

## The demise of flavour tagging and its $\Delta t$ -dependence

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In this work we discuss how the loss of particle-antiparticle identity due to CPT violation affects the observables in the decay of two neutral EPR-correlated  $B$ -mesons. We study this possible new effect in the context of equal-sign flavour specific decays and we find a considerable modification in the  $\Delta t$ -dependence of the equal-sign dilepton charge asymmetry,  $A_{sl}$ . Although the more important changes occur right outside the  $\Delta t$  region that has been up-to-the-date effectively explored, we show that a deeper experimental research may be able to distinguish a possible existence of this new CPT violating parameter,  $\omega$ . In any case, using the available data for  $A_{sl}$ , we put the first limits on  $\omega$ .

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## 1. Introduction

We analyze a novel kind of CPT violation which occurs in the B-factories through the loss of indistinguishability of particle-antiparticle [1].

In the usual formulations of *entangled* meson states in the B-factories, one imposes the requirement of Bose statistics for the state  $B^0\bar{B}^0$ , which implies that the physical system must be *symmetric* under the combined operation of charge conjugation (C) and permutation of the spatial coordinates ( $\mathcal{P}$ ),  $C\mathcal{P}$ . If CPT is violated then  $B^0$  cannot be considered indistinguishable to  $\bar{B}^0$  and therefore the previous reasoning does not hold any more. In fact, if the  $C\mathcal{P} = +$  requirement of Bose statistic is relaxed, we can re-write the initial state as

$$|\psi(0)\rangle = \frac{1}{\sqrt{2(1+|\omega|^2)}} \times \left\{ |B^0(+\vec{k}), \bar{B}^0(-\vec{k})\rangle - |\bar{B}^0(+\vec{k}), B^0(-\vec{k})\rangle + \omega \left( |B^0(+\vec{k}), \bar{B}^0(-\vec{k})\rangle + |\bar{B}^0(+\vec{k}), B^0(-\vec{k})\rangle \right) \right\}, \quad (1.1)$$

where the  $\vec{k}$  vector is along the direction of the momenta of the mesons in the center of mass system. Here  $\omega = |\omega|e^{i\Omega}$  is a complex CPT violating parameter, associated with the non-indistinguishable particle nature of the neutral meson and antimeson states, which parameterizes the loss of Bose symmetry. (It is worth noticing that this new parameter,  $\omega$ , it is unrelated to the violation of CPT in the time evolution of the B mixing.) Observe the symmetry in Eq. (1.1) in which a change in the sign of  $\omega$  is equivalent to the exchange of the particles  $B^0 \leftrightarrow \bar{B}^0$ . Moreover, once defined through Eq. (1.1) the modulus and phase of  $\omega$  have physical meaning which could be in principle measured.

We interpret Eq. (1.1) as a description of a state of two *distinguishable* particles at first-order in perturbation theory, written in terms of correlations of the zeroth-order one-particle states. As it is easily seen, the probabilities for the two states connected by a permutation are different due to the presence of  $\omega$ . Therefore, in order to give physical meaning to  $\omega$  we *define*, in Eq. (1.1),  $+\vec{k}$  as the direction of the *first* decay, and  $-\vec{k}$  as the direction of the second decay. Of course, when both decays are simultaneous there is no way to distinguish the particles; although the effect of  $\omega$  is still present [2].

It is clear that the modification of the initial state, Eq. (1.1), will introduce modifications in all the observables of the B factories, since it is the departure point of every analysis.

## 2. The demise of flavour tagging and the $\Delta t$ -dependence in the $A_{sl}$ asymmetry

As it may be seen in Eq. (1.1), setting  $\omega \neq 0$  produces a loss in the definite antisymmetry of the state. This antisymmetry, when  $\omega = 0$ , forbids the system to have the same decay at the same time on both sides,

$$\langle X, X | U(t) \otimes U(t) | \psi(0) \rangle_{\omega=0} = 0, \quad (2.1)$$

