependent fit of the data with the $\overline{B}{}^0_s$ lifetime and the difference in widths of the heavy and light eigenstates constrained to the values obtained from $\overline{B}{}^0_s \to J/\psi\phi$ yields a value of the *CP* violating phase of $-0.44 \pm 0.44 \pm 0.02$ rad, consistent with the Standard Model expectation.

1. Introduction

An important goal of heavy flavour experiments is to measure the mixing-induced *CP* violation phase in $\overline{B}{}^0_s$ decays, ϕ_s. As this phase is predicted to be small in the Standard Model (SM) [1], new physics can induce large changes [2]. Here we use the decay mode $\overline{B}{}^0_s \to J/\psi f_0(980)$. If only the dominant decay diagrams shown in Fig. 1 contribute, then the value of ϕ_s using $\overline{B}{}^0_s \to J/\psi f_0(980)$ is the same as that measured using $\overline{B}{}^0_s \to J/\psi\phi$ decay.

Motivated by a prediction in Ref. [3], LHCb searched for and made the first observation of $\overline{B}{}^0_s \to J/\psi f_0(980)$ decays [4] that was subsequently confirmed by other experiments [5,6]. Time-dependent *CP* violation can be measured without an angular analysis, as the final state is a *CP* eigenstate. From now on f_0 will stand only for $f_0(980)$.

In the Standard Model, in terms of CKM matrix elements, $\phi_s = -2\arg[\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}]$. The equations below are written assuming that there is only one decay amplitude, ignoring possible small contributions from other diagrams [7]. The decay time evolutions for initial B^0_s and $\overline{B}{}^0_s$ are [8]

$$\Gamma\big(\overset{(-)}{B}{}^0_s \to J/\psi f_0\big) = \mathcal{N} e^{-\Gamma_s t}\big\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) \pm \sin\phi_s \sin(\Delta m_s t)\big\}, \quad (1)$$

where $\Delta\Gamma_s$ is the decay width difference between light and heavy mass eigenstates, $\Delta\Gamma_s = \Gamma_{\rm L} - \Gamma_{\rm H}$. The decay width Γ_s is the average of the widths $\Gamma_{\rm L}$ and $\Gamma_{\rm H}$, and $\mathcal{N}$ is a time-independent normalisation factor. The plus sign in front of the $\sin\phi_s$ term applies to an initial $\overline{B}{}^0_s$ and the minus sign for an initial B^0_s meson. The time evolution of the untagged rate is then

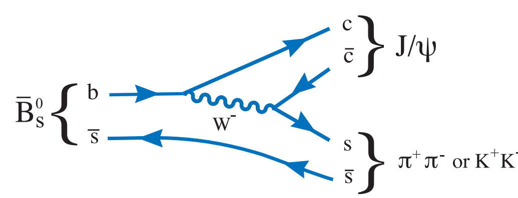

Fig. 1. Dominant decay diagrams for $\overline{B}{}^0_s \to J/\psi f_0(980)$ or $J/\psi\phi$ decays.

$$\Gamma\big(B^0_s \to J/\psi f_0\big) + \Gamma\big(\overline{B}{}^0_s \to J/\psi f_0\big) = \mathcal{N} e^{-\Gamma_s t}\big\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s)\big\}. \quad (2)$$

Note that there is information in the shape of the lifetime distribution that correlates $\Delta\Gamma_s$ and ϕ_s. In this analysis we will use both samples of flavour tagged and untagged decays. Both Eqs. (1) and (2) are insensitive to the change $\phi_s \to \pi - \phi_s$ when $\Delta\Gamma_s \to -\Delta\Gamma_s$.

2. Selection requirements

We use a data sample of 0.41 fb^{-1} collected in 2010 and the first half of 2011 at a centre-of-mass energy of 7 TeV. This analysis is restricted to events accepted by a $J/\psi \to \mu^+\mu^-$ trigger. The LHCb detector and the track reconstruction are described in Ref. [9]. The detector elements most important for this analysis are the VELO, a silicon strip device that surrounds the *pp* interaction region, and other tracking devices. Two Ring Imaging

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Cherenkov (RICH) detectors are used to identify charged hadrons, while muons are identified using their penetration through iron.

