RESULTS ON THE CKM ANGLE $\phi_1$ ($\beta$)

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I review results related to the CKM angle $\phi_1(\beta)$. These results include recent measurements of $CP$-violation from the BaBar and Belle experiments in $b \rightarrow c\bar{c}s$, $b \rightarrow c\bar{c}d$ and $b \rightarrow sq\bar{q}$ processes.

1 Introduction

1.1 The B Physics Program

The $B$ physics program addresses several fundamental questions. Is the irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix the source of all $CP$-violating phenomena in the $B$ system? Or is $CP$-violation, the first manifestation of physics beyond the Standard Model? A related question is whether there are new $CP$-violating phases from physics beyond the Standard Model.

The unitarity of the CKM matrix implies the existence of three measurable phases. In the convention favored at KEK and Belle, these are denoted

$$\phi_1 \equiv \arg \left( -\frac{V_{cd}^*V_{ub}}{V_{td}V_{ub}} \right)$$

$$\phi_2 \equiv \arg \left( -\frac{V_{td}^*V_{ub}}{V_{cd}V_{ub}} \right)$$

$$\phi_3 \equiv \arg \left( -\frac{V_{td}^*V_{ub}}{V_{cd}V_{ub}} \right),$$

while at SLAC and at BaBar these angles are usually referred to as $\beta$, $\alpha$ and $\gamma$, respectively.

As first noted by Bigi, Carter and Sanda, there are large measurable $CP$-asymmetries in the decays of neutral $B$ mesons to $CP$-eigenstates. In the decay chain $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_{CP}f_{tag}$, where one of the $B$ mesons decays at time $t_{CP}$ to a final state $f_{CP}$ and the other decays at time $t_{tag}$ to a final state $f_{tag}$ that distinguishes between $B^0$ and $\bar{B}^0$, the decay rate has a time dependence given by

$$e^{-\frac{|\Delta d|}{\tau_{B^0}} } \left( 1 + q \cdot \left[ S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t) \right] \right),$$

where $\tau_{B^0}$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two $B^0$ mass eigenstates, $\Delta t = t_{CP} - t_{tag}$, and the $b$-flavor charge $q = +1 (-1)$ when the tagging $B$ meson is a $B^0$ ($\bar{B}^0$). The $CP$-violation parameters $S$ and $A$ are given by

$$S \equiv \frac{2Im(\lambda)}{|\lambda|^2 + 1}, \quad A \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1},$$

where $\lambda$ is a complex parameter that depends on both the $B^0\bar{B}^0$ mixing and on the amplitudes for $B^0$ and $\bar{B}^0$ to decay to $f_{CP}$. To a good approximation, the SM predicts $S = -\xi f \sin 2\phi_1$, where $\xi f = +1 (-1)$ corresponds to $CP$-even (-odd) final states. Direct $CP$-violation, $A = 0$ (or equivalently $|\lambda| = 1$), is expected for both $b \rightarrow c\bar{c}s$ and $b \rightarrow s\bar{q}q$ transitions.

1.2 Accelerators and Detectors

The $B$-factory accelerators, PEP-II and KEKB, were commissioned with remarkable speed starting in late 1998. The experiments, BaBar and Belle, started physics data taking in 1999. In the summer of 2001, the two experiments announced the observation of the first statistically significant signals for $CP$-violation outside of the kaon system.

Due to the extraordinary performance of the two accelerators, the most recent results reported in the summer of 2003 at the Lepton-Photon Symposium are based on very large data samples. BaBar has integrated 113 fb$^{-1}$ on the $\Upsilon(4S)$ resonance while Belle has integrated a sample of 140 fb$^{-1}$. KEK-B also achieved a peak luminosity above $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

1.3 The Principle of the Measurement

The measurement of time-dependent $CP$-asymmetry requires:

- A large sample of $\Upsilon(4S)$ decays into $B^0\bar{B}^0$ pairs. To boost the $\Upsilon(4S)$ decay frame so that the $B$ mesons’ flight length can be measured with solid-state vertex detector technology, both the KEKB and PEP-II accelerators use asymmetric energy beams with energies of 8.0 and 3.5 GeV or 9.0 and 3.1 GeV, respectively.
• Efficient reconstruction of $B \to X_c \pi K^0$ decays. This implies accurate measurements of momenta and energies of neutrals using CsI(Tl) crystal calorimeters in addition to good charged particle tracking in small cell drift chambers and efficient identification of leptons and $K^0_S$ as well as $K^0_L$ mesons.

• A measurement of $\Delta t$. This is related to the measurement of $\Delta z$, the spatial distance between the decay vertices and achieved at both experiments by using double-sided silicon strip detectors situated at small radii close to the interaction point.

• A determination of the flavor of the accompanying $B$ (“tagging”); this is based on the identification of electrons, muons and charged kaons and the measurement of their charge.

More detailed descriptions of the detectors and the experimental analysis procedure are available elsewhere.

2 Status of $CP$-Violation in $b \to c\bar{c}s$ Processes

Belle and BaBar reconstruct $B^0$ decays to the following $b \to c\bar{c}s$ $CP$-eigenstates: $J/\psi K_S$, $\psi(2S) K_S$, $\chi_{c1} K_S$, $\eta_c K_S$, $J/\psi K^*(K_S \pi^0)$ for $\xi_f = -1$ and $J/\psi K_L$ for $\xi_f = +1$. The two classes ($\xi_f = \pm 1$) should have $CP$-asymmetries that are opposite in sign.

Both experiments also use $B^0 \to J/\psi K^{*0}$ decays where $K^{*0} \to K_S \pi^0$. Here the final state is a mixture of even and odd $CP$. The $CP$ content can, however, be determined from an angular analysis of other $\psi K^*$ decays. The $CP$-odd fraction is found to be small (i.e. $(19 \pm 4\%)$ ($(16 \pm 3.5\%)$) in the Belle (BaBar) analysis).

The most recent BaBar analysis is based on a data sample with an integrated luminosity of $81 \text{ fb}^{-1}$ and was first presented in 2002. There is a corresponding published Belle result also shown in 2002 with $78 \text{ fb}^{-1}$. At this Symposium, Belle provided a new preliminary result for their $140 \text{ fb}^{-1}$ sample.

