Measurement of the $B^0 \rightarrow \phi K^{*0}$ Decay Amplitudes

B. Aubert, R. Barate, D. Boutigny, F. Coudere, J.-M. Gaillard, A. Hicheur, Y. Karyotakis, J. P. Lees, V. Tisserand, A. Zghiche, A. Palano, A. Pomplii, J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu, G. Eigen, I. Ofte, B. Stugu, G. S. Abrams, A. W. Borgland, A. B. Breaun, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, C. T. Day, M. S. Gill, A. V. Gritsan, Y. Groyssman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, V. G. Shkelov, W. A. Wenzel, M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson, M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, M. Steinke, J. T. Boyd, N. Chevalier, W. N. Cottingham, M. P. Kelly, T. E. Latham, F. F. Wilson, T. Cuhadar-Donszelmann, N. S. Knecht, T. S. Mattison, J. A. McKenna, D. Thiessen, A. Khan, P. Kyberd, L. Teodorescu, A. E. Blinov, V. E. Blinov, V. P. Druzhinin, V. B. Golubev, V. N. Ivanchenko, E. A. Kravchenko, A. P. Omuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov, M. Bruniisma, M. Chao, I. Eschrich, D. Kirkby, A. J. Lankford, M. Mandelkern, R. K. Monnksen, W. Roethel, D. P. Stoker, C. Buchanan, B. L. Hartfel, S. D. Foulkes, J. W. Gary, B. C. Shen, K. Wang, D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, Sh. Rahatlou, V. Sharma, J. W. Berryhill, C. Campagnari, B. Dahmes, J. Long, A. Tu, M. A. Mazur, J. D. Richman, W. Verkerke, W. T. Beck, A. M. Eiser, C. H. Amsch, J. Kroseberg, W. S. Lockman, T. Nomski, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. W. Wilson, J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Piatenok, F. C. Porter, A. Ryd, A. Samuel, S. Yang, J. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff, T. Abe, F. Blanc, P. Bloom, S. Chen, W. T. Ford, U. Nauenberg, A. P. Rankin, J. G. Smith, J. Zhang, L. Zhang, A. Chen, J. L. Harton, A. Soffer, W. H. Toki, R. J. Wilson, Q. L. Zeng, D. Altenburg, T. Brandt, J. Brose, M. Dickop, E. Feltes, A. Hauke, H. M. Lacker, R. Müller-Pfefferkorn, R. Nogowski, S. Otto, A. Petzold, J. Schubert, K. R. Schubert, R. Schwierz, B. Spaan, J. E. Sundermann, D. Bernard, G. Bonneau, B. Brochard, P. Grenier, S. Schrenk, Ch. Thiebaux, G. Vasileiadis, M. Verderi, D. J. Bard, P. J. Clark, D. Lavin, F. Muheim, S. Playfer, Y. Xie, M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, L. Piemontese, A. Sarti, E. Treadwell, F. Anuli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi, M. Piccolo, A. Zallo, B. Buzzo, R. Capra, R. Contri, G. Crosetti, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi, S. Bailey, G. Brandenban, K. S. Chaisanguantham, M. Morii, E. Won, R. S. Dubitzky, U. Langenegger, W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, J. R. Gaillard, G. W. Morton, J. A. Nash, M. B. Nikolich, G. P. Taylor, J. M. Charles, G. J. Grenier, U. Mallik, J. Cochran, H. B. Crawley, J. Lambs, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, J. Yi, M. Biasini, R. Covarelli, M. Pioppi, M. Davier, X. Giroux, G. Grosdiedler, A. Höcker, S. Laplace, F. Le Diberder, V. Lepeltier, A. M. Lutz, T. C. Petersen, S. Plaszczynski, M. H. Schone, L. Tantot, G. Wormser, C. H. Cheng, D. J. Lange, M. C. Simani, D. M. Wright, A. J. Bevan, C. A. Chavez, J. P. Coleman, I. J. Förster, J. R. Fry, E. Gabathuler, R. Gamet, D. E. Hutchcroft, J. R. Parry, D. J. Payne, R. J. Sloane, C. Touramanis, J. J. Back, C. M. Cormack, P. F. Harrison, D. Fi Lodovico, G. B. Mohanty, C. L. Brown, G. Cowan, R. L. Flack, H. U. Flach, M. G. Green, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, M. A. Winter, D. Brown, C. L. Davis, J. Allison, N. R. Barlow, R. J. Barlow, P. A. Hart, M. C. Hodgkinson, G. D. Lafferty, A. J. Lyon, J. C. Williams, A. Farbin, W. D. Hulsbergen, A. Jawahery, D. Kovalskyi, C. K. Lae, V. Lillard, D. A. Roberts, G. Blaylock, C. Dallapiccola, K. T. Flood, S. S. Hertzbach, R. Kofler, V. B. Koptchek, T. B. Moore, S. Saremi, H. Staengle, S. Willocq, R. Cowan, G. Scicli, S. J. Sekula, F. Taylor, R. K. Yamamoto,
