Vol. 42 (2011) ACTA PHYSICA POLONICA B No 7

PROSPECTS FOR CP VIOLATION IN $B_s \to J/\psi\phi$ FROM FIRST LHCB DATA*

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(Received May 6, 2011)

One of the key physics goals of the LHCb experiment at the LHC is the measurement of mixing induced CP violation in decays of $B_s \to J/\psi\phi$. The interference between mixing and decay gives rise to a CP-violating phase, $\phi_s^{J/\psi\phi}$. Assuming a proper-time resolution and tagging performance as observed in simulated data, together with an expected luminosity of 1 fb^{-1} by the end of 2011, LHCb is expected to be able to measure $\phi_s^{J/\psi\phi}$ with an error of 0.07 rad.

DOI:10.5506/APhysPolB.42.1353
PACS numbers: 11.30.Er, 13.25.Hw, 14.40.Nb

1. Introduction

The LHCb experiment [1] at the LHC pursues two main physics goals: to further constrain the parameters of the CKM-matrix [2] and to search for physics beyond the Standard Model. In pursuit of the first goal, measurements are focused on the observation of CP-violation of b- and c-hadron decays, while the second goal also involves measurements of branching fractions of rare decays of the same hadrons. One of the important searches for physics beyond the Standard Model is the measurement of CP-violation in the decay $B_s \to J/\psi\phi$.

Diagrams such as the one shown in Fig. 1 enable the mixing of neutral B-mesons in the Standard Model. This can be described by an effective Hamiltonian and using this ansatz to solve the Schrödinger equation gives two distinct mass eigenstates labelled heavy and light. The mass difference gives rise to oscillation between these states and the CDF experiment has measured the frequency of these oscillations to be 17.7 ± 0.10 ps^{-1} [3] and the

* Presented at the Cracow Epiphany Conference on the First Year of the LHC, Cracow, Poland, January 10–12, 2011.

decay width difference to be $\Delta\Gamma_s = 0.075 \pm 0.045$ ps^{-1} [4]. The possibility for both the B_s and $\overline{B}_s$ to decay to the final state $J/\psi\ \phi$, allows for time-dependent CP-violation in the interference between mixing and decay. The amplitude of the time-dependent asymmetry between the rate of B_s or $\overline{B}_s$ decaying to $J/\psi\ \phi$ is suppressed in the Standard Model and predicted to be $\sin(\phi_s^{J/\psi\phi}) = -0.04$. Both the D0 and CDF collaborations have measured $\phi_s^{J/\psi\phi}$ as reported in [5] and [4], respectively.

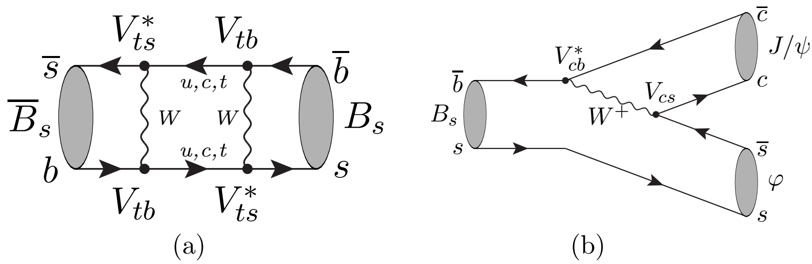

Fig. 1. Diagrams for mixing and decay in $B_s \to J/\psi\phi$: (a) shows one of the Standard Model box diagrams which enable mixing of neutral B_s mesons; (b) shows the leading order Standard Model diagram for the decay $B_s \to J/\psi\phi$.

2. $B_s \to J/\psi\phi$ in LHCb

The measurement of $\phi_s^{J/\psi\phi}$ in LHCb poses several experimental challenges. Due to the rapid oscillations of B_s mesons, an excellent proper-time resolution is required to be able to resolve the oscillations. Because the $B_s \to J/\psi\phi$ decay is a pseudo-scalar to vector–vector decay, the final state is a superposition of CP-even and CP-odd states. This requires an angular analysis of the final state particles to be able to statistically disentangle the CP-even and CP-odd components. Since the decay-width difference between the mass eigenstates cannot be neglected, correlations between angular and proper-time distributions must be taken into account. Finally, of crucial importance to the measurement of $\phi_s^{J/\psi\phi}$ is to determine the initial flavour of the decaying meson. This is complicated by the high particle multiplicities produced by the hadronic interactions in the LHC.