The data sample used for the recent Belle measurement is shown in Fig. 1 and Fig. 2. Table 1 lists the numbers of candidates, $N_{ev}$, and the estimated signal purity for each $f_{CP}$ mode. It is clear that the $CP$-eigenstate samples that are used for the $CP$-violation measurements in $b \to c\bar{c}s$ are large and clean.

In the summer of 2001, the first statistically significant measurements of the $CP$-violating parameter $\sin 2\phi_1$ were reported by Belle and BaBar. Belle
Table 1. The yields from Belle for reconstructed $B \to f_{CP}$ candidates after flavor tagging and vertex reconstruction, $N_{ev}$, and the estimated signal purity, $p$, in the signal region for each $f_{CP}$ mode. $J/\psi$ mesons are reconstructed in $J/\psi \to \mu^+\mu^-$ or $e^+e^-$ decays. Candidate $K_S^0$ mesons are reconstructed in $K_S^0 \to \pi^+\pi^-$ decays unless otherwise written explicitly.

| Mode                  | $\xi_f$ | $N_{ev}$ | $p$    |
|-----------------------|---------|----------|--------|
| $J/\psi K_S^0$        | $-1$    | $1997$   | $0.976 \pm 0.001$ |
| $J/\psi K_S^0(e^0\pi^0)$ | $-1$    | $288$    | $0.82 \pm 0.02$ |
| $\psi(2S)(\ell^+\ell^-)K_S^0$ | $-1$    | $145$    | $0.93 \pm 0.01$ |
| $\psi(2S)(J/\psi\pi^+\pi^-)K_S^0$ | $-1$    | $163$    | $0.88 \pm 0.01$ |
| $\chi_{cs}(J/\psi\gamma)K_S^0$ | $-1$    | $101$    | $0.92 \pm 0.01$ |
| $\eta_c(K_S^0\pi^-\pi^+)K_S^0$ | $-1$    | $123$    | $0.72 \pm 0.03$ |
| $\eta_c(K_S^0\pi^-\pi^0)K_S^0$ | $-1$    | $74$     | $0.70 \pm 0.04$ |
| $\eta_c(J/\psi\ell^-)K_S^0$ | $-1$    | $20$     | $0.91 \pm 0.02$ |
| All with $\xi_f = -1$ | $-1$    | $291$    | $0.933 \pm 0.002$ |
| $J/\psi K_S^0(K_S^0\pi^0)$ | $+1(81\%)$ | $174$    | $0.93 \pm 0.01$ |
| $J/\psi K_L^0$        | $+1$    | $2332$   | $0.60 \pm 0.03$ |

found

$$\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06$$  \hspace{1cm} (5)

while BaBar obtained

$$\sin 2\phi_1 = 0.59 \pm 0.14 \pm 0.05.$$  \hspace{1cm} (6)

The results were based on data samples of comparable size (31 million and 32 million $B\bar{B}$ pairs, respectively).

The new Belle data are shown in Fig. 3. This figure shows the $\Delta t$ distributions where a clear shift between $B^0$ and $\bar{B}^0$ tags is visible as well as the raw asymmetry plots in two bins of the flavor tagging quality variable $r$. For low-quality tags ($0 < r < 0.5$), which have a large background dilution, only a modest asymmetry is visible while in the subsample with high quality tags ($0.5 < r < 1.0$), a very clear asymmetry with a sine-like time modulation is present. The final results are extracted from an unbinned maximum-likelihood fit to the $\Delta t$ distributions that takes into account resolution, mistagging and background dilution. The new Belle result with 140 fb$^{-1}$ (152 million $B\bar{B}$ pairs) is

$$\sin 2\phi_1 = 0.733 \pm 0.057 \pm 0.028.$$  \hspace{1cm} (7)

The new Belle result may be compared to the BaBar result with 78 fb$^{-1}$ of

$$\sin 2\phi_1 = 0.741 \pm 0.067 \pm 0.03.$$  \hspace{1cm} (8)

Both experiments are now in very good agreement. A new world average can be calculated from these results,

$$\sin 2\phi_1 = 0.736 \pm 0.049.$$  \hspace{1cm} (9)

This world average can be interpreted as a constraint on the CKM angle $\phi_1$. This constraint can be compared to the indirect determinations on the unitarity triangle. This comparison is shown in Fig. 4 and is consistent with the hypothesis that the Kobayashi-Maskawa phase is the source of $CP$-violation.

The measurement of $\sin(2\phi_2)$ in $b \to c\bar{c}s$ modes, although still statistically limited, is becoming a precision measurement. The systematics are small and well-understood. Recently, BaBar physicists discovered a new small source of systematic uncertainty due to $CP$-violation in $b \to c\bar{u}d$ decays on the tagging side.

The presence of an asymmetry with a cosine dependence ($|\lambda| \neq 1$) would indicate direct $CP$-violation. In order to test for this possibility in $b \to c\bar{c}s$ modes, Belle also performed a fit with $a_{CP} = -\xi_f \text{Im} \lambda/|\lambda|$ and $|\lambda|$ as free parameters, keeping everything else the same. They obtain

$$|\lambda| = 1.007 \pm 0.041 \text{(stat)}$$  \hspace{1cm} (10)

$$a_{CP} = 0.733 \pm 0.057 \text{(stat)}$$
The corresponding result from Belle is based on 140 fb\(^{-1}\) and uses 89 ± 10 events.\(^{16}\) They obtain

\[
\sin 2\phi_{1\text{eff}}(B \to \psi\pi^0) = 0.72^{+0.37}_{-0.42} \pm 0.08. \quad (12)
\]

In both cases, the systematic error includes the possibility of CP-violation in a small component of the background that peaks under the signal.

The \(b \to c\bar{c}d\) mode \(B \to D^{++}D^{*-}\) has a vector-vector final state and requires special treatment since it includes contributions from both CP-even and odd components. To extract the CP-odd fraction, one fits the angular distribution in the transversity basis. The result from BaBar based on a sample with 156 ± 14 signal events is,

\[
R_\perp = 0.063 \pm 0.055 \pm 0.009, \quad (13)
\]

where the quantity \(R_\perp\) is the fraction of the CP-odd component. The measurement indicates that \(B^0 \to D^{++}D^{*-}\) is mostly CP-even.

