UA0501296

Recent results of *BABAR*

D. Bernard, For the *BABAR* Collaboration

Ecole Polytechnique, Palaiseau, France

October 31, 2001

Abstract

The *BABAR* detector at SLAC's PEP-II storage ring has collected data amounting to about 30.4 fb^{-1} until june 2001. Results on *CP* violation, and in particular search for direct *CP* violation, and measurement of rare *B* decays are presented.

1 Introduction

We present a sample of recent results of *BABAR* including the observation of *CP* violation with the measurement of $\sin 2\beta$ and of rare decay modes.

The *BABAR* experiment has been running at the PEP-II asymmetric e^+e^- collider since 1999. Its main goal is a high statistics study of *B* decays, including a study of *CP* violation in the *B* sector. The center of mass energy is tunned at the $\Upsilon(4S)$ just above the $B\overline{B}$ threshold. The asymmetry of the energies of the two beams provides a longitudinal boost so that the average *B* flight length is ≈ 250 μm and can be measured. The high nominal luminosity of $3\ 10^{33}$ $\text{cm}^{-2}\text{s}^{-1}$ allows the study of the many rare *B* decay channels.

The *BABAR* detector is described elsewhere [1]. Charged particle track parameters are obtained from measurements in a 5-layer double-sided silicon vertex tracker and a 40-layer drift chamber located in a 1.5-T magnetic field; both devices provide $\mathrm{d}E/\mathrm{d}x$ information. Additional charged particle identification (PID) information is obtained from a detector of internally reflected Cherenkov light (DIRC) consisting of quartz bars that carry the light to a volume filled with water, and equipped with 10752 photomultiplier tubes. Electromagnetic showers are measured in a calorimeter (EMC) consisting of 6580 CsI(Tl) crystals. An instrumented flux return (IFR), containing multiple layers of resistive plate chambers, provides μ identification.

Most results presented here are obtained on a data sample of 30.4 fb^{-1} collected until june 2001, and that contains about 32 $10^6 B\overline{B}$ pairs.

2 Measurement of $\sin 2\beta$

The flag result of the experiment is the observation of *CP* violation in the *B* sector. In the standard model (SM), *CP* violation occurs via a complex term in the Cabbibo-Kobayashi-Maskawa (CKM) matrix. The phase of such a complex term can eventually be measured in the interference of two amplitudes contributing to the same final state. In the Wolfenstein parametrization[2] of V_{CKM}, all the matrix elements are real, but V_{td} and V_{ub}. Most of the envisaged strategies to observe *CP* violation therefore use the interference between an amplitude containing one of these target elements and a real amplitude, to a *CP* eigenstate.

In the case of a $b \to c\bar{c}s$ decay like $B \to J/\psi K^0_s$, the B can either decay directly via a real amplitude $\propto V^*_{cb}V_{cs}$, or decay after a $B^0 \to \overline{B}^0$ oscillation that proceeds through a box diagram with an amplitude $(V^*_{tb}V_{td})^2$ that has a phase -2β. The measurement is theoretically clean, as the main higher order diagrams have the same weak phase as the first order ones. It is also experimentally pure due to the presence of a J/ψ in the final state, and benefits from a branching ratio $\mathcal{B} \approx 10^{-3}$, a rather high value in the land of B decays.

The resulting evolution function $g_\pm(t)$, for a decay to a final state f, involves a complex quantity λ_f. If the (so called direct) CP violation in the decay itself can be neglected – as it is the case here, within 1 %, in the standard model – we have $|\lambda_f| = 1$, and we get:

$$g_\pm(t) = \frac{e^{-t/\tau_B}}{\tau_B} \times [1 \mp \mathcal{I}m\lambda_f \sin(\Delta m_d t)],$$

where t is the B proper time and $\pm$ is $+$ for an initial B^0, and $-$ for an initial $\overline{B}^0$. In the present case of a $b \to c\bar{c}s$ decay, λ_f is $\eta_f e^{-2i\beta}$, where η_f is the CP eigenvalue of f, and g resumes to