D. J. J. Mangeol, P. M. Patel, S. H. Robertson, A. Lazzaro, V. Lombardo, F. Palombo, J. M. Bauer, L. Cremaldi, V. Eschenhagen, R. Godang, R. Kroeger, J. Reidy, D. A. Sanders, D. J. Summers, H. W. Zhao, S. Brunet, D. Côté, P. Taras, H. Nicholson, N. Cavallo, F. Fabozzi, C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciaccia, M. Baak, H. Bulten, G. Raven, H. L. Snoek, L. Wilden, C. P. Jessop, J. M. LoSecco, T. Allmendinger, K. K. Gan, K. Honscheid, D. Hufnagel, H. Kagan, R. Kass, T. Pulliam, A. M. Rahimi, R. Ter-Antonyan, Q. K. Wong, J. Braun, R. Frey, O. Igonkina, C. T. Potter, N. B. Sinev, D. Strom, E. Torrence, F. Colecchia, A. Dorigo, F. Galeazzi, M. Margoni, M. Morandin, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, G. Tiozzo, C. Voci, M. Benayoun, H. Briand, J. Chauveau, P. David, Ch. de la Vaissière, L. Del Buono, O. Hamon, M. J. J. John, Ph. Leruste, J. M. Alcâes, J. Ocariz, M. Pivk, L. Roos, S. T'Jampens, G. Therin, P. F. Manfredi, V. Re, P. K. Behera, L. Gladney, Q. H. Guo, J. Panetta, C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, F. Bucc, G. Calderini, M. Carpinelli, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, F. Martinez-Vidal, M. Morganti, N. Neri, E. Paoloni, M. Rama, G. Rizzo, F. Sandrelli, J. Walsh, M. Haire, D. Judd, K. Paick, D. E. Wagoner, N. Danielson, P. Elmer, Y. P. Lau, C. Lu, V. Miftakov, J. Olsen, A. J. S. Smith, A. V. Telnov, F. Bellini, G. Cavoto, R. Facci, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni, S. Morganti, M. Pierini, G. Piredda, F. Safai Tehrani, C. Voena, S. Christ, G. Wagner, R. Waldi, T. Adye, N. De Groot, B. Frank, N. I. Geddes, G. P. Gopal, E. O. Olaifa, R. Aleksan, S. Emery, A. A. Telnov, F. F. Ganzhur, P. F. Giraud, G. Hamel de Monchencki, W. Kozanecki, M. Legendre, G. W. London, B. Mayer, G. Schott, G. Vassey, Ch. Yeche, M. Zito, M. V. Purohit, A. W. Weidemann, J. R. Wilson, F. X. Umiecema, D. Aston, R. Bartoldus, N. Berger, A. M. Boyarsky, O. L. Buchmueller, R. Claus, M. R. Convery, M. Cristinzian, G. De Nardo, D. Dong, J. Dorfan, D. Dujnic, W. Dunwoodie, E. E. Elsen, S. Fan, R. C. Field, T. Glanzman, S. J. Gowdy, T. Hadig, V. Halyo, C. Hwang, T. Hryn’ova, W. R. Innes, M. H. Kelsey, P. Kim, M. L. Kocian, D. W. G. S. Leith, J. Libby, S. Luiz, V. Luth, H. L. Lynch, H. Marsiske, R. Messner, D. R. Muller, C. P. O’Grady, V. E. Ozcan, A. Perazzo, M. Perl, S. Petrak, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, G. Simi, A. Snyder, A. Solna, J. Stelzer, D. Su, M. R. Sullivan, J. Va’vra, S. R. Wagner, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, C. C. Young, P. R. Burchat, A. J. Edwards, T. I. Meyer, B. A. Petersen, C. Roat, S. Ahmed, M. S. Alam, J. A. Ernst, M. A. Saeed, M. Saleem, F. R./Wappler, W. Bugg, M. Krishnamurthy, S. M. Spanier, R. Eckman, H. Kim, J. L. Ritchie, A. Satpathy, R. F. Schwitter, J. M. Izen, J. Kitayama, X. C. Lou, S. Ye, F. Bianchi, M. Bona, F. Gallo, D. Gamba, L. Bossio, C. Cartaro, F. Cosulti, G. Della Ricca, S. Dittongo, S. Grancagnolo, L. Lanceri, P. Poropat, L. Vitale, G. Vuagnin, R. S. Panvini, Sw. Banerjee, C. M. Brown, D. Fortin, P. D. Jackson, R. Kowalewski, J. M. Roney, R. J. Sobie, H. R. Band, B. Cheng, S. Dasu, M. Datta, A. M. Eichenbaum, M. Graham, J. J. Hollar, J. R. Johnson, P. E. Kutter, H. Li, R. Liu, A. Mihalyi, A. K. Mohapatra, Y. Pan, R. Repost, P. Tan, J. H. von Wimmersperg-Toeller, J. Wu, S. L. Wu, Z. Yu, M. G. Greene, and H. Neal