The time distributions from BaBar for \(B \to D^+D^-\) are shown in Fig. 5. BaBar finds

\[
\sin 2\phi_{1\text{eff}}(B \to D^+D^-) = -0.05 \pm 0.29 \pm 0.10, \quad (14)
\]

which is about 2.5\(\sigma\) from the result in \(b \to c\bar{c}s\) modes. This may be a statistical fluctuation or could be an indication that the Standard Model \(b \to d\) penguin contribution is large. The fit includes the possibility of direct CP-violation. The parameter \(\lambda\) is found to be 0.75 ± 0.19 ± 0.02, which is consistent with unity, as expected for no direct CP-violation.

Since \(B^0 \to D^{*+}D^-\) and its charge conjugate are not CP-eigenstates, a modified treatment is required. There are four rather than two CP-violating observables that are determined from a time-dependent fit to the different \(D^*D\) charge states.

BaBar finds,

\[
S_{+-} = -0.82 \pm 0.75 \pm 0.14, \quad (15)
\]
\[
S_{-+} = -0.24 \pm 0.69 \pm 0.12, \quad (16)
\]
\[
A_{+-} = +0.47 \pm 0.40 \pm 0.12, \quad (17)
\]
\[
A_{-+} = +0.22 \pm 0.37 \pm 0.10. \quad (18)
\]

In the limit of no penguins and assuming factorization in these hadronic decays, \(S_{-+} = S_{+-} = -\sin 2\phi_1\) and \(A_{+-} = A_{-+} = 0\). The above results for CPV in \(B \to D^*D\) decays are consistent with this limit.
Observation of the $CP$-eigenstate mode $B \to D^+ D^-$ was reported by Belle at this conference. With $140 \text{ fb}^{-1}$, the $5\sigma$ signal contains $24.3 \pm 6.0$ events. In the future, this mode can also be used for time-dependent measurements of $CPV$ in $b \to cc\bar{d}$ processes.

The results of $CP$-violation measurements for $b \to cc\bar{d}$ decays are summarized in Fig. 6. The measurements are not yet precise enough to definitively demonstrate the presence of penguin pollution.

4 Status of $CP$-Violation in $b \to sq\bar{q}$ Penguin Processes

In addition to the program of measuring the other remaining angles of the unitarity triangle that is discussed in the contribution by Jawahery, there is also the question of whether there are additional $CP$-violating phases from new interactions or physics beyond the Standard Model. At the moment, such new phases are poorly constrained.

One way to attack this question is to measure the time-dependent $CP$-asymmetry in penguin-dominated modes such as $B^0 \to \phi K_S^0$, $B^0 \to \eta ' K_S^0$ or $B^0 \to K_S^0 \pi^0$, where heavy new particles may contribute inside the loop, and compare it to the asymmetry in $B^0 \to J/\psi K_S^0$ and related $b \to c\bar{c}s$ charmonium modes.

The mode $B \to K_S^0 \pi^0$ proceeds through a $b \to sdd$ transition. The BaBar data on $B \to K_S^0 \pi^0$ are shown in Fig. 7. To be useful for time-dependent $CPV$ studies at least one of charged pions from the $K_S^0$ must be detected in the BaBar silicon vertex detector. There are $123 \pm 16$ events of this type that are then used to obtain

$$\sin 2\phi_{1\text{eff}}(B \to K_S^0 \pi^0) = 0.48^{+0.38}_{-0.47} \pm 0.11. \quad (19)$$

The time distributions are shown in Fig. 8. The direct $CP$-violation parameter is $A = -0.40^{+0.28}_{-0.27} \pm 0.10^{+0.41}_{-0.48}$. When $A$ is fixed to zero, the value of $S = \sin(2\phi_{1\text{eff}})$ shifts slightly to $0.41^{+0.41}_{-0.48} \pm 0.11$. The results for $B \to K_S \pi^0$ are consistent with the value from the $b \to c\bar{c}s$ modes, $\sin 2\phi_s = 0.736 \pm 0.049$.

The mode $B \to \eta ' K_S^0$ is expected to include contributions from $b \to su\bar{u}$ and $b \to sdd$ penguin processes. The beam constrained mass distribution for the $B \to \eta ' K_S^0$ sample used by Belle is shown in
Fig. 9 and contains 244 ± 21 signal events.\textsuperscript{21} Belle finds (Fig. 10),

\[ \sin 2\phi_{1,\text{eff}}(B \to \eta' K_S^0) = 0.43 \pm 0.27 \pm 0.05 \quad (20) \]

The BaBar data is shown in Fig. 11. They obtain,

\[ \sin 2\phi_{1,\text{eff}}(B \to \eta' K_S^0) = 0.02 \pm 0.34 \pm 0.03 \quad (21) \]

The average of these two results for \( B \to \eta' K_S^0 \) is about 2.2\sigma from the \( b \to c\bar{c}s \) measurement, which is the Standard Model expectation.

The decay mode \( B \to K^+ K^- K_S^0 \), where \( K^+ K^- \) combinations consistent with the \( \phi \) have been removed, is found by Belle to be dominantly \( CP \)-odd\textsuperscript{22} and thus can be treated as a \( CP \)-eigenstate and used for studies of time-dependent \( CP \)-violation in \( b \to sq\bar{q} \) processes. The beam constrained mass distribution for the \( B \to K^+ K^- K_S^0 \) sample used by Belle is shown in Fig. 9. There are 199 ± 18 signal events. Belle obtains,

\[ \sin 2\phi_{1,\text{eff}}(B \to K^+ K^- K_S^0) = 0.51 \pm 0.26 \pm 0.05 \pm 0.18 \pm 0.00 \quad (22) \]

where the third error is due to the uncertainty in the \( CP \) content of this final state\textsuperscript{22}. The results for \( B \to K^+ K^- K_S^0 \) are also consistent with \( b \to c\bar{c}s \) decays. However, in this decay there is also the possibility of “tree-pollution”, the contribution of the \( b \to u\bar{u}s \) tree amplitude that may complicate the interpretation of the results\textsuperscript{23}.

The \( B^0 \to \phi K_S^0 \) decay, which is dominated by the \( b \to s\bar{s}s \) transition, is an especially unambiguous and sensitive probe of new \( CP \)-violating phases from physics beyond the SM\textsuperscript{24}. The SM predicts that measurements of \( CP \)-violation in this mode should yield \( \sin 2\phi_1 \) to a very good approximation\textsuperscript{25,23} A significant deviation in the time-dependent \( CP \)-asymmetry in this mode from what is observed in \( b \to c\bar{c}s \) decays would be evidence for a new \( CP \)-violating phase.

