5 BABAR Experiment at PEP-II

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5.1 Introduction

The BABAR experiment has recently completed operation at the PEP-II Electron Positron Storage Ring at Stanford Linear Accelerator Center (SLAC). PEP-II collided electrons and positrons at the center-of-mass energy of 10.58 GeV, so-called the Upsilon(4S) resonance, to produce a large number of B mesons, and their decays were observed by the BABAR Detector. During its 9-year operation, the BABAR experiment accumulated an integrated luminosity of 531 fb^{-1}, of which 433 fb^{-1} was on the Upsilon(4S) resonance.

Taking advantage of the huge data sample, BABAR has published a large number of measurements that explore the CP sector of the Standard Model (SM). Most notable is the precise determination of the CP-violation phase β of the Cabibbo-Kobayashi-Maskawa (CKM) matrix: $\sin 2\beta = 0.697 \pm 0.035(\text{stat}) \pm 0.016(\text{syst})$ 0. This and other measurements of CP violation in the B^0 system impose strong constraints on the structure of the CKM matrix. It remains to be seen, however, if the CKM mechanism is the only source of the CP violation, or there are other sources beyond the Standard Model. To pursue this question, one needs to measure other quantities, such as the phases α and γ, and the magnitudes of the CKM matrix elements, with comparable precisions. The Harvard BABAR group's physics program focuses on several aspects of such tests as discussed in the following sections.

The current membership of the Harvard *BABAR* group consists of the following: **Masahiro Morii** is the Principal Investigator. **Kris Chaisanguanthum** has been a graduate student since 2001. **Corry Lee** has been a graduate student since 2004. The past members of the group include George Brandenburg, postdoctoral scholars Stephen Bailey, Eunil Won, and Jinwei Wu, and a number of undergraduate students.

5.2 Measurement of $|V_{ub}|$

The measurement of $\sin 2\beta$ through CP violation is already more accurate than our knowledge of the angle β through indirect, non-CPV, measurements. The uncertainty of the latter is dominated by $|V_{ub}|$, the magnitude of the CKM matrix element between the up and the bottom quarks. Improvement in $|V_{ub}|$ would directly translate to a more stringent test of the CKM mechanism and is therefore highly desirable.

The BABAR experiment devotes a considerable amount of efforts into the studies of charmless semileptonic B decays from which $|V_{ub}|$ can be determined. Many such measurements have been published, and many are currently being pursued by the members of the semileptonic analysis working group (AWG). Morii coordinated these efforts as a co-convener of the AWG from 2004 through 2006. The differential decay rate of the $B \to \pi\ell\nu$ decay, where ℓ is an electron or a muon, is given by

$$\frac{d\Gamma(B \to \pi\ell\nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} \left| f_+(q^2) \right|^2 p_\pi^3,$$

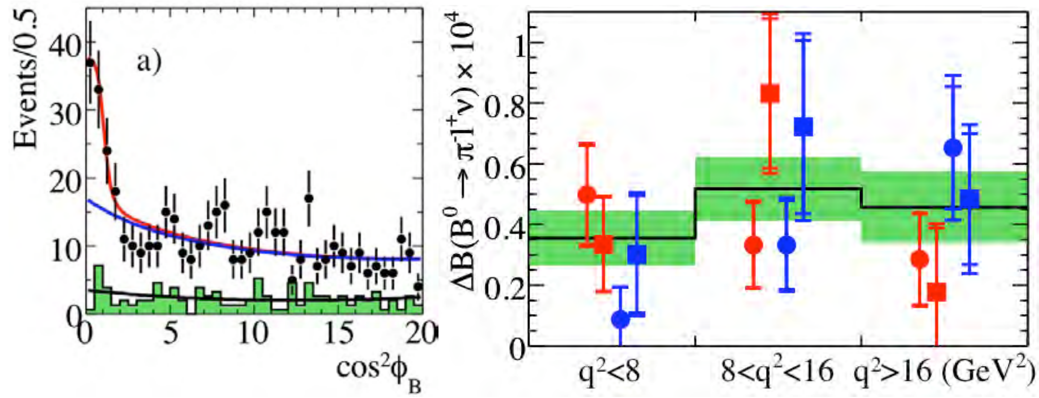

Figure 5.1: Distribution of $\cos^2\phi_B$ (left) for $B^0 \to \pi^- \ell^- \nu$, and the measured partial branching fractions (right).

where $f_+(q^2)$ is the B-to-π form factor. Recent theoretical calculations of the form factor use two techniques, light-cone sum rules (LCSR) 0 and unquenched lattice QCD (LQCD) 00, to achieve theoretical uncertainties of 11–13%. These calculations, however, are valid in limited regions of q^2, i.e., $q^2 < 16$ GeV^2 for LCSR and $q^2 > 16$ GeV^2 for LQCD. It is therefore necessary for us to measure the partial decay rate $\Delta\mathcal{B}(B \to \pi\ell\nu)$ in appropriate regions of q^2.

