Evidence for Direct CP Violation in $B^0 \rightarrow K^+\pi^-$ Decays

Y. Chao,29 P. Chang,29 K. Abe,10 K. Abe,46 N. Abe,49 I. Adachi,10 H. Aihara,48 K. Akai,10 M. Akatsu,24 M. Akemoto,10 Y. Asano,53 T. Aso,52 V. Aulchenko,2 T. Ausuhev,14 T. Aziz,44 S. Bahinipati,6 A. M. Bakich,43 Y. Ban,36 M. Barbero,9 A. Bay,20 I. Bedny,2 U. Bitenc,15 I. Bizjak,15 S. Blyth,29 A. Bondar,2 A. Bozek,30 M. Bračko,22,15 J. Brodzicka,30 T. E. Browder,9 M.-C. Chang,29 A. Chen,26 K.-F. Chen,29 W. T. Chen,26 B. G. Cheon,4 R. Chistov,14 S.-K. Choi,8 Y. Choi,42 Y. K. Choi,42 A. Chuvikov,37 S. Cole,43 M. Danilov,14 M. Dash,55 L. Y. Dong,12 R. Dowd,23 J. Dragic,23 A. Drutskoy,6 S. Eidelman,2 V. Eiges,14 Y. Enari,24 D. Epifanov,2 C. W. Everton,23 F. Fang,9 J. Flanagan,10 S. Fratina,15 H. Fujii,10 Y. Funakoshi,10 K. Furukawa,10 N. Gabyshev,2 A. Garmash,27 T. Gershon,10 A. Go,26 G. Gokhroo,44 B. Golob,21,15 M. Grosse Perdekamp,38 H. Guler,9 R. Guo,27 J. Haba,10 C. Hagner,55 F. Handa,47 K. Haro,34 T. Hara,34 N. C. Hastings,10 K. Hasuko,38 K. Hayasaka,24 H. Hayashii,29 M. Hazumi,10 E. M. Heenan,23 I. Higuchi,47 T. Higuchi,10 L. Hinz,20 T. Hojo,34 T. Hokume,24 Y. Hoshi,46 K. Hoshina,51 S. Hou,26 W.-S. Hou,29 Y. B. Hsiung,24 H.-C. Huang,29 T. Igaki,24 Y. Igarashi,10 T. Iijima,24 H. Ikeda,10 A. Imoto,25 K. Inami,24 A. Ishikawa,10 H. Ishino,49 K. Itoh,48 R. Itoh,10 M. Iwamoto,3 M. Iwasaki,48 Y. Iwasaki,10 R. Kagan,14 H. Kakuno,48 T. Kamitani,10 J. H. Kang,56 J. S. Kang,17 P. Kapusta,30 S. U. Kataoka,25 N. Katayama,10 H. Kawai,3 H. Kawai,48 Y. Kawakami,24 N. Kawamura,1 T. Kawasak,32 N. Kent,9 H. R. Khan,49 A. Kibayashi,49 H. Kichimi,10 M. Kikuchi,10 E. Kikutani,10 H. J. Kim,19 H. O. Kim,42 Hyunwoo Kim,17 J. H. Kim,42 S. K. Kim,41 T. H. Kim,56 K. Kinoshita,6 S. Kobayashi,39 H. Koiso,10 P. Koppenburg,10 S. Korpar,22,15 P. Križan,21,15 P. Krokovný,2 T. Kubo,10 R. Kulasiri,6 S. Kumar,35 C. C. Kuo,26 H. Kurashiro,49 E. Kurihara,3 A. Kusaka,48 A. Kuzmin,2 Y.-J. Kwon,56 J. S. Lange,7 G. Leder,13 S. E. Lee,13 S. H. Lee,41 Y.-J. Lee,29 T. Lesiak,30 J. Li,40 A. Limosani,23 S.