Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

STRONG INTERACTIONS PHYSICS AT *BABAR*

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Recent results obtained by *BABAR* experiment and related to strong interactions physics are presented, with particular attention to the extraction of the first four hadronic-mass moments and the the first three lepton-energy moments in semileptonic decays. From a simultaneous fit to the moments, the CKM element $|V_{cb}|$, the inclusive $B \to X_c l\nu$ and other heavy quark parameters are derived. The second topic is the ambiguity-free measurement of $\cos(2\beta)$ in $B \to J/\Psi K^*$ decays. With approximately 88 million of $B\overline{B}$ pairs, negative solutions for $\cos(2\beta)$ are excluded at 89%.

1 Moments of inclusive distribution in semileptonic decays

Moments of inclusive distributions and rates for semileptonic and rare B decay s can be related via Operator Product Expansions (OPE) [1] to fundamental parameters of the Standard Model, such as the Cabibbo-Kobayashi-Maskawa matrix elements V_{cb} and V_{ub} [2] and the heavy quark masses m_b and m_c. These expansions in $1/m_b$ and the strong coupling constant α_s involve non-perturbative quantities that can be extracted from moments of inclu sive distributions. In the kinetic-mass scheme [3] for example, these expansions to order $\mathcal{O}(1/m_b^3)$ contain six parameters: the running kinetic masses of the $b-$ and $c-$quarks, $m_b(\mu)$ and $m_c(\mu)$, and four non-perturbative parameters. We determine these parameters from a fit to the moments of the hadronic-mass and electron energy distributions in semileptonic B decays to charm particles, $B \to X_c l\nu$. These measurements are based on data recorded with the *BABAR* detector [4] at the $\Upsilon(4S)$ resonance.

1.1 hadronic-mass moments

The measurement of hadronic-mass moments is based on a sample of 89 million $B\overline{B}$ pairs corresponding to an integrated luminosity of 82 fb^{-1}. The analysis uses $\Upsilon(4S)$ to $B\overline{B}$ events in which one of the B mesons decays to hadrons and is fully reconstructed ($B_{\rm reco}$) [5] and the semileptonic decay of the recoiling $\bar{B}$ meson ($B_{\rm recoil}$) is identified by the presence of an electron or muon. This approach allows for the determination of the momentum, charge, and flavor of the B mesons. Semileptonic decays are identified by the presence of exactly one electron or muon above a minimum cut-off energy $E_{\rm cut}$, measured in the rest frame of the $B_{\rm recoil}$ meson recoiling against the $B_{\rm reco}$. The hadronic system X in the decay $B \to X_c l\nu$ is reconstructed from charged tracks and energy depositions in the calorimeter that are not associated with the $B_{\rm reco}$ candidate or the charged lepton. We impose the following criteria to ensure well reconstructed events: $E_{\rm miss} > 0.5$ GeV, $|\vec{p}_{\rm miss}| > 0.5$ GeV, and $|E_{\rm miss} - |\vec{p}_{\rm miss}|| < 0.5$ GeV ($p_{\rm miss} = p_{\Upsilon(4S)} - p_{B_{\rm reco}} - p_X - p_\ell$). We select 7114 signal events over a combinatorial background of 2102 events.

The hadronic-mass moments $\langle M_X^n \rangle$ after background subtraction, calibration and correction for detection and selection efficiencies are shown in the upper half of Fig. 1. The full numerical results can be found in [6]. The four moments increase as $E_{\rm cut}$ decreases due to the presence of higher mass charm states. The moment measurements are highly correlated. The statistical and systematic errors are of comparable size.

1.2 Electron energy spectrum and moments

The measurement of the electron energy spectrum and its moments is based on a data sample of 47.4 fb^{-1} recorded at the $\Upsilon(4S)$ resonance and 9.1 fb^{-1} at an energy 40 MeV below the resonance, measured in the electron-positron center of mass frame. We identify $B\overline{B}$ events by observing an electron, e_{tag}, with a momentum of $1.4 < p^* < 2.3$ GeV$/c$ in the $\Upsilon(4S)$ rest frame and a second electron, e_{sig}, for which we require $p^* > 0.5$ GeV$/c$.

Defining $R_i(E_{\rm cut}, \mu)$ as $\int_{E_{\rm cut}}^{\infty} (E_e - \mu)^i (d\Gamma/dE_e)\, dE_e$, we present measurements of the partial branching fraction $M_0(E_{\rm cut})$, the first moment $M_1(E_{\rm cut}) = R_1(E_{\rm cut}, 0)/R_0(E_{\rm cut}, 0)$ and the central moments $M_n(E_{\rm cut}) = R_n(E_{\rm cut}, M_1(E_{\rm cut}))/R_0(E_{\rm cut}, 0)$ for $n = 2$, 3. The results are shown in the lower part of Fig. 1. The full numerical results can be found in [7].