$$g_\pm(t) = \frac{e^{-t/\tau_B}}{\tau_B} \times [1 \mp \eta_f \sin 2\beta \sin(\Delta m_d t)], \quad (1)$$

allowing the measurement of $\sin 2\beta$. The "initial" state of the CP B can be known thanks to the EPR paradox: the $\Upsilon(4S)$ resonance having spin-parity 1^{--}, it decays to a coherent $B\overline{B}$ pair in an antisymmetric state, so that when the first B decays, say to a B^0, the other one is in the opposite state, a $\overline{B}^0$. The oscillation time is then the difference Δt of the time of flight of the two B's, measured from the difference Δz of their flight lengths. The vertexing of the CP B is performed with an excellent precision, $\sigma_z \approx 60$ μm, thanks to the presence of the hard leptons from the J/ψ. The other B is vertexed inclusively, with a χ^2 cut that limits the systematics due to cascade charmed decays; the contribution of the other B dominates the resolution on Δz, that is of the order of 180 μm, and independent of the CP channel used.

The flavor determination of the other B, called tagging, is also performed inclusively: events are classified in four mutually exclusive categories, using respectively the charge of the fastest lepton, the total charge of identified kaons, the output of neural networks that use the information carried by non-identified leptons and kaons, and by soft pions from D^*'s, or are not tagged [3]. The effective tagging efficiency Q_i of each category i is defined as the product of its efficiency ϵ_i and of its dilution $(1-2w_i)$. The total effective tagging efficiency $Q = \sum_{i=1}^{4} \epsilon_i(1-2w_i)$ is measured on a large sample of exclusively reconstructed B decays of specific flavor ($B \to D^{(*)-}h^+, h = \pi, \rho, a_1$, and $B \to J/\psi K^{*0}(K^+\pi^-)$), and is equal to (26.1 ± 1.2) %.

With a real detector, sin2β is multiplied by a dilution factor $(1-2w)$ in eq. 1, and $g_\pm(\Delta t)$ is convoluted by a Δt resolution function. The value of sin2β is obtained from an unbinned maximum likelihood fit to the Δt distribution of a combined event sample consisting of the CP sample and of the flavor sample. (The number of tagged events, the purity, and the CP effective value of the channels used are given in table 1). In this way, the mistagging probabilites w_i and the parameters of the resolution function are determined on the data, and their correlation with sin2β is taken into account.

Background events are taken into account by a separate *pdf* that enters the likelihood. When the CP B has no K_L^0 in the final state, the probability for an event to be a signal event is computed from the value of the energy substitued mass $m_{\rm ES} = (s/2 - \vec{p}_B^{*2})^{1/2}$ where s is the total energy and $\vec{p}_B^*$ the measured momentum of the B candidate, in the $\Upsilon(4S)$ rest frame (fig. 1a). For a CP B with a K_L^0 in the final state, only the direction of the K_L^0 is measured in the detector, and a kinematic fit of $m_{\rm ES}$ to the nominal B mass is performed. The signal probability of the event is computed from the difference $\Delta E = E_B^* - E_{beam}^*$ between the energy of the B candidate and the beam energy, in the $\Upsilon(4S)$ rest frame (fig. 1b).

The slight asymmetry of the time distributions (fig. 2) is barely visible, but the effect is clear of the plot of the asymmetry itself $\mathcal{A}_{CP}(\Delta t) = (1-2w)\eta_f \sin 2\beta \sin(\Delta m_d \Delta t)$. We obtain sin2$\beta$ = $0.59 \pm 0.14(stat) \pm 0.05(syst)$. If there were no CP violation, ie $\beta = 0$, the probability of such a measurement would be 3. 10^{-5}, so that we have here a 4.1 standard deviation observation of CP violation [4].