-W. Lin,29 D. Liventsev,14 J. MacNaughton,13 G. Majumder,44 F. Mandl,13 D. Marlow,37 M. Masuzawa,10 T. Matsushita,24 H. Matsumoto,32 S. Matsumoto,5 T. Matsumoto,50 A. Matyja,30 S. Michizono,10 Y. Mikami,47 T. Mimashita,10 W. Mitaroff,13 K. Miyabayashi,25 Y. Miyabayashi,24 H. Miyake,34 H. Miyata,32 R. Mizuk,14 D. Mohapatra,55 R. G. Moloney,23 G. F. Moorhead,23 T. Mori,49 J. Mueller,10 A. Murakami,39 T. Nagamine,47 Y. Nagasaka,11 T. Nakadaira,48 I. Nakamura,10 T. T. Nakamura,10 E. Nakano,33 M. Nakao,10 H. Nakayama,10 H. Nakazawa,10 Z. Natkaniec,30 K. Nechi,46 S. Nishida,10 O. Nitoh,51 S. Noguchi,25 T. Nozaki,10 A. Ogawa,38 S. Ogawa,45 Y. Ogawa,10 K. Ohmi,10 Y. Ohnishi,10 T. Ohshima,24 N. Ohuchi,10 K. Oide,10 T. Okabe,24 S. Okuno,16 S. L. Olsen,9 Y. Onuki,32 W. Ostrowicz,30 H. Ozaki,10 P. Pakhlov,14 H. Palka,30 C. W. Park,42 H. Park,19 K. S. Park,42 N. Parslov,43 L. S. Peak,43 M. Perlicka,13 J.-P. Perrard,20 M. Peters,9 L. E. Piilonen,55 A. Poeluekov,2 F. J. Ronga,10 N. Root,2 M. Rozanska,30 H. Sagawa,10 M. Saigo,47 S. Saitoh,10 Y. Sakai,10 H. Sakamoto,18 H. Sakaue,33 T. R. Sarangi,10 M. Satapathy,54 N. Sato,24 T. Schietinger,20 O. Schneider,20 J. Schümann,29 C. Schwanda,13 A. J. Schwartz,6 T. Seki,50 S. Semenov,14 K. Senyo,24 Y. Settai,5 R. Seuster,9 M. E. Sevior,23 T. Shibata,32 H. Shibuya,45 T. Shidara,10 B. Shwhartz,2 V. Sidorov,2 V. Siegle,28 J. B. Singh,35 A. Somov,6 N. Soni,35 R. Stamen,10 S. Stanić,53 M. Starić,15 R. Sugahara,10 A. Sugi,24 T. Sugimura,10 A. Sugiyama,9 K. Sumisawa,34 T. Sumiyoshi,50 S. Suzuki,39 S. Y. Suzuki,10
S. K. Swain,9 O. Tajima,10 F. Takasaki,10 K. Tamai,10 N. Tamura,32 K. Tanabe,48 M. Tanaka,10 M. Tawada,10 G. N. Taylor,23 Y. Teramoto,33 X. C. Tian,36 S. Tokuda,24 S. N. Tovey,23 K. Trabelsi,9 T. Tsuboyama,10 T. Tsukamoto,10 K. Uchida,9 S. Uehara,10 T. Uglov,14 K. Ueno,29 Y. Unno,3 S. Uno,10 Y. Ushiroda,10 G. Varner,9 K. E. Varvell,43 S. Villa,20 C. C. Wang,29 C. H. Wang,28 J. G. Wang,55 M.-Z. Wang,29 M. Watanabe,32 Y. Watanabe,49 L. Widhalm,13 Q. L. Xie,12 B. D. Yabsley,55 A. Yamaguchi,47 H. Yamamoto,47 N. Yamamoto,10 S. Yamamoto,50 T. Yamanaka,34 Y. Yamashita,31 M. Yamauchi,10 Heyoung Yang,41 P. Yeh,29 J. Ying,36 K. Yoshida,24 M. Yoshida,10 Y. Yuan,12 Y. Yusa,47 H. Yuta,1 S. L. Zang,12 C. C. Zhang,12 J. Zhang,10 L. M. Zhang,40 Z. P. Zhang,40 Y. Zheng,9 V. Zhilich,2 T. Ziegler,37 D. Žontar,21,15 and D. Zürcher20