2 Determination of the Branching Fraction for $B \to X_c \ell \nu$ Decays and of $|V_{cb}|$ from Hadronic-Mass and Lepton-Energy Moments

The $E_{\rm cut}$-dependent moment measurements discussed in the previous two sections are used to extract the total branching fraction $\mathcal{B}_{c\ell\nu}$, $|V_{cb}|$ and other heavy quark parameters from a simultaneous χ^2 fit of OPE calculations in the kinetic mass scheme.

The global fit takes into account the statistical and systematic errors and correlations of the individual measurements, as well as the uncertainties of the expressions for the individual moments. The resulting fit, shown in Fig. 1, describes the data well with $\chi^2 = 15.0$ for 20 degrees of freedom. Table 1 lists the fitted parameters and their errors [a]. An additional error on V_{cb} has been derived from the limited knowledge of the OPE expression for the decay rate, including various perturbative corrections and higher-order non-perturbative corrections [8]. As expected, m_b and m_c are highly correlated and for the mass difference we obtain $m_b - m_c = (3.436 \pm 0.025_{exp} \pm 0.018_{HQE} \pm 0.010_{\alpha_s})$ GeV.

[a] The correlations between the fit parameters can be found in [9].

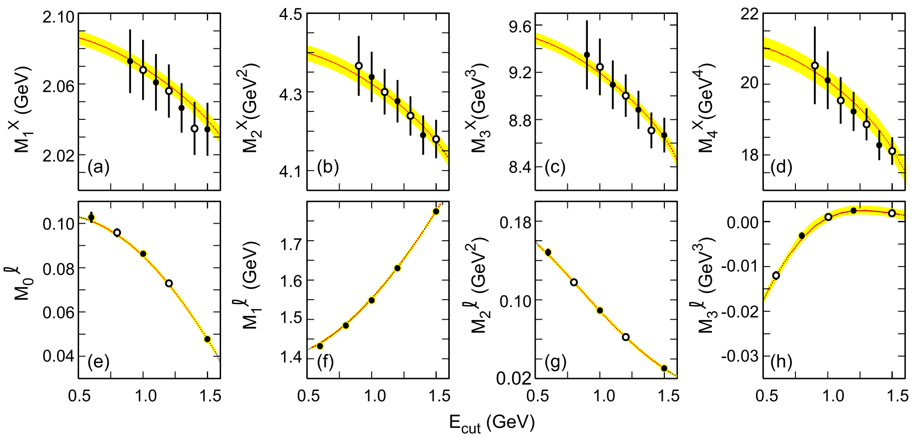

Figure 1. The measured hadronic-mass (a-d) and electron-energy (e-h) moments as a function of the cut-off energy, E_{cut}, compared with the result of the simultaneous fit (line), with the theoretical uncertainties indicated as shaded bands. Moment measurements for different E_{cut} are highly correlated. The solid data points mark the measurements included in the fit. Not all the data have been used to avoid measurements of large correlation. The vertical bars indicate the experimental errors; *i.e.*, the statistical and systematic errors added in quadrature; in some cases they are comparable in size to the data points.

Table 1. Fit results and error contributions from the moment measurements, approximations to the HQEs, and additional theoretical uncertainti es from α_s terms and other perturbative and non-perturbative terms contributing to $\Gamma_{c\ell\nu}$.
$\mu_\pi^2(\mu)$ and $\mu_G^2(\mu)$ (expectation values of kinetic and chromomagnetic operators) parametrize the leading non-perturbative effects at $\mathcal{O}(1/m_b^2)$; while $\rho_D^3(\mu)$ and $\rho_{LS}^3(\mu)$ (expectation values of the Darwin and spin-orbit operators) arise at $\mathcal{O}(1/m_b^3)$.

	$\lvert V_{cb}\rvert$ (10^{-3})	m_b (GeV)	m_c (GeV)	μ_π^2 (GeV^2)	ρ_D^3 (GeV^3)	μ_G^2 (GeV^2)	ρ_{LS}^3 (GeV^3)	$\mathcal{B}_{c\ell\nu}$ (%)
Results	41.390	4.611	1.175	0.447	0.195	0.267	-0.085	10.611
δ_{exp}	0.437	0.052	0.072	0.035	0.023	0.055	0.038	0.163
δ_{HQE}	0.398	0.041	0.056	0.038	0.018	0.033	0.072	0.063
δ_{α_s}	0.150	0.015	0.015	0.010	0.004	0.018	0.010	0.000
δ_Γ	0.620							
δ_{tot}	0.870	0.068	0.092	0.053	0.029	0.067	0.082	0.175

