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Time-dependent angular analysis of $B_s^0 \to J/\psi\,\phi$ events at LHCb

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The determination of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\,\phi$ decays through a time dependent angular analysis is one of the key goals of the LHCb experiment. Here, the first LHCb measurement of the mixing phase ϕ_s using a data sample corresponding to 36 pb^{-1} of proton-proton collision taken in 2010 at a center-of-mass energy of 7 GeV is presented. The analysis of (860 ± 60) selected $B_s^0 \to J/\psi\,\phi$ candidates constrains ϕ_s to $-2.7 < \phi_s < -0.5$ at 68% CL.

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1. Introduction

For neutral B_s^0 mesons short range quantum-loop corrections lead to the phenomenon of particle-antiparticle mixing. The flavor states B_s^0 and $\bar{B}_s^0$ therefore differ from the mass eigenstates. For the latter one finds a mass difference Δm_s which determines the frequency of the mixing process, and a decay width difference $\Delta\Gamma_s$ which separates the two different lifetimes of the mass states. In the Wolfenstein parametrization of the quark mixing (CKM) matrix, the dominating amplitude carries a non-trivial phase ϕ_s related to the CKM-element $V_{\rm ts}$.

The B_s^0 decay $B_s^0 \to J/\psi\,\phi$ is sensitive to the phase ϕ_s of the mixing process: the interference between the direct decay to the final state $J/\psi\phi$ and the decay where the B_s^0 meson first mixes to a $\bar{B}_s^0$ and then decays give rise to a time-dependent CP asymmetry, i.e. a time-dependent decay rate difference between B_s^0 and $\bar{B}_s^0$ which is proportional to $\sin(\phi_s + 2\phi_D)$. The argument $(\phi_s + 2\phi_D)$ is the observable phase difference between the decay $B_s^0 \to J/\psi\,\phi$ with and without mixing process and the phase ϕ_D is the phase of the decay amplitude. Neglecting higher-order penguin corrections to the decay the phase $\phi_D \approx 0$ and the time dependent CP asymmetry directly measures the mixing phase which, in the Standard Model, is given by $\phi_s = -2\beta_s$ where $\beta_s = \arg(-V_{\rm ts}V_{\rm tb}^*/V_{\rm cs}V_{\rm cb}^*)$. The indirect determination within the Standard Modell via global fits to experimental data gives $2\beta_s = (0.0363 \pm 0.0017)\,\text{rad}$ [1]. Although first results of direct determination of ϕ_s exists [2] they are not yet very constraining. The precise determinataion of ϕ_s is one of the key goals of the LHCb experiment.

LHCb is a dedicated B physics experiment at the Large Hadron Collider (LHC). The detector exhibits an efficient low-p_T trigger system, an excellent mass and proper time resolution as well as good particle identification over the full relevant momentum range. In the following the main steps towards a measurement of ϕ_s at LHCb will be discussed. Using the data taken in the year 2010 at a center-of-mass energy of 7 TeV and corresponding to an integrated luminosity of 36 pb^{-1} constraints on the phase ϕ_s will be given.

2. Event selection and lifetime measurement

The measurement of the time-dependent CP asymmetry for the channel $B_s^0 \to J/\psi\,\phi$ requires a good understanding of detector effects such as proper time acceptance and resolution, angular acceptance, flavor tagging, and backgrounds. Several control channels are used to determine detector effects and validate the analysis procedures: several b-hadron decays to $J/\psi + X$ are used to understand the the proper-time reconstruction and calibration; the channel $B^0 \to J/\psi\,K^{*0}$ is used to validate the angular analysis which is required to disentangle the different polarization states of the decay to two vector mesons; the channel $B^+ \to J/\psi\,K^+$ is used to calibrate the tagging algortithms. To allow the extrapolation from the control channels to the signal decays the same trigger condition and a very similar event selection are used for the all decay channels. Details on trigger and event selection are given in [3].

Event yields. Events of the following b-hadron decay channels have been selected [3] : $B_d^0 \to J/\psi\,K^*$, $B_d^0 \to J/\psi\,K_S^0$, $B^+ \to J/\psi\,K^+$, $B_s^0 \to J/\psi\,\phi$ and $\Lambda_b \to J/\psi\,\Lambda$. The corresponding event yields are summarized in Table 1. Figure 1 shows for the channel $B_s^0 \to J/\psi\,\phi$ the reonstructed

