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SENSITIVITY OF TIME-DEPENDENT CP-ASYMMETRY MEASUREMENT VERSUS TIME-INTEGRATED ONE IN B SYSTEM

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Abstract

Roinishvili V. Sensitivity of Time-Dependent CP-Asymmetry Measurement Versus Time-Integrated One in B System: IHEP Preprint 99-7. – Protvino, 1999. – p. 4, figs. 2, refs.: 4.

Simple expressions for the sensitivities of time-dependent and time-integrated measurements of CP-asymmetry in B system are obtained.

Аннотация

Ройнишвили В. Соотношения между точностями измерения зависящей от времени и интегрированной по ней CP-асимметрии при распаде нейтральных B-мезонов: Препринт ИФВЭ 99-7. – Протвино, 1999. – 4 с., 2 рис., библиогр.: 4.

Получены простые соотношения между точностями измерения параметров нарушения CP-четности при распаде нейтральных B-мезонов в случаях измерения асимметрии, зависящей от времени и интегрированной по ней.

CP-violation in B^0-decay leads to the difference between the rates of B^0 and $\bar{B}^0$ decay into a CP eigenstate f_{CP}. If only a single diagram contributes to some decay, the decay rates, for example, for $f_{CP} \equiv J/\psi K_s$, are:

$$\Gamma_f(t) = e^{-\Gamma t} \times (1 - sin2\beta \times sin\Delta mt) \quad and \quad \bar{\Gamma}_f(t) = e^{-\Gamma t} \times (1 + sin2\beta \times \sin \Delta mt),$$

where $\Gamma(t)$ stands for $B_d \to f_{CP}$, $\bar{\Gamma}(t)$ for $\bar{B}_d \to f_{CP}$, Δm is the mass difference between B_d and $\bar{B}_d$ and β - the angle in the unitarity triangle of CKM matrix. In terms of $\tau = \Gamma t$ and the mixing parameter $x_d = \Delta m/\Gamma$ the time-dependent CP-asymmetry can be written as

$$A_{t-d}(\tau) = \frac{\Gamma(\tau) - \bar{\Gamma}(\tau)}{\Gamma(\tau) + \bar{\Gamma}(\tau)} = -\sin 2\beta \times \sin x_d \tau. \tag{1}$$

In Fig.1 the distribution of $A_{t-d}(\tau)$ (points with error bars) is shown for a sample of $N = 2.4 \cdot 10^6$ generated events of B_d decay into $J/\psi K_s$ with $\sin 2\beta = 0.5$ and $x_d = 0.7$. For any bin of τ one can define the magnitude of $\sin 2\beta$ as $A_{t-d}(\tau)/\sin x_d \tau$ with the statistical error:

$$\delta_{\sin 2\beta}(\tau) \approx \frac{1}{\sqrt{\Delta N(\tau)} \times |\sin x_d \tau|},$$

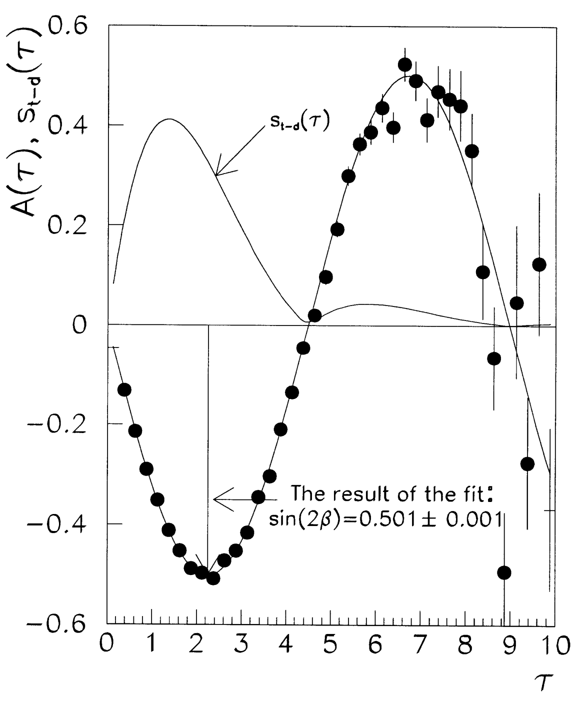

Fig. 1. CP-asymmetry $A_{t-d}(\tau)$ for $2.4 \cdot 10^6$ event — points and the sensitivity per events $s_{t-d}(\tau)$ —curve.