The design of the LHCb detector has been optimised for the measurement of decays of B-mesons and several of the LHCb subsystems are of particular importance for the successful analysis of $B_s \to J/\psi\phi$ decays. The vertex separation power of the LHCb vertex locator (VELO) allows efficient triggering and selection of events containing a $B_s \to J/\psi\phi$ decay. It is also the dominant factor in obtaining the proper-time resolution required to resolve B_s-meson oscillations. The excellent particle-momentum resolution provided by the LHCb tracking system is an essential ingredient in the triggering and selection of signal events. This is augmented by the RICH and muon particle identification detectors. Together with the calorimeters the muon detector also plays an important role in the first trigger level, implemented in hardware.

3. Trigger

The first steps in selecting events which contain a $B_s \to J/\psi\phi$ decay are taken in the LHCb online environment; first by the hardware level trigger (L0) and then by two levels of software triggers (HLT1 and HLT2). The L0 triggers used to select signal events are the single and dimuon channels. The L0 single muon channel looks for a muon candidate with a transverse momentum of more that 1.4 GeV/c, while the L0 dimuon channel searches for two muon candidates with a transverse momentum of approximately 500 MeV/c each. Events which pass the L0 trigger are sent to a large PC farm and enter HLT1. Two sets of selections in HLT1 provide efficient triggers for $B_s \to J/\psi\phi$ in HLT1. The first set of selections starts from the muon candidate(s) provided by L0 and attempts to find track segments in the T-stations and VELO which match the L0 candidate. For the single muon HLT1 trigger, a cut on the transverse momentum of the muon candidate is used to reduce the rate to a manageable level, while for the dimuon trigger a cuts on the invariant mass of the dimuon and its vertex quality are applied. These selections do not include any cuts which might bias the lifetime of the B_s meson. The second set of HLT1 selections searches for a single hadron or muon track with high impact parameter (IP) and impact parameter significance; these cuts bias the lifetime of the B_s meson. Once events are accepted by HLT1, they enter HLT2 where a global reconstruction is run, followed by a set of inclusive and exclusive selections. The selection which yields the highest efficiency for $B_s \to J/\psi\phi$ decays searches for a dimuon with an invariant within 70 MeV/c of the J/ψ mass.

4. Offline selection

To select events for the analysis, an offline selection is applied which does not involve any lifetime biasing cuts. This implies no cuts are applied on IP, IPS, lifetime or vertex separation. The quantities which are used in the selection are thus based on kinematic properties, particle identification (PID) and several lifetime-independent quality variables such as the χ^2 of the fitted tracks and vertices. An important effect of this selection is that most background is present at low lifetimes: $B/S \approx 3$ at $\tau = 0$. If the event yield obtained in the 34 pb^{-1} of luminosity recorded in 2010 is extrapolated, the expected yield is approximately 30 k/fb^{-1}. Figure 2 shows the invariant mass spectrum of the $J/\psi\phi$ combinations in the 2010 data sample with a 0.3 ps cut applied to remove the prompt background.

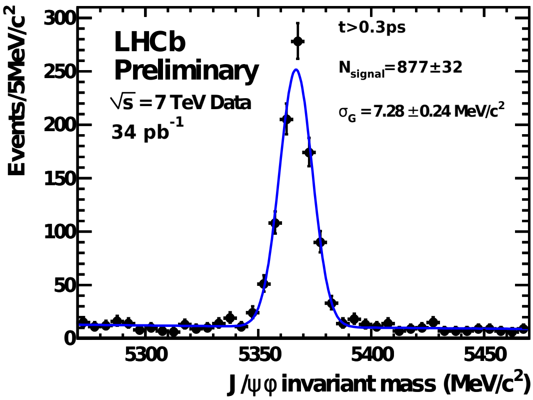

Fig. 2. The invariant mass spectrum for B_s candidates in 34 pb^{-1} obtained in 2010.

5. Tagging

Of crucial importance for the measurement of $\phi_s^{J/\psi\phi}$ is the determination whether the decaying B_s meson initially contained a b or a $\bar{b}$ quark. This is accomplished by a set of algorithms and is generally called flavour tagging. During the hadronisation process, b quarks are always produced in pairs and because the time scale at which hadronisation occurs is much shorter than the oscillation period, the flavour of the produced quarks remains strongly correlated. The initial flavour of the B_s meson can thus be inferred from the flavour of the other B hadron. Tagging algorithms which rely on the other B hadron decaying into a final state which identifies the flavour of the b quark are called opposite side taggers and several types are used in LHCb: muon, electron, kaon and inclusive secondary vertex.