since a permutation of the particles introduces a minus sign in  $|\psi(0)\rangle_{\omega=0}$ , whereas the rest remains the same. If, on the contrary, we have  $\omega \neq 0$ , then there is nothing to be said and the same decay on both sides at the same time it is, in principle, allowed. In fact, the time evolution of the initial state gives a projection on the usually *forbidden* states  $|B^0B^0\rangle$  and  $|\bar{B}^0\bar{B}^0\rangle$ , proportional to  $\omega$ . Due

to these states, a first flavour-specific  $B^0$  decay filters at that time the wave function of the meson on the other side to be  $\sim \mathcal{O}(1)|\bar{B}^0\rangle + \mathcal{O}(\omega)|B^0\rangle$ , and vice-versa. Therefore, the probability of having the same flavour specific decay *at the same time on both sides* goes as

$$I(\ell^\pm, \ell^\pm, \Delta t = 0) \sim |\omega|^2. \quad (2.2)$$

This constitutes the demise of flavour tagging [2], which introduces conceptual changes in the analysis, but its observability goes as  $|\omega|^2$ .

If we study the time dependence of the intensities in Eq. (2.2) then the interference terms will give rise to linear correction in  $\omega$  [3]. When analyzing the equal-sign dilepton events,  $I(\ell^\pm, \ell^\pm, \Delta t)$ , we find a linear-in- $\omega$  *opposite* behaviour of the intensities at short  $\Delta t$ 's depending on the sign of the leptons, pointing then to their asymmetry as a good observable where to detect traces of the  $\omega$ -effect.

In the  $\omega = 0$  case, the dilepton charge asymmetry it is expected to be *exactly* time independent:

$$A_{sl} = \left. \frac{I(\ell^+, \ell^+, \Delta t) - I(\ell^-, \ell^-, \Delta t)}{I(\ell^+, \ell^+, \Delta t) + I(\ell^-, \ell^-, \Delta t)} \right|_{\omega=0} = 4 \frac{\text{Re}(\varepsilon)}{1 + |\varepsilon|^2} + \mathcal{O}((\text{Re } \varepsilon)^2). \quad (2.3)$$

On the other hand, if  $\omega \neq 0$ , the opposite behaviour of the equal-sign dilepton intensities for small  $\Delta t$ 's produces a cancellation in the denominator of their asymmetry and its behaviour changes drastically. The time-dependence of  $A_{sl}$  is highly altered by a pronounced peak whose position and height are

$$\Delta t_{peak} = \frac{1}{\Gamma} 1.12 |\omega| \quad \text{and} \quad A_{sl}(\Delta t_{peak}) = 0.77 \cos(\Omega), \quad (2.4)$$

respectively. This is seen in Fig. (1a), where the  $A_{sl}$  asymmetry is plotted for short  $\Delta t$ 's and different values of  $\omega$ . Since the intensity is quasi-periodic for  $\Delta\Gamma/\Gamma \ll 1$ , then we expect a second peak-behaviour to be found again around  $\Delta m \Delta t \approx 2\pi$  ( $\Delta t \approx 8.2\Gamma^{-1}$ ), see Fig. (1b).

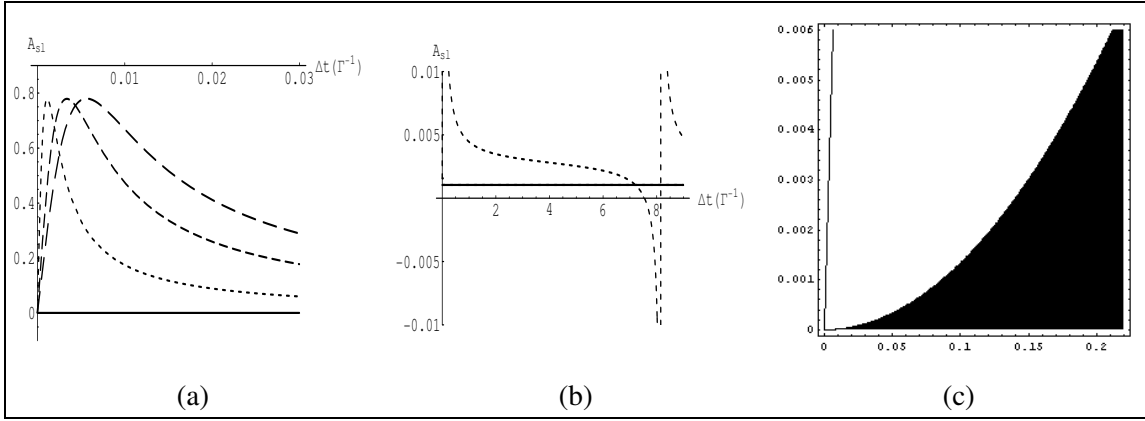
Since the main difference between the  $\omega = 0$  and  $\omega \neq 0$  cases is that in the latter the asymmetry is time-dependent we may define, with operative purposes, a criterion of experimental observability regarding the value of the time derivative  $dA_{sl}/d\Delta t$ . We may *expect* that the limit detectable time furnishes