(The Belle Collaboration)

1 Aomori University, Aomori
2 Budker Institute of Nuclear Physics, Novosibirsk
3 Chiba University, Chiba
4 Chonnam National University, Kwangju
5 Chuo University, Tokyo
6 University of Cincinnati, Cincinnati, Ohio 45221
7 University of Frankfurt, Frankfurt
8 Gyeongsang National University, Chinju
9 University of Hawaii, Honolulu, Hawaii 96822
10 High Energy Accelerator Research Organization (KEK), Tsukuba
11 Hiroshima Institute of Technology, Hiroshima
12 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
13 Institute of High Energy Physics, Vienna
14 Institute for Theoretical and Experimental Physics, Moscow
15 J. Stefan Institute, Ljubljana
16 Kanagawa University, Yokohama
17 Korea University, Seoul
18 Kyoto University, Kyoto
19 Kyungpook National University, Taegu
20 Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne
21 University of Ljubljana, Ljubljana
22 University of Maribor, Maribor
23 University of Melbourne, Victoria
24 Nagoya University, Nagoya
25 Nara Women’s University, Nara
26 National Central University, Chung-li
27 National Kaohsiung Normal University, Kaohsiung
28 National United University, Miaoli
29 Department of Physics, National Taiwan University, Taipei
30 H. Niewodniczanski Institute of Nuclear Physics, Krakow
31 Nihon Dental College, Niigata
32 Niigata University, Niigata
33 Osaka City University, Osaka
34 Osaka University, Osaka
Abstract

We report evidence for direct CP violation in the decay $B^0 \rightarrow K^+\pi^-$ with 253 fb$^{-1}$ of data collected with the Belle detector at the KEKB $e^+e^-$ collider. Using 275 million $B\bar{B}$ pairs we observe a $B \rightarrow K^\pm\pi^\mp$ signal with $2140 \pm 53$ events. The measured CP violating asymmetry is $A_{CP}(K^+\pi^-) = -0.101 \pm 0.025\text{(stat)} \pm 0.005\text{(syst)}$, corresponding to a significance of 3.9$\sigma$ including systematics. We also search for CP violation in the decays $B^+ \rightarrow K^+\pi^0$ and $B^+ \rightarrow \pi^+\pi^0$. The measured CP violating asymmetries are $A_{CP}(K^+\pi^0) = 0.04 \pm 0.05\text{(stat)} \pm 0.02\text{(syst)}$ and $A_{CP}(\pi^+\pi^0) = -0.02 \pm 0.10\text{(stat)} \pm 0.01\text{(syst)}$, corresponding to the intervals $-0.05 < A_{CP}(K^+\pi^0) < 0.13$ and $-0.18 < A_{CP}(\pi^+\pi^0) < 0.14$ at 90% confidence level.

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In the Standard Model (SM), $CP$ violation arises via the interference of at least two diagrams with comparable amplitudes but different $CP$ conserving and violating phases. Mixing induced $CP$ violation in the $B$ sector has been established in $b \to c\bar{s}s$ transitions \cite{2,3}. In the SM, direct $CP$ violation is also expected to be sizable in the $B$ meson system \cite{3}. The first experimental evidence for direct $CP$ violation in $B$ mesons was shown by Belle for the decay mode $B^0 \to \pi^+\pi^-$ \cite{4}. This result suggests large interference between tree and penguin diagrams and the existence of final state interactions \cite{5}. Recently, both Belle \cite{6} and BaBar \cite{7} have reported searches for direct $CP$ violation in another decay mode $B^0 \to K^+\pi^-$, where direct $CP$ violation is also expected.

The $CP$ violating partial rate asymmetry is measured as:

$$A_{CP} = \frac{N(B \to f) - N(B \to \bar{f})}{N(B \to f) + N(B \to \bar{f})},$$  

where $N(B \to f)$ is the yield for the $B \to K\pi/\pi\pi$ decay and $N(B \to f)$ denotes that of the charge-conjugate mode. Theoretical predictions with different approaches suggest that $A_{CP}(K^+\pi^-)$ could be either positive or negative \cite{8}. Although there are large uncertainties related to hadronic effects in the theoretical predictions, results for $A_{CP}(K^+\pi^-)$ and $A_{CP}(K^+\pi^0)$ are expected to have the same sign and be comparable in magnitude \cite{8}. In this Letter, we report $A_{CP}$ measurements for $B^0 \to K^+\pi^-, B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ using 275 million $B\bar{B}$ pairs collected with the Belle detector at the KEKB $e^+e^-$ asymmetric-energy (3.5 on 8 GeV) collider \cite{9} operating at the $\Upsilon(4S)$ resonance.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K$ mesons and tracks with $R_{K/\pi}$ likelihood, where $R_{K/\pi}$ is the likelihood of kaon (pion). Charged tracks with $R_{K/\pi} > 0.6$ are regarded as kaons and tracks with $R_{K/\pi} < 0.4$ as pions. Furthermore, charged tracks that are positively identified as electrons are rejected. The electron identification uses the information composed of $E/p$ and $dE/dx$, shower shape, track matching $\chi^2$, and ACC light yields. The $K/\pi$ identification efficiencies and misidentification rates are determined from a sample of kinematically identified $D^{\ast+} \to D^0\pi^+, D^0 \to K^-\pi^+$ decays, where the kaon and pion from the $D$ decay are selected in the same kinematic region as in the $B^0 \to K^+\pi^-$ decay. The $CP$ violation in the $B^0 \to K^+\pi^-$ decay is found to be 1.0% greater than that for $K^+\pi^-$; this small difference is corrected for in the $A_{CP}$ measurement.

