

## Measurement of the $CP$ Asymmetry Amplitude $\sin 2\beta$

B. Aubert,<sup>1</sup> D. Boutigny,<sup>1</sup> J.-M. Gaillard,<sup>1</sup> A. Hicheur,<sup>1</sup> Y. Karyotakis,<sup>1</sup> J. P. Lees,<sup>1</sup> P. Robbe,<sup>1</sup> V. Tisserand,<sup>1</sup>  
A. Zghiche,<sup>1</sup> A. Palano,<sup>2</sup> A. Pompili,<sup>2</sup> J. C. Chen,<sup>3</sup> N. D. Qi,<sup>3</sup> G. Rong,<sup>3</sup> P. Wang,<sup>3</sup> Y. S. Zhu,<sup>3</sup> G. Eigen,<sup>4</sup> I. Ofte,<sup>4</sup>  
B. Stugu,<sup>4</sup> G. S. Abrams,<sup>5</sup> A. W. Borgland,<sup>5</sup> A. B. Breon,<sup>5</sup> D. N. Brown,<sup>5</sup> J. Button-Shafer,<sup>5</sup> R. N. Cahn,<sup>5</sup>  
E. Charles,<sup>5</sup> M. S. Gill,<sup>5</sup> A. V. Gritsan,<sup>5</sup> Y. Groysman,<sup>5</sup> R. G. Jacobsen,<sup>5</sup> R. W. Kadel,<sup>5</sup> J. Kadyk,<sup>5</sup> L. T. Kerth,<sup>5</sup>  
Yu. G. Kolomensky,<sup>5</sup> J. F. Kral,<sup>5</sup> C. LeClerc,<sup>5</sup> M. E. Levi,<sup>5</sup> G. Lynch,<sup>5</sup> L. M. Mir,<sup>5</sup> P. J. Oddone,<sup>5</sup>  
T. J. Orimoto,<sup>5</sup> M. Pripstein,<sup>5</sup> N. A. Roe,<sup>5</sup> A. Romosan,<sup>5</sup> M. T. Ronan,<sup>5</sup> V. G. Shelkov,<sup>5</sup> A. V. Telnov,<sup>5</sup>  
W. A. Wenzel,<sup>5</sup> T. J. Harrison,<sup>6</sup> C. M. Hawkes,<sup>6</sup> D. J. Knowles,<sup>6</sup> S. W. O'Neale,<sup>6</sup> R. C. Penny,<sup>6</sup> A. T. Watson,<sup>6</sup>  
N. K. Watson,<sup>6</sup> T. Deppermann,<sup>7</sup> K. Goetzen,<sup>7</sup> H. Koch,<sup>7</sup> B. Lewandowski,<sup>7</sup> K. Peters,<sup>7</sup> H. Schmuecker,<sup>7</sup>  
M. Steinke,<sup>7</sup> N. R. Barlow,<sup>8</sup> W. Bhimji,<sup>8</sup> J. T. Boyd,<sup>8</sup> N. Chevalier,<sup>8</sup> P. J. Clark,<sup>8</sup> W. N. Cottingham,<sup>8</sup> C. Mackay,<sup>8</sup>  
F. F. Wilson,<sup>8</sup> K. Abe,<sup>9</sup> C. Hearty,<sup>9</sup> T. S. Mattison,<sup>9</sup> J. A. McKenna,<sup>9</sup> D. Thiessen,<sup>9</sup> S. Jolly,<sup>10</sup> A. K. McKemey,<sup>10</sup>  
V. E. Blinov,<sup>11</sup> A. D. Bukin,<sup>11</sup> A. R. Buzykaev,<sup>11</sup> V. B. Golubev,<sup>11</sup> V. N. Ivanchenko,<sup>11</sup> A. A. Korol,<sup>11</sup>  
E. A. Kravchenko,<sup>11</sup> A. P. Onuchin,<sup>11</sup> S. I. Serebnyakov,<sup>11</sup> Yu. I. Skovpen,<sup>11</sup> A. N. Yushkov,<sup>11</sup> D. Best,<sup>12</sup>  
M. Chao,<sup>12</sup> D. Kirkby,<sup>12</sup> A. J. Lankford,<sup>12</sup> M. Mandelkern,<sup>12</sup> S. McMahon,<sup>12</sup> D. P. Stoker,<sup>12</sup> C. Buchanan,<sup>13</sup>  
S. Chun,<sup>13</sup> H. K. Hadavand,<sup>14</sup> E. J. Hill,<sup>14</sup> D. B. MacFarlane,<sup>14</sup> H. Paar,<sup>14</sup> S. Prell,<sup>14</sup> Sh. Rahatlou,<sup>14</sup> G. Raven,<sup>14</sup>  
U. Schwanke,<sup>14</sup> V. Sharma,<sup>14</sup> J. W. Berryhill,<sup>15</sup> C. Campagnari,<sup>15</sup> B. Dahmes,<sup>15</sup> P. A. Hart,<sup>15</sup> N. Kuznetsova,<sup>15</sup>  
S. L. Levy,<sup>15</sup> O. Long,<sup>15</sup> A. Lu,<sup>15</sup> M. A. Mazur,<sup>15</sup> J. D. Richman,<sup>15</sup> W. Verkerke,<sup>15</sup> J. Beringer,<sup>16</sup> A. M. Eisner,<sup>16</sup>  
M. Grothe,<sup>16</sup> C. A. Heusch,<sup>16</sup> W. S. Lockman,<sup>16</sup> T. Pulliam,<sup>16</sup> T. Schalk,<sup>16</sup> R. E. Schmitz,<sup>16</sup> B. A. Schumm,<sup>16</sup>  
A. Seiden,<sup>16</sup> M. Turri,<sup>16</sup> W. Walkowiak,<sup>16</sup> D. C. Williams,<sup>16</sup> M. G. Wilson,<sup>16</sup> E. Chen,<sup>17</sup> G. P. Dubois-Felsmann,<sup>17</sup>  
A. Dvoretzki,<sup>17</sup> D. G. Hitlin,<sup>17</sup> F. C. Porter,<sup>17</sup> A. Ryd,<sup>17</sup> A. Samuel,<sup>17</sup> S. Yang,<sup>17</sup> S. Jayatilleke,<sup>18</sup> G. Mancinelli,<sup>18</sup>  
B. T. Meadows,<sup>18</sup> M. D. Sokoloff,<sup>18</sup> T. Barillari,<sup>19</sup> P. Bloom,<sup>19</sup> W. T. Ford,<sup>19</sup> U. Nauenberg,<sup>19</sup> A. Olivas,<sup>19</sup>  
P. Rankin,<sup>19</sup> J. Roy,<sup>19</sup> J. G. Smith,<sup>19</sup> W. C. van Hoek,<sup>19</sup> L. Zhang,<sup>19</sup> J. L. Harton,<sup>20</sup> T. Hu,<sup>20</sup> M. Krishnamurthy,<sup>20</sup>  
A. Soffer,<sup>20</sup> W. H. Toki,<sup>20</sup> R. J. Wilson,<sup>20</sup> J. Zhang,<sup>20</sup> D. Altenburg,<sup>21</sup> T. Brandt,<sup>21</sup> J. Brose,<sup>21</sup> T. Colberg,<sup>21</sup>  
M. Dickopp,<sup>21</sup> R. S. Dubitzky,<sup>21</sup> A. Hauke,<sup>21</sup> E. Maly,<sup>21</sup> R. Müller-Pfefferkorn,<sup>21</sup> S. Otto,<sup>21</sup> K. R. Schubert,<sup>21</sup>  
