PROCEEDINGS OF SCIENCE

Violation of CP in $B_d^0 \to \tau^+\tau^-$ decays

Jan Kalinowski[∗†]
Institute of Theoretical Physics, Warsaw University, Poland
E-mail: kalino@fuw.edu.pl

Discovering CP violation in $B^0(\overline{B}^0) \to l^+l^-$ decays requires a measurement of polarization of the final lepton pair, or a precise determination of the $B^0 \to l^+l^-$ and $\overline{B}^0 \to l^+l^-$ rates. In supersymmetry with large $\tan\beta$ the decays $B^0(\overline{B}^0) \to l^+l^-$ are dominated by the scalar and pseudoscalar Higgs penguin diagrams. As a result, strong enhancement of leptonic decay rates, potentially measurable by BELLE or BABAR experiments, can be expected. Second, the induced CP asymmetries in these decays depend practically on only one CP violating phase, which can be large, of the order of the CKM phase, leading to large CP asymmetries in the $\tau^+\tau^-$ decay channel of $B_d^0(\overline{B}_d^0)$ mesons. The existing TAUOLA τ-lepton decay library supplemented by its universal interface can efficiently be used to search for $B^0(\overline{B}^0) \to \tau^+\tau^-$ decays, and to investigate how the CP asymmetry is reflected in realistic experimental observables.

International Europhysics Conference on High Energy Physics
July 21st - 27th 2005
Lisboa, Portugal

∗Speaker.

†Supported by KBN Grant 2 P03B 040 24

1. *Introduction.* The origin of CP violation remains a mystery of particle physics. New insight can be obtained by more precise measurements and joint analysis of CP asymmetries to test the conventional CKM description and/or by observation of a non-zero signal where no (or negligibly small) CP violating effects are predicted by the Standard Model (SM). This talk presents results of recent analyses of flavour changing $B^0_{d,s} \to l^+l^-$ decays [1], for which the SM predicts no CP violating effects.

Theoretically leptonic B-meson decays are very clean, but none of these decays have been seen so far. The upper limits on the branching fractions at present are $Br(B_d \to \mu^+\mu^-) < 8.3\times 10^{-8}$ [2], $< 3.8\times 10^{-8}$ [3], $Br(B_d \to \tau^+\tau^-) < 3.2\times 10^{-3}$ [4], $Br(B_s \to \mu^+\mu^-) < 1.5\times 10^{-7}$ [3], which are at least two orders of magnitude above the SM expectations. New physics (like supersymmetry) can increase the rates to a level observable at BABAR, BELLE or Tevatron. In addition, in the $\tau^+\tau^-$ channel, in which the τ polarization measurement is possible, the CP asymmetry in the $B^0_d(\bar{B}^0_d) \to \tau^+\tau^-$ channel can be quite large and potentially measurable.

2. *CP asymmetries.* In leptonic B-meson decays CP is violated if, for example,

$$\Gamma(B^0 \to l^+_L l^-_L) \neq \Gamma(\bar{B}^0 \to l^+_R l^-_R)\,, \qquad \Gamma(B^0 \to l^+_R l^-_R) \neq \Gamma(\bar{B}^0 \to l^+_L l^-_L) \tag{1}$$

because the initial and final states on both sides transform into each other under CP. Writing the effective Lagrangian for the $B^0(\bar{B}^0)l^+l^-$ coupling as

$$\mathscr{L}_{\rm eff} = B^0_{s,d}\,\bar{\psi}_l(b_{s,d} + a_{s,d}\gamma^5)\psi_l + \bar{B}^0_{s,d}\,\bar{\psi}_l(\bar{b}_{s,d} + \bar{a}_{s,d}\gamma^5)\psi_l \tag{2}$$