(The BABAR Collaboration)
With a sample of about 227 million $B \bar{B}$ pairs recorded with the BABAR detector at the PEP-II storage ring we perform a full angular analysis of the decay $B^0 \rightarrow \phi K^{*0}(892)$. We measure the branching fraction to be $(9.2 \pm 0.9 \pm 0.5) \times 10^{-6}$ and determine the fractions of longitudinal and parity-odd transverse contributions as $f_L = 0.52 \pm 0.05 \pm 0.02$ and $f_\perp = 0.22 \pm 0.05 \pm 0.02$, respectively. The phases of the parity-even and parity-odd transverse amplitudes relative to the longitudinal amplitude are found to be $\phi_\parallel = 2.34^{+0.23}_{-0.20} \pm 0.05$ rad and $\phi_\perp = 2.47 \pm 0.25 \pm 0.05$ rad, respectively. We measure five $CP$ asymmetries which provide important limits on $CP$ violation originating from new physics. We also observe the decay $B^0 \rightarrow \phi K^{*0}(1430)$.

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The decay $B \rightarrow \phi K^*(892)$ is expected to have contributions from $b \rightarrow s$ loop transitions while the tree-level transition is suppressed in the Standard Model. Angular correlation measurements and asymmetries are particularly sensitive to amplitudes arising outside the Standard Model $^1$. The first evidence for this decay was provided by the CLEO $^2$ and BABAR $^3$ experiments. The large fraction of transverse polarization observed by BABAR $^3$ and confirmed by BELLE $^4$ enables a full angular analysis described by ten parameters for contributing amplitudes and their relative phases.

The angular distribution of the $B \rightarrow \phi K^*$ decay products can be expressed as a function of $H_i = \cos \theta_i$ and $\Phi$, where $\theta_i$ is the angle between the direction of the $K$ from the $K^* \rightarrow K \pi$ ($\theta_1$) or $\phi \rightarrow K \bar{K}$ ($\theta_2$) and the direction opposite the $B$ in the vector resonance rest frame, and $\Phi$ is the angle between the two resonance decay planes. The differential decay width has three complex amplitudes $A_i$ corresponding to the vector meson helicity $\lambda = 0$ or $\pm 1$ $^1, \bar{1}$. When the last two are expressed in terms of $A_{\|} = (A_{+1} + A_{-1})/\sqrt{2}$ and $A_{\perp} = (A_{+1} - A_{-1})/\sqrt{2}$ we have