R. Schwierz,<sup>21</sup> B. Spaan,<sup>21</sup> L. Wilden,<sup>21</sup> D. Bernard,<sup>22</sup> G. R. Bonneaud,<sup>22</sup> F. Brochard,<sup>22</sup> J. Cohen-Tanugi,<sup>22</sup>  
S. Ferrag,<sup>22</sup> S. T'Jampens,<sup>22</sup> Ch. Thiebaux,<sup>22</sup> G. Vasileiadis,<sup>22</sup> M. Verderi,<sup>22</sup> A. Anjomshoaa,<sup>23</sup> R. Bernet,<sup>23</sup>  
A. Khan,<sup>23</sup> D. Lavin,<sup>23</sup> F. Muheim,<sup>23</sup> S. Playfer,<sup>23</sup> J. E. Swain,<sup>23</sup> J. Tinslay,<sup>23</sup> M. Falbo,<sup>24</sup> C. Borean,<sup>25</sup> C. Bozzi,<sup>25</sup>  
L. Piemontese,<sup>25</sup> A. Sarti,<sup>25</sup> E. Treadwell,<sup>26</sup> F. Anulli,<sup>27,\*</sup> R. Baldini-Ferrolì,<sup>27</sup> A. Calcaterra,<sup>27</sup> R. de Sangro,<sup>27</sup>  
D. Falciari,<sup>27</sup> G. Finocchiaro,<sup>27</sup> P. Patteri,<sup>27</sup> I. M. Peruzzi,<sup>27,\*</sup> M. Piccolo,<sup>27</sup> A. Zallo,<sup>27</sup> S. Bagnasco,<sup>28</sup> A. Buzzo,<sup>28</sup>  
R. Contri,<sup>28</sup> G. Crosetti,<sup>28</sup> M. Lo Vetere,<sup>28</sup> M. Macri,<sup>28</sup> M. R. Monge,<sup>28</sup> S. Passaggio,<sup>28</sup> F. C. Pastore,<sup>28</sup>  
C. Patrignani,<sup>28</sup> E. Robutti,<sup>28</sup> A. Santroni,<sup>28</sup> S. Tosi,<sup>28</sup> S. Bailey,<sup>29</sup> M. Morii,<sup>29</sup> R. Bartoldus,<sup>30</sup> G. J. Grenier,<sup>30</sup>  
U. Mallik,<sup>30</sup> J. Cochran,<sup>31</sup> H. B. Crawley,<sup>31</sup> J. Lamsa,<sup>31</sup> W. T. Meyer,<sup>31</sup> E. I. Rosenberg,<sup>31</sup> J. Yi,<sup>31</sup> M. Davier,<sup>32</sup>  
G. Grosdidier,<sup>32</sup> A. Höcker,<sup>32</sup> H. M. Lacker,<sup>32</sup> S. Laplace,<sup>32</sup> F. Le Diberder,<sup>32</sup> V. Lepeltier,<sup>32</sup> A. M. Lutz,<sup>32</sup>  
T. C. Petersen,<sup>32</sup> S. Plaszczynski,<sup>32</sup> M. H. Schune,<sup>32</sup> L. Tantot,<sup>32</sup> S. Trincaz-Duvoid,<sup>32</sup> G. Wormser,<sup>32</sup>  
R. M. Bionta,<sup>33</sup> V. Brigljević,<sup>33</sup> D. J. Lange,<sup>33</sup> K. van Bibber,<sup>33</sup> D. M. Wright,<sup>33</sup> A. J. Bevan,<sup>34</sup> J. R. Fry,<sup>34</sup>  
E. Gabathuler,<sup>34</sup> R. Gamet,<sup>34</sup> M. George,<sup>34</sup> M. Kay,<sup>34</sup> D. J. Payne,<sup>34</sup> R. J. Sloane,<sup>34</sup> C. Touramanis,<sup>34</sup>  
M. L. Aspinwall,<sup>35</sup> D. A. Bowerman,<sup>35</sup> P. D. Dauncey,<sup>35</sup> U. Egede,<sup>35</sup> I. Eschrich,<sup>35</sup> G. W. Morton,<sup>35</sup> J. A. Nash,<sup>35</sup>  
P. Sanders,<sup>35</sup> D. Smith,<sup>35</sup> G. P. Taylor,<sup>35</sup> J. J. Back,<sup>36</sup> G. Bellodi,<sup>36</sup> P. Dixon,<sup>36</sup> P. F. Harrison,<sup>36</sup> R. J. L. Potter,<sup>36</sup>  
H. W. Shorthouse,<sup>36</sup> P. Strother,<sup>36</sup> P. B. Vidal,<sup>36</sup> G. Cowan,<sup>37</sup> H. U. Flaecher,<sup>37</sup> S. George,<sup>37</sup> M. G. Green,<sup>37</sup>  
A. Kurup,<sup>37</sup> C. E. Marker,<sup>37</sup> T. R. McMahon,<sup>37</sup> S. Ricciardi,<sup>37</sup> F. Salvatore,<sup>37</sup> G. Vaitsas,<sup>37</sup> M. A. Winter,<sup>37</sup>  
D. Brown,<sup>38</sup> C. L. Davis,<sup>38</sup> J. Allison,<sup>39</sup> R. J. Barlow,<sup>39</sup> A. C. Forti,<sup>39</sup> F. Jackson,<sup>39</sup> G. D. Lafferty,<sup>39</sup> A. J. Lyon,<sup>39</sup>  
N. Savvas,<sup>39</sup> J. H. Weatherall,<sup>39</sup> J. C. Williams,<sup>39</sup> A. Farbin,<sup>40</sup> A. Jawahery,<sup>40</sup> V. Lillard,<sup>40</sup> D. A. Roberts,<sup>40</sup>  
J. R. Schieck,<sup>40</sup> G. Blaylock,<sup>41</sup> C. Dallapiccola,<sup>41</sup> K. T. Flood,<sup>41</sup> S. S. Hertzbach,<sup>41</sup> R. Kofler,<sup>41</sup> V. B. Koptchev,<sup>41</sup>  
T. B. Moore,<sup>41</sup> H. Staengle,<sup>41</sup> S. Willocq,<sup>41</sup> B. Brau,<sup>42</sup> R. Cowan,<sup>42</sup> G. Sciolla,<sup>42</sup> F. Taylor,<sup>42</sup> R. K. Yamamoto,<sup>42</sup>  
M. Milek,<sup>43</sup> P. M. Patel,<sup>43</sup> F. Palombo,<sup>44</sup> J. M. Bauer,<sup>45</sup> L. Cremaldi,<sup>45</sup> V. Eschenburg,<sup>45</sup> R. Kroeger,<sup>45</sup> J. Reidy,<sup>45</sup>  
D. A. Sanders,<sup>45</sup> D. J. Summers,<sup>45</sup> C. Hast,<sup>46</sup> P. Taras,<sup>46</sup> H. Nicholson,<sup>47</sup> C. Cartaro,<sup>48</sup> N. Cavallo,<sup>48</sup> G. De  
Nardo,<sup>48</sup> F. Fabozzi,<sup>48</sup> C. Gatto,<sup>48</sup> L. Lista,<sup>48</sup> P. Paolucci,<sup>48</sup> D. Piccolo,<sup>48</sup> C. Sciacca,<sup>48</sup> J. M. LoSecco,<sup>49</sup>