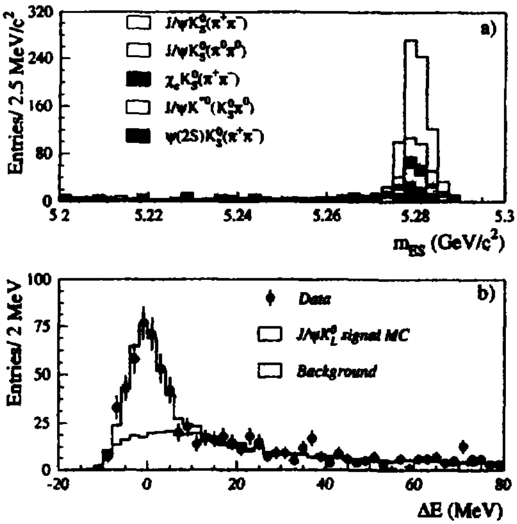

Figure 1: a) *Distribution of* m_{ES} for B candidates having a K_S^0 in the final state; b) distribution of ΔE for $J/\psi\, K_L^0$ candidates.

Table 1: Number of tagged events, signal purity and *CP* content of the *CP* and flavor samples.

	Channel	N_{tag}	Purity (%)	$\langle\eta_f\rangle$
CP sample	$J/\psi\ K_S^0\ (\pi^+\ \pi^-)$	316	98.	-1
	$J/\psi\ K_S^0\ (\pi^0\ \pi^0)$	64	94.	-1
	$\psi(2S)\ K_S^0\ (\pi^+\ \pi^-)$	67	98.	-1
	$\chi_{c1}\ K_S^0\ (\pi^+\ \pi^-)$	33	97.	-1
	$J/\psi\ K^{*0}\ (K_S^0\ \pi^0)$	50	74.	0.65 ± 0.07
	$J/\psi\ K_L^0$	273	51.	$+1$
non *CP* sample	Flavor	7591	86	

The impact of the present measurement on the knowledge of the CKM matrix is shown in fig. 3. The set of measurements is clearly consistent within the standard model, while the present

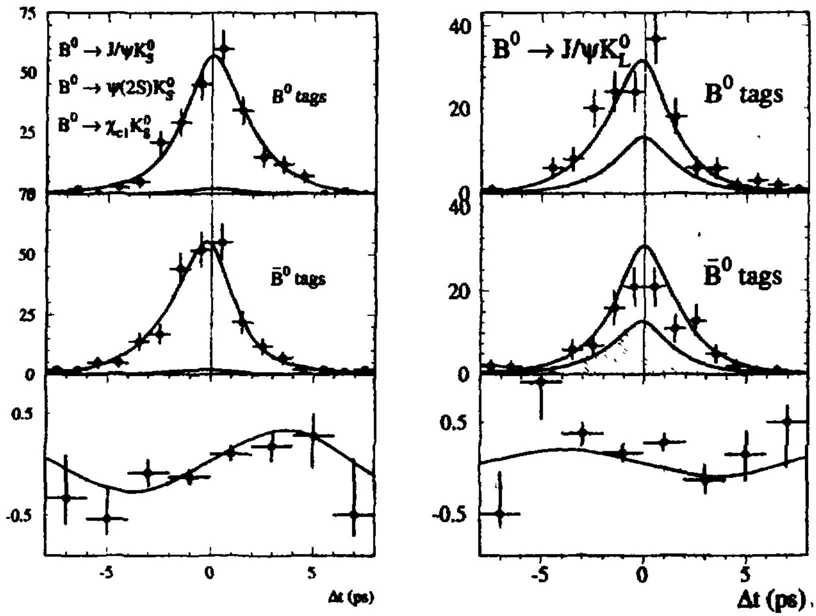

Figure 2: Left: Time distribution of $\eta_f = -1$ candidates with a B^0 tag N_{B^0} and with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and the asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$. The solid curves represent the result of the combined fit to all selected *CP* events; the shaded regions represent the background contributions. Right: Corresponding information for the $\eta_f = +1$ mode $(J/\psi\, K_L^0)$.

measurement significantly decreases the size of the 2σ allowed region.

We have also searched for direct *CP* violation in the decay. Releasing the constraint [1] $|\lambda_f| = 1$, the evolution equation becomes:

$$g_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B(1 + |\lambda_f^2|)} \times$$

[1]but still assuming that there is no *CP* violation in mixing.