(the subscripts d and s referring to non-strange and strange B^0 mesons, unless explicitly written, will be omitted), the amplitudes of B^0 decays into two helicity eigenstates read

$$\mathscr{A}_L \equiv \langle l^+_L l^-_L|B^0\rangle = M_B\,(a + b\,\beta_l)\,, \qquad \mathscr{A}_R \equiv \langle l^+_R l^-_R|B^0\rangle = M_B\,(a - b\,\beta_l)\,, \tag{3}$$

where $\beta_l = (1-4m_l^2/M_B^2)^{1/2}$. The amplitudes $\bar{\mathscr{A}}_L$ and $\bar{\mathscr{A}}_R$ for the corresponding $\bar{B}^0$ decays are given by (3) with a and b replaced by $\bar{a}$ and $\bar{b}$. CPT invariance implies $\bar{b} = b^*$ and $\bar{a} = -a^*$.

Since in leptonic decays no strong phases are involved, inequality (1) can occur only through the mixing of the B^0 and $\bar{B}^0$ mesons. The simplest quantitative measures of CP violation are provided by the asymmetries constructed out of time integrated polarized decay rates [5]

$$A^1_{\rm CP} = \frac{\int dt\;[\Gamma(B^0_{\rm phys}(t)\to l^+_L l^-_L) - \Gamma(\bar{B}^0_{\rm phys}(t)\to l^+_R l^-_R)]}{\int dt\;[\Gamma(B^0_{\rm phys}(t)\to l^+_L l^-_L) + \Gamma(\bar{B}^0_{\rm phys}(t)\to l^+_R l^-_R)]}\,, \tag{4}$$

$$A^2_{\rm CP} = \frac{\int dt\;[\Gamma(B^0_{\rm phys}(t)\to l^+_R l^-_R) - \Gamma(\bar{B}^0_{\rm phys}(t)\to l^+_L l^-_L)]}{\int dt\;[\Gamma(B^0_{\rm phys}(t)\to l^+_R l^-_R) + \Gamma(\bar{B}^0_{\rm phys}(t)\to l^+_L l^-_L)]} \tag{5}$$

and the ratio of integrated unpolarized decay rates

$$R_l = \frac{\int dt\;\Gamma(B^0_{\rm phys}(t)\to l^+l^-)}{\int dt\;\Gamma(\bar{B}^0_{\rm phys}(t)\to l^+l^-)}\,, \tag{6}$$

where $B^0_{\rm phys}(t)$ ($\bar{B}^0_{\rm phys}(t)$) is the state which at $t=0$ is a pure B^0 ($\bar{B}^0$).

In the limit $|p/q| \equiv (H^*_{12}/H_{12})^{1/2} = 1$ (with $H_{12} = \langle B^0|\mathscr{H}_{\rm eff}|\bar{B}^0\rangle$), as in the SM and many SUSY extensions, the asymmetries $A^1_{\rm CP}$, $A^2_{\rm CP}$ are bounded by $|A^{1,2}_{\rm CP}| \le (2+x^2)^{-1/2}$, where $x = \Delta\Gamma/M$.

Since $x_s > 20.6$, the CP asymmetries in the leptonic $B_s^0(\bar{B}_s^0)$ decays can reach at best $\sim 4.5\%$ irrespectively of the amount of CP violation. In contrast $x_d = 0.771 \pm 0.012$, and the CP asymmetries in the $B_d^0(\bar{B}_d^0)$ decays can be as large as $\sim 60\%$ and hopefully measurable at BABAR and BELLE in a relatively clean environment.