Candidate $\pi^0$ mesons are reconstructed by combining two photons with invariant mass between 115 MeV/$c^2$ and 152 MeV/$c^2$, which corresponds to $\pm 2.5$ standard deviations around
The signal yields are extracted by applying unbinned two dimensional maximum likelihood (ML) fits to the \((M_{bc} \text{ and } \Delta E)\) distributions of the \(B\) and \(\bar{B}\) samples. The likelihood

| Set I | Set II |
|-------|--------|
| Eff. (%) | Fake rate (%) | Eff. (%) | Fake rate (%) |
| \(K^+\) | 83.74 ± 0.18 | 5.10 ± 0.12 | 82.41 ± 0.20 | 6.57 ± 0.15 |
| \(K^-\) | 84.73 ± 0.18 | 5.69 ± 0.12 | 83.26 ± 0.20 | 7.14 ± 0.15 |
| \(\pi^+\) | 91.25 ± 0.15 | 10.74 ± 0.15 | 89.48 ± 0.18 | 11.82 ± 0.17 |
| \(\pi^-\) | 90.54 ± 0.16 | 10.09 ± 0.15 | 88.56 ± 0.19 | 11.57 ± 0.17 |

The dominant background is from \(e^+e^- \rightarrow q\bar{q}\) \((q = u, d, s, c)\) continuum events. To distinguish the signal from the jet-like continuum background, event topology variables and \(B\) flavor tagging information are employed. We combine a set of modified Fox-Wolfram moments into a Fisher discriminant. The probability density function (PDF) for this discriminant, and that for the cosine of the angle between the \(B\) flight direction and the \(z\) axis, are obtained using signal and continuum Monte Carlo (MC) events. The likelihood is provided by \(B\) flavor tagging. The standard Belle flavor tagging algorithm gives two outputs: a discrete variable indicating the flavor of the tagging \(B\) and a MC-determined dilution factor \(r\), which ranges from zero for no flavor information to unity for unambiguous flavor assignment. An event with a high value of \(r\) (typically containing a high-momentum lepton) is more likely to be a \(B\bar{B}\) event so a looser \(\mathcal{R}\) requirement can be applied. We divide the data into \(r > 0.5\) and \(r < 0.5\) regions. The continuum background is reduced by applying a selection requirement on \(\mathcal{R}\) for events in each \(r\) region of Set I and Set II according to the figure of merit defined as \(N_s^{\exp}/\sqrt{N_s^{\exp} + N_{q\bar{q}}^{\exp}}\), where \(N_s^{\exp}\) denotes the expected signal yields based on MC simulation and our previous branching fraction measurements and \(N_{q\bar{q}}^{\exp}\) denotes the expected \(q\bar{q}\) yields from sideband data \((M_{bc} < 5.26 \text{ GeV}/c^2)\). A typical requirement suppresses 92–99% of the continuum background while retaining 48–67% of the signal.

Backgrounds from \(\Upsilon(4S) \rightarrow B\bar{B}\) events are investigated using a large MC sample. After the \(\mathcal{R}\) requirement, we find a small charmless three-body background at low \(\Delta E\), and reflections from \(B^0 \rightarrow \pi^+\pi^-\) decays due to \(K\pi\) misidentification.