The Harvard BABAR group started the measurement of exclusive $B \to \pi\ell\nu$ branching fraction in November 2004. The measurement uses a sample of B mesons that are "tagged" by reconstruction of the accompanying anti-B meson in semileptonic decays. The tagged B helps us to constrain the event kinematics, reduce combinatorial backgrounds, and determine the charge of the B meson. The original analysis, based on 232 million $B\bar{B}$ pair events, was done by Morii with help from Kevin Chan, who at the time was a research assistant in our group. (Chan is now a graduate student at UC Berkeley.)

Figure 5.1, left, shows the fit of the distribution of a kinematic variable, $\cos^2\phi_B$, which should lie between 0 and 1 for the correctly-reconstructed signal events. We combine the results of the Harvard analysis with two other analyses performed in BABAR, and obtain the partial branching fractions shown in Figure 5.1, right. Combining the partial branching fractions with the theoretical calculations of the form factor, we derive the values of $|V_{ub}|$ in the table below, in which the last errors are due to the uncertainties of the form factor. The result has been published in Phys. Rev. Lett. 0 in 2006.

FF calculation	q^2 range	$\lvert V_{ub}\rvert$ (10^{-3})
Ball-Zwicky 0	< 16 GeV^2	3.2 ± 0.2(stat) ± 0.1(syst) +0.5/–0.4(FF)
HPQCD 0	> 16 GeV^2	4.5 ± 0.5(stat) ± 0.3(syst) +0.7/–0.5(FF)
FNAL 0	> 16 GeV^2	4.0 ± 0.5(stat) ± 0.3(syst) +0.7/–0.5(FF)

Kris Chaisanguanthum is working on the second phase of the analysis with two goals: a) to improve the precision of the $B \to \pi\ell\nu$ branching fraction using additional data collected in 2004–2006; and b) to investigate final states with other light pseudo scalar mesons, namely, $B \to \eta\ell\nu$ and $B \to \eta'\ell\nu$. Measurements of the latter decays are further motivated by the recent LCSR calculation of the B-to-$\eta^{(\prime)}$ form factors 0.

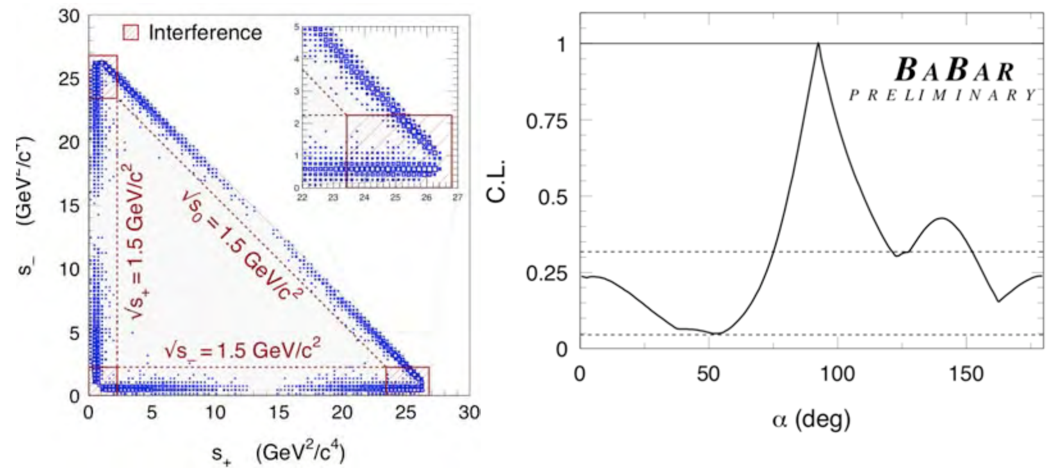

Figure 5.2: Dalitz plot (left) and the constraint on the CKM phase □ (right) obtained from B^0 □ $\pi^+\pi^-\pi^0$. *The variables* s^+ *and* s^- *are invariant masses squared of the* $\pi^+\pi^0$ *and* $\pi^-\pi^0$ *pairs, respectively.*

The new analysis, based on 383 million $B\bar{B}$ pair events, has been completed, and in the final stage of internal review before publication. The upcoming publication will form the basis of Chaisanguamthum's Ph.D. thesis.

