MEASUREMENTS OF $\sin 2\beta$*

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(Received August 17, 2000)

A review of the most recent measurements of the CP violating parameter $\sin 2\beta$ from LEP and CDF is reported. These yield an average value of $\sin 2\beta = 0.91 \pm 0.35$, giving a confidence level that CP violation in the B system has been observed of almost 99%.

PACS numbers: 11.30.–j, 13.20.He, 13.20.Gd

1. Introduction

The first evidence of CP violation was found in the kaon system in 1964 [1]. To date, no evidence in other systems has been reported. The study of CP violation in the B system is particularly important to test the predictions of the Standard Model. The decay $B^0 \to J/\psi K^0_{\rm S}$ is considered as the "golden channel" to study CP violation, due to its clear experimental signature and to the small theoretical uncertainties. Previous works searching for CP violation in the $B^0 \to J/\psi K^0_{\rm S}$ channel have been reported by the OPAL collaboration [2] and by the CDF collaboration [3]. Here the update presented by the CDF collaboration [4] and the new preliminary result presented this winter by the Aleph collaboration [5] are discussed.

Within the framework of the Standard Model, CP violation arises through a non trivial phase in the CKM matrix [6]. The unitarity of this matrix leads to several relations, the most important of which is given by

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0,$$

which can be visualised as a triangle in the (ρ, η) plane and is known as the unitary triangle [7]. Constraints on the CKM elements from other measurements, such as Δm_d, the rate of charmless b hadron decays and CP violation

* Presented at the Meson 2000, Sixth International Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 19–23, 2000.

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in the K sector, lead to a prediction that $\sin 2\beta = 0.72 \pm 0.06$ [8]. One of the most stringent reason to measure $\sin 2\beta$ directly is to verify whether CP violation can be explained in the framework of the Standard Model.

CP violation is expected to manifest itself in the decay of B^0, $\overline{B}^0$ mesons into a common final state. CP violating effects arise from the interference between direct decays to J/ψ and indirect decay via B^0–$\overline{B}^0$ mixing. The measured asymmetry, $\mathcal{A}_{CP}(t)$, can be related to the CP violating parameter β by:

$$\mathcal{A}_{CP}(t) = \frac{\frac{dN}{dt}(\overline{B}^0 \to J/\psi K^0_{\mathrm{S}}) - \frac{dN}{dt}(B^0 \to \mathrm{J}/\psi K^0_{\mathrm{S}})}{\frac{dN}{dt}(\overline{B}^0 \to J/\psi \mathrm{K}^0_{\mathrm{S}}) + \frac{dN}{dt}(B^0 \to J/\psi K^0_{\mathrm{S}})} = \sin 2\beta \sin \Delta m_d t\,.$$ [1]

To measure this asymmetry, the flavour of the B meson at production time must be tagged. The tagging power is limited by the tagging efficiency, ε, and its dilution, $\mathcal{D}$, which measures the fraction of incorrectly tagged mesons. The observed asymmetry, $\mathcal{A}^{\mathrm{obs}}_{CP} = \mathcal{D}A_{CP}$, is reduced in magnitude by this dilution parameter. The statistical uncertainty on $\sin 2\beta$ is inversely proportional to $\sqrt{\varepsilon\mathcal{D}^2}$.

2. The CDF result

From the entire data set collected by during Run I about 400 $B^0 \to J/\psi K^0_{\mathrm{S}}$ events have been selected. The flavour of the neutral B meson at production time is identified by combining the information of three different tagging algorithms: one same-side tag and two opposite-side tags. The same-side tag exploits the correlation between the B meson and the charge of nearby tracks to tag the flavour of the B. The two other methods aim to reconstructing the charge of the b hadron in the hemisphere opposite to the J/ψ $\mathrm{K}^0_{\mathrm{S}}$ decay. The Soft-Lepton Tagging algorithm (SLT) associates the charge of a lepton candidate with the flavour of the parent b hadron. The jet charge algorithm (JETQ) uses a momentum-weighted charge average of particles in the b jet to infer the charge of the b quark. If more than one tag is present the information is combined. Overall, a figure of $\varepsilon\mathcal{D}^2 = (6.3 \pm 1.7)\%$ is achieved.

To extract $\sin 2\beta$ a maximum likelihood method has been used, in which each candidate is weighted by its predicted dilution, observed decay length and mass. The results of the fit are shown in Fig. 1 separately for the SVX and non-SVX data samples. From the combination of the two samples a value of $\sin 2\beta = 0.79^{+0.41}_{-0.44}$ is derived, where the quoted uncertainties include both statistical and systematic effects. From this value, depending on the method chosen [9], the probability that $\sin 2\beta = 0$ is excluded with 93% to 96% C.L.

[1] It should be noted that this definition is the negative of that in Ref. [5].

