PROCEEDINGS OF SCIENCE

First measurements of $\sin 2\beta$ at LHCb with $B^0 \to J/\psi K_s$

Marc Grabalosa Gandara[*†]
Universitat de Barcelona
E-mail: mgrabalosa@ecm.ub.es, mgrabalo@cern.ch

We report on the measurement of the well-established CP violation in $B^0 \to J/\psi K_s$ decays. We have performed a time-dependent analysis of the decays reconstructed in ~ 35 pb^{-1} of data from the LHCb 2010 physics run. We measured the CP asymmetry parameter $S_{J\psi K_S^0} \equiv \sin 2\beta$, finding $S_{J\psi K_S^0} = 0.53^{+0.28}_{-0.29}$(stat) ± 0.07(syst).

The 13th International Conference on B-Physics at Hadron Machines - Beauty2011,
April 4-8 2011
Amsterdam, The Netherlands

*Speaker.
†on behalf of the LHCb collaboration

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1. Introduction

In the Standard Model the weak eigenstates of the quarks are related to the mass eigenstates through the CKM matrix. This matrix can be expanded in terms of $\lambda = \sin\theta_C$, where θ_C is the Cabbibo angle (eq 1.1). Using this representation, known as the Wolfenstein parametrization, it can be seen easily that one complex phase is enough to explain all the CP violation effects in the Standard Model.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \tag{1.1}$$

The unitarity conditions of the mixing matrix can be represented as 6 Unitary Triangles. For the (bd) triangle the unitarity condition is $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$.

The decay $B^0 \to J/\psi K_s$ is well known as the golden mode for the study of CP violation in the B_d^0 meson system. Here, the B_d^0 meson decays to a CP eigenstate common to both B^0 and $\bar{B}^0$. CP violation can be caused by differences between the B^0 and $\bar{B}^0$ amplitudes in either mixing, decay or in interference between mixing and decay. The Standard Model predicts negligible CP violation in the $b \to c\bar{c}s$ decay amplitude.

The CKM angle $\sin 2\beta$ is connected to the parameters $S_{J\psi K_S^0}$ and $C_{J\psi K_S^0}$, which govern the time-dependent decay rate asymmetry of the $B^0 \to J/\psi K_s$ decays,

$$\mathscr{A}_{J/\psi K_s} \equiv \frac{\Gamma(\bar{B}^0 \to J/\psi K_s) - \Gamma(B^0 \to J/\psi K_s)}{\Gamma(\bar{B}^0 \to J/\psi K_s) + \Gamma(B^0 \to J/\psi K_s)} = S_{J\psi K_S^0}\sin(\Delta m_d t) - C_{J\psi K_S^0}\cos(\Delta m_d t). \tag{1.2}$$

Assuming no direct CP violation, $S_{J\psi K_S^0} = \sin 2\beta$. Therefore, the measurement of the decay $B^0 \to J/\psi K_s$ has a good sensitivity to the CKM angle β. During the last decade the B-Factories Babar and Belle reached an outstanding precision in the measurement of $S_{J\psi K_S^0}$. The most recent Babar measurement in $B^0 \to J/\psi K_s$ ($K_S^0 \to \pi^+\pi^-$) reports $S_{J\psi K_S^0} = 0.663 \pm 0.039$(stat) ± 0.012(syst) and $C_{J\psi K_S^0} = 0.017 \pm 0.028$(stat) [1]. The most recent Belle result in $B^0 \to J/\psi K_s$ ($K_S^0 \to \pi^+\pi^-$, $\pi^0\pi^0$) is $S_{J\psi K_S^0} = 0.642 \pm 0.031$(stat) and $C_{J\psi K_S^0} = 0.001 \pm 0.028$(stat) [2]. Currently, the world average of $\sin 2\beta$ has a 3% uncertainty: $\sin 2\beta = 0.673 \pm 0.023$ (stat) ± 0.012 (syst) [3].

The LHCb detector, situated at CERN, is an experiment dedicated to study CP violation and rare decays in the beauty sector. LHCb is a forward spectrometer ($2 < \eta < 5$) characterized by excellent tracking, vertexing and particle identification system. Details on the LHCb experiment can be found in [4]. The performance of the LHCb detector in the 2010 run has been excellent, collecting a data sample of around 37 pb^{-1} at center-of-mass of 7 TeV. Hereby we will present the first measurement of $\sin 2\beta$ at LHCb using the $B^0 \to J/\psi K_s$ channel. The paper is organized as follows: first, the selection and the trigger, then we explain how the flavour tagging is and follow with the fit to the asymmetry and the computation of the systematic errors.