The signal yields are extracted by applying unbinned two dimensional maximum likelihood (ML) fits to the \((M_{bc} \text{ and } \Delta E)\) distributions of the \(B\) and \(\bar{B}\) samples. The likelihood
for each mode is defined as

\[ \mathcal{L} = \exp \left( - \sum_{s,k,j} N_{s,k,j} \right) \times \prod_i \left( \sum_{s,k,j} N_{s,k,j} P_{s,k,j,i} \right) \] (2)

\[ P_{s,k,j,i} = \frac{1}{2} \left[ 1 - q_i A_{CP,j} \right] P_{s,k,j}(M_{bc,i}, \Delta E_i), \] (3)

where \( s \) indicates Set I or Set II, \( k \) distinguishes events in the \( r < 0.5 \) or \( r > 0.5 \) regions, \( i \) is the identifier of the \( i \)-th event, \( P(M_{bc}, \Delta E) \) is the two-dimensional PDF of \( M_{bc} \) and \( \Delta E \), \( q \) indicates the \( B \) meson flavor, \( B(q = +1) \) or \( \overline{B}(q = -1) \), \( N_j \) is the number of events for the category \( j \), which corresponds to either signal, \( \bar{q} \bar{q} \) continuum, a reflection due to \( K^- \pi^+ \) misidentification, or background from other charmless three-body \( B \) decays.

The situation is more complicated for the \( B \) modes. Since the \( K^+ \pi^- \) and \( \pi^+ \pi^- \) reflections are difficult to distinguish with \( \Delta E \) and \( M_{bc} \), we fit these two modes simultaneously with a fixed reflection-to-signal ratio based on the measured \( K^- \pi^+ \) identification efficiencies and fake rates. All the signal PDFs \( P(M_{bc}, \Delta E) \) are obtained using MC simulations based on the Set I and Set II detector configurations. The same signal PDFs are used for events in the two different \( r \) regions. No strong correlations between \( M_{bc} \) and \( \Delta E \) are found for the \( B \to K^+\pi^- \) signal. Therefore, its PDF is modeled by a product of a single Gaussian for \( M_{bc} \) and a double Gaussian for \( \Delta E \). For the modes with neutral pions in the final state, there are correlations between \( M_{bc} \) and \( \Delta E \) in the tails of the signals; hence, their PDFs are described by smoothed two-dimensional histograms. Discrepancies between the signal peak positions in data and MC are calibrated using \( B^+ \to \pi^- \pi^+ \) decays, where the \( \pi^- \pi^+ \) sub-decay is used for the modes with a \( \pi^0 \) meson while \( \pi^- \pi^+ \) is used for the \( K^+\pi^- \) mode. The MC-predicted \( \Delta E \) resolutions are verified using the invariant mass distributions of high momentum \( D \) mesons. The decay mode \( \pi^- \pi^+ \) is used for \( B^0 \to K^+\pi^- \), and \( \pi^- \pi^+ \) for the modes with a \( \pi^0 \) in the final state. The parameters that describe the shapes of the PDFs are fixed in all of the fits.

The continuum background in \( \Delta E \) is described by a first or second order polynomial while the \( M_{bc} \) distribution is parameterized by an ARGUS function \( f(x) = x \sqrt{1 - x^2} \exp \left[ -\xi(1 - x^2) \right] \), where \( x \) is \( M_{bc} \) divided by half of the total center of mass energy \([15]\). The continuum PDF is the product of an Argus function and a polynomial, where \( \xi \) and the coefficients of the polynomial are free parameters. These free parameters are \( r \)-dependent. A large MC sample is used to investigate the background from charmless \( B \) decays and a smoothed two-dimensional histogram is taken as the PDF. The functional forms of the PDFs are the same for the \( B \) and \( \overline{B} \) samples.

The efficiency of particle identification is slightly different for positively and negatively charged particles; consequently the raw number of asymmetry in Eq. 3 no longer gives \( A_{CP} \) correctly and must be corrected. For the \( K^+\pi^- \) and \( \pi^+\pi^- \) modes, this raw asymmetry can be expressed as:

\[ A_{CP}^{raw} = \frac{A_{\pi^\pm} + A_{CP}}{1 + A_{\pi^\pm} A_{CP}}, \] (4)

where \( A_{CP} \) is the true partial rate asymmetry and the efficiency asymmetry \( A_{\pi^\pm} \) is the efficiency difference between \( K^-\pi^+ \) and \( K^+\pi^- \) divided by the sum of their efficiencies. The situation is more complicated for the \( K^+\pi^- \) mode because, in addition to the bias due to the efficiency difference between \( K^-\pi^+ \) and \( K^+\pi^- \), a \( K^-\pi^+ \) signal event can be
FIG. 1: $M_{bc}$ (top) and $\Delta E$ (bottom) distributions for $B^0 \to K^- \pi^+$ (left) and $B^0 \to K^+ \pi^-$ (right) candidates. The histograms represent the data, while the curves represent the various components from the fit: signal (dashed), continuum (dotted), three-body $B$ decays (dash-dotted), background from mis-identification (hatched), and sum of all components (solid).