The \( B \to \phi K_S^0 \) sample used by BaBar is shown in Fig. 12. The signal, obtained from a sample with an integrated luminosity of 110 fb\(^{-1}\), contains 70 ± 9 events\textsuperscript{20}. The time distributions for the BaBar data are shown in Fig. 13. They obtain

\[ \sin 2\phi_{1,\text{eff}}(B \to \phi K_S^0) = 0.45 \pm 0.43 \pm 0.07. \quad (23) \]
This value is consistent with the Standard Model expectation, but is somewhat different from the value obtained with the 81 fb\(^{-1}\) sample, which was \(\sin 2\phi_{\text{eff}} = -0.18 \pm 0.51 \pm 0.09\). The new result includes more data and a reprocessing of the old data sample. After extensive checks with data and Toy Monte Carlo studies, the large change in the central value is attributed to a 1\(\sigma\) statistical fluctuation.\(^{26}\)

The \(B \to \phi K_S^0\) sample used by Belle is shown in the right panel of Fig. 12. The selection criteria are described in detail elsewhere.\(^{27,28}\) The signal contains 68 \(\pm 11\) events. Figure 15 shows the raw asymmetries from Belle in two regions of the flavor-tagging parameter \(r\). While the numbers of events in the two regions are similar, the effective tagging efficiency is much larger and the background dilution is smaller in the region \(0.5 < r \leq 1.0\). The solid curves show the results of the unbinned maximum-likelihood fit to the \(\Delta t\) distribution.

The observed \(CP\)-asymmetry for \(B^0 \to \phi K_S^0\) in the region \(0.5 < r \leq 1.0\) (Fig. 15 (lower panel)) indicates the difference from the SM expectation (dashed curve). Note that these projections onto the \(\Delta t\) axis do not take into account event-by-event information (such as the signal fraction, the wrong tag fraction and the vertex resolution) that is used in the unbinned maximum likelihood fit.

The contamination of \(K^+K^-K_S^0\) events in the \(\phi K_S^0\) sample (7.2 \(\pm 1.7\%)\) is small. Finally, backgrounds from the \(B^0 \to f_0(980)K_S^0\) decay, which has the opposite \(CP\)-eigenvalue to \(\phi K_S^0\), are found to be
small ($1.6^{+1.9}_{-1.5}$%). The influence of these backgrounds is treated as a source of systematic uncertainty.

Belle obtains

$$\sin 2\phi_{\text{eff}}(B \rightarrow \phi K^0_S) = -0.96 \pm 0.5^{+0.09}_{-0.11} \quad (24)$$

from their likelihood fit to the $\phi K^0_S$ data. The likelihood function is parabolic and well-behaved. An evaluation of the significance of the result using the Feldman-Cousins method and allowing for systematic uncertainties shows that this result deviates by 3.5$\sigma$ from the Standard Model expectation.28

The Belle group performed a number of validation checks for their $B \rightarrow \phi K^0_S \ CP$-violation result. Fits to the same samples with the direct $CP$-violation parameter $A$ fixed at zero yield $\sin 2\phi_{\text{eff}} = -0.99 \pm 0.50(\text{stat})$ for $B^0 \rightarrow \phi K^0_S$. As a consistency check for the $S$ term, the same fit procedure is applied to the charged $B$ meson decays $B^+ \rightarrow \phi K^+$. The result is $S = -0.09 \pm 0.26(\text{stat})$, $A = +0.18 \pm 0.20(\text{stat})$ for $B^+ \rightarrow \phi K^+$ decay. The results for the $S$ term is consistent with no $CP$-asymmetry, as expected. The asymmetry distribution is shown in Fig. 16. In addition, the $\phi K^0_S$ side-band has been examined as shown in Fig. 16. No asymmetry is found in that sample.

5 Conclusion

Belle presented a new measurement of time-dependent $CP$-violation in $b \rightarrow c\bar{c}s$ $CP$-eigenstates. This result and previous results from BaBar are in good agreement with each other and with the hypothesis that the Kobayashi-Maskawa phase is the source of $CP$-violation.

Studies of $CP$-violation in $b \rightarrow c\bar{c}d$ modes are progressing. $B \rightarrow D^{**}D^{*-}$ decays, BaBar observes a 2.5$\sigma$ hint for penguin pollution. More data and measurements are needed to clarify whether penguin pollution is present in this class of decays.

In $B \rightarrow \phi K^0_S$ decays there was a surprise. With 140 fb$^{-1}$ Belle observed a 3.5$\sigma$ deviation from the Standard Model expectation. This could be an indication of new physics from heavy particles in the
$b \to s\bar{s}$ penguin loop. However, BaBar’s value moved closer to the Standard Model with the addition of new data and reprocessing. More precise measurements of the other $b \to sq\bar{q}$ modes can further constrain phases from new physics. For example, new physics may contribute differently to pseudoscalar-vector and pseudoscalar-pseudoscalar modes.\footnote{The results of $CP$-violation measurements for $b \to sq\bar{q}$ penguin decays are summarized in Fig. 17. The world average for all $b \to s$ penguin decays (shown by the dotted line) appears to be displaced from the average for $b \to cc\bar{s}$ modes. The high energy physics community will require that this experimental issue be resolved conclusively in the future. This will require large data samples with integrated luminosities of at least 1 ab$^{-1}$ or 1000 fb$^{-1}$.}

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DISCUSSION

Stefan Spanier (University of Tennessee):

1) Unfortunately, the plenary session gives the audience only a limited chance to help you to establish the results by asking detailed questions.

2) Knowing the previous value of $S = -0.7 \pm 0.6$ from Belle, the newly added statistics must lead to an unphysical value of $S < -1.4$ leading typically to large correlations in $S$ and $C$ (pathological behavior) in this new sample. How probable is the value in the new sample?

3) How strong is the $CP$-asymmetry in the background?

Tom Browder:

1) A special breakout session is planned later in the Symposium.

2) For a true value near $S = -1$, the values in the new sample are quite consistent with Toy Monte Carlo studies. There is no statistically pathological behaviour in either old or new data samples. The observed errors are actually slightly larger than expected.

3) The background from $B \to f_0 K_S^0$ and $B \to K^+ K^- K_S^0$ decays is small and the $CP$-asymmetry from these backgrounds is included in the systematic error.

Alex Kagan (Cincinnati): Can you show the raw BaBar data for $S(\phi K^0_S)$ again?