3. *Supersymmetry scenarios.* In Ref. [1] it has been found for two different supersymmetric scenarios: minimal (MFV) and non-minimal (NMFV) flavour violating - both with large ratio of VEVs, that the $B_{d,s}^0 \to l^+l^-$ amplitudes are dominated by the exchange of H^0 and A^0 Higgs bosons. As a

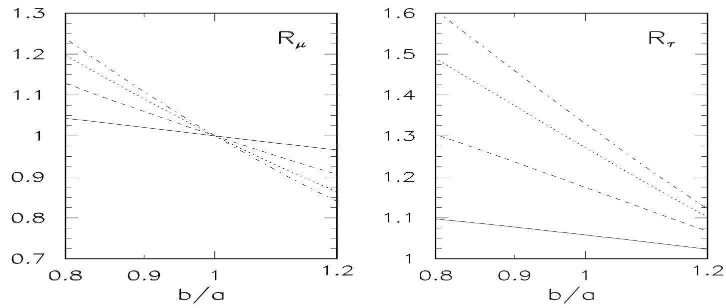

Figure 1: *The ratios R_μ and R_τ as functions of b/a for the phase $\delta_{\rm CP} = 0.1$ (solid line), 0.3 (dashed), 0.5 (dotted) and 0.75 (dash-dotted). $R_l(-\delta_{\rm CP}) = R_l^{-1}(\delta_{\rm CP})$. From [1].*

result $a \approx b$ or $a \approx -b$ (up to $\lesssim 15\%$), and all CP-sensitive quantities could be expressed in terms of one effective phase which can be taken as $\delta_{\rm CP} = -\frac{1}{2}\arg(q\bar{\mathscr{A}}_L/p\mathscr{A}_L)$. The immediate consequence of $a = b$ with $|q/p| \sim 1$ is that for the $\mu^+\mu^-$ final state, for which β_μ is almost 1, the expected asymmetries are very small, while for the $\tau^+\tau^-$ final states $\beta_\tau \sim 0.74$ and the asymmetries can be large, as seen Fig. 1 in which the ratio (6) is shown as a function of b/a for four different values of the phase $\delta_{\rm CP}$ (keeping $\arg(a)$ =$\arg(b)$ and $|p/q| = 1$).

4. *Numerical results.* The coefficients a and b are constrained by the experimental limits, which in the case $a \approx \pm b$ give $|a| \approx |b| \lesssim 4.9 \times 10^{-9}$. We set $|a| = |b| \lesssim 10^{-9}$ and treat both scenarios simultaneously, as all what matters are the values of $|a| = |b|$ (a and b different by $15 \div 20\%$ are also investigated) and the single CP violating phase $\delta_{\rm CP}$ which can be of order 1.

The τ polarisations are best identified by measuring (a) $\pi^\pm$ *energy spectra* from $\tau \to \pi\nu$ decays (sensitive to longitudinal τ polarizations) and (b) *acoplanarity angle* φ^* between two planes spanned by the decay products of $\rho^\pm$ coming from $\tau \to \rho\nu_\tau$ (sensitive to transverse τ-polarizations) [6]. The CP violation is signaled if (a) the $\pi^-(\pi^+)$ spectra from $B^0(\bar{B}^0)$ are different from $\pi^+(\pi^-)$ spectra from $\bar{B}^0(B^0)$, (b) the distributions of the angle φ^* measured in B^0 decays are different from the angle $2\pi - \varphi^*$ measured in $\bar{B}^0$ decays (for the same signs of y_1y_2, see [1]).

Fig. 2 shows simulations obtained with TAUOLA [7]. Top panels show the pion energy spectra and the acoplanarity distributions assuming $|q/p| = 1$, $a = b = 10^{-9}$ and the CP violating phase $\delta_{\rm CP} = 0.7$. The CP violation is seen in both observables. On the other hand, for $a \sim b\beta_\tau$ (bottom panels) the effects of CP violation in the $\pi^\pm$ energy spectra disappear, while they are clearly visible in the acoplanarities. This demonstrates the complementarity of the energy and acoplanarity distributions as a means to detect CP violation.