3 Measurement of the $\cos 2\beta$ sign with $B^0 \to J/\psi$ "K^{*0}" events

The *CP* violating parameter $\sin 2\beta$ is measured with high precision, but this leaves a four–fold ambiguity on the angle β itself. This can be reduced to a two–fold ambiguity if measuring the sign of $\cos 2\beta$. The measurement of this sign provides a direct test of the Standard Model (SM), since $\cos 2\beta > 0$ is expected in the SM. The $\cos 2\beta$ parameter can be measured with $B^0 \to J/\psi K^{*0}; K^{*0} \to K_S^0 \pi^0$ events, but, precisely, with a sign ambiguity, coming itself from a two–fold ambiguity in the determination of the strong phases involved in the decay. We present a new

method, based on the analysis of the $K\pi$ phase variation with mass, to break this strong phases ambiguity and the first ambiguity-free measurement of $\cos 2\beta$, with $B^0 \to J/\psi$ "K^{*0}" events.
The *CP* content of the decay $B^0 \to J/\psi K^{*0}(892); K^{*0}(892) \to K^0_S\pi^0$ is both even an odd. The $\cos 2\beta$ parameter appears through *CP*–even – *CP*–odd interferences in the time and angular dependant distribution in the observables [10]:

$$\cos(\delta_\parallel - \delta_\perp)\cdot\cos 2\beta,\ \cos(\delta_\perp - \delta_0)\cdot\cos 2\beta, \tag{1}$$

where $\delta_0, \delta_\parallel$ and $\delta_\perp$ are the strong phases of the decay amplitudes $A_0 = |A_0|e^{i\delta_0}, A_\parallel = |A_\parallel|e^{i\delta_\parallel}$, which are *CP*–even, and $A_\perp = |A_\perp|e^{i\delta_\perp}$, which is *CP*–odd. These strong phases are measured on a large sample of neutral and charged $B \to J/\psi K^*$ decays (tab. 2), but up to the two-fold mathematical ambiguity $(\delta_\parallel - \delta_0, \delta_\perp - \delta_0) \leftrightarrow (-(\delta_\parallel - \delta_0), \pi - (\delta_\perp - \delta_0))$. Under this transformation,

Table 2. $B \to J/\psi K^*$ decay amplitude moduli (left) and strong phases (right) measured by an angular analysis on a sample of $B^0 \to J/\psi (K^+\pi^-)^{*0}, B^+ \to J/\psi (K^0_S\pi^+)^{*+}, B^+ \to J/\psi (K^+\pi^0)^{*+}$, and related charged conjugate decays. The integrated luminosity is $82\mathrm{fb}^{-1}$. The yields corresponding to the three above channels are 2376 ± 51, 670 ± 27 and 791 ± 33 respectively. For the strong phases (right table), the values corresponding to the two ambiguous solutions (see text) are given. Note that we observe a 7.6 σ significant strong phase: $\delta_\parallel - \delta_\perp = 0.597 \pm 0.077 \pm 0.017$.

$\lvert A_0\rvert^2$	$0.566 \pm 0.012 \pm 0.005$
$\lvert A_\parallel\rvert^2$	$0.204 \pm 0.015 \pm 0.005$
$\lvert A_\perp\rvert^2$	$0.230 \pm 0.015 \pm 0.004$

	Solution I	Solution II
$\delta_\parallel - \delta_0$	$2.729 \pm 0.101 \pm 0.052$	$3.554 \pm 0.101 \pm 0.052$
$\delta_\perp - \delta_0$	$0.184 \pm 0.070 \pm 0.046$	$2.958 \pm 0.070 \pm 0.046$

$\cos(\delta_\parallel - \delta_\perp)$ and $\cos(\delta_\perp - \delta_0)$ (eqn. (1)) change of sign, meaning that the two set of parameters $(\delta_\parallel - \delta_0, \delta_\perp - \delta_0, \cos 2\beta) \leftrightarrow (-(\delta_\parallel - \delta_0), \pi - (\delta_\perp - \delta_0), -\cos 2\beta)$ are mathematically equivalent [10]. But this is considering the P–wave $K^{*0}(892)$ only...

A $K\pi$ S–wave is known to lie in the $K^*(892)$ region [11]. The interference with the main $K\pi$ P–wave $K^*(892)$ is the key to break the strong phases ambiguity. Taking into account a $B \to J/\psi (K\pi)_{S-\mathrm{wave}}$ amplitude, in addition to the three $B \to J/\psi (K\pi)_{P-\mathrm{wave}}$ ones $(A_0, A_\parallel, A_\perp)$, introduces the relative strength of the P and S contributions and a new relative phase $\gamma = \delta_S - \delta_0$. There is still an ambiguity:

$$(\delta_\parallel - \delta_0, \delta_\perp - \delta_0, \gamma) \leftrightarrow (-(\delta_\parallel - \delta_0), \pi - (\delta_\perp - \delta_0), -\gamma), \tag{2}$$

but the ambiguity on γ can be broken.