Tom Browder: Yes. Note that a figure with this data was included in the talk and appears in the Proceedings.

Hitoshi Murayama (Berkeley): On the $\phi K^0_S$ mode, the change in the BaBar result was attributed to a statistical fluctuation. They have added only 40% more data. How is that possible? Do you have a breakdown of the asymmetry between the previous and new data samples?

Tom Browder: Not only was more data added, but the old BaBar data sample was also reprocessed. After reprocessing, a small number of events changed from $B^0$ tags to $\bar{B}^0$ tags (or vice versa). This accounts for the shift in the central value.
$-2\ln\left(\frac{L}{L_{\text{max}}}\right)$ vs $S$
$B^0 \rightarrow K^+ K^- K_S$
Events / (0.001 GeV)

$m_{ES}$ (GeV)
Study of Time-Dependent $CP$ Asymmetry in Neutral $B$ Decays to $J/\psi\pi^0$

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We present the first study of the time-dependent $CP$-violating asymmetry in $B^0 \rightarrow J/\psi \phi^0$ decays using $e^+ e^-$ annihilation data collected with the BABAR detector at the $T(4S)$ resonance during the years 1999-2002 at the PEP-II asymmetric-energy $B$ Factory at SLAC. Using approximately 88 million $B \bar{B}$ pairs, our results for the coefficients of the cosine and sine terms of the $CP$ asymmetry are $C_{J/\psi \phi^0} = 0.38 \pm 0.41$ (stat) $\pm 0.09$ (syst) and $S_{J/\psi \phi^0} = 0.05 \pm 0.49$ (stat) $\pm 0.16$ (syst).

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The Standard Model of electroweak interactions describes $CP$ violation in $B$-meson decays by a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The $b \rightarrow c \bar{c}s$
modes such as $B^0 \to J/\psi K^0$ yield precise measurements of the quantity $\sin 2\beta$, where $\beta \equiv \arg \left[ -V_{td} V_{ts}^* / V_{ub} V_{cb}^* \right]$ (see for example Refs. [2-4]). The decay $B^0 \to J/\psi \pi^0$ is a Cabibbo-suppressed $b \to c\pi d$ transition. In the Standard Model both $B^0 \to J/\psi K^0_s$ and $B^0 \to J/\psi \pi^0$ have penguin amplitudes with the same weak phase as the tree amplitude, and an additional penguin amplitude with a different phase. In $B^0 \to J/\psi K^0_s$, the penguin amplitude with a different weak phase is suppressed by $\lambda_{c,KM}$, where $\lambda_{c,KM}$ is the sine of the Cabibbo angle, while in $B^0 \to J/\psi \pi^0$, the tree and each penguin amplitude are equal to leading order in $\lambda_{c,KM}$. Therefore, $B^0 \to J/\psi \pi^0$ may have a CP asymmetry that differs from that of $B^0 \to J/\psi K^0_s$, with the size of the asymmetry serving as a probe of the penguin decay amplitudes in both modes.

BABAR has previously measured the $B^0 \to J/\psi \pi^0$ branching fraction, $(2.0 \pm 0.6 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-5}$ [5], using $\Upsilon(4S) \to B \bar{B}$ decays. For the CP asymmetry measurement, the flavor ($B^0$ or $\bar{B}^0$) of the $B$ meson that decays to $J/\psi \pi^0$ is inferred, or tagged, using properties of the other $B$ meson and the time evolution of the $B \bar{B}$ system. The decay time distributions, $f_\pm(t)$, of $B$ decays to a CP eigenstate with a $B^0$ ($\bar{B}^0$) flavor tag, are given by

$$f_\pm(t) = \frac{e^{-|t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 \pm S_{J/\psi \pi^0} \sin(\Delta m_B|t|) \right] \cos(\Delta m_B|t|),$$

(1)

where $\Delta t = t_{\text{rec}} - t_{\text{tag}}$ is the difference between the proper decay time of the reconstructed $B$ meson and the proper decay time of the tagging $B$ meson, $\tau_{B^0}$ is the $B^0$ lifetime, and $\Delta m_B$ is the $B^0$, $\bar{B}^0$ oscillation frequency. The coefficients can be expressed in terms of a complex parameter $\lambda$, which depends on both the $B^0$, $\bar{B}^0$ oscillation amplitude and the $B^0$ and $\bar{B}^0$ decay amplitudes to this final state [6]: $S_{J/\psi \pi^0} = 2 \Im \lambda / (1 + |\lambda|^2)$ and $C_{J/\psi \pi^0} = (1 - |\lambda|^2) / (1 + |\lambda|^2)$. A decay amplitude with only a tree component would give $S_{J/\psi \pi^0} = -\sin 2\beta$ and $C_{J/\psi \pi^0} = 0$.

The data used in this measurement were collected with the BABAR detector [7] at the PEP-II storage ring in the years 1999 to 2002. Approximately 81 fb$^{-1}$ of $e^+e^-$ annihilation data recorded at the $\Upsilon(4S)$ resonance are used, corresponding to a sample of approximately 88 million $B \bar{B}$ pairs. An additional 5 fb$^{-1}$ of data collected approximately 40 MeV below the $\Upsilon(4S)$ resonance are used to characterize non-$B\bar{B}$ background sources.

$B^0 \to J/\psi \pi^0$ candidates are selected (details are given in Ref. [5]) by identifying $J/\psi \to e^+e^-$ or $J/\psi \to \mu^+\mu^-$ decays and $\pi^0 \to \gamma\gamma$ decays. For the $J/\psi \to e^+e^-$ ($J/\psi \to \mu^+\mu^-$) channel, each lepton candidate must be consistent with the electron (muon) hypothesis. The invariant mass of the lepton pair is required to be between 2.95 and 3.14 GeV/c$^2$, and 3.06 and 3.14 GeV/c$^2$, for the electron and muon channels, respectively. The photon candidates used to reconstruct the $\pi^0$ candidate are identified as clusters in the electromagnetic calorimeter (EMC) with polar angles between 0.410 and 2.409 rad, that are spatially separated from each charged track, and have a minimum energy of 30 MeV. The lateral energy distribution in the cluster is required to be consistent with that of a photon. The invariant mass of the photon pair is required to between 100 and 160 MeV/c$^2$. Finally, the $J/\psi$ and $\pi^0$ candidates are assigned their nominal masses and combined using 4-momentum addition.