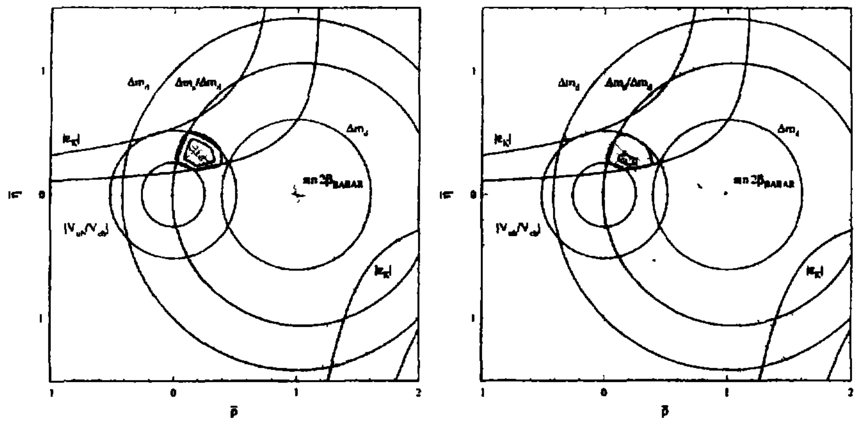

Figure 3: Allowed region (light (dark) grey: two (one) standard deviation) in the CKM parameters ρ, η plane. Left: the present sin2β measurement is overlaid on preceding fit. Right: the present sin2β measurement is included in the fit. The fit method is described in ref. [5].

$$\left[(1+|\lambda_f|^2)/2 \mp \left(-\frac{1}{2}(1-|\lambda_f|^2)\cos(\Delta m_d \Delta t) + \mathcal{I}m\lambda_f \sin(\Delta m_d \Delta t)\right)\right]$$

Fitting for $|\lambda_f|, \mathcal{I}m\lambda_f/|\lambda_f|$ on the $\eta_f = -1$ sample, we obtain[4] $|\lambda_f| = 0.93 \pm 0.09 \pm 0.03$, showing the absence of direct *CP* violation at the 10% level.

3 Charmless two body B decays

The V_{ub} term that appears in the amplitude of the decay $b \to u$ carries a γ phase: this makes the measurement of sin2α in $B \to \pi^+\pi^-$ decay-mixing interference attractive, by a time distribution analysis similar to that for sin2β. But the decay envisaged here suffers a strong CKM suppression ($V_{ub} \propto \lambda^3$), so that the higher order, so called penguins, diagrams contribute at the same level as the tree diagram. This leads to a complication of the measurement of $\sin 2\alpha$, but also to a sensitivity to the contribution of new heavy objects (Higgs, SUSY) in the penguin, detectable in direct CP violation via tree-penguin interference in $B \to K^+\pi^-$ decays.

On the experimental side, the difficulty is background rejection. The decaying B's are almost at rest in the $\Upsilon(4S)$ rest frame, and their 2 body decay products are approximately back-to-back in that frame, while continuum ($e^+e^- \to q\bar{q}$) events have a two-jet topology that provides a lot of back-to-back track pairs. $B\overline{B}$ decay products are roughly isotropically distributed in the $\Upsilon(4S)$ frame and we use this behaviour to separate signal from noise.

Preselection cuts on global event shape parameters (Fox-Wolfram moment, sphericity), on the angle between the sphericity axes of the B and that of the rest of event, and on a Fisher discriminant $\mathcal{F}$ that optimizes the use of the energy flow wrt the decay axis [6]. Kaon/pion separation is achieved using the Čerenkov angle θ_c measured in the DIRC and the value of ΔE (computed with the pion hypothesis for both tracks).

The branching fractions are obtained by an unbinned maximum likelihood fit on the 4 variables: $m_{\rm ES}$, ΔE, $\mathcal{F}$, θ_c and are given in table 2. The corresponding $m_{\rm ES}$ and ΔE spectra, after

Table 2: Detection efficiencies (ε), fitted signal yields (N_S), statistical significances (S), branching fractions ($\mathcal{B}$), and charge asymmetries of the charmless two body decays (20.7 fb^{-1}).