According the Wigner's causality principle [12], the phase of a resonance rotates counterclockwise with increasing mass. In the $K^*(892)$ region, the $(K\pi)_{S-\mathrm{wave}}$ phase moves slow, while the $(K\pi)_{P-\mathrm{wave}}$ phase moves rapidly. The phase $\gamma = \delta_S - \delta_0$ must then rotates clockwise in the $K^*(892)$ region. Figure 2 shows the P and S wave intensities as function of the $K\pi$ mass, as well as γ where the open points are for strong phases "Solution I" and the full points for "Solution II". The physical variation of γ is observed for "Solution II". As a cross-check of the phase evolution with mass, the γ phase evolution is compared in figure 2 with the evolution observed in the $Kp \to K\pi(n)$ high statistics LASS experiment [11]. The agreement is remarkable.

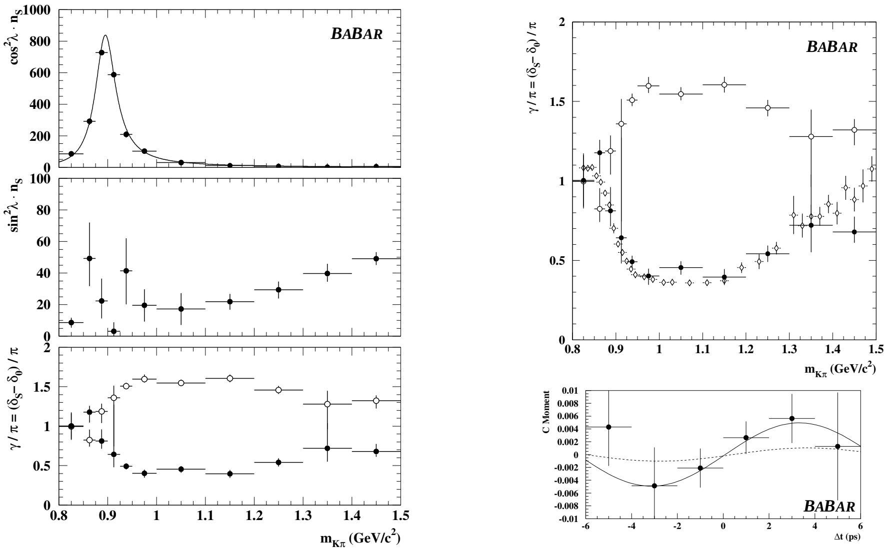

Figure 2. **Left:** Top(Middle): $P(S)$ wave intensity as function of the $K\pi$ mass ($K^{\pm}\pi^{\mp}$ channel only). The P wave intensity is fitted with a Breit-Wigner lineshape, including centrifugal effect. Bottom: $\gamma = \delta_S - \delta_0$ as function of the $K\pi$ mass, where the open points are obtained with strong phases "Solution I" (tab. 2) and the full points with "Solution II" (tab. 2). **Right, top:** Comparison of the $\gamma = \delta_S - \delta_0$ phase with the $K\pi$ mass, as in previous plots, with the LASS data, shown as diamond markers. These data correspond to the isospin 1/2 contribution, i.e., the one existing in the $B \to J/\psi(K\pi)$ decay. A global π offset was added to the LASS data, which obviously does not change the slope. **Right, bottom:** Moment of the angular function weighting the cos2β contribution in the time and angular dependant distribution. The full line corresponds to cos$2\beta = +3.32$, the dashed line to cos$2\beta = \sqrt{1-0.731^2} = +0.68$.

We perform a time and angular dependant analysis of the $B^0 \to J/\psi(K^0_S\pi^0)^{*0}$ sample (104 events), fixing the angular structure of the decay using above amplitude moduli and strong phases "Solution II" (tab. 2). With sin2β and cos2β free in the fit, we obtain [10] sin$2\beta = -0.10 \pm 0.57(\mathrm{stat}) \pm 0.14(\mathrm{syst})$ and cos$2\beta = +3.32^{+0.76}_{-0.96}(\mathrm{stat}) \pm 0.27(\mathrm{syst})$. Using the world average sin$2\beta = 0.731$ value, we obtain

$$\cos 2\beta = +2.72^{+0.50}_{-0.79}(\mathrm{stat}) \pm 0.27(\mathrm{syst}). \tag{3}$$

We thus measure a *positive* cos2β value, in agreement with the SM expectation. The fit result for cos2β can be illustrated making the moment of the angular term weighting cos2β in the time and angular dependant distribution, as shown on figure right bottom plot of figure 2.

Assuming sin2β and cos2β measure the same angle 2β, we estimate on Monte Carlo that we exclude the negative cos2β solution at 89% CL. This is preliminary estimate.

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