J. R. G. Alsmiller,<sup>50</sup> T. A. Gabriel,<sup>50</sup> J. Brau,<sup>51</sup> R. Frey,<sup>51</sup> M. Iwasaki,<sup>51</sup> C. T. Potter,<sup>51</sup> N. B. Sinev,<sup>51</sup> D. Strom,<sup>51</sup> E. Torrence,<sup>51</sup> F. Colecchia,<sup>52</sup> A. Dorigo,<sup>52</sup> F. Galeazzi,<sup>52</sup> M. Margoni,<sup>52</sup> M. Morandin,<sup>52</sup> M. Posocco,<sup>52</sup> M. Rotondo,<sup>52</sup> F. Simonetto,<sup>52</sup> R. Stroili,<sup>52</sup> C. Voci,<sup>52</sup> M. Benayoun,<sup>53</sup> H. Briand,<sup>53</sup> J. Chauveau,<sup>53</sup> P. David,<sup>53</sup> Ch. de la Vaissière,<sup>53</sup> L. Del Buono,<sup>53</sup> O. Hamon,<sup>53</sup> Ph. Leruste,<sup>53</sup> J. Ocariz,<sup>53</sup> M. Pivk,<sup>53</sup> L. Roos,<sup>53</sup> J. Stark,<sup>53</sup> P. F. Manfredi,<sup>54</sup> V. Re,<sup>54</sup> V. Speziali,<sup>54</sup> L. Gladney,<sup>55</sup> Q. H. Guo,<sup>55</sup> J. Panetta,<sup>55</sup> C. Angelini,<sup>56</sup> G. Batignani,<sup>56</sup> S. Bettarini,<sup>56</sup> M. Bondioli,<sup>56</sup> F. Bucci,<sup>56</sup> G. Calderini,<sup>56</sup> E. Campagna,<sup>56</sup> M. Carpinelli,<sup>56</sup> F. Forti,<sup>56</sup> M. A. Giorgi,<sup>56</sup> A. Lusiani,<sup>56</sup> G. Marchiori,<sup>56</sup> F. Martinez-Vidal,<sup>56</sup> M. Morganti,<sup>56</sup> N. Neri,<sup>56</sup> E. Paoloni,<sup>56</sup> M. Rama,<sup>56</sup> G. Rizzo,<sup>56</sup> F. Sandrelli,<sup>56</sup> G. Triggiani,<sup>56</sup> J. Walsh,<sup>56</sup> M. Haire,<sup>57</sup> D. Judd,<sup>57</sup> K. Paick,<sup>57</sup> L. Turnbull,<sup>57</sup> D. E. Wagoner,<sup>57</sup> J. Albert,<sup>58</sup> N. Danielson,<sup>58</sup> P. Elmer,<sup>58</sup> C. Lu,<sup>58</sup> V. Miftakov,<sup>58</sup> J. Olsen,<sup>58</sup> S. F. Schaffner,<sup>58</sup> A. J. S. Smith,<sup>58</sup> A. Tumanov,<sup>58</sup> E. W. Varnes,<sup>58</sup> F. Bellini,<sup>59</sup> G. Cavoto,<sup>58,59</sup> D. del Re,<sup>59</sup> R. Faccini,<sup>14,59</sup> F. Ferrarotto,<sup>59</sup> F. Ferroni,<sup>59</sup> E. Leonardi,<sup>59</sup> M. A. Mazzoni,<sup>59</sup> S. Morganti,<sup>59</sup> G. Piredda,<sup>59</sup> F. Safai Tehrani,<sup>59</sup> M. Serra,<sup>59</sup> C. Voena,<sup>59</sup> S. Christ,<sup>60</sup> G. Wagner,<sup>60</sup> R. Waldi,<sup>60</sup> T. Adye,<sup>61</sup> N. De Groot,<sup>61</sup> B. Franek,<sup>61</sup> N. I. Geddes,<sup>61</sup> G. P. Gopal,<sup>61</sup> S. M. Xella,<sup>61</sup> R. Aleksan,<sup>62</sup> S. Emery,<sup>62</sup> A. Gaidot,<sup>62</sup> P.-F. Giraud,<sup>62</sup> G. Hamel de Monchenault,<sup>62</sup> W. Kozanecki,<sup>62</sup> M. Langer,<sup>62</sup> G. W. London,<sup>62</sup> B. Mayer,<sup>62</sup> G. Schott,<sup>62</sup> B. Serfass,<sup>62</sup> G. Vasseur,<sup>62</sup> Ch. Yeche,<sup>62</sup> M. Zito,<sup>62</sup> M. V. Purohit,<sup>63</sup> A. W. Weidemann,<sup>63</sup> F. X. Yumiceva,<sup>63</sup> I. Adam,<sup>64</sup> D. Aston,<sup>64</sup> N. Berger,<sup>64</sup> A. M. Boyarski,<sup>64</sup> M. R. Convery,<sup>64</sup> D. P. Coupal,<sup>64</sup> D. Dong,<sup>64</sup> J. Dorfan,<sup>64</sup> W. Dunwoodie,<sup>64</sup> R. C. Field,<sup>64</sup> T. Glanzman,<sup>64</sup> S. J. Gowdy,<sup>64</sup> E. Grauges,<sup>64</sup> T. Haas,<sup>64</sup> T. Hadig,<sup>64</sup> V. Halyo,<sup>64</sup> T. Himel,<sup>64</sup> T. Hryn'ova,<sup>64</sup> M. E. Huffer,<sup>64</sup> W. R. Innes,<sup>64</sup> C. P. Jessop,<sup>64</sup> M. H. Kelsey,<sup>64</sup> P. Kim,<sup>64</sup> M. L. Kocian,<sup>64</sup> U. Langenegger,<sup>64</sup> D. W. G. S. Leith,<sup>64</sup> S. Luitz,<sup>64</sup> V. Luth,<sup>64</sup> H. L. Lynch,<sup>64</sup> H. Marsiske,<sup>64</sup> S. Menke,<sup>64</sup> R. Messner,<sup>64</sup> D. R. Muller,<sup>64</sup> C. P. O'Grady,<sup>64</sup> V. E. Ozcan,<sup>64</sup> A. Perazzo,<sup>64</sup> M. Perl,<sup>64</sup> S. Petrak,<sup>64</sup> H. Quinn,<sup>64</sup> B. N. Ratcliff,<sup>64</sup> S. H. Robertson,<sup>64</sup> A. Roodman,<sup>64</sup> A. A. Salnikov,<sup>64</sup> T. Schietinger,<sup>64</sup> R. H. Schindler,<sup>64</sup> J. Schwiening,<sup>64</sup> G. Simi,<sup>64</sup> A. Snyder,<sup>64</sup> A. Soha,<sup>64</sup> S. M. Spanier,<sup>64</sup> J. Stelzer,<sup>64</sup> D. Su,<sup>64</sup> M. K. Sullivan,<sup>64</sup> H. A. Tanaka,<sup>64</sup> J. Va'vra,<sup>64</sup> S. R. Wagner,<sup>64</sup> M. Weaver,<sup>64</sup> A. J. R. Weinstein,<sup>64</sup> W. J. Wisniewski,<sup>64</sup> D. H. Wright,<sup>64</sup> C. C. Young,<sup>64</sup> P. R. Burchat,<sup>65</sup> C. H. Cheng,<sup>65</sup> T. I. Meyer,<sup>65</sup> C. Roat,<sup>65</sup> R. Henderson,<sup>66</sup> W. Bugg,<sup>67</sup> H. Cohn,<sup>67</sup> J. M. Izen,<sup>68</sup> I. Kitayama,<sup>68</sup> X. C. Lou,<sup>68</sup> F. Bianchi,<sup>69</sup> M. Bona,<sup>69</sup> D. Gamba,<sup>69</sup> L. Bosisio,<sup>70</sup> G. Della Ricca,<sup>70</sup> S. Dittongo,<sup>70</sup> L. Lanceri,<sup>70</sup> P. Poropat,<sup>70</sup> L. Vitale,<sup>70</sup> G. Vuagnin,<sup>70</sup> R. S. Panvini,<sup>71</sup> Sw. Banerjee,<sup>72</sup> C. M. Brown,<sup>72</sup> D. Fortin,<sup>72</sup> P. D. Jackson,<sup>72</sup> R. Kowalewski,<sup>72</sup> J. M. Roney,<sup>72</sup> H. R. Band,<sup>73</sup> S. Dasu,<sup>73</sup> M. Datta,<sup>73</sup> A. M. Eichenbaum,<sup>73</sup> H. Hu,<sup>73</sup> J. R. Johnson,<sup>73</sup> R. Liu,<sup>73</sup> F. Di Lodovico,<sup>73</sup> A. Mohapatra,<sup>73</sup> Y. Pan,<sup>73</sup> R. Prepost,<sup>73</sup> I. J. Scott,<sup>73</sup> S. J. Sekula,<sup>73</sup> J. H. von Wimmersperg-Toeller,<sup>73</sup> J. Wu,<sup>73</sup> S. L. Wu,<sup>73</sup> Z. Yu,<sup>73</sup> and H. Neal<sup>74</sup>