2. Selection and Trigger

For the analysis we use a data sample corresponding to an integrated luminosity of 35 pb^{-1} at a center-of-mass energy of $\sqrt{s}$ = 7 TeV collected during the 2010 run. A common selection has been used for all the b $\to J/\psi$ X decays at LHCb (i.e. transverse momentum $p_T > 500$ MeV/c for each of the muons that form the J/ψ) [5], plus some specific cuts (i.e. distance between the K_S^0 decay vertex and the B decay vertex divided by its error must be $L/\sigma_L > 5$) [6]. The LHCb trigger system consists of a hardware based L0 trigger and a two staged high level trigger (HLT1 and HLT2) implemented in software. The HLT1 performs a partial event reconstruction to confirm the L0 trigger decision. The second stage, HLT2, performs a full event reconstruction and applies more stringent selection criteria that are looser than the final selections. The HLT contains trigger lines which do not bias the proper life-time distribution as they are based on detecting dimuon events. Some trigger lines, however contain selection criteria on the decay tracks requiring them to have significant impact parameters with respect to the primary vertex. To increase the data sample both the lifetime unbiased and biased ($\sim 20\%$ of the data) trigger lines are used.

3. Flavour Tagging

Flavour tagging is the procedure to determine the flavour of the reconstructed B^0 meson at the production time. At LHCb, the initial B flavour is determined by the combination of various tagging algorithms [7]. These algorithms either determine the flavour of the non-signal b hadron produced in the event (*opposite side*, OS), or they search for an additional pion accompanying the signal B^0 or $\bar{B^0}$ (*same side*, SSπ). There are four OS taggers: they use the charge of the lepton (μ, e) from semileptonic B decays, that of the kaon from the $b \to c \to s$ decay chain, or the charge of the inclusive secondary vertex reconstructed from b decay products is used. All of these algorithms have an intrinsic mistag rate, due to picking up tracks from the underlying event, or due to flavour oscillations of neutral tag B mesons.

For each signal B^0 candidate the tagging algorithms also predict the mistag probability, depending on the output of a neural net based on several kinematic variables like momenta, angles of the tagging particles, etc. The neural nets are trained on MC simulated events, therefore, it is crucial to validate the predicted mistag probability on a self tagging control channel that is kinematically similar to the signal decay. For $B^0 \to J/\psi K_s$ such control channels are $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^*$.

The calibration of the mistag probability (ω) is accomplished by examining how ω varies from the mean. Defining η as the mistag probability estimated from the tagging algorithms with a mean value of $< \eta >$ we examine the linear calibration function $\omega = p_0 + p_1 \cdot (\eta - \langle\eta\rangle)$. If the calibrated mistag probability is valid we expect $p_0 = \langle\eta\rangle = 0.35$ and $p_1 = 1$ [7]. For the $B^0 \to J/\psi K^*$ channel we find $p_0 = 0.333 \pm 0.025$ and $p_1 = 0.71 \pm 0.36$.

The flavour asymmetry that is accessible in $B^0 \to J/\psi K_s$ decays directly depends on the dilution D due to the mistag probability, $D = 1 - 2\omega$. Its statistical precision is proportional to the inverse square root of the tagging power $Q = \varepsilon_{tag} D^2$, where ε_{tag} is the probability that a tagging decision is found. It is important to have the mistag well established to use as observable the per event mistag probability. Only the tagged events are sensitive to $\sin 2\beta$, so a good performance of the tagging is crucial. In this analysis we have selected ~ 280 tagged $B^0 \to J/\psi K_s$ events, with $Q = 2.8\%$.

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4. Likelihood Fit

The CP violation parameters $S_{J\psi K_S^0}$ and $C_{J\psi K_S^0}$ are extracted through a simultaneous multidimensional unbinned extended maximum likelihood fit [6]. The fit is simultaneous in four subsamples: triggered by the lifetime biased/unbiased lines; and by whether or not a tagging decision is available (tagged/untagged). We consider four observables: the reconstructed mass m of the B_d^0 candidate, its proper time t, the flavour tag decision d, and the calibrated $(OS+SS\pi)$ combined per-event mistag prediction ω. The flavour tag d can take the discrete values $d=1$ if tagged as initial B_d^0 and $d=-1$ if tagged as initial $\bar{B}_d^0$.