Two kinematic consistency requirements are applied to each $B$ candidate. The difference, $\Delta E$, between the $B$-candidate energy and the beam energy in the $e^+e^-$ center-of-mass (CM) frame must be $-0.4 < \Delta E < 0.4\text{ GeV}$. The beam-energy-substituted mass, $m_{ES} = \sqrt{\sqrt{s}/2 - (p_B^*)^2}$, must be greater than 5.2 GeV/c$^2$, where $\sqrt{s}$ is the total CM energy and $p_B^*$ is the $B$-candidate momentum in the CM frame.

A linear combination of several kinematic and topological variables, determined with a Fisher discriminant, provides additional separation between signal and $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum background events. The Fisher discriminant uses the following inputs: the zeroth- and second-order Legendre polynomial momentum moments $(L_0 = \sum_i |p_i^*|^2$ and $L_2 = \sum_i |p_i^*|^4 / 2$), where $p_i^*$ are the CM momenta for the tracks and neutral calorimeter clusters that are not associated with the signal candidate, and $\theta_i$ is the angle between $p_i^*$ and the thrust axis of the signal candidate); the ratio of the second-order to zeroth-order Fox-Wolfram moments, again using just tracks and clusters not associated with the signal candidate; $|\cos \theta_T|$, where $\theta_T$ is the angle between the thrust axis of the $B$ candidate and the thrust axis of the remaining tracks and clusters in the event; and $|\cos \theta_e|$, where $\theta_e$ is defined as the angle between the negative lepton and $B$ candidate directions in the $J/\psi$ rest frame. The requirement placed on the Fisher discriminant is 99% efficient for signal and rejects 71% of the continuum background. The efficiencies for satisfying this requirement are summarized in Table I.

| Type of event        | Efficiency (%) | Tagging |
|----------------------|---------------|---------|
| $B^0 \to J/\psi \pi^0$ | 99.2 ± 0.1    | 65.6 ± 0.6 |
| $B^0 \to J/\psi K^0_s(\pi^0 \pi^0)$ | 98.9 ± 0.1    | 65.6 ± 0.6 |
| Inclusive $J/\psi \pi^0$ | 94.9 ± 0.7    | 70.4 ± 1.4 |
| $B\bar{B}$ generic bkg. | 98.5 ± 0.4    | 61.1 ± 1.6 |
| Continuum bkg. | 28.6 ± 0.7    | 52.3 ± 0.8 |
We split the backgrounds into four mutually exclusive categories, two of which have a $J/\psi$ from $B$ decays ($B \to J/\psi \ X$). The first background category is $B^0 \to J/\psi K^0_S (\pi^0 \pi^0)$ decays where one of the $\pi^0$ mesons is nearly at rest in the $e^+e^-$ CM frame. The second background category consists of other $B \to J/\psi X$ decays (inclusive $J/\psi$), which contribute through random combinations of $J/\psi$ and $\pi^0$ candidates. The third and fourth categories consist of random combinations of particles in $B\bar{B}$ decays ($B\bar{B}$ generic) and continuum events, respectively. Monte Carlo simulation [8] is used to model aspects of the $B^0 \to J/\psi K^0_S (\pi^0 \pi^0)$, inclusive $J/\psi$, and $B\bar{B}$ generic backgrounds. A sample ($J/\psi_{\text{fake}}$) selected from data taken below the $Y(4S)$ resonance is used to model the continuum background. In this case, the $J/\psi$ candidate is reconstructed from two tracks that are not consistent with a lepton hypothesis. Monte Carlo simulation is used to check that this procedure, which increases the size of the sample, correctly models the continuum background.

The algorithm for $B$-flavor tagging assigns events to one of four hierarchical, mutually exclusive tagging categories, and is described in detail in Ref. [3]. The total tagging efficiency for the signal and each background source is given in Table I. Untagged events are excluded from further consideration. Vertex reconstruction and the determination of $\Delta t$ follow the techniques detailed in Ref. [9]. We require $-20 < \Delta t < 20$ ps and an estimated uncertainty on $\Delta t$ of less than 2.4 ps.

We extract the CP asymmetry by performing an unbinned extended maximum likelihood fit. The likelihood is constructed from the probability density functions (PDFs) for the variables $m_{ES}$, $\Delta E$, and $\Delta t$. The quantity that is maximized is the logarithm of

$$L = \frac{e^{-\sum_{i=1}^{n_j} n_j \sum_{j=1}^{N} f_{j,i} n_j \prod_{d} \mathcal{P}_{d,j}^{j}}}{N!},$$

where $n_j$ is the number of events for each of the five hypotheses (one signal and four background) and $N$ is the number of input events. The $\mathcal{P}_{d,j}^{j}$ are the one- or two-dimensional PDFs for variables $d$, for each signal or background type. The parameters $f_{j,i}^{a}$ are the tagging fractions for each of the tagging categories $a_i$ (assigned for each event $i$) and each of the signal or background types $j$. For the $B^0 \to J/\psi \pi^0$ signal and $B^0 \to J/\psi K^0_S (\pi^0 \pi^0)$ background, the values of $f_{j,i}^{a}$ are measured with a sample ($B_{\text{data}}$) of neutral $B$ decays to flavor eigenstates consisting of the channels $D^{(*)-}h^+ (h^+ = \pi^+, \rho^+, \rho^0)$ and $J/\psi K^{*0} (K^{*0} \to K^+\pi^-)$ [3]. Monte Carlo simulation is used to estimate the $f_{j,i}^{a}$ values for the inclusive $J/\psi$ and $B\bar{B}$ generic backgrounds, while the $J/\psi_{\text{fake}}$ sample is used for the continuum background.

The signal $m_{ES}$ distribution is modeled as the sum of two components. The first is a modified Gaussian function that, for values less than the mean, has a width parameter that scales linearly with the distance from the mean. The second component, accounting for less than 6% of the distribution, is a threshold function [10], which is a phase-space distribution of the form $m_{ES} \sqrt{1 - \frac{m_{ES}^2}{m_{T,\text{beam}}^2}} \exp(\xi(1 - \frac{m_{ES}^2}{m_{T,\text{beam}}^2}))$, with a kinematic cut-off at $E_{\text{beam}} = 5.289$ GeV and one free parameter $\xi$. The signal $\Delta E$ distribution is modeled by the sum of a Gaussian core with an asymmetric power-low tail [11] and a second order polynomial. The parameters of these PDFs are determined by fitting to a signal Monte Carlo sample. The peak position of the $\Delta E$ distribution is a free parameter of the full CP likelihood fit to allow for EMC energy scale uncertainties.