(The BABAR Collaboration)

<sup>1</sup>Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France

<sup>2</sup>Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

<sup>3</sup>Institute of High Energy Physics, Beijing 100039, China

<sup>4</sup>University of Bergen, Inst. of Physics, N-5007 Bergen, Norway

<sup>5</sup>Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA

<sup>6</sup>University of Birmingham, Birmingham, B15 2TT, United Kingdom

<sup>7</sup>Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

<sup>8</sup>University of Bristol, Bristol BS8 1TL, United Kingdom

<sup>9</sup>University of British Columbia, Vancouver, BC, Canada V6T 1Z1

<sup>10</sup>Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

<sup>11</sup>Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

<sup>12</sup>University of California at Irvine, Irvine, CA 92697, USA

<sup>13</sup>University of California at Los Angeles, Los Angeles, CA 90024, USA

<sup>14</sup>University of California at San Diego, La Jolla, CA 92093, USA

<sup>15</sup>University of California at Santa Barbara, Santa Barbara, CA 93106, USA

<sup>16</sup>University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

<sup>17</sup>California Institute of Technology, Pasadena, CA 91125, USA

<sup>18</sup>University of Cincinnati, Cincinnati, OH 45221, USA

<sup>19</sup>University of Colorado, Boulder, CO 80309, USA

<sup>20</sup>Colorado State University, Fort Collins, CO 80523, USA

<sup>21</sup>Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

<sup>22</sup>Ecole Polytechnique, LLR, F-91128 Palaiseau, France

<sup>23</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

<sup>24</sup>Elon University, Elon University, NC 27244-2010, USA

<sup>25</sup>Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

<sup>26</sup>Florida A&M University, Tallahassee, FL 32307, USA

- <sup>27</sup>Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
- <sup>28</sup>Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
- <sup>29</sup>Harvard University, Cambridge, MA 02138, USA
- <sup>30</sup>University of Iowa, Iowa City, IA 52242, USA
- <sup>31</sup>Iowa State University, Ames, IA 50011-3160, USA
- <sup>32</sup>Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
- <sup>33</sup>Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
- <sup>34</sup>University of Liverpool, Liverpool L69 3BX, United Kingdom
- <sup>35</sup>University of London, Imperial College, London, SW7 2BW, United Kingdom
- <sup>36</sup>Queen Mary, University of London, E1 4NS, United Kingdom
- <sup>37</sup>University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
- <sup>38</sup>University of Louisville, Louisville, KY 40292, USA
- <sup>39</sup>University of Manchester, Manchester M13 9PL, United Kingdom
- <sup>40</sup>University of Maryland, College Park, MD 20742, USA
- <sup>41</sup>University of Massachusetts, Amherst, MA 01003, USA
- <sup>42</sup>Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA
- <sup>43</sup>McGill University, Montréal, QC, Canada H3A 2T8
- <sup>44</sup>Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
- <sup>45</sup>University of Mississippi, University, MS 38677, USA
- <sup>46</sup>Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7
- <sup>47</sup>Mount Holyoke College, South Hadley, MA 01075, USA
- <sup>48</sup>Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
- <sup>49</sup>University of Notre Dame, Notre Dame, IN 46556, USA
- <sup>50</sup>Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
- <sup>51</sup>University of Oregon, Eugene, OR 97403, USA
- <sup>52</sup>Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
- <sup>53</sup>Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France
- <sup>54</sup>Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy
- <sup>55</sup>University of Pennsylvania, Philadelphia, PA 19104, USA
- <sup>56</sup>Università di Pisa, Scuola Normale Superiore and INFN, I-56010 Pisa, Italy
- <sup>57</sup>Prairie View A&M University, Prairie View, TX 77446, USA
- <sup>58</sup>Princeton University, Princeton, NJ 08544, USA
- <sup>59</sup>Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
- <sup>60</sup>Universität Rostock, D-18051 Rostock, Germany
- <sup>61</sup>Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
- <sup>62</sup>DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France
- <sup>63</sup>University of South Carolina, Columbia, SC 29208, USA
- <sup>64</sup>Stanford Linear Accelerator Center, Stanford, CA 94309, USA
- <sup>65</sup>Stanford University, Stanford, CA 94305-4060, USA
- <sup>66</sup>TRIUMF, Vancouver, BC, Canada V6T 2A3
- <sup>67</sup>University of Tennessee, Knoxville, TN 37996, USA
- <sup>68</sup>University of Texas at Dallas, Richardson, TX 75083, USA
- <sup>69</sup>Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
- <sup>70</sup>Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
- <sup>71</sup>Vanderbilt University, Nashville, TN 37235, USA
- <sup>72</sup>University of Victoria, Victoria, BC, Canada V8W 3P6
- <sup>73</sup>University of Wisconsin, Madison, WI 53706, USA
- <sup>74</sup>Yale University, New Haven, CT 06511, USA