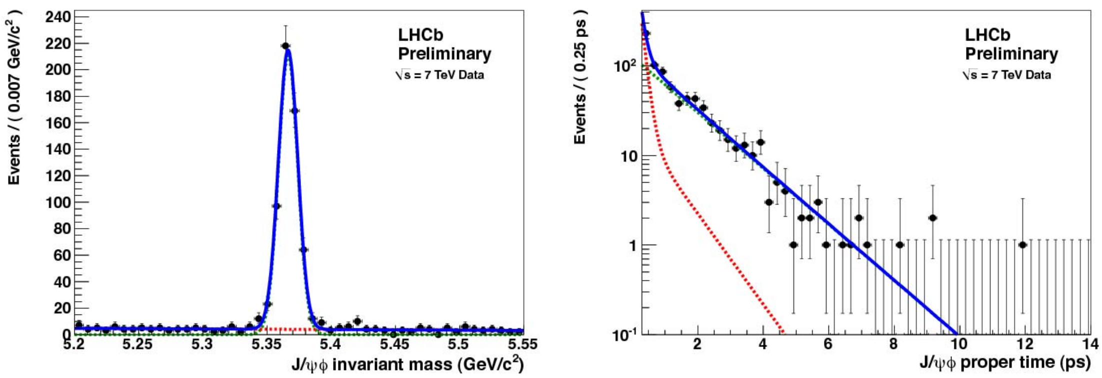

Figure 1: Invariant mass distribution (left) and proper time distribution (right) of the selected $B_s^0 \to J/\psi\,\phi$ candidates. The red dotted line indicates the background component. Figures are taken from [3].

Decay channel	Yield	LHCb fit result for τ[ps]	PDG value for τ[ps]
$B^+ \to J/\psi K^+$	6741 ± 85	$1.689 \pm 0.022_{\text{stat.}} \pm 0.047_{\text{syst.}}$	1.638 ± 0.011
$B_d^0 \to J/\psi K^*$	2668 ± 58	$1.512 \pm 0.032_{\text{stat.}} \pm 0.042_{\text{syst.}}$	1.5252 ± 0.009
$B_d^0 \to J/\psi K_S^0$	838 ± 31	$1.558 \pm 0.056_{\text{stat.}} \pm 0.022_{\text{syst.}}$	1.525 ± 0.009
$B_s^0 \to J/\psi\,\phi$	570 ± 24	$1.447 \pm 0.064_{\text{stat.}} \pm 0.056_{\text{syst.}}$	1.477 ± 0.046
$\Lambda_b \to J/\psi\Lambda$	187 ± 16	$1.353 \pm 0.108_{\text{stat.}} \pm 0.035_{\text{syst.}}$	$1.391^{+0.038}_{-0.037}$

Table 1: Event yields and lifetimes determined for the selected b-hadron $\to J/\psi X$ candidates. Numbers are taken from [3]

invariant mass of the selected B_s^0 candidqtes. The signal-to-background ratio in a 3σ signal window is 12.5.

Lifetimes. The selected events are used to determine the b-hadron lifetimes from a fit of a single exponential to the reconstructed proper time distribution. For the latter an effective resolution of 50 fs is found. Figure 1 shows the lifetime fit for the $B_s^0 \to J/\psi\,\phi$ candidates. The fit results for all considered b-hadron decays are summarized in Table 1. While the mean values of the obtained lifetimes are compatible with the current world average the measurements have not yet reached competitive errors with the sample sizes accumulated in 2010. The quoted systematic error is dominated by the uncertainty of a preliminary proper time acceptance correction.

3. Angular analysis and the determination of polarization amplitudes

The decays $B_s^0 \to J/\psi\,\phi$ and $B^0 \to J/\psi K^{*0}$ are both decays of a pseudo-scalar meson to two vector mesons. Both decays are described by three time dependent decay amplitudes corresponding to transitions in which the J/ψ and the ϕ (or K^*) have a relative orbital momentum L of 0, 1, or 2. In the transversity formalism [4], the initial ($t = 0$) amplitudes $A_0(0)$ and $A_\parallel(0)$ describe the decays with $L = 0$; 2 while the amplitude $A_\perp(0)$ describes the $L = 1$ final states. The phases of the amplitudes are denoted by δ_0, $\delta_\parallel$ and $\delta_\perp$. The amplitudes and two of the phases[1] are determined from a fit to the 3-dimensional transversity angle distribution of the selected events. Information on the initial flavor of the decaying B meson (i.e. *tagging information*) is not used (*untagged analysis*). Acceptance corrections due to the detector acceptance are taken into account.

The fitting procedure is checked by determining the polarization amplitudes also for the channel $B^0 \to J/\psi K^{*0}$ for which experimental results are available. A fit of the 3-dimensional transversity angle distribution and the reconstructed mass the selected signal candidates results into the following values of the polarization amplitudes:

$$\begin{aligned}
|A_\parallel|^2 &= 0.252 \pm 0.020 \pm 0.016 \\
|A_\perp|^2 &= 0.178 \pm 0.022 \pm 0.017 \\
\delta_\parallel [\mathrm{rad}] &= -2.87 \pm 0.11 \pm 0.10 \\
\delta_\perp [\mathrm{rad}] &= 3.02 \pm 0.10 \pm 0.07.
\end{aligned}$$

The first error is the statistical uncertainty from the fit, the second error is the systematic uncertainty for which details are given in [5].