5.3 Measurement of CKM Phase *α*

The CKM phase α, defined as $-\arg(V_{ud}V_{cb}^*/V_{cd}V_{cb}^*)$, can be measured through CP violation in charmless hadronic B decays, e.g., $B \to \pi\pi$, $\rho\pi$, and $\rho\rho$. These decays proceed through combinations of three amplitudes, and the presence of so-called penguin diagram with a different weak phase from the other diagrams poses a major difficulty in determination of α.

One powerful method to overcome this difficulty was proposed by Quinn and Snyder 0. It uses the Dalitz plot of the $B^0 \to \pi^+\pi^-\pi^0$ decay, in which three possible charge combinations of $\rho + \pi$ final states interfere with each other. (See Figure 5.2, left.) By expressing the Dalitz plot with a combination of ρ and other resonances, one can determine the relative strong phases between different regions of the Dalitz plane, which in turn can be used to disentangle the contributions of the different weak amplitudes.

Jinwei Wu, who was a Harvard postdoc at the time, has been a key player in the development of the Quinn-Snyder technique in BABAR. The result of his analysis based on 346 fb^{-1} has been published in Phys. Rev. D 0 in 2007. Figure 5.2 shows the Dalitz plot and the constraint on the CKM phase α obtained in this analysis.

Another, independent determination of the CKM phase α comes from $B \to \rho\rho$ decays. Contribution from the penguin diagram in this case is constrained by the small branching fraction, $(1.1 \pm 0.4) \times 10^{-6}$, of the $B^0 \to \rho^0\rho^0$ decay. Such constraint can be improved by taking advantage of the SU(3) flavor relation between the $B^0 \to \rho^+\rho^-$ and $B^0 \to \rho^- K^{*+}$ decays, the latter being dominated by the penguin diagram. Systematic measurements of the branching fractions, polarizations, and charge asymmetries of the B decays into two vector mesons will allow us to test the flavor SU(3) relations and QCD factorization, and may also shed light to the polarization puzzle in the $B \to \phi K^*$ decays.

Corry Lee has started working on the study of the $B \to \rho K^*$ decays. Of the four charge combinations ($B^0 \to \rho^+ K^{*-}$, $B^0 \to \rho^0 K^{*0}$, $B^+ \to \rho^0 K^{*+}$, and $B^+ \to \rho^+ K^{*0}$), the first three will be Lee's Ph.D. work, and the last will be done by a collaborator from Saclay. Previous publication by BABAR 0 has established two of the four channels, but the significances of the $B^+ \to \rho^0 K^{*+}$ and $B^0 \to \rho^+ K^{*-}$ charnels were only 2.5σ and 1.6σ, respectively. With the full statistics of the BABAR experiment, Lee has an excellent chance of observing these decays.

5.4 Level-1 Trigger System

The success of the BABAR/PEP-II project depended critically on the integrated luminosity we accumulated. The Harvard BABAR group contributed to improving the detector's ability to operate under ever-increasing luminosity through its commitment in the Level-1 Trigger System. In particular, we played a leading role in the development, production, and deployment of the Level-1 Trigger System upgrade. We were in charge of the design, engineering, and production of the key component of the new trigger system, the Z-PT discriminator (ZPD) modules 0. The full set of the production system was delivered to SLAC in 2003 and has been integrated in the BABAR trigger system since July 2004. The operation in the past 4 years has been smooth, helped by the work by Kris Chaisanguanthum to improve the online and offline software that monitored the performance of the trigger system.

5.5 Outlook

The BABAR experiment has been a phenomenal success. With one billion B mesons on tape, the experiment will continue to produce excellent physics results for the coming years. The Harvard BABAR group has contributed significantly to the success of the experiment.

The completion of the data taking and the publication of the physics analyses described in earlier sections have brought us to a point where the group's involvement with BABAR is naturally decreasing. Masahiro Morii has shifted his main focus from BABAR to ATLAS since January 2007. Kris Chaisanguanthum will publish his update of the $B \to \pi \ell \nu$ measurement with additional decay channels $B \to \eta \ell \nu$ and $B \to \eta' \ell \nu$, and graduate in spring 2008. Corry Lee's analysis of the $B \to \rho K^*$ decays will continue through 2009, when she is expected to complete her Ph.D. Lee's academic-year tuition and stipend are paid by Harvard University; we are therefore requesting a 3-month (summer of 2009) research assistant position for Lee in this proposal.