(Dated: October 2, 2002)

We present results on time-dependent  $CP$  asymmetries in neutral  $B$  decays to several  $CP$  eigenstates. The measurements use a data sample of about 88 million  $\Upsilon(4S) \rightarrow B\bar{B}$  decays collected between 1999 and 2002 with the BABAR detector at the PEP-II asymmetric-energy  $B$  Factory at SLAC. We study events in which one neutral  $B$  meson is fully reconstructed in a final state containing a charmonium meson and the other  $B$  meson is determined to be either a  $B^0$  or  $\bar{B}^0$  from its decay products. The amplitude of the  $CP$  asymmetry, which in the Standard Model is proportional to  $\sin 2\beta$ , is derived from the decay-time distributions in such events. We measure  $\sin 2\beta = 0.741 \pm 0.067$  (stat)  $\pm 0.034$  (syst) and  $|\lambda| = 0.948 \pm 0.051$  (stat)  $\pm 0.030$  (syst). The magnitude of  $\lambda$  is consistent with unity, in agreement with the Standard Model expectation of no direct  $CP$  violation in these modes.

PACS numbers: 13.25.Hw, 12.15.Hh, 11.30.Er

The Standard Model of electroweak interactions describes  $CP$  violation in weak interactions as a con-

sequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In this framework, measurements of  $CP$  asymmetries in the proper-time distribution of neutral  $B$  decays to charmonium final states provide a direct measurement of  $\sin 2\beta$  [2], where  $\beta \equiv \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$ .

Observations of  $CP$  violation in  $B^0$  decays were reported last year by the BABAR [3] and Belle [4] collaborations. The PEP-II collider has since delivered an additional  $63 \text{ fb}^{-1}$ , thereby approximately tripling the data sample near the  $\Upsilon(4S)$  resonance. In this Letter we report a more precise measurement of  $\sin 2\beta$  using the full sample of about 88 million  $B\bar{B}$  decays. The BABAR detector and the measurement technique are described in detail in Refs. [5] and [6], respectively. Changes in the analysis with respect to the published result [3] include processing of all data with a uniform event reconstruction, a new flavor-tagging algorithm, and the addition of the decay mode  $B^0 \rightarrow \eta_c K_s^0$ .

We reconstruct a sample of neutral  $B$  mesons ( $B_{CP}$ ) decaying to the final states  $J/\psi K_s^0$ ,  $\psi(2S)K_s^0$ ,  $\chi_{c1}K_s^0$ ,  $\eta_c K_s^0$ ,  $J/\psi K^{*0}$  ( $K^{*0} \rightarrow K_s^0 \pi^0$ ), and  $J/\psi K_L^0$ . The  $J/\psi$  and  $\psi(2S)$  mesons are reconstructed through their decays to  $e^+e^-$  and  $\mu^+\mu^-$ ; the  $\psi(2S)$  is also reconstructed through its decay to  $J/\psi \pi^+\pi^-$ . We reconstruct  $\chi_{c1}$  mesons in the decay mode  $J/\psi \gamma$  and  $\eta_c$  mesons in the  $K_s^0 K^+\pi^-$  and  $K^+K^-\pi^0$  final states [7]. The  $K_s^0$  is reconstructed in its decay to  $\pi^+\pi^-$  (and to  $\pi^0\pi^0$  for the  $J/\psi K_s^0$  mode). We examine each event in the  $B_{CP}$  sample for evidence that the recoiling  $B$  meson decayed as a  $B^0$  or  $\bar{B}^0$  (flavor tag).

The proper-time distribution of  $B$  meson decays to a  $CP$  eigenstate with a  $B^0$  or  $\bar{B}^0$  tag can be expressed in terms of a complex parameter  $\lambda$  that depends on both the  $B^0$ - $\bar{B}^0$  oscillation amplitude and the amplitudes describing  $\bar{B}^0$  and  $B^0$  decays to this final state [8]. The decay rate  $f_+(f_-)$  when the tagging meson is a  $B^0(\bar{B}^0)$  is given by

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 \pm \frac{2\mathcal{I}m\lambda}{1+|\lambda|^2} \sin(\Delta m_d \Delta t) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m_d \Delta t) \right], \quad (1)$$

where  $\Delta t = t_{\text{rec}} - t_{\text{tag}}$  is the difference between the proper decay times of the reconstructed  $B$  meson ( $B_{\text{rec}}$ ) and the tagging  $B$  meson ( $B_{\text{tag}}$ ),  $\tau_{B^0}$  is the  $B^0$  lifetime, and  $\Delta m_d$  is the  $B^0$ - $\bar{B}^0$  oscillation frequency. The sine term in Eq. 1 is due to the interference between direct decay and decay after flavor change, and the cosine term is due to the interference between two or more decay amplitudes with different weak and strong phases.  $CP$  violation can be observed as a difference between the  $\Delta t$  distributions of  $B^0$ - and  $\bar{B}^0$ -tagged events or as an asymmetry with respect to  $\Delta t = 0$  for either flavor tag.

In the Standard Model,  $\lambda = \eta_f e^{-2i\beta}$  for charmonium-containing  $b \rightarrow c\bar{c}s$  decays, where  $\eta_f$  is the  $CP$  eigenvalue

of the final state  $f$ . Thus, the time-dependent  $CP$  asymmetry is

$$A_{CP}(\Delta t) \equiv \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \sin(\Delta m_d \Delta t), \quad (2)$$

with  $\eta_f = -1$  for  $J/\psi K_s^0$ ,  $\psi(2S)K_s^0$ ,  $\chi_{c1}K_s^0$ , and  $\eta_c K_s^0$ , and  $+1$  for  $J/\psi K_L^0$ . Due to the presence of even ( $L=0, 2$ ) and odd ( $L=1$ ) orbital angular momenta in the  $B \rightarrow J/\psi K^{*0}$  final state, there can be  $CP$ -even and  $CP$ -odd contributions to the decay rate. When the angular information in the decay is ignored, the measured  $CP$  asymmetry in  $J/\psi K^{*0}$  is reduced by a factor  $1 - 2R_{\perp}$ , where  $R_{\perp}$  is the fraction of the  $L=1$  component. We have measured  $R_{\perp} = (16.0 \pm 3.5)\%$  [9], which gives  $\eta_f = 0.65 \pm 0.07$  after acceptance corrections in the  $J/\psi K^{*0}$  mode.

The event selection, lepton and  $K^{\pm}$  identification, and  $J/\psi$  and  $\psi(2S)$  reconstruction used in this analysis are similar to those described in Ref. [6], as are the selection criteria for the channels  $J/\psi K_s^0$ ,  $\psi(2S)K_s^0$ ,  $\chi_{c1}K_s^0$ ,  $J/\psi K^{*0}$ , and  $J/\psi K_L^0$ . The  $B^0 \rightarrow \eta_c K_s^0$  sample selection is described in Ref. [10]. In brief, the  $K^{\pm}$  candidates must satisfy kaon identification criteria and the  $K_s^0 \rightarrow \pi^+\pi^-$  and  $\pi^0 \rightarrow \gamma\gamma$  candidates are required to have reconstructed masses within 12.5 and 15 MeV/ $c^2$ , respectively, of their nominal masses [11]. The  $\eta_c$  candidates (with  $2.90 < M_{KK\pi} < 3.15 \text{ GeV}/c^2$ ) are combined with  $K_s^0 \rightarrow \pi^+\pi^-$  candidates reconstructed within 10 MeV/ $c^2$  of the  $K_s^0$  nominal mass to form a  $B^0$  candidate. This sample includes a contribution of  $(15 \pm 2)\%$  from hadronic  $J/\psi$  decays to the  $KK\pi$  final states.