Mode	ε (%)	N_S	S (σ)	$\mathcal{B}/10^{-6}$	A_{CP}
$\pi^+\pi^-$	45	$41 \pm 10 \pm 7$	4.7	$4.1 \pm 1.0 \pm 0.7$	
$K^+\pi^-$	45	$169 \pm 17 \pm 13$	15.8	$16.7 \pm 1.6 \pm 1.3$	$-0.19 \pm 0.10 \pm 0.03$
K^+K^-	43	$8.2^{+7\ 8}_{-6\ 4} \pm 3.5$	1.3	< 2.5 (90% C.L.)	
$\pi^+\pi^0$	32	$37 \pm 14 \pm 6$	3.4	< 9.6 (90% C.L.)	
$K^+\pi^0$	31	$75 \pm 14 \pm 7$	8.0	$10.8^{+2\ 1}_{-1\ 9} \pm 1.0$	$0.00 \pm 0.18 \pm 0.04$
$K^0\pi^+$	14	$59^{+11}_{-10} \pm 6$	9.8	$18.2^{+3\ 3}_{-3\ 0} \pm 2\ 0$	$-0.21 \pm 0.18 \pm 0.03$
$\overline{K}^0K^+$	14	$-4.1^{+4\ 5}_{-3\ 8} \pm 2.3$	–	< 2.4 (90% C.L.)	
$K^0\pi^0$	10	$17\ 9^{+6\ 8}_{-5\ 8} \pm 1.9$	4 5	$8.2^{+3\ 1}_{-2\ 7} \pm 1.2$	

proper cut on the likelihood ratio, are given in fig. 4. Self tag-

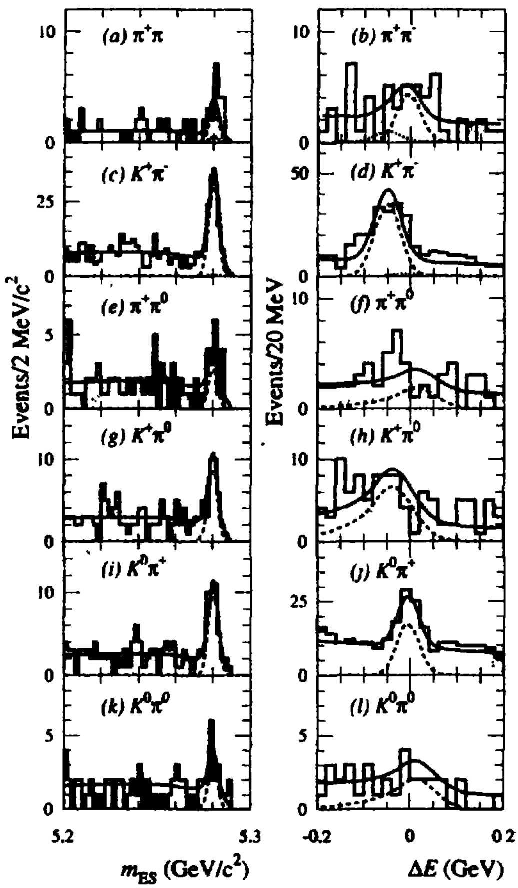

Figure 4: The $m_{\rm ES}$ and ΔE distributions of charmless two body decays, after a likelihood ratio cut. The solid curves represent the fit predictions for both signal and background; the dashed curve represents the given signal mode only and the dotted curve represents other modes of the same topology (20.7 fb^{-1}).

ging modes are used to search for direct *CP* violation in the charge asymmetry $A_{CP} = (\mathcal{B}(\overline{B} \to \bar{f}) - \mathcal{B}(B \to f))/(\mathcal{B}(\overline{B} \to \bar{f}) + \mathcal{B}(B \to f))$.

A vigorous effort is under way to control the shift in $\sin 2\alpha$ due to the presence of the penguins[7]. The quantity that is actually measured is denoted $\sin 2\alpha_{eff}$.