Similar to the correlations between the b and $\bar{b}$ quarks, correlations also exist between the spectator quark in the B meson and the quark together with which it was created during hadronisation. If the partner quark further hadronises into a charged pion or kaon, the charge of this particle is correlated to the initial flavour of the B meson. Taggers which exploit this correlation are called same-side taggers. Two same-side taggers are using in LHCb: a same-side-pion tagger for B^0 decays and a same-side-kaon tagger for B_s decays.

To calibrate and optimise the different tagging algorithms, control channels are used where the charge of (one of) the final state particles uniquely identifies the flavour of the B meson. Since all of the taggers use an inclusive strategy to determine the flavour of the tagging meson, they can be optimised using any of the control channels. The following control channels with their respective methods have so far been used to optimise the opposite-side taggers: a fit to the time evolution of $B^0 \to D^{*-}\mu^+\nu_\mu$ decays, counting correctly and wrongly tagged decays of $B^+ \to J/\psi K^+$ and a fit to the time evolution in the decay of $B^0 \to J/\psi K^*$. Since calibration of the taggers requires a control channel whose selection is as close as possible to the one used to select $B_s \to J/\psi\phi$ decays, decays of $B^+ \to J/\psi K^+$ are used for that purpose. The same-side-kaon tagger is optimised by fitting the time evolution in $B_s \to D_s^-\pi^+$ decays and calibrated using decays of $B^+ \to J/\psi K^+$. The calibration is then cross-checked using $B^0 \to J/\psi K^*$ decays. For all of the taggers both simulated and real data are used. Table I summarises the expected performance of the tagging obtained from simulations in terms of the effective tagging power $D = \epsilon(1-2\omega)^2$, where ϵ is the tagging efficiency and ω the fraction of wrongly assigned tags. The final output of the tagging algorithms is a combination of the results of different tagging algorithms, together with a per-event wrong-tag fraction.

TABLE I

Performance of different categories of taggers obtained from simulated data.

Algorithm	$\epsilon(1-2\omega)^2$
All opposite-side	3.32 ± 0.15
Same-side-kaon	2.39 ± 0.10
Total	6.23 ± 0.15

6. Expectations

If a proper-time resolution and tagging performance as observed in simulated data are assumed [6], together with a recorded luminosity of 1 fb^{-1} by the end of 2011, LHCb is expected to be able to measure $\phi_s^{J/\psi\phi}$ with an error of 0.07 rad. This includes the observation in realistic simulations that systematic errors are sufficiently small. The expected LHCb sensitivity as a function of the recorded luminosity under these assumptions is shown in Fig. 3; the amount of data recorded in 2010 corresponds to the first tick on the horizontal axis and that the data expected to be recorded in 2011 corresponds to its full range.

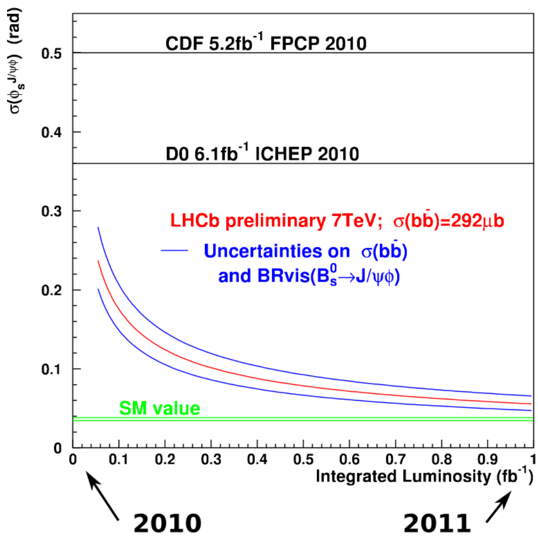

Fig. 3. The expected sensitivity for LHCb to measure $\phi_s^{J/\psi\phi}$ as a function of recorded luminosity.

7. Epilogue

While completing these proceedings, the LHCb experiment has released its first preliminary results on $\phi_s^{J/\psi\phi}$ [7]. An important highlight of these results is that although the data set was too small to calibrate the same-side tagger, the opposite-side tagger has a measured performance of 2.2 ± 0.5 %, not so far from the performance expected from simulation. While it was not yet possible to give a point estimate for $\phi_s^{J/\psi\phi}$, contours in $\phi_s^{J/\psi\phi}$–$\Delta\Gamma$ space could be calculated.

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