where $\Delta N(\tau) = N \times e^{-\tau} \times \Delta\tau$ is the number of B_d events in the bin. It is convenient to introduce sensitivity — s (a quantity inverse to the statistical error) per event, whose square is an additive quantity. For the time-dependent measurement

$$s^2_{t-d}(\tau) = e^{-\tau} \times \sin^2 x_d \tau.$$

The sensitivity $s_{t-d}(\tau)$ is also presented in Fig.1 as a solid curve for $x_d = 0.7$. The total sensitivity for a full range of τ per event is defined as

$$S_{t-d} = [\int_0^\infty s_{t-d}^2(\tau)d\tau]^{1/2} = \sqrt{\frac{2x_d^2}{1+4x_d^2}}. \quad (2)$$

The statistical error for the time-dependent CP-violation measurement with the total number of $B_d(\bar{B}_d) \to f_{CP}$ events N will be

$$\delta_{t-d}[\sin 2\beta] = \frac{1}{S_{t-d} \times \sqrt{N}} = \sqrt{\frac{1+4x_d^2}{2x_d^2 N}}. \quad (3)$$

$S_{t-d} = 0.575$ for $x_d = 0.7$ and the error for $\sin 2\beta$ in the above mentioned sample should be equal to 0.0011. This figure coincides, as it must be, with that obtained by fitting (MINUIT) $A_{t-d}(\tau)$ in Fig.1.

In the case of time-integrated measurements the CP-asymmetry A_{int} is

$$A_{int} = \frac{\int_0^\infty [\Gamma(\tau) - \bar{\Gamma}(\tau)]d\tau}{\int_0^\infty [\Gamma(\tau) + \bar{\Gamma}(\tau)]d\tau} = -\sin 2\beta \times \frac{x_d}{1+x_d^2}. \quad (4)$$

The value of $\sin 2\beta$ now can be obtained as $A_{int} \times \frac{1+x_d^2}{x_d}$ with the sensitivity per event

$$S_{int} = \frac{x_d}{1+x_d^2} \quad (5)$$

and with the statistical error for N events (a well known result)

$$\delta_{int}[\sin 2\beta] = \frac{1}{\sqrt{N} \times S_{int}} = \frac{1}{\sqrt{N}} \times \frac{1+x_d^2}{x_d}. \quad (6)$$

Time-dependent measurements are statistically more precise than time-integrated ones, as it follows from (2) and (5), by a factor

$$R = \frac{S_{t-d}}{S_{int}} = (1+x_d^2) \times \sqrt{\frac{2}{1+4x_d^2}} \quad (7)$$

which is equal to 1.22 for $x_d = 0.7$. Relation (7) holds if the efficiency of the B_d vertex reconstruction ε is equal to 1, otherwise it will be less by a factor of $\sqrt{\varepsilon}$.

Selection of reconstructed B events with the decay vertex separated from the primary one reduces the background under B signal. In this case the lower limits of the integrals in (4) - $\tau_L \neq 0$ and the CP-asymmetry $A_{int}(\tau_L)$ for τ range $\tau_L \leq \tau \leq \infty$ is equal to

$$A_{int}(\tau_L) = -\sin 2\beta \times \frac{\sin x_d\tau_L + x_d \cos x_d\tau_L}{1+x_d^2}. \quad (8)$$

The sensitivity per event

$$S_{int}(\tau_L) = e^{-\frac{\tau_L}{2}} \times \frac{|\sin x_d\tau_L + x_d \cos x_d\tau_L|}{1+x_d^2} \quad (9)$$

has the maximum at $\tau_L^{max} = \frac{1}{x_d} \times \arctan \frac{x_d}{1+2x_d^2}$.