To be considered a $J/\psi \to \mu^+\mu^-$ candidate particles of opposite charge are required to have transverse momentum, p_{T}, greater than 500 MeV, be identified as muons, and form a vertex with fit χ^2 per number of degrees of freedom (ndof) less than 11. We work in units where $c = \hbar = 1$. Only candidates with dimuon invariant mass between −48 MeV to +43 MeV of the J/ψ mass peak are selected. Pion candidates are selected if they are inconsistent with having been produced at the primary vertex. The impact parameter (IP) is the minimum distance of approach of the track with respect to the primary vertex. We require that the χ^2 formed by using the hypothesis that the IP is zero be > 9 for each track. For further consideration particles forming di-pion candidates must be positively identified in the RICH system, and must have their scalar sum $p_{\mathrm{T}} > 900$ MeV.

To select $\overline{B}{}^0_s$ candidates we further require that the two pions form a vertex with a $\chi^2 < 10$, that they form a candidate $\overline{B}{}^0_s$ vertex with the J/ψ where the vertex fit $\chi^2/\mathrm{ndof} < 5$, that this vertex is > 1.5 mm from the primary, and points to the primary vertex at an angle not different from its momentum direction by more than 11.8 mrad.

The invariant mass of selected $\mu^+\mu^-\pi\pi$ combinations, where the di-muon pair is constrained to have the J/ψ mass, is shown in Fig. 2 for both opposite-sign and like-sign di-pion combinations, requiring di-pion invariant masses within 90 MeV of 980 MeV. Here like-sign combinations are defined as the sum of $\pi^+\pi^+$ and $\pi^-\pi^-$ candidates. The signal shape, the same for both $\overline{B}{}^0_s$ and $\overline{B}{}^0$, is a double-Gaussian, where the core Gaussian's mean and width are allowed to vary, and the fraction and width ratio for the second Gaussian are fixed to the values obtained in a separate fit to $\overline{B}{}^0_s \to J/\psi\phi$. The mean values of both Gaussians are required to be the same. The combinatoric background is described by an exponential function. Other background components are $B^- \to J/\psi h^-$, where h^- can be either a K^- or a π^- and an additional π^+ is found, $\overline{B}{}^0_s \to J/\psi\eta'$, $\eta' \to \rho\gamma$, $\overline{B}{}^0_s \to J/\psi\phi$, $\phi \to \pi^+\pi^-\pi^0$, and $\overline{B}{}^0 \to J/\psi\overline{K}{}^{*0}$. The shapes for these background sources are taken from Monte Carlo simulation based on PYTHIA [10] and GEANT-4 [11] with their normalisations allowed to vary. We performed a simultaneous fit to the opposite-sign and like-sign di-pion event distributions. There are 1428 ± 47 signal events within ±20 MeV of the $\overline{B}{}^0_s$ mass peak. The background under the peak in this interval is 467 ± 11 events, giving a signal purity of 75%. Importantly, the like-sign di-pion yield at masses higher than the $\overline{B}{}^0_s$ gives an excellent description of the shape and level of the background. Simulation studies have demonstrated that it also describes the background under the peak.

The invariant mass of di-pion combinations is shown in Fig. 3 for both opposite-sign and like-sign di-pion combinations within ±20 MeV of the $\overline{B}{}^0_s$ candidate mass peak. A large signal is present near the nominal $f_0(980)$ mass. Other $\overline{B}{}^0_s \to J/\psi\pi^+\pi^-$ signal events are present at higher masses. In what follows we only use events in the f_0 signal region from 890 to 1070 MeV.