misidentified as a $K^+ \pi^-$ candidate and dilute $A_{CP}$. The efficiency asymmetry results in an $A_{CP}$ bias of $+0.01$ while the small dilution factor due to double misidentification reduces $A_{CP}$ by a factor of $0.99$. These effects are included in the raw asymmetry correction and their errors are included in the systematic uncertainty.

Table II gives the signal yields and $A_{CP}$ values for each mode. The asymmetries for the background components are consistent with zero within errors. Projections of the fits are shown in Figs. 1-3. The systematic errors from fitting are estimated from the deviations in $A_{CP}$ after varying each parameter of the signal PDFs by one standard deviation. The uncertainty in modeling the three-body background is studied by excluding the low $\Delta E$ region ($< -0.12$ GeV) and repeating the fit. Systematic uncertainties due to particle identification are estimated by checking the fit after varying the $K/\pi$ efficiencies and fake rates by one standard deviation. At each step, the deviation in $A_{CP}$ is added in quadrature to provide the systematic errors, which are less than 0.01 for all modes. A possible bias from the fitting procedure is checked in MC and a bias due to the $R$ cut is investigated using the $B^+ \to D^0 \pi^+$ samples. No significant bias is observed. The systematic uncertainties due to the detector bias are obtained using the fit results for the continuum background listed in Table II. The final systematic errors are then obtained by quadratically summing the errors due to the detector bias and the fitting systematics.

The partial rate asymmetry $A_{CP}(K^+ \pi^-)$ is found to be $-0.101 \pm 0.025 \pm 0.005$, which is $3.9\sigma$ from zero. The significance calculation includes the effects of systematic uncertainties. Our result is consistent with the value reported by BaBar, $A_{CP}(K^+ \pi^-) = -0.133 \pm 0.030 \pm 0.009$ [7]. The combined experimental result has a significance greater than $5\sigma$, indicating that direct $CP$ violation in the $B$ meson system is established. Our
FIG. 2: \( M_{bc} \) (top) and \( \Delta E \) (bottom) distributions for \( B^- \to K^-\pi^0 \) (left) and \( B^+ \to K^+\pi^0 \) (right) candidates. The curves are described in the caption of Fig. I.

TABLE II: Fitted signal yields, \( A_{CP} \) results and background asymmetries for individual modes.

| Mode     | Signal Yield | \( A_{CP} \)          | Bkg \( A_{CP} \) |
|----------|--------------|------------------------|-------------------|
| \( K^+\pi^0 \) | 2140 ± 53    | -0.101 ± 0.025 ± 0.005 | -0.001 ± 0.005   |
| \( K^0\pi^0 \)  | 728 ± 34     | 0.04 ± 0.05 ± 0.02     | -0.02 ± 0.01     |
| \( \pi^0\pi^0 \) | 315 ± 29     | -0.02 ± 0.10 ± 0.01    | -0.01 ± 0.01     |

measurement of \( A_{CP}(K^+\pi^0) \) is consistent with no asymmetry; the central value is 2.4\( \sigma \) away from \( A_{CP}(K^+\pi^-) \). If this result is confirmed with higher statistics, the difference may be due to the contribution of the electroweak penguin diagram or other mechanisms [16].

No evidence of direct \( CP \) violation is observed in the decay \( B^+ \to \pi^+\pi^0 \). We set 90\% C.L. intervals \(-0.05 < A_{CP}(K^+\pi^0) < 0.13 \) and \(-0.18 < A_{CP}(\pi^+\pi^0) < 0.14 \).

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* on leave from Nova Gorica Polytechnic, Nova Gorica
FIG. 3: $M_{bc}$ (top) and $\Delta E$ (bottom) distributions for $B^- \rightarrow \pi^-\pi^0$ (left) and $B^+ \rightarrow \pi^+\pi^0$ (right) candidates. The curves are described in the caption of Fig. 1.