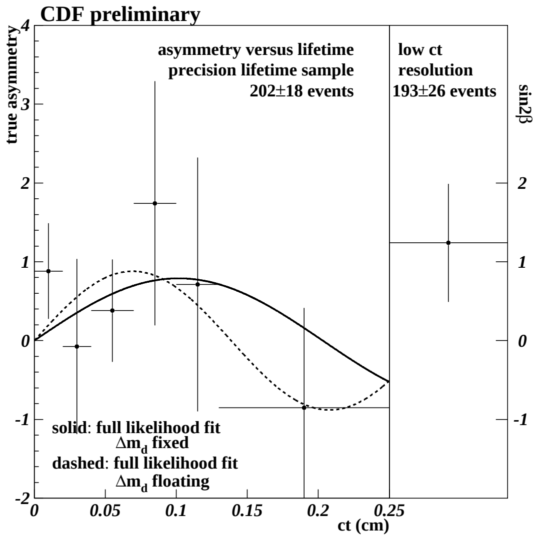

Fig. 1. Observed asymmetry: on the left, the events with precise vertex information are plotted as a function of decay time. On the right, the non-SVX events are shown.

3. The ALEPH result

The ALEPH Collaboration has presented a preliminary result of $\sin 2\beta$ from 23 J/ψ $K^0_{\rm S}$ candidates selected from the full LEP1 data set. Loose cuts are applied in order to keep high efficiency. The decay products are reconstructed in the modes $J/\psi\!\to e^+e^-$ or $\mu^+\mu^-$ and $K^0_{\rm S} \to \pi^+\pi^-$, with an overall efficiency of 28%. For each candidate, the proper time is measured combining the decay length (determined by vertexing the decay products) and the reconstructed momentum, with a resolution of about 0.1 ps.

The flavour of the neutral B meson at production time is determined by combining the information of 9 discriminating variables into a single one, x_B, that peaks at 0 for events produced as $\overline{B}^0$ and at 1 for events produced as B^0. To extract a measurement of the asymmetry an unbinned likelihood is calculated, summing over the 23 signal events. This is repeated for different input values of $\sin 2\beta$ and the resulting scan is plotted in Fig. 2. The minimum is reached at 0.93 and the statistical error is evaluated as the point at which the likelihood has changed by 0.5 units. Several different systematic effects have been studied. The main contributions come from the uncertainty in the tagging purity and the background level. Adding the systematic errors in quadrature, the final results is $\sin 2\beta = 0.93^{+0.64}_{-0.88}(\mathrm{stat})^{+0.36}_{-0.24}(\mathrm{syst})$.

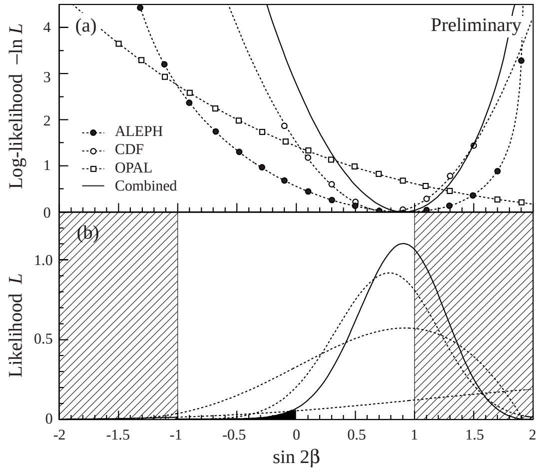

Fig. 2. (a) Log-likelihood and (b) likelihood distribution of the ALEPH, CDF and OPAL measurements, and combined result.

4. Combined results

In Table I all the existing measurements of $\sin 2\beta$ are summarised.

TABLE I

Summary of all the existing measurements of $\sin 2\beta$.

Experiment	$\sin 2\beta$
OPAL	$3.2^{+1.8}_{-2.0}(\mathrm{stat}) \pm 0.5(\mathrm{syst})$
CDF (update)	$0.79 \pm 0.39(\mathrm{stat}) \pm 0.16(\mathrm{syst})$
ALEPH (preliminary)	$0.93^{+0.64}_{-0.88}(\mathrm{stat})^{+0.36}_{-0.24}(\mathrm{syst})$
Combined result	0.91 ± 0.35
CKM model fit	0.75 ± 0.09 [10] 0.72 ± 0.06 [8]

The OPAL collaboration published in 1998 a first measurement from a sample of 24 $J/\psi\ K^0_{\mathrm{S}}$ candidates including background [2].

In Fig. 2(a) the log-likelihood of all these measurements are compared. The solid line represents the combined result, which corresponds to $\sin 2\beta = 0.91 \pm 0.35$. These log-likelihoods can be converted back to likelihood distributions as shown in Fig. 2(b).

The integral of the likelihood for $\sin 2\beta < 0$ for the combination of the three analyses is 1.0%, or 1.5% if the total integral is limited to the physical region $|\sin 2\beta| < 1$, indicating that the C.L. that CP violation has been observed is increased from 93% to almost 99%.

5. Conclusions

First measurements of the CP violating parameter $\sin 2\beta$ have been made, both at LEP and at the Tevatron, looking at the $B^0 \to J/\psi K^0_{\rm S}$ decay mode. The measurements made so far only hint at CP violation in B meson decays. The combined result, prior the first measurements coming from B factory experiments, gives $\sin 2\beta = 0.91 \pm 0.39$, which excludes $\beta \le 0$ at almost 99% C.L. Dedicated B factory experiments have started to take data last winter and first results are expected for the summer conferences. Several measurements of $\sin 2\beta$ with precision $\simeq 0.1$ can be expected giving almost immediate prospects for observing CP violation in B meson decays.

I thank those who provided me information included in this review, especially R. Forty and D. Lucchesi. I also thank the conference organizers for their kind hospitality.

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