An unbinned maximum likelihood fit similar to that used for the branching fractions is used to measure $\sin 2\alpha_{eff}$: the variable Δt is added in the likelihood. The vertexing and tagging are similar to that used for $\sin 2\beta$. There is here a (strong) probability of direct CP violation so that the evolution equation used is:

$$g_{\pm}(t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \times [1 \mp (-C_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t))]$$

Fitting for the coefficients $C_f = (1 - |\lambda_f|^2)/(1 + |\lambda_f|^2)$ and $S_f = 2\mathcal{I}m\lambda_f/(1 + |\lambda_f|^2)$ we get [8], on 30.4 fb^{-1}, $S_f = 0.03^{+0.53}_{-0.56} \pm 0.11$ and $C_f = -0.25^{+0.45}_{-0.47} \pm 0.14$ (preliminary), where S_f would be equal to $\sin 2\alpha_{eff}$ if $|\lambda_f| = 1$ (No direct CP violation).

4 Radiative penguin decays

$b \to s\gamma$ decays like $B \to K^*\gamma$ are of particular interest, because flavor changing neutral currents (FCNC) are forbidden in the standard model. Effective FCNC are induced by one-loop penguins in which the top quark dominates. Again, unknown heavy objects like charged Higgses or SUSY partners can contribute in the loop, and the interference with the SM diagram can induce CP violating charge asymmetries as large as 20 %, while the SM predicts $A_{CP} < 1$ % [9].

Monochromatic photons are selected ($2.30 < E^*_\gamma < 2.85$ GeV). As already noticed before, a large background from continuum events is present in this two body decay mode. The direction of the photon and the thrust of the rest of the event, in the $\Upsilon(4S)$ rest frame, are uncorrelated for $B \to K^*\gamma$ events, and strongly correlated for background, and a cut on their respective angle is the most powerfull rejection mean used here. The branching fractions are measured with an unbinned maximum likelihood fit to m_{ES} (fig. 5, table 3).

Table 3: Number of events, significance, and branching fraction of $B \to K^{*}\gamma$ decays (20.7 fb^{-1}).

Mode	$\mathcal{B}(B \to K^{*}\gamma)/10^{-5}$
$K^{+}\ \pi^{-}$	$4.39 \pm 0.41 \pm 0.27$
$K^{0}_{S}\ \pi^{0}$	$4.10 \pm 1.71 \pm 0.42$
$K^{0}_{S}\ \pi^{+}$	$3.12 \pm 0.76 \pm 0.21$
$K^{+}\ \pi^{0}$	$5.52 \pm 1.07 \pm 0.33$

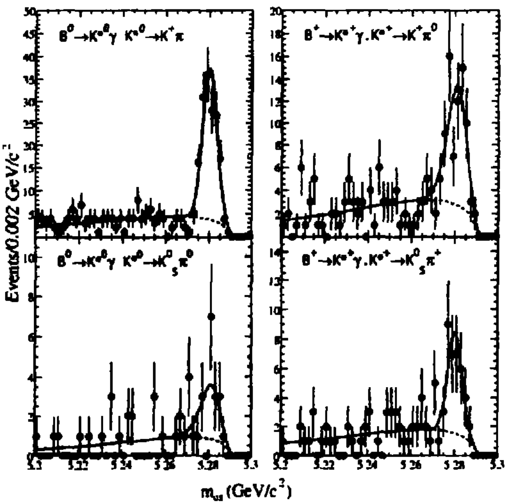

Figure 5: m_{ES} distributions of the four $K^{*}\gamma$ channels (20.7 fb^{-1}).

Charge asymmetry is measured on self tagging modes (ie not $\gamma K^{0}_{S}\pi^{0}$) and is found compatible with zero, $A_{CP} = -0.035 \pm 0.076 \pm 0.012$: we are already constraining the possible physics beyond the SM.

Table 4: $B \to \phi K^{(*)}$ fitted number of signal event $n_{\rm sig}$, statistical significance S, and measured branching ratio $\mathcal{B}$. The subscripts in the ϕK^{*+} modes refer to the kaon daughter of the ϕK^{*+} (20.7 $\rm fb^{-1}$).