$$\frac{1}{\Gamma} \left| \frac{dA_{sl}}{d\Delta t}(\Delta t_{limit}) \right| = 0.1, \quad (2.5)$$

and hence –in reference to the first peak– for  $\Delta t < \Delta t_{limit}$  it is (expected to be) possible to observe the effect of  $\omega$  as a time-dependence in the  $A_{sl}$  asymmetry. In Fig. (1c) it is plotted the level curve of  $\frac{1}{\Gamma} |dA_{sl}/d\Delta t| = 0.1$  as a function of  $|\omega|$  and  $\Delta t$  for  $\Omega = 0$ . As it can be seen, a value for instance of  $\omega \sim 5 \times 10^{-3}$  gives a  $\Delta t_{limit} \sim 0.2\Gamma^{-1}$  as compared to  $\Delta t_{peak} = 0.005\Gamma^{-1}$ . We conclude that, in much later  $\Delta t$ 's than  $\Delta t_{peak}$  the time dependence is still detectable.

The experimental measurements of the  $A_{sl}$  asymmetry [4], unfortunately, have been performed in the  $0.8\Gamma^{-1} \lesssim \Delta t \lesssim 10\Gamma^{-1}$  region, and hence have not explored effectively the interesting regions. The short- $\Delta t$ -peak and its tail are out of the explored region, and the region of the second peak is poor in statistics, since the asymmetry at those times is suppressed by a  $e^{-2\pi\Gamma/\Delta m} \sim 10^{-4}$  factor.

Although the experimentally explored region is not the optimal to see the effects of  $\omega$ , we can still put *indirect* limits on it by using the available fitted-to-a-constant data of the asymmetry,  $A_{sl}^{exp}$ .



**Figure 1:** Figs. (a-b) plot the  $A_{sl}$  asymmetry in different ranges of  $\Delta t$  for different values of  $\omega$ :  $\omega = 0$  (solid-line),  $\omega = 0.001$  (short-dashed),  $\omega = 0.003$  (medium-dashed) and  $\omega = 0.005$  (long-dashed), where the last two are not plotted in Fig. (b). Fig. (c) plots in  $|\omega|$  vs.  $\Delta t (\Gamma^{-1})$  the level curve of Eq. (2.5), the white area represents the measurable region, which is quite favoured in  $\Delta t$  with respect to the peak (tiny line in the left). Different phases  $\Omega$  may be visualized in all three plots through the modification in the peak's height in Eq. (2.4). In all plots we have taken  $Re(\varepsilon)/1 + |\varepsilon|^2 \approx 0.001$ , according to Standard Model expectations.

By requiring that  $A_{sl}(\Delta t, \omega)$  lies, when statistically weighted, within the two standard-deviations of  $A_{sl}^{exp}$ , we find the 95% confidence limit allowed values for  $\omega$ , namely

$$-0.0084 \leq Re(\omega) \leq 0.0100 \quad 95\%C.L. \quad (2.6)$$

These are the first known limits on  $\omega$ .

In order to inquire deeper the possible existence of CPT violation through indistinguishability of particle-antiparticle, the results of this work endorse the experimentalists to either explore the small- $\Delta t$  region to look for possible effects of the first peak, or either accumulate statistics to study the region of the second peak with a higher  $\Delta t$ -precision.

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