For $x_d = 0.7$ $\tau_L^{max} = 0.49$ and $S_{int}(\tau_L^{max}) = 0.523$. This figure can be increased up to 0.536 if the upper limits for the integrals in (4) are $\tau_U = \tau_U^{max} = \frac{1}{x_d} \times [\arctan(-x_d) + \pi] = 3.615$ - the first value of $\tau_L \geq 0$ at which A_{int} in (8) vanished. The sensitivities $S_{int}(\tau_L)$ — solid curve and $S_{int}(\tau_L^{max}, \tau_U)$ — dotted curve are plotted in Fig.2. Particularly, one can see from the figure that there is a range of $\tau_L \leq 1$ where $S_{int}(\tau_L)$ is more sensitive than the time-integrated one over a full range of τ — $S_{int} = 0.47$.

The time-dependent sensitivity for τ range $\tau \geq \tau_L^{max}$ decreases a little from 0.575 to 0.564 since the sensitivity for $\tau \leq 0.5$ is small (see Fig.1). Now ratio R

$$R = \frac{S_{t-d}(\tau \geq \tau_L^{max})}{S_{int}(\tau_L^{max}, \tau_U^{max})} = 1.05 \qquad (10)$$

is rather close to 1.

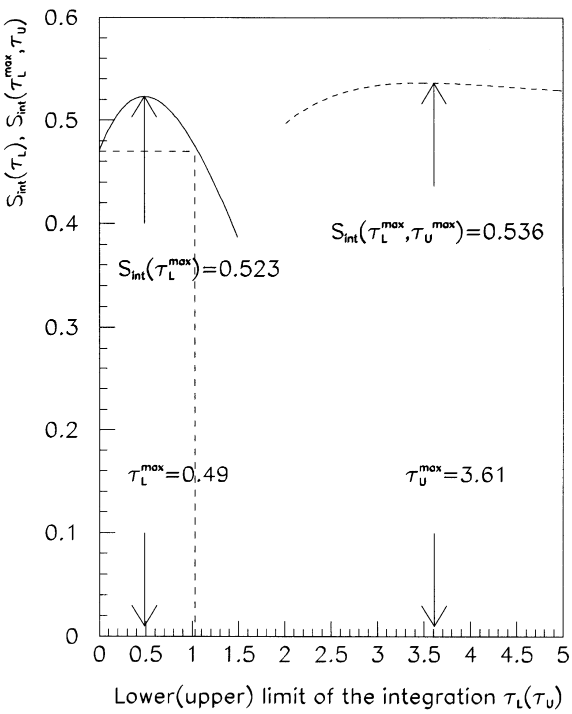

Fig. 2. Sensitivity for the range $\tau > \tau_L$ — solid curve and for the range $\tau_L^{max} < \tau < \tau)_u$ — dotted curve.

Important note: In the above considerations it is assumed that B_d flavor at the production stage is known. In practice some dilution effects will arise because of backgrounds and/or a wrong definition of B_d flavor. All the sensitivities will be decreased by a factor $D = \frac{N_R - N_W}{N_R + N_W}$, where $N_R(N_W)$ is the number of events with right (wrong) definition of B_d flavor.

Magnitudes of D for different methods (and/or different experiments) of B_d flavor definition are different (for LHC experiments see, for example, /1/-/4/). However, it seems that there will be no significant difference in D between time-dependent and time-integrated CP-asymmetry measurements and relation (7) and (10) for R will be valid.

Conclusion.

Simple expression (2) for the sensitivity of time-dependent CP-asymmetry measurements has been obtained. Time-dependent measurements are more sensitive than time-integrated ones by a factor

$$R = (1 + x_q^2) \times \sqrt{\frac{2}{1 + 4x_q^2}},$$

which is equal to 1.22 for $x_q = 0.7$.

For the optimal range of integration $\tau_L^{max} \leq \tau \leq \tau_U^{max}$ (see text), the factor R is 1.05 only. But in this case it is necessary to measure the decay time of B^0 as for time-dependent methods.

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