The probability density functions (p.d.f.) consist of three components, signal (S), prompt background (P), and long lived background (L). The mass p.d.f. of the signal component consists of a single Gaussian. We assume both background components have similar mass distributions, and we use the same parameterization for both (an exponential with a single shape parameter).

The proper time p.d.f. of the signal component can be written as $\mathscr{P}_S(t,d,\omega) = \mathscr{P}_S(t,d|\omega) \cdot \mathscr{P}_S(\omega)$. The first term is a conditional p.d.f. as it depends on the value of ω, the second term describes the distribution of ω. The background parameterization of the proper time factorizes, $\mathscr{P}_B(t,d,\omega) = \mathscr{P}_B(t,d) \cdot \mathscr{P}_B(\omega)$.

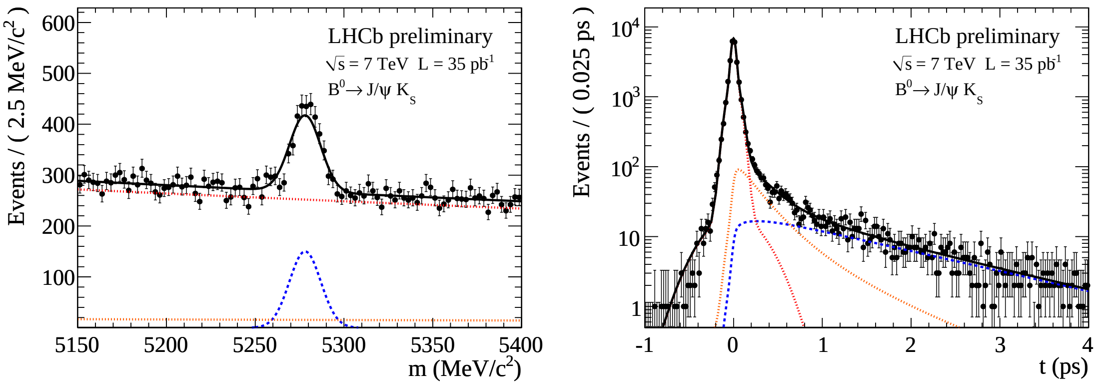

Figure 1: Reconstructed mass (left) and proper time (right) distributions of $B^0 \to J/\psi K_s$ candidates. Overlayed are projections of the component p.d.f.s used in the fit: full p.d.f. (solid black), signal (dashed blue), prompt background (dotted red), long lived background (dotted orange).

The conditional proper time p.d.f. of the $B^0 \to J/\psi K_s$ signal is given by $\mathscr{P}_S(t,d|\omega) = \varepsilon_s(t) \cdot \left(\mathscr{P}_{S,CP}(t,d|\omega) \otimes \mathscr{R}(t)\right)$. Here, the p.d.f. $\mathscr{P}_{S,CP}(t,d|\omega)$ describes decay, mixing and CP violation in the B_d^0 system, and thus depends on the CP violation parameters $S_{J\psi K_S^0}$ and $C_{J\psi K_S^0}$. It is convoluted with a triple Gaussian resolution function $\mathscr{R}(t)$ which is chosen equal between all subsamples of the simultaneous fit. The efficiency function $\varepsilon_s(t)$ describes acceptance effects observed in the biased subsample at low proper times.

The proper time p.d.f. of the prompt background is just $\mathscr{R}(t)$. That of the long lived background in the unbiased samples is the sum of two exponentials with different pseudo lifetimes. In the biased samples we simplify to a single exponential. These exponentials are also convoluted with the proper time resolution $\mathscr{R}(t)$, in order to properly describe the drop-off at $t<0$.