Mode	$n_{\rm sig}$	S	$\mathcal{B}(10^{-6})$
ϕK^{+}	$31.4^{+6.7}_{-5.9}$	10.5	$7.7^{+1.6}_{-1.4} \pm 0.8$
ϕK^{0}	$10.8^{+4.1}_{-3.3}$	6.4	$8.1^{+3.1}_{-2.5} \pm 0.8$
ϕK^{*+}	–	4.5	$9.7^{+4.2}_{-3.4} \pm 1.7$
$\phi K^{*+}_{K^+}$	$7.1^{+4.3}_{-3.4}$	2.7	$12.8^{+7.7}_{-6.1} \pm 3.2$
$\phi K^{*+}_{K^0}$	$4.4^{+2.7}_{-2.0}$	3.6	$8.0^{+5.0}_{-3.7} \pm 1.3$
ϕK^{*0}	$20.8^{+5.9}_{-5.1}$	7.5	$8.7^{+2.5}_{-2.1} \pm 1.1$

5 Gluonic penguins

The $B \to \phi K^{(*)}$ decays present several interesting peculiarities: the decay is dominated by a gluonic penguin contribution, making this decay a smoking gun for the observation of this process; the CP final eigenstate and the real decay amplitude make the measurement of sin2β possible, in a system that has a different sensitivity to physics beyond the SM than $b \to c\bar{c}s$ decays [11].

Branching fractions are measured (table 4) with an unbinned maximum likelihood fit to $m_{\rm ES}$, ΔE, $\mathcal{F}$, $m(K^+K^-)$ (and $K\pi$ mass and K^* helicity angle for ϕK^* modes). The decays $B^+ \to \phi K^{*+}$ and $B^0 \to \phi K^0$ are first observations.

6 Summary

We have presented a sample of recent results of the *BABAR* experiment. CP violation is observed in the B sector with a significance of 4.1 standard deviations. The observation of several rare B decays is reported, several of which allowed a search for direct CP

violation in charge asymmetries.

The measurements presented here are statistically limited. The increase in integrated luminosity that is expected in the next future - 500 fb^{-1} in year 2005 - will allow a significant improvment in the precision of these results.

References

[1] *BABAR* Collaboration, B. Aubert *et al.*, "The *BABAR* Detector, " hep-ex/0105044 (2001), submitted to Nucl. Instr. and Meth.

[2] L. Wolfenstein, Phys. Rev. Lett. **51**(1983)1945.

[3] B. Aubert *et al.* *BABAR* Collaboration, Phys. Rev. Lett. **86** 2515 (2001).

[4] B. Aubert *et al.* *BABAR* Collaboration, Phys. Rev. Lett. **87**:091801 (2001).

[5] A. Höcker *et al.*, Eur. Phys. Jour. C **21** 225 (2001).

[6] B. Aubert *et al.*, *BABAR* Collaboration, Phys. Rev. Lett. **87**:151802 (2001).

[7] . M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990); N.G. Deshpande and X.G. He, Phys. Rev. Lett. **74**, 26 (1995); S. Gardner, Phys. Rev. D **59**, 077502 (1999); Y. Grossman and H.R. Quinn, Phys. Rev. D **58**, 017504 (1998); J. Charles, Phys. Rev. D **59**, 054007 (1999); M. Gronau, D. London, N. Sinha, and R. Sinha, Phys. Lett. B **514**315 (2001).

[8] Study of CP Violating Asymmetries in $B \to \pi^+\pi^-, K^+\pi^-$ Decays, By BABAR Collaboration (B. Aubert et al.). SLAC-PUB-8929, BABAR-CONF-01-05. Contributed to 20th International Symposium on Lepton and Photon Interactions at

High Energies (Lepton Photon 01), Rome, Italy, 23-28 Jul 2001. hep-ex/0107074.

[9] A. Kagan and M. Neubert, Phys. Rev. D **58** 094012 (1998).

[10] B. Aubert *et al.*, *BABAR* Collaboration, Phys. Rev. Lett. **87**:151801 (2001).

[11] Y. Grossman and M. P. Worah, Phys. Lett. B **395** 241 (1997).