$$
\frac{8\pi}{9f} \frac{d^3\Gamma}{dH_1dH_2d\Phi} = \frac{1}{|A_0|^2 + |A_{\|}|^2 + |A_{\perp}|^2} \times \{ |A_0|^2 \frac{4}{3} \left( |A_0|^2 + |A_{\perp}|^2 \right) \left( 1 - H_1^2 \right) \left( 1 - H_2^2 \right) \\
+ \frac{1}{4} \left( |A_{\|}|^2 - |A_{\perp}|^2 \right) \left( 1 - H_1^2 \right) \left( 1 - H_2^2 \right) \cos 2\Phi \\
- \text{Im}(A_{\|}^* A_{\perp}) \left( 1 - H_1^2 \right) \left( 1 - H_2^2 \right) \sin 2\Phi \\
+ \sqrt{2} \text{Re}(A_{\|}^* A_{\perp}) H_1 H_2 \sqrt{1 - H_1^2} \sqrt{1 - H_2^2} \cos \Phi \\
- \sqrt{2} \text{Im}(A_{\|}^* A_{\perp}) H_1 H_2 \sqrt{1 - H_1^2} \sqrt{1 - H_2^2} \sin \Phi \}. \quad (1)
$$

In this analysis, we measure the branching fraction, obtained from the number of reconstructed signal events $n_{\text{sig}}$, the polarization parameters $f_L = |A_0|^2/\Sigma |A_i|^2$, $f_{\perp} = |A_{\perp}|^2/\Sigma |A_i|^2$, and the relative phases $\phi_\parallel = \text{arg}(A_1/A_0)$, $\phi_\perp = \text{arg}(A_{\perp}/A_0)$. We allow for $CP$-violating differences between the $B^0$ ($Q = +1$) and $B^0$ ($Q = -1$) decay amplitudes ($A_{\parallel}$ and $A_{\perp}$), where the flavor sign $Q$ is determined in the self-tagging final state with a $K^*$ or $K^*$:

$$
n_{\text{sig}}^Q = n_{\text{sig}} (1 + Q A_{CP})/2; \quad (2)$$

$$
f_L^Q = f_L (1 + Q A_{CP}^0); \quad f_{\perp}^Q = f_{\perp} (1 + Q A_{CP}^0);$$

$$
\phi_\parallel^Q = \phi_\parallel + Q \Delta \phi_\parallel; \quad \phi_\perp^Q = \phi_\perp + \frac{Q}{2} \left( \Delta \phi_\parallel + \Delta \phi_\perp \right) .
$$

If one loop diagram dominates the decay amplitude, the three direct $CP$ asymmetries $A_{CP}$, $A_{CP}^0$, and $A_{CP}^\perp$ and the two weak-phase differences $\Delta \phi_\parallel$ and $\Delta \phi_\perp$ are expected to be negligible. From the above parameters one can derive vector triple-product asymmetries $A_T^\parallel$ and $A_T^\perp$ as discussed in Ref. $^1$:

$$
A_T^{\parallel,0} = \frac{1}{2} \left( \frac{\text{Im}(A_{\parallel}^* A_{\parallel,0})}{|A_{\parallel,0}|^2} + \frac{\text{Im}(A_{\perp}^* A_{\perp,0})}{|A_{\perp,0}|^2} \right) . \quad (3)
$$

We use data collected with the BABAR detector $^7$ at the PEP-II asymmetric-energy $e^+ e^-$ collider $^8$ operated at the center-of-mass (CM) energy of the $T(4S)$ resonance ($\sqrt{s} = 10.58$ GeV). These data represent an integrated luminosity of about 205 fb$^{-1}$, corresponding to 226.6 $\pm$ 2.5 million $B \bar{B}$ pairs.

Charged-particle momenta are measured in a tracking system consisting of a five-layer double-sided silicon vertex tracker and a 40-layer central drift chamber, both immersed in a 1.5-T solenoidal magnetic field. Charged-particle identification is provided by measurements of the energy loss ($dE/dx$) in the tracking devices and by a ring-imaging Cherenkov detector.