We select candidates in the  $B^0 \rightarrow J/\psi K_s^0$ ,  $\psi(2S)K_s^0$ ,  $\chi_{c1}K_s^0$ , and  $J/\psi K^{*0}$  sample by requiring that the difference  $\Delta E$  between their energy and the beam energy in the center-of-mass frame be less than three standard deviations from zero. The  $\Delta E$  resolution is about 10 MeV, except for the mode with  $K_s^0 \rightarrow \pi^0\pi^0$  (33 MeV) and with  $K^{*0}$  (20 MeV). The  $B^0 \rightarrow \eta_c K_s^0$  candidates are required to have  $|\Delta E|$  less than 40 (70) MeV for the  $K_s^0 K^+\pi^-$  ( $K^+K^-\pi^0$ ) modes. For all modes except  $J/\psi K_L^0$ , the beam-energy substituted mass  $m_{\text{ES}} = \sqrt{(E_{\text{beam}}^{\text{cm}})^2 - (p_B^{\text{cm}})^2}$  must be greater than 5.2 GeV/ $c^2$ . To determine numbers of events and purities, a signal region  $5.270 (5.273) < m_{\text{ES}} < 5.290 (5.288) \text{ GeV}/c^2$  is used for modes containing  $K_s^0$  ( $K^{*0}$ ). In the  $J/\psi K_L^0$  mode, the  $\Delta E$  resolution is 3.5 MeV (after  $B$  mass constraint) and the signal region is defined by  $|\Delta E| < 10 \text{ MeV}$ .

A measurement of  $A_{CP}$  requires a determination of the experimental  $\Delta t$  resolution and the fraction  $w$  of events in which the tag assignment is incorrect. This mistag fraction reduces the observed  $CP$  asymmetry by a factor  $1 - 2w$ . Mistag fractions and  $\Delta t$  resolution functions are determined from a sample of neutral  $B$  mesons that decay to flavor eigenstates ( $B_{\text{flav}}$ ) consisting of the channels  $D^{(*)-}h^+(h^+ = \pi^+, \rho^+, \text{ and } a_1^+)$  and

$J/\psi K^{*0}(K^{*0} \rightarrow K^+\pi^-)$ . Validation studies are performed with a control sample of  $B^+$  mesons decaying to the final states  $J/\psi K^{(*)+}$ ,  $\psi(2S)K^+$ ,  $\chi_{c1}K^+$ ,  $\eta_c K^+$ , and  $\bar{D}^{(*)0}\pi^+$ .

We use multivariate algorithms to identify signatures of  $B$  decays that determine the flavor of  $B_{\text{tag}}$ . Primary leptons from semileptonic  $B$  decays are selected from identified electrons and muons as well as isolated energetic tracks. We use the charges of identified kaon candidates to define a kaon tag. Soft pions from  $D^{*+}$  decays are selected on the basis of their momentum and direction with respect to the thrust axis of  $B_{\text{tag}}$ . A neural network, which combines the outputs of these physics-based algorithms, takes into account correlations between different sources of flavor information and provides an estimate of the mistag probability for each event.

By using the outputs of the physics-based algorithms and the estimated mistag probability, each event is assigned to one of four hierarchical, mutually exclusive tagging categories. The **Lepton** category contains events with an identified lepton, and a supporting kaon tag if present. Events with a kaon candidate and soft pion with opposite charge and similar flight direction are assigned to the **Kaon I** category. Events with only a kaon tag are assigned to the **Kaon I** or **Kaon II** category depending on the estimated mistag probability. The **Kaon II** category also contains the remaining events with a soft pion. All other events are assigned to the **Inclusive** category or excluded from further analysis based on the estimated mistag probability. The tagging efficiencies  $\varepsilon_i$  for the four tagging categories are measured from data and summarized in Table I. The figure of merit for tagging is the effective tagging efficiency  $Q \equiv \sum_i \varepsilon_i (1 - 2w_i)^2$ . This algorithm improves  $Q$  by about 7% (relative) over the algorithm used in Ref. [6].

The time interval  $\Delta t$  between the two  $B$  decays is calculated from the measured separation  $\Delta z$  between the decay vertices of  $B_{\text{rec}}$  and  $B_{\text{tag}}$  along the collision ( $z$ ) axis [6]. We determine the  $z$  position of the  $B_{\text{rec}}$  vertex from its charged tracks. The  $B_{\text{tag}}$  decay vertex is determined by fitting tracks not belonging to the  $B_{\text{rec}}$  candidate to a common vertex, employing constraints from the beam spot location and the  $B_{\text{rec}}$  momentum [6]. We accept events with a  $\Delta t$  uncertainty of less than 2.5 ps and  $|\Delta t| < 20$  ps. The fraction of events satisfying these requirements is 95%. The r.m.s.  $\Delta t$  resolution for 99.7% of these events is 1.1 ps.

The signal region contains 2641 events which satisfy the tagging and vertexing requirements. In Table II we list the number of events and the signal purity for the tagged  $B_{CP}$  candidates. The purities are determined from fits to the  $m_{\text{ES}}$  (all  $K_S^0$  modes) or  $\Delta E$  ( $K_L^0$  mode) distributions in data, or from Monte Carlo simulation ( $K^{*0}$  mode). Figure 1 shows the  $m_{\text{ES}}$  distribution for modes containing a  $K_S^0$  or  $K^{*0}$  and  $\Delta E$  dis-

TABLE I: Efficiencies  $\varepsilon_i$ , average mistag fractions  $w_i$ , mistag fraction differences  $\Delta w_i = w_i(B^0) - w_i(\bar{B}^0)$ , and  $Q$  extracted for each tagging category  $i$  from the  $B_{\text{flav}}$  and  $B_{CP}$  samples.