The kinematic variables $m_{ES}$ and $\Delta E$ are correlated in the $B^0 \to J/\psi K^0_S (\pi^0 \pi^0)$ and inclusive $J/\psi$ backgrounds, so two-dimensional PDFs are employed for these modes. Variably-binned interpolated two-dimensional histograms of these variables are constructed from the relevant Monte Carlo samples.

The $m_{ES}$ PDFs for the $B\bar{B}$ generic and continuum backgrounds are modeled by the threshold function given above, and the $\Delta E$ PDFs for these two backgrounds are modeled by second order polynomials. The parameters for these PDFs are obtained from the $B\bar{B}$ generic Monte Carlo sample and the $J/\psi_{\text{fake}}$ sample.

The PDFs used to describe the $\Delta t$ distributions of the signal and background sources are each a convolution of a resolution function $\mathcal{R}$ and decay time distribution $D$: $\mathcal{P}(\Delta t, \sigma_{\Delta t}) = \mathcal{R}(\Delta t, \sigma_{\Delta t}) \otimes D(\Delta t_{\text{true}})$, where $\Delta t$ and $\Delta t_{\text{true}}$ are the measured and true decay time differences, $\Delta t = \Delta t - \Delta t_{\text{true}}$, and $\sigma_{\Delta t}$ is the estimated event-by-event error on $\Delta t$.

For the signal, the resolution function consists of the sum of three Gaussian distributions, the parameters of which are determined from the $B_{\text{data}}$ sample, as in the $B^0 \to J/\psi K^0_S$ measurement [9]. The decay time distribution is given by Eq. 1 modified for the effects of $B$-flavor tagging:

$$\mathcal{P}_{a,f}^{\pm}(\Delta t) = \frac{e^{-|\Delta t| \tau_{\Delta t}}}{4\tau_{B}^{\pm}} \left\{ (1 \mp \Delta w_{a}) \right. + \left. \pm S_f (1 - 2w_{a}) \sin(\Delta m_{d} \Delta t) \mp C_f (1 - 2w_{a}) \cos(\Delta m_{d} \Delta t) \right\},$$

where $\mathcal{P}_{a,f}^{+}(\Delta t)$ is for a $B^0 (B_{\text{data}})$ tagging meson. The variable $w_{a}$ is the average probability of incorrectly tagging a $B^0$ as a $B^0$ ($w_{f}$) or a $B^{0*}$ as a $B^{0}$ ($w_{f}$), and $\Delta w_{a} = w_{a}^{m} - w_{a}^{p}$. Both $w_{a}$ and $\Delta w_{a}$ are determined using the $B_{\text{data}}$ data sample [3]. We use the values $\Delta m_{d} = 0.189$ ps$^{-1}$ and $\tau_{B} = 1.542$ ps [12].

The PDF used to model the $\Delta t$ distribution for the $B^0 \to J/\psi K^0_S (\pi^0 \pi^0)$ background, which also includes a CP asymmetry, takes the same form as that for signal, but with $S_{J/\psi K^0_S} = \sin2\beta = 0.74$ [3] and $C_{J/\psi K^0_S} = 0$.

The parameterizations of the $\Delta t$ PDFs for the inclu-
Table 1: Results of the CP likelihood fit, for the full region $-0.4 < \Delta E < 0.4$ GeV and $m_{ES} > 5.27$ GeV/c^2. Errors are statistical only. The global correlation coefficient is 0.14 for $C_{J/\psi \pi^0}$ and 0.15 for $S_{J/\psi \pi^0}$.

| Fit results                                           | $C_{J/\psi \pi^0}$ | $S_{J/\psi \pi^0}$ |
|-------------------------------------------------------|---------------------|---------------------|
| $C_{J/\psi \pi^0}$                                   | $0.38 \pm 0.41$     | $0.05 \pm 0.49$     |
| Signal \Delta E peak position (MeV)                  | $-13.2 \pm 7.2$     |                     |
| $B^0 \rightarrow J/\psi \pi^0$ signal (events)      | $40 \pm 7$          |                     |
| $B^0 \rightarrow J/\psi K_S^0 (\pi^0 \pi^0)$ background (events) | $140 \pm 19$       |                     |
| Inclusive $J/\psi$ background (events)               | $109 \pm 35$        |                     |
| $B \bar{B}$ generic background (events)              | $52 \pm 25$         |                     |
| Continuum background (events)                        | $97 \pm 22$         |                     |

The $\Delta t$ PDF for the continuum background has only a prompt component and the resolution parameter values are obtained by fitting the $J/\psi_{fake}$ sample.

The results of the CP asymmetry fit, for all free parameters, are shown in Table II. There are $40 \pm 7$ signal events in the total sample of 438 selected events. The projection in $m_{ES}$ is shown in Fig. 1. The yields and asymmetry as functions of $\Delta t$, overlaid with projections of the likelihood fit results, are shown in Fig. 2. Repeating the fit with the added constraint $C_{J/\psi \pi^0} = 0$ does not significantly change the result for $S_{J/\psi \pi^0}$.

The dominant contributions to the systematic errors in $C_{J/\psi \pi^0}$ and $S_{J/\psi \pi^0}$ are summarized in Table III. The first class of uncertainties are those obtained by variation of the parameters used in the $m_{ES}$, $\Delta E$, and $\Delta t$ PDFs, where the dominant sources are the uncertainties in the signal $\Delta E$ PDF parameters. A systematic error to account for a correlation between the tails of the signal $m_{ES}$ and $\Delta E$ distributions is obtained by using a two-dimensional PDF. Another contribution stems from the impact of EMC energy scale uncertainties on the modeling of the $B^0 \rightarrow J/\psi K_S^0 (\pi^0 \pi^0)$ background. An additional systematic uncertainty comes from the choice of the binning of the two-dimensional PDFs for the $B^0 \rightarrow J/\psi K_S^0 (\pi^0 \pi^0)$ and inclusive $J/\psi$ backgrounds.