In the fit to the $B^0 \to J/\psi K_s$ channel we fix the mixing frequency Δm_d to its nominal value of $\Delta m_d = (0.507 \pm 0.005) \cdot 10^{12}\,\hbar s^{-1}$ [8], and $C_{J\psi K_S^0} = 0$. In total, there are 27 floating parameters: the CP parameter $S_{J\psi K_S^0}$, the B_d^0 lifetime, the B_d^0 mass, twelve event yields, four parameters of the long-lived proper time background, five parameters of the time resolution, the mass signal resolution, and two parameters of the mass background shape.

5. Systematic uncertainties

We consider several sources of systematic uncertainties [6], possibly affecting the measurement of $S_{J\psi K_S^0}$. They are summarized in Table 1. This measurement is clearly statistically limited, we therefore, estimate the systematic errors in a conservative fashion.

Source	uncertainty
tagger calibration	0.067
per-event mistags p.d.f.	0.012
Δm_d uncertainty, z scale	0.0017
proper time resolution	0.0085
high proper-time acceptance	0.00065
biased events acceptance	0.0042
biased TIS events acceptance	0.0063
production asymmetry	0.024
total (sum in squares)	0.073

Table 1: Systematic uncertainties to $S_{J\psi K_S^0}$ in absolute terms.

The leading contribution arises from the uncertainty in the tagger calibration, expressed through the uncertainties of the calibration parameters p_0, p_1, which is propagated to the effective dilution. Another contribution comes from the fact that the nominal p.d.f. contains histogram descriptions of the distributions of the per-event mistag probabilities. Other contributions are due to: the proper-time resolution model, the acceptance at high proper-times, the uncertainty of the proper-time acceptance corrections for the events triggered by the biased lines and also for the events triggered independently of the signal (TIS), as well as the propagation of the B_d^0 mixing frequency Δm_d uncertainty into $S_{J\psi K_S^0}$.

Any CP violation measurement can possibly be altered by a non-zero production asymmetry. The production asymmetry at LHCb was estimated to be compatible with zero [9]. To estimate the influence to our measurement, we refit with a small asymmetry in the tagging efficiency. The difference in the fit is assigned as systematic uncertainty.

6. Results

The result of the maximum likelihood fit to the full data sample give the first measurement of $\sin 2\beta$ at LHCb. The measured value fixing $C_{J\psi K_S^0} = 0$, is

$$S_{J\psi K_S^0} = 0.53^{+0.28}_{-0.29}(stat) \pm 0.07(syst). \tag{6.1}$$

This result is compatible with the world average [3] ($\sin 2\beta = 0.673 \pm 0.023$) and dominated by the statistical uncertainty. The calculated statistical significance of a non-zero CP violation is 1.8 sigma. This is the measurement of this important quantity by LHCb; it will be greatly improved with ~ 30 times higher statistics expected next year.

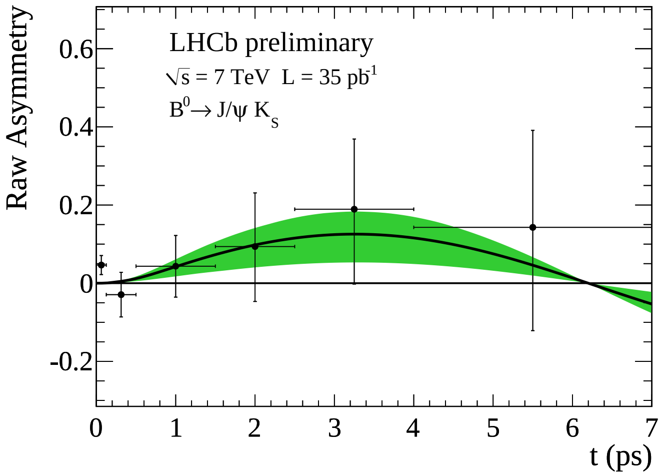

Figure 2: Time dependent raw CP asymmetry in $B^0 \to J/\psi K_s$. The solid curve is the full p.d.f. (signal and background) overlayed to the data points. The green band corresponds to the one standard deviation statistical error.

We also perform the nominal fit without the Standard Model constraint $C_{J\psi K^0_S} = 0$. In this case, we find $C_{J\psi K^0_S} = 0.28^{+0.32}_{-0.32}$, $S_{J\psi K^0_S} = 0.38^{+0.34}_{-0.35}$, quoting statistical errors only. The correlation between both parameters is $\rho(S_{J\psi K^0_S}, C_{J\psi K^0_S}) = 0.53$.

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