Category	$\varepsilon$ (%)	$w$ (%)	$\Delta w$ (%)	$Q$ (%)
<b>Lepton</b>	$9.1 \pm 0.2$	$3.3 \pm 0.6$	$-1.5 \pm 1.1$	$7.9 \pm 0.3$
<b>Kaon I</b>	$16.7 \pm 0.2$	$10.0 \pm 0.7$	$-1.3 \pm 1.1$	$10.7 \pm 0.4$
<b>Kaon II</b>	$19.8 \pm 0.3$	$20.9 \pm 0.8$	$-4.4 \pm 1.2$	$6.7 \pm 0.4$
<b>Inclusive</b>	$20.0 \pm 0.3$	$31.5 \pm 0.9$	$-2.4 \pm 1.3$	$2.7 \pm 0.3$
All	$65.6 \pm 0.5$			$28.1 \pm 0.7$

tribution for the  $J/\psi K_L^0$  candidates. For all modes except  $\eta_c K_S^0$  and  $J/\psi K_L^0$ , we use simulated events to estimate the fractions of events in the Gaussian component of the  $m_{\text{ES}}$  fits due to cross-feed from other decay modes. For the  $\eta_c K_S^0$  mode the cross-feed fraction is determined from a fit to the  $M_{KK\pi}$  and  $m_{\text{ES}}$  distributions. These fractions range from  $(0.3 \pm 0.1)\%$  for  $J/\psi K_S^0$  ( $K_S^0 \rightarrow \pi^+\pi^-$ ) to  $(13.1 \pm 5.9)\%$  for  $\eta_c K_S^0$ . For the  $J/\psi K_L^0$  and  $J/\psi K^{*0}$  decay modes, the composition, effective  $\eta_f$ , and  $\Delta E$  distribution ( $J/\psi K_L^0$  only) of the individual background sources are determined either from simulation (for  $B \rightarrow J/\psi X$ ) or from the  $m_{\ell+\ell^-}$  sidebands in data (for fake  $J/\psi \rightarrow \ell^+\ell^-$ ).

We determine  $\sin 2\beta$  with a simultaneous unbinned maximum likelihood fit to the  $\Delta t$  distributions of the tagged  $B_{CP}$  and  $B_{\text{flav}}$  samples. In this fit the  $\Delta t$  distributions of the  $B_{CP}$  sample are described by Eq. 1 with  $|\lambda| = 1$ . The  $\Delta t$  distributions of the  $B_{\text{flav}}$  sample evolve according to the known frequency for flavor oscillation in

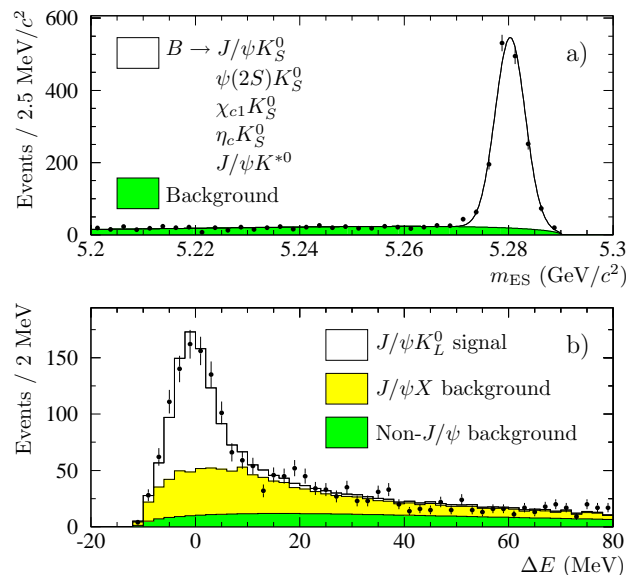


FIG. 1: Distributions for  $B_{CP}$  candidates satisfying the tagging and vertexing requirements: a)  $m_{\text{ES}}$  for the final states  $J/\psi K_S^0$ ,  $\psi(2S)K_S^0$ ,  $\chi_{c1}K_S^0$ ,  $\eta_c K_S^0$ , and  $J/\psi K^{*0}(K^{*0} \rightarrow K_S^0\pi^0)$ , and b)  $\Delta E$  for the final state  $J/\psi K_L^0$ .

TABLE II: Number of events  $N_{\text{tag}}$  in the signal region after tagging and vertexing requirements, signal purity  $P$ , and results of fitting for  $CP$  asymmetries in the  $B_{CP}$  sample and in various subsamples, as well as in the  $B_{\text{flav}}$  and charged  $B$  control samples. Errors are statistical only.

Sample	$N_{\text{tag}}$	$P(\%)$	$\sin 2\beta$
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0, \eta_c K_S^0$	1506	94	$0.76 \pm 0.07$
$J/\psi K_L^0$ ( $\eta_f = +1$ )	988	55	$0.72 \pm 0.16$
$J/\psi K^{*0}$ ( $K^{*0} \rightarrow K_S^0 \pi^0$ )	147	81	$0.22 \pm 0.52$
Full $CP$ sample	2641	78	$0.74 \pm 0.07$
<hr/>			
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0, \eta_c K_S^0$ only ( $\eta_f = -1$ )			
$J/\psi K_S^0$ ( $K_S^0 \rightarrow \pi^+ \pi^-$ )	974	97	$0.82 \pm 0.08$
$J/\psi K_S^0$ ( $K_S^0 \rightarrow \pi^0 \pi^0$ )	170	89	$0.39 \pm 0.24$
$\psi(2S)K_S^0$ ( $K_S^0 \rightarrow \pi^+ \pi^-$ )	150	97	$0.69 \pm 0.24$
$\chi_{c1}K_S^0$	80	95	$1.01 \pm 0.40$
$\eta_c K_S^0$	132	73	$0.59 \pm 0.32$
Lepton category	220	98	$0.79 \pm 0.11$
Kaon I category	400	93	$0.78 \pm 0.12$
Kaon II category	444	93	$0.73 \pm 0.17$
Inclusive category	442	92	$0.45 \pm 0.28$
$B^0$ tags	740	94	$0.76 \pm 0.10$
$\bar{B}^0$ tags	766	93	$0.75 \pm 0.10$
<hr/>			
$B_{\text{flav}}$ sample	25375	85	$0.02 \pm 0.02$
$B^+$ sample	22160	89	$0.02 \pm 0.02$

$B^0$  mesons. The observed amplitudes for the  $CP$  asymmetry in the  $B_{CP}$  sample and for flavor oscillation in the  $B_{\text{flav}}$  sample are reduced by the same factor  $1 - 2w$  due to flavor mistags. Events are assigned signal and background probabilities based on the  $m_{\text{ES}}$  (all modes except  $J/\psi K^{*0}$  and  $J/\psi K_L^0$ ) or  $\Delta E$  ( $J/\psi K_L^0$ ) distributions. The  $\Delta t$  distributions for the signal are convolved with a common resolution function, modeled by the sum of three Gaussians [6]. Backgrounds are incorporated with an empirical description of their  $\Delta t$  spectrum, containing prompt and non-prompt components convolved with a resolution function [6] distinct from that of the signal.

There are 34 free parameters in the fit:  $\sin 2\beta$  (1), the average mistag fractions  $w$  and the differences  $\Delta w$  between  $B^0$  and  $\bar{B}^0$  mistag fractions for each tagging category (8), parameters for the signal  $\Delta t$  resolution (8), and parameters for background time dependence (6),  $\Delta t$  resolution (3), and mistag fractions (8). We fix  $\tau_{B^0} = 1.542 \text{ ps}$  and  $\Delta m_d = 0.489 \text{ ps}^{-1}$  [11]. The determination of the mistag fractions and  $\Delta t$  resolution function parameters for the signal is dominated by the high-statistics  $B_{\text{flav}}$  sample. The measured mistag fractions are listed in Table I. Background parameters are determined from events with  $m_{\text{ES}} < 5.27 \text{ GeV}/c^2$  (except  $J/\psi K_L^0$  and  $J/\psi K^{*0}$ ). The largest correlation between  $\sin 2\beta$  and any linear combination of the other free parameters is 0.13. We observe a bias of  $0.014 \pm 0.005$  in the fitted value of  $\sin 2\beta$  in simulated events. Part of this bias (0.004) is due to a correlation between the mistag fractions and the  $\Delta t$  resolution not explicitly incorpo-

rated in the fit. Therefore we subtract 0.014 from the fitted value of  $\sin 2\beta$  in data and include 0.010 in the systematic error.