To conclude: in the supersymmetry scenario with $\tan\beta \sim 40 \div 50$ the rates of $B_d^0(\bar{B}_d^0) \to \tau^+\tau^-$

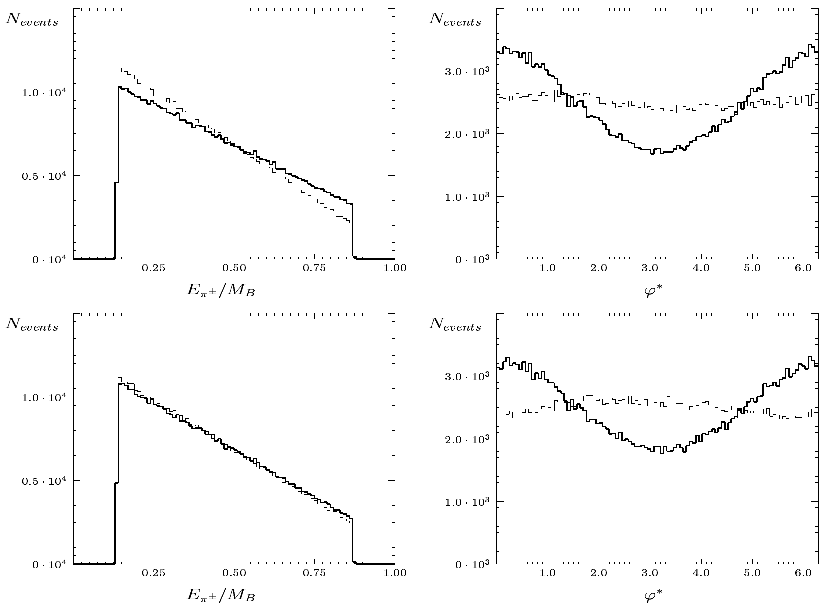

Figure 2: *Results for the CP violating phase $\delta_{\rm CP} = 0.7$ and for $a = b$ (top) and $a = 0.8\,b$ (bottom). Left – $\pi^\pm$ energy spectra in $B^0(\overline{B}^0) \to \tau^+\tau^-$, $\tau^\pm \to \pi^\pm\nu_\tau(\overline{\nu}_\tau)$: π^- from B^0 decays (thick line), and π^+ from $\overline{B}^0$ (thin line). Right – acoplanarity distributions of the $\rho^+\rho^-$ decay products in $B^0(\overline{B}^0) \to \tau^+\tau^-$, $\tau^\pm \to \rho^\pm\nu_\tau(\overline{\nu}_\tau)$, $\rho^\pm \to \pi^\pm\pi^0$ (for events with $y_1y_2 > 0$): acoplanarity angle φ^* measured in B^0 decays (thick line) and the angle $2\pi - \varphi^*$ measured in $\overline{B}^0$ decays (thin line). From [1].*

decays are enhanced and the CP asymmetries can be quite large. Possible effects of CP violation in two realistic experimental observables have been investigated with Monte-Carlo simulations demonstrating that they might be detectable if the CP violating phase is reasonably large.

Acknowledgments: I thank P. Chankowski, Z. Was and M. Worek for a fruitful collaboration. Discussions with C. Potter are greatly acknowledged.

References

[1] P. H. Chankowski, J. Kalinowski, Z. Was, M. Worek, Nucl. Phys. B **713** (2005) 555; Acta Phys. Polon. B36 (2005) 3463.

[2] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **94** (2005) 221803.

[3] A. Abulencia *et al.* [CDF Collaboration], arXiv:hep-ex/0508036.

[4] B. Aubert *et al.* [BABAR Collaboration], arXiv:hep-ex/0511015.

[5] C. S. Huang and W. Liao, Phys. Lett. B **525** (2002) 107.

[6] K. Desch, A. Imhof, Z. Was and M. Worek, Phys. Lett. B **579** (2004) 157.

[7] S. Jadach, J. H. Kuhn and Z. Was, Comput. Phys. Commun. **64** (1990) 275. M. Jezabek, Z. Was, S. Jadach and J. H. Kuhn, Comput. Phys. Commun. **70** (1992) 69. S. Jadach, Z. Was, R. Decker and J. H. Kuhn, Comput. Phys. Commun. **76** (1993) 361.