We fully reconstruct $\bar{B}^0 \rightarrow \phi K^{*0}$ candidates from their decay products $\phi \rightarrow K^+ K^-$ and $K^{*0} \rightarrow K^+ \pi^-$ as discussed in Ref. $^4$. Charged track candidates are required to originate from a single vertex near the interaction point. We identify $B$ meson candidates kinematically using the beam-energy-substituted mass $m_{\text{ES}} = [(s/2 + p_t \cdot p_B)^2/E_B^2 - p_B^2]^{1/2}$ and the energy difference $\Delta E = (E_B - E_B - p_t \cdot p_B - s/2)/\sqrt{s}$, where $(E_t, p_t)$ is the initial state four-momentum obtained from the beam momenta, and $(E_B, p_B)$ is the four-momentum of the reconstructed $B$ candidate. The requirements on the $K^*$ and $\phi$ invariant masses are $0.75 < m_{K^*} < 1.05$ and $0.99 < m_{\phi} < 1.05$ (GeV). We move the selection window to $1.13 < m_{K^*} < 1.73$ (GeV) in the study of the higher-mass $K^*$ resonances.
To reject the dominant quark-antiquark continuum background, we require $|\cos \theta_T| < 0.8$, where $\theta_T$ is the angle between the $B$-candidate thrust axis and that of the rest of the tracks and neutral clusters in the event, calculated in the CM frame. We also construct a Fisher discriminant, $\mathcal{F}$, further discriminating between signal and background, that combines the following variables: the polar angles of the $B$-momentum vector and the $B$-candidate thrust axis with respect to the beam axis in the CM frame, and the two Legendre moments $L_0$ and $L_2$ of the energy flow around the $B$-candidate thrust axis.

Contamination from other $B$ decays is small (about 2% of the total background) according to Monte Carlo (MC) simulation and is taken into account in the fit described below. We remove signal candidates that have decay products with invariant mass within 12 MeV of the nominal mass values for $D^{\pm}_s$ or $D^{\pm} \to \phi \pi^{\pm}$.

We use an unbinned, extended maximum-likelihood fit to extract simultaneously the signal yield and angular distributions from Eq. (1) multiplied by an acceptance function, which is used for the resonance masses.

The event yields $n_{\text{sig}}$ (events) is defined as $L_i = \sum_{j,k} n_{j,k}^k \mathcal{P}_j^k(\hat{x}_i; \hat{\alpha}; \hat{\beta})$, where each of the $\mathcal{P}_j^k(\hat{x}_i; \hat{\alpha}; \hat{\beta})$ is the probability density function (PDF) for variables $\hat{x}_i = \{m_{\text{ES}}, \Delta E, F, m_K, m_{K^*}, m_{K^0}, \mathcal{H}_1, \mathcal{H}_2, \Phi, Q\}$. The flavor index $k$ corresponds to the measured value of $Q$, that is $\mathcal{P}_j^k \equiv \mathcal{P}_j \delta_{kQ}$. The $n_{j,k}^k$ is the number of events with the flavor $k$ in the category $j$.

The PDF $\mathcal{P}_j^k(\hat{x}_i; \hat{\alpha}; \hat{\beta})$ for a given candidate $i$ is the product of the PDFs for each of the variables and a joint PDF for the helicity angles and resonance masses as discussed below. The signal angular distributions are parameterized with the set $\hat{\alpha} = \{f_L, f_\perp, \phi_\|, \phi_\perp, A_{\mathcal{CP}}, A_{\mathcal{CP}}^\parallel, A_{\mathcal{CP}}^\perp, \Delta \phi_\|, \Delta \phi_\perp\}$ which are left free to vary in the fit. The other PDF parameters $\hat{\beta}$ are extracted from MC simulation and data in $m_{\text{ES}}$ and $\Delta E$ sidebands and are fixed in the fit. The MC resolutions are adjusted by comparing data and MC in calibration channels with similar kinematics and topology, such as $B^0 \to D^- \pi^+$ with $D^- \to K^+ \pi^- \pi^-$. The PDF parameterization for each event candidate accounts for the loss of acceptance near $\mathcal{H}_1 = 0.8$ due to the $D^{\pm}_s$ and $D^{\pm}$ rejection requirements.