For the decay $B_s^0 \to J/\psi\,\phi$, in addition to the polarization amplitudes, also the value $\Delta\Gamma_s$ can be determined. Beside the transversity angle distribution and the invariante mass the *untagged* analysis also uses the proper time distribution of the selected signal candidates. The 5D-fit of the selected $B_s^0 \to J/\psi\,\phi$ candidates gives the following physics parameters,

$$\begin{aligned}
\Gamma_s &= 0.679 \pm 0.036 \pm 0.027 \ \mathrm{ps}^{-1} \\
\Delta\Gamma_s &= 0.077 \pm 0.119 \pm 0.021 \ \mathrm{ps}^{-1} \\
|A_0(0)|^2 &= 0.528 \pm 0.040 \pm 0.028 \\
|A_\perp(0)|^2 &= 0.263 \pm 0.056 \pm 0.014 \\
\cos\delta_\parallel &= -1.24 \pm 0.27 \pm 0.09 \,,
\end{aligned}$$

where the first error is the statistical error from the fit and the second error is the systematic uncertainty for which details are given in [5]. The 1-dimensional projections of the 5-dimensional fit function are compared to the measured data in Figure 2.

4. Tagged time-dependent angular analysis of $B_s^0 \to J/\psi\,\phi$ events

The measurement of the time dependent CP asymmetry for $B_s^0 \to J/\psi\,\phi$ requires the determination of the initial flavor of the decaying B_s^0 meson. The flavor tagging algorithm used in this analysis is described in detail in [6]. It exploits charged tracks originating from the b-hadron opposite to the selected signal B_s^0 meson. The so called *opposite-side* flavor tagging algorithm is optimized using $B^0 \to D^{*-}\mu^+\nu_\mu$ and $B^+ \to J/\psi K^+$ events. Beside the flavor information, the algorithm provides the mistag probability for every event. To use this information in the fitting procedure the per-event mistag probability was calibrated using the self-tagging decays $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$. For the $B_s^0 \to J/\psi\,\phi$ event sample a mean tagging efficiency of 17% and a mean mistag probability $32 \pm 2\%$ of was found. These quanities translate into an effective tagging power of $2.2 \pm 0.4\%$.

[1] Only phase differences can be observed, therefore the phase δ_0 is chosen to be zero.