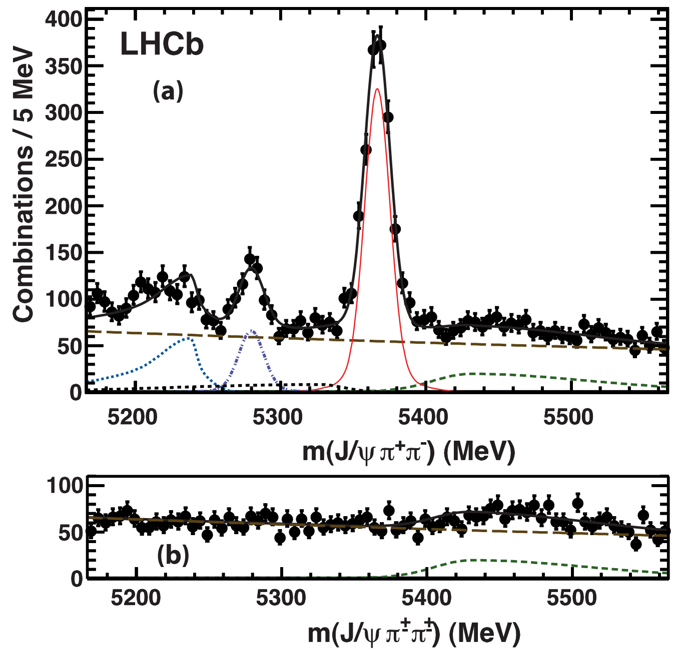

Fig. 2. (a) Invariant mass of $J/\psi\pi^+\pi^-$ combinations when the $\pi^+\pi^-$ pair is required to be within ±90 MeV of the nominal $f_0(980)$ mass. The data have been fitted with a double-Gaussian signal and several background functions. The thin (red) solid line shows the signal, the long-dashed (brown) line the combinatoric background, the dashed (green) line the B^- background (mostly at masses above the signal peak), the dotted (blue) line the $\overline{B}{}^0 \to J/\psi\overline{K}{}^{*0}$ background, the dash-dot line (purple) the $\overline{B}{}^0 \to J/\psi\pi^+\pi^-$ background, the dotted line (black) the sum of $\overline{B}{}^0_s \to J/\psi\eta'$ and $J/\psi\phi$ backgrounds (barely visible), and the thick-solid (black) line the total. (b) The mass distribution for like-sign candidates. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this Letter.)

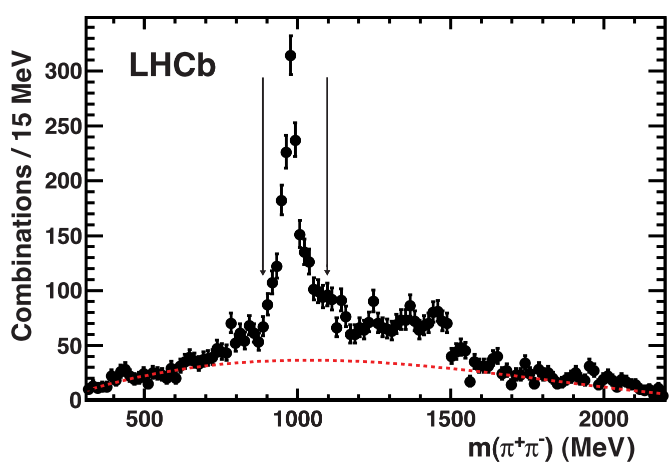

Fig. 3. Invariant mass of $\pi^+\pi^-$ combinations (points) and a fit to the $\pi^\pm\pi^\pm$ data (dashed line) for events in the $\overline{B}{}^0_s$ signal region. The region between the vertical arrows contains the events selected for further analysis.

3. *S*-wave content

Since the initial isospin of the $s\bar{s}$ system that produces the two pions is zero, and since the G-parity of the two pions is even, only even spin is allowed for the $\pi^+\pi^-$ pair. Since no spin-4 resonances have been observed below 2 GeV, the angular distributions are described by the coherent combination of spin-0 and spin-2 resonant decays. We use the helicity basis and define the decay angles as $\theta_{J/\psi}$, the angle of the μ^+ in the J/ψ rest frame with respect to the $\overline{B}{}^0_s$ direction, and θ_{f_0}, the angle of the π^+ in the $\pi^+\pi^-$ rest frame with respect to the $\overline{B}{}^0_s$ direction. The spin-0 amplitude is labelled as A_{00}, the three spin-2 amplitudes as A_{2i}, $i = -1, 0, 1$, and δ is the strong phase between the A_{20} and A_{00} amplitudes.

After integrating over the angle between the two decay planes the joint angular distribution is given by [12]

$$\frac{d\Gamma}{d\cos\theta_{f_0}\, d\cos\theta_{J/\psi}} = \left| A_{00} + \frac{1}{2} A_{20} e^{i\delta} \sqrt{5}\left(3\cos^2\theta_{f_0} - 1\right)\right|^2$$