We use a three-dimensional description for the helicity part of the signal PDF, using the ideal angular distribution from Eq. (1) multiplied by an acceptance function $\mathcal{G}(\mathcal{H}_1, \mathcal{H}_2, \Phi)$ parameterized with empirical polynomial functions. The detector acceptance effects are found to be uniform in $\Phi$, and we factor the $\mathcal{H}_1$ and $\mathcal{H}_2$ dependence as $\mathcal{G} \equiv G_1(\mathcal{H}_1) \times G_2(\mathcal{H}_2)$. We use two Gaussian functions for the parameterization of the signal PDFs for $\Delta E$, $m_{\text{ES}}$, and $\mathcal{F}$. A relativistic $P$-wave Breit-Wigner distribution, convoluted with a Gaussian resolution function, is used for the resonance masses.

Parameterization of the non-resonant $B$-decay contributions is identical to that of the signal for $m_{\text{ES}}$, $\Delta E$, and $\mathcal{F}$, but is different for the angular and invariant mass distributions. In particular, a broad invariant mass distribution accounts for all potential S-wave contributions leaking into the mass selection window. For the combinatorial background, we use polynomials, except for $m_{\text{ES}}$ and $\mathcal{F}$ distributions which are parameterized by an empirical phase-space function and by the two Gaussian functions, respectively. Resonance production occurs in the background and this is taken into account in the PDF. The background $\mathcal{H}_i$ distribution is separated into contributions from combinatorial background and from real vector mesons.

We allow for multiple candidates in a given event by assigning to each a weight of 1/$N_i$, where $N_i$ is the number of candidates in the same event. The average number of candidates per event is 1.04. The extended likelihood for a sample of $N_{\text{cand}}$ candidates is

$$L = \exp \left( -\sum_j n_j \right) \prod_{i=1}^{N_{\text{cand}}} \exp \left( \frac{\ln \mathcal{L}_i}{N_i} \right).$$

The event yields $n_j$, asymmetries $A_j$, and the signal po-

| Fit parameter | Fit result | Correlation |
|---------------|------------|-------------|
| $n_{\text{sig}}$ (events) | $201 \pm 20 \pm 6$ | -46% |
| $f_L$ (rad) | $0.52 \pm 0.05 \pm 0.02$ | 70% |
| $f_\perp$ (rad) | $0.22 \pm 0.05 \pm 0.02$ | 70% |
| $\phi_\|$(rad) | $2.34^{+0.23}_{-0.20} \pm 0.05$ | 45% |
| $\phi_\perp$(rad) | $2.47 \pm 0.25 \pm 0.05$ | 70% |
| $A_{\mathcal{CP}}$ | $-0.01 \pm 0.09 \pm 0.02$ | 45% |
| $A_{\mathcal{CP}}^\parallel$ | $-0.06 \pm 0.10 \pm 0.01$ | 70% |
| $A_{\mathcal{CP}}^\perp$ | $-0.10 \pm 0.24 \pm 0.05$ | 70% |
| $\Delta \phi_\|$(rad) | $0.27^{+0.20}_{-0.23} \pm 0.05$ | 70% |
| $\Delta \phi_\perp$(rad) | $0.36 \pm 0.25 \pm 0.05$ | 70% |
| $\epsilon$ (%) | $9.7 \pm 0.5$ | 70% |
| $B$ | $(9.2 \pm 0.9 \pm 0.5) \times 10^{-6}$ | 70% |
| $A_T^\parallel$ | $-0.02 \pm 0.04 \pm 0.01$ | 70% |
| $A_T^\perp$ | $+0.11 \pm 0.05 \pm 0.01$ | 70% |
The formation. We observe $181 \pm 1\sigma$ probability ratio shown with a requirement on the signal-to-background

so we calculate the efficiencies using the f youre interested in. We vary the PDF parameters within their respective uncertainties, and derive the associated systematic errors. The biases from the finite resolution of the helicity angle measurement and the dilution due to the presence of fake combinations are estimated with MC simulation.