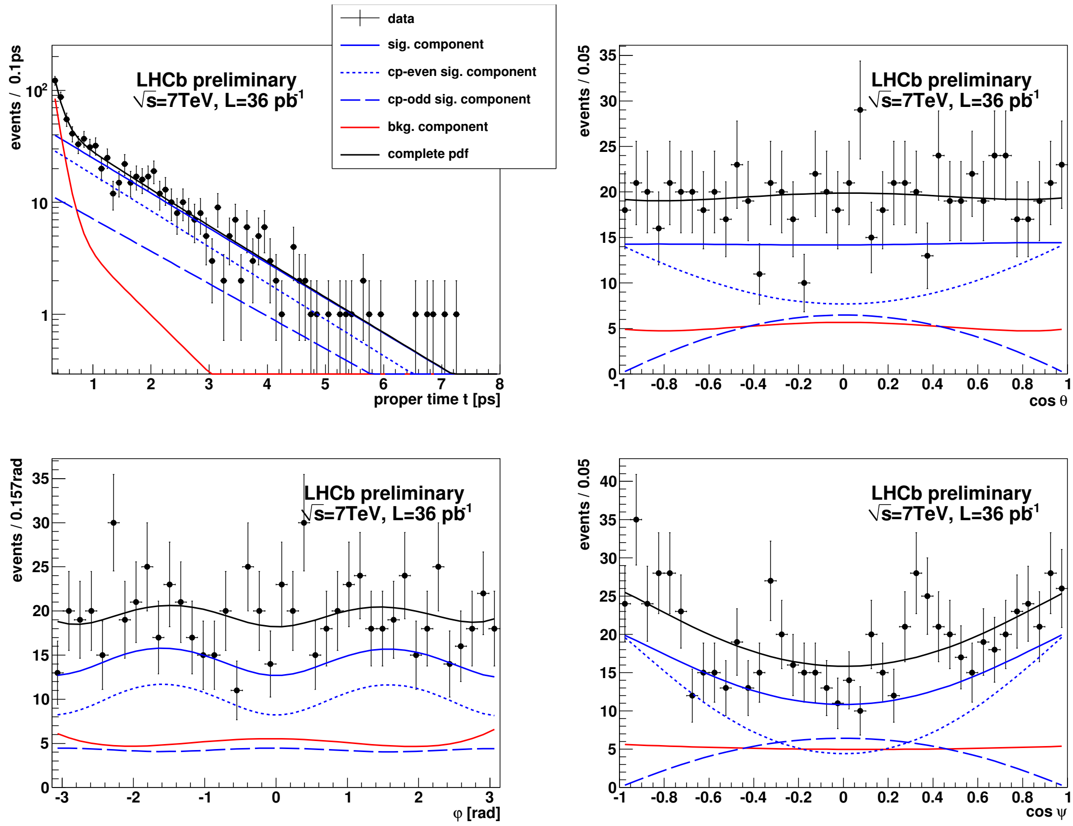

Figure 2: Fitted PDF of the untagged analysis of the selected $B_s^0 \to J/\psi\phi$ candidates projected on the reconstructed proper time and the transversity angles compared to the data distributions. Shown are the total PDF, the PDFs for signal, the PDFs for the CP-even and CP-odd signal components and the total background PDF. Figure is taken from [5].

Using the opposite-side tagging information to define the initial B-meson a time-dependent angular fit to the (836 ± 60) $B_s^0 \to J/\psi\,\phi$ signal candidates[2] is performed to determine the mixing phase ϕ_s [7]. As the event statistics of the 2010 data set does not allow to quote a meaningful parabolic 1σ error for ϕ_s the fit result is presented as a two-dimensional confidence level region in the $\Delta\Gamma_s - \phi_s$ plane. Figure 3 shows the 68, 90 and 95% confidence level (CL) contours where the CL coverage is adjusted following the Feldman-Cousins prescription [8]. The contours exhibit a symmetry due to a two-fold ambiguity of the signal PDF. Compared to the statistical uncertainites the effect of systematic uncertainties on the contours is small and is negelected, with the exception of the uncertainties due to flavour tagging calibration and the uncertainty of the mixing frequency, which were floated in the fit. The Standard Model expectation is also shown in Figure 3 ($\Delta\Gamma_s = 0.087 \pm 0.021$ ps^{-1} and $\phi_s = -0.0363 \pm 0.0017$ rad and has a P-value of 22% ("1.2σ"). When projecting the CL contour to get a 1-dimensional confidence range one obtains $\phi_s \in [-2.7;.-0.5]$ at 68 % CL and $\phi_s \in [-3.5;0.2]$ at 95 % CL. Further details are given in [7].

[2]The used event sample is slightly larger than in sections 2 and 3 because events triggered by a second trigger line (with lifetime bias) have been included for the *tagged analysis*.

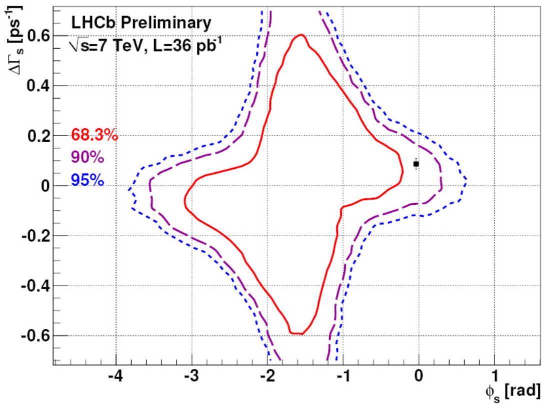

Figure 3: Feldman-Cousins confidence regions in the ($\phi_s - \Delta\Gamma_s$) plane. The CL at the Standard Model point (black square) is 0.785 which corresponds to a deviation of "1.2σ". Figure is taken from [7].

5. Conclusion

With the data taken in 2010 corresponding to an intergated luminosity of 36 pb^{-1} LHCb has performed a first time-dependent CP analysis of $B_s^0 \to J/\psi\,\phi$ decays. The determination of the B_s^0 mixing phase in an tagged time-dependent angular analyis required several control measurements being peformed beforehand: lifetimes have been determined for diferent b-hadron decays to $J/\psi + X$; the channel $B^0 \to J/\psi\,K^{*0}$ has been used to validate the angular fit procedure by measuring the polarization amplitudes; the polarization amplitudes and width difference $\Delta\Gamma_s$ have been determined from an untagged time-dependent angular fit of selected $B_s^0 \to J/\psi\,\phi$ candidates; the tagging algortihms have been calibrated using $B^+ \to J/\psi\,K^+$ decays. Finally a tagged analysis of (836 ± 60) selected $B_s^0 \to J/\psi\,\phi$ candidates has been performed and resulted in a first determination of the mixing phase ϕ_s at the LHC. The observed value of the mixing phase, $\phi_s \in [-2.7;.-0.5]$ at 68 % CL, has still a rather large statistical uncertainty. With the data taken in 2011, LHCb expects to perform the world best measurement of the mixing phase.

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