The fit to the  $B_{CP}$  and  $B_{\text{flav}}$  samples yields

$$\sin 2\beta = 0.741 \pm 0.067 \text{ (stat)} \pm 0.034 \text{ (syst)}.$$

Figure 2 shows the  $\Delta t$  distributions and asymmetries in yields between  $B^0$  tags and  $\bar{B}^0$  tags for the  $\eta_f = -1$  and  $\eta_f = +1$  samples as a function of  $\Delta t$ , overlaid with the projection of the likelihood fit result.

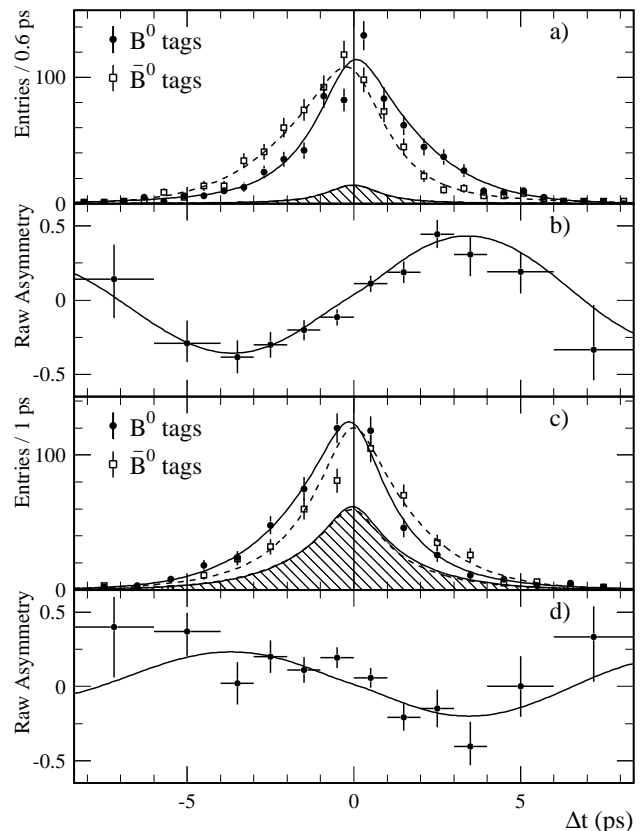


FIG. 2: a) Number of  $\eta_f = -1$  candidates ( $J/\psi K_S^0$ ,  $\psi(2S)K_S^0$ ,  $\chi_{c1}K_S^0$ , and  $\eta_c K_S^0$ ) in the signal region with a  $B^0$  tag  $N_{B^0}$  and with a  $\bar{B}^0$  tag  $N_{\bar{B}^0}$ , and b) the raw asymmetry  $(N_{B^0} - N_{\bar{B}^0}) / (N_{B^0} + N_{\bar{B}^0})$  as functions of  $\Delta t$ . The solid (dashed) curves represent the fit projection in  $\Delta t$  for  $B^0$  ( $\bar{B}^0$ ) tags. The shaded regions represent the background contributions. Figures c) and d) contain the corresponding information for the  $\eta_f = +1$  mode  $J/\psi K_L^0$ .

The dominant sources of systematic error are the uncertainties in the level, composition, and  $CP$  asymmetry of the background in the selected  $CP$  events (0.023), the assumed parameterization of the  $\Delta t$  resolution function (0.017), due in part to residual uncertainties in the internal alignment of the vertex detector, and possible differences between the  $B_{\text{flav}}$  and  $B_{CP}$  mistag fractions (0.012). The total systematic error is 0.034. Most sys-

tematic errors are determined with data and will continue to decrease with additional statistics.

The large  $B_{CP}$  sample allows a number of consistency checks, including separation of the data by decay mode, tagging category, and  $B_{\text{tag}}$  flavor. The results of fits to these  $\eta_f = -1$  subsamples are shown in Table II and found to be statistically consistent. The results of fits to the control samples of non- $CP$  decay modes indicate no statistically significant asymmetry.

We also measure the parameter  $|\lambda|$  in Eq. 1 from a fit to the  $\eta_f = -1$  sample, which has high purity and requires minimal assumptions on the effect of backgrounds. This parameter is sensitive to the difference in the number of  $B^0$ - and  $\bar{B}^0$ -tagged events. In order to account for differences in reconstruction and tagging efficiencies for  $B^0$  and  $\bar{B}^0$  mesons, we incorporate five additional free parameters in this fit. We obtain  $|\lambda| = 0.948 \pm 0.051$  (stat)  $\pm 0.030$  (syst). The coefficient of the  $\sin(\Delta m_d \Delta t)$  term in Eq. 1 is measured to be  $0.759 \pm 0.074$  (stat). The dominant contribution to the systematic error for  $|\lambda|$ , conservatively estimated to be 0.025, is due to interference between the suppressed  $\bar{b} \rightarrow \bar{u}c\bar{d}$  amplitude with the favored  $b \rightarrow c\bar{u}d$  amplitude for some tag-side  $B$  decays. The other sources of systematic error for  $|\lambda|$  are the same as in the  $\sin 2\beta$  measurement.

This measurement of  $\sin 2\beta$  supersedes our previous result [3] and improves upon the precision of each of the previous measurements [3, 4] by a factor of two. While the measured value is consistent with the range implied by the measurements and theoretical estimates of the magnitudes of CKM matrix elements in the context of the Standard Model, it provides a precise and model-independent constraint on the position of the apex of the Unitarity Triangle [12].

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the comput-

ing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

- 
- \* Also with Università di Perugia, I-06100 Perugia, Italy
- [1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Th. Phys. **49**, 652 (1973).
  - [2] A.B. Carter and A.I. Sanda, Phys. Rev. **D23**, 1567 (1981); I.I. Bigi and A.I. Sanda, Nucl. Phys. **B193**, 85 (1981).
  - [3] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 091801 (2001).
  - [4] BELLE Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **87**, 091802 (2001).
  - [5] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instr. and Methods **A479**, 1 (2002).
  - [6] *BABAR* Collaboration, B. Aubert *et al.*, SLAC-PUB-9060, hep-ex/0201020, to appear in Phys. Rev. D .
  - [7] Charge conjugation is implied throughout this letter, unless explicitly stated.
  - [8] See, for example, L. Wolfenstein, Phys. Rev. **D66**, 010001 (2002).
  - [9] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 241801 (2001).
  - [10] *BABAR* Collaboration, B. Aubert *et al.*, SLAC-PUB-9170, hep-ex/0203040.
  - [11] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. **D66**, 010001 (2002).
  - [12] See, for example, F.J. Gilman, K. Kleinknecht and B. Renk, Phys. Rev. **D66**, 010001 (2002)