The systematic errors in efficiencies are dominated by those in track finding and particle identification. Other systematic effects arise from event-selection criteria, $\phi$ and $K^{*0}$ branching fractions, MC statistics, and number of $B$ mesons. We calculate the efficiencies using the measured polarization and assign a systematic error corresponding to the total polarization uncertainty. We find the uncertainty in the charge asymmetry due to the track reconstruction and identification to be less than 0.02.

In summary, we have performed a full angular analysis and searched for CP violation in the angular distribution with the decays $B^0 \to \phi \bar{K}^{*0}(892)$. Our results are summarized in Table II. We observe, with more than $5\sigma$ significance, non-zero contributions from all of the three amplitudes $|A_0|$, $|A_\perp|$, and $|A_\parallel|$, see Fig. 2(a). We also find $3\sigma$ evidence for non-zero final-state-interaction

FIG. 1: Projections onto the variables $m_{ES}$ (a), $\Delta E$ (b), $m_{KK}$ (c), and $m_{K\pi}$ (d) for the signal $B^0 \to \phi K^{*0}(892)$ and $\phi K^{*0}(1430)$ candidates combined.

FIG. 2: Projections onto the variables $H_1$ (a), $H_2$ (b), $Q \Phi$ (c), and the differences between the $Q \Phi$ projections for events with $H_1 H_2 > 0$ and with $H_1 H_2 < 0$ (d) for the signal $B^0 \to \phi K^{*0}(892)$ candidates.

FIG. 3: Projections onto the variables $H_1$ (a) and $H_2$ (b) for the signal $B^0 \to \phi K^{*0}(1430)$ candidates. The difference between the solid and dotted lines in (a) shows the contribution of the tensor state to the angular distribution.

FIG. 4: Projections onto the variables $Q \Phi$ (degrees) for the signal $B^0 \to \phi K^{*0}(892)$ candidates. We observe evidence for non-zero final-state-interaction $\pi, \pi, \pi, \pi$ chosen. In Fig. 4 we show likelihood function contour plots.

We find the decay $B^0 \to \phi K^{*0}(1430)$ to be predominantly longitudinally polarized based on the $H_2$ angular distribution in Fig. 4(b). The width $12$ and the angular distribution of the $K^{*0}(1430)$ resonance structure are not consistent with the pure $K^{*0}(1430)$ tensor state at more than $10\sigma$. However, the angular distribution provides evidence (with statistical significance of $3.2\sigma$) of the longitudinally polarized tensor $K^{*0}(1430)$ contribution in addition to the scalar $K^{0}(1430)$, see Fig. 4(a).

Our $B^0 \to \phi K^{*0}(892)$ fit is performed with the $B \to f_0 K^*$ and $B \to \phi K\pi$ contributions unconstrained. We obtain the event yields $25 \pm 10$ and $11 \pm 15$, respectively. The systematic uncertainties due to interference are estimated using generated samples with conservative assumptions about the S-wave intensity and the interference phase. Additional systematic uncertainty originating from $B$ background is taken as the difference between the fit results with the combinatoric $B\bar{B}$ background component fixed to zero and fixed to the expectation from MC.
phases, see Fig. 4(b). These results supersede our earlier measurements in this channel \[3, 4\]. We also observe the decay \(B^0 \rightarrow \phi K^{*0}(1430)\).

For \(B\) decays to light charmless particles we expect the hierarchy of decay amplitudes to be \(|A_0| \gg |A_{+1}| \gg |A_{-1}|\) under the assumption of pure loop diagram contribution, which is analogous to the discussion in Ref. [11].

Our measurements with the decay \(B^0 \rightarrow \phi K^{*0}(892)\) do not agree with the first inequality but agree with the previous measurements in Ref. [4, 5]. This suggests other contributions to the decay amplitude, previously neglected, either within or beyond the Standard Model \[1, 13\].

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* Now at Department of Physics, University of Warwick, Coventry, United Kingdom
† Also with Università della Basilicata, Potenza, Italy
‡ Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain
§ Deceased

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