In summary, an unbinned extended maximum likelihood fit yields $40 \pm 7$ signal events and the parameters of time-dependent CP asymmetry for the decay $B^0 \rightarrow J/\psi \pi^0$: $C_{J/\psi \pi^0} = 0.38 \pm 0.41$ (stat) $\pm 0.09$ (syst) and $S_{J/\psi \pi^0} = 0.05 \pm 0.49$ (stat) $\pm 0.16$ (syst). Within the Standard Model formulation of CP asymmetries, these results demonstrate the possibility, with additional integrated luminosity, of observing penguin contributions in

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**FIG. 1:** Projection in $m_{ES}$ for the results of the CP fit, displayed with the added requirement $-0.11 < \Delta E < 0.11$ GeV. In contrast, the CP fit uses the full $\Delta E$ region. In the further restricted region $m_{ES} > 5.27$ GeV/c^2, there are 49 data events (points), of which about 12 events are fit as background. Here, $B^0 \rightarrow J/\psi K_S^0 (\pi^0 \pi^0)$ and inclusive $J/\psi$ decays contribute to the enhancement in the background distribution at large $m_{ES}$.

**FIG. 2:** Distributions of events a) with a $B^0$ tag ($N_{B^0}$), b) with a $\bar{B}^0$ tag ($N_{\bar{B}^0}$), and c) the raw asymmetry ($N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, as functions of $\Delta t$. Candidates in these plots are required to satisfy $-0.11 < \Delta E < 0.11$ GeV and $m_{ES} > 5.27$ GeV/c^2. Of the 49 signal and background events in this region, 25 have a $B^0$ tag and 24 have a $\bar{B}^0$ tag, with fit background contributions of approximately 5 and 7 events, respectively. The curves are projections that use the values of the other variables in the likelihood to determine the contributions to the signal and backgrounds.
TABLE III: Summary of systematic uncertainties.

| Source | \( C_{J/\psi \pi^0} \) | \( S_{J/\psi \pi^0} \) |
|--------|----------------|----------------|
| Parameter variations | | |
| \( m_{Z\ell} \) and \( \Delta E \) parameters | 0.05 | 0.13 |
| Tagging fractions | 0.00 | 0.01 |
| \( \Delta t \) parameters | 0.03 | 0.02 |
| Additional systematics | | |
| \( \Delta E-m_{Z\ell} \) correlation in signal | 0.07 | 0.08 |
| EMC energy scale \( B^0 \to J/\psi K^0_S(\pi^0 \pi^0) \) | 0.01 | 0.00 |
| Choice of two-D histogram PDFs | 0.01 | 0.03 |
| Beam spot, boost/vtx., misalignment | 0.01 | 0.01 |
| Total systematic uncertainty | 0.09 | 0.16 |

\( B^0 \to J/\psi \pi^0 \). Such a measurement may experimentally constrain similar amplitudes in \( B^0 \to J/\psi K^0_S \).

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sive \(J/\psi\) and \(B \bar{B}\) generic backgrounds each consist of prompt and exponential decay components. Decays appear to be prompt when particles from the reconstructed \(B\) are erroneously included in the tagging \(B\) vertex. For the \(B \bar{B}\) generic background, the prompt and exponential components correspond to the cases where the two decay products forming the \(J/\psi\) come from both or just one of the \(B\) mesons, respectively. The fraction that is in the exponential component, the decay lifetime parameter, and the resolution parameters are determined from the Monte Carlo simulation.

The \(\Delta t\) PDF for the continuum background has only a prompt component and the resolution parameter values are obtained by fitting the \(J/\psi\) fake sample.

The results of the \(CP\) asymmetry fit, for all free parameters, are shown in Table II. There are 40 \(\pm\) 7 signal events in the total sample of 438 selected events. The projection in \(m_{ES}\) is shown in Fig. 1. The yields and asymmetry as functions of \(\Delta t\), overlaid with projections of the likelihood fit results, are shown in Fig. 2. Repeating the fit with the added constraint \(C_{J/\psi \pi^0} = 0\) does not significantly change the result for \(S_{J/\psi \pi^0}\).

The dominant contributions to the systematic errors in \(C_{J/\psi \pi^0}\) and \(S_{J/\psi \pi^0}\) are summarized in Table III. The first class of uncertainties are those obtained by variation of the parameters used in the \(m_{ES}\), \(\Delta E\), and \(\Delta t\) PDFs, where the dominant sources are the uncertainties in the signal \(\Delta E\) PDF parameters. A systematic error to account for a correlation between the tails of the signal \(m_{ES}\) and \(\Delta E\) distributions is obtained by using a two-dimensional PDF. Another contribution stems from the impact of EMC energy scale uncertainties on the modeling of the \(B^0 \rightarrow J/\psi K_{S}^{0}(\pi^0 \pi^0)\) background. An additional systematic uncertainty comes from the choice of the binning of the two-dimensional PDFs for the \(B^0 \rightarrow J/\psi K_{S}^{0}(\pi^0 \pi^0)\) and inclusive \(J/\psi\) backgrounds.

In summary, an unbinned extended maximum likelihood fit yields 40 \(\pm\) 7 signal events and the parameters of time-dependent \(CP\) asymmetry for the decay \(B^0 \rightarrow J/\psi \pi^0\): \(C_{J/\psi \pi^0} = 0.38 \pm 0.41\) (stat) \(\pm 0.09\) (syst) and \(S_{J/\psi \pi^0} = 0.05 \pm 0.49\) (stat) \(\pm 0.16\) (syst). Within the

Standard Model formulation of \(CP\) asymmetries, these results demonstrate the possibility, with additional integrated luminosity, of observing penguin contributions in
Entries / 0.6 ps

Raw Asymmetry

Entries / 1 ps

Raw Asymmetry

\( \Delta t (\text{ps}) \)
d) $B^0 \rightarrow K^+ K^- K^0_S$

$0.0 < r \leq 0.5$

$0.5 < r \leq 1.0$
\[(\text{OF-SF})/(\text{OF+SF})\]

- $0 < r \leq 0.25$
- $0.25 < r \leq 0.5$
- $0.5 < r \leq 0.625$
- $0.625 < r \leq 0.75$
- $0.75 < r \leq 0.875$
- $0.875 < r \leq 1$

\[|\Delta t| (\text{ps})\]
Beam Constrained Mass (GeV/c²)

- Sum
- $J/\psi K_S (\pi^+ \pi^-)$
- $J/\psi K_S (\pi^0 \pi^0)$
- $\psi(2S) K_S$
- $\chi_{c1} K_S$
- $\eta_c K_S$
- $J/\psi K^* (K_S \pi^0)$