

## Measurement of $CP$ asymmetries in $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ decays

B. Aubert,<sup>1</sup> M. Bona,<sup>1</sup> D. Boutigny,<sup>1</sup> Y. Karyotakis,<sup>1</sup> J. P. Lees,<sup>1</sup> V. Poireau,<sup>1</sup> X. Prudent,<sup>1</sup> V. Tisserand,<sup>1</sup> A. Zghiche,<sup>1</sup> J. Garra Tico,<sup>2</sup> E. Grauges,<sup>2</sup> L. Lopez,<sup>3</sup> A. Palano,<sup>3</sup> G. Eigen,<sup>4</sup> I. Ofte,<sup>4</sup> B. Stugu,<sup>4</sup> L. Sun,<sup>4</sup> G. S. Abrams,<sup>5</sup> M. Battaglia,<sup>5</sup> D. N. Brown,<sup>5</sup> J. Button-Shafer,<sup>5</sup> R. N. Cahn,<sup>5</sup> Y. Groyzman,<sup>5</sup> R. G. Jacobsen,<sup>5</sup> J. A. Kadyk,<sup>5</sup> L. T. Kerth,<sup>5</sup> Yu. G. Kolomensky,<sup>5</sup> G. Kukartsev,<sup>5</sup> D. Lopes Pegna,<sup>5</sup> G. Lynch,<sup>5</sup> L. M. Mir,<sup>5</sup> T. J. Orimoto,<sup>5</sup> M. Pripstein,<sup>5</sup> N. A. Roe,<sup>5</sup> M. T. Ronan,<sup>5,\*</sup> K. Tackmann,<sup>5</sup> W. A. Wenzel,<sup>5</sup> P. del Amo Sanchez,<sup>6</sup> C. M. Hawkes,<sup>6</sup> A. T. Watson,<sup>6</sup> T. Held,<sup>7</sup> H. Koch,<sup>7</sup> B. Lewandowski,<sup>7</sup> M. Pelizaeus,<sup>7</sup> T. Schroeder,<sup>7</sup> M. Steinke,<sup>7</sup> J. T. Boyd,<sup>8</sup> J. P. Burke,<sup>8</sup> W. N. Cottingham,<sup>8</sup> D. Walker,<sup>8</sup> D. J. Asgeirsson,<sup>9</sup> T. Cuhadar-Donszelmann,<sup>9</sup> B. G. Fulsom,<sup>9</sup> C. Hearty,<sup>9</sup> N. S. Knecht,<sup>9</sup> T. S. Mattison,<sup>9</sup> J. A. McKenna,<sup>9</sup> A. Khan,<sup>10</sup> M. Saleem,<sup>10</sup> L. Teodorescu,<sup>10</sup> V. E. Blinov,<sup>11</sup> A. D. Bukin,<sup>11</sup> V. P. Druzhinin,<sup>11</sup> V. B. Golubev,<sup>11</sup> A. P. Onuchin,<sup>11</sup> S. I. Serednyakov,<sup>11</sup> Yu. I. Skovpen,<sup>11</sup> E. P. Solodov,<sup>11</sup> K. Yu Todyshev,<sup>11</sup> M. Bondioli,<sup>12</sup> M. Bruinsma,<sup>12</sup> S. Curry,<sup>12</sup> I. Eschrich,<sup>12</sup> D. Kirkby,<sup>12</sup> A. J. Lankford,<sup>12</sup> P. Lund,<sup>12</sup> M. Mandelkern,<sup>12</sup> E. C. Martin,<sup>12</sup> D. P. Stoker,<sup>12</sup> S. Abachi,<sup>13</sup> C. Buchanan,<sup>13</sup> S. D. Foulkes,<sup>14</sup> J. W. Gary,<sup>14</sup> F. Liu,<sup>14</sup> O. Long,<sup>14</sup> B. C. Shen,<sup>14</sup> L. Zhang,<sup>14</sup> H. P. Paar,<sup>15</sup> S. Rahatlou,<sup>15</sup> V. Sharma,<sup>15</sup> J. W. Berryhill,<sup>16</sup> C. Campagnari,<sup>16</sup> A. Cunha,<sup>16</sup> B. Dahmes,<sup>16</sup> T. M. Hong,<sup>16</sup> D. Kovalskiy,<sup>16</sup> J. D. Richman,<sup>16</sup> T. W. Beck,<sup>17</sup> A. M. Eisner,<sup>17</sup> C. J. Flacco,<sup>17</sup> C. A. Heusch,<sup>17</sup> J. Kroseberg,<sup>17</sup> W. S. Lockman,<sup>17</sup> T. Schalk,<sup>17</sup> B. A. Schumm,<sup>17</sup> A. Seiden,<sup>17</sup> D. C. Williams,<sup>17</sup> M. G. Wilson,<sup>17</sup> L. O. Winstrom,<sup>17</sup> E. Chen,<sup>18</sup> C. H. Cheng,<sup>18</sup> A. Dvoretzkii,<sup>18</sup> F. Fang,<sup>18</sup> D. G. Hitlin,<sup>18</sup> I. Narsky,<sup>18</sup> T. Piatenko,<sup>18</sup> F. C. Porter,<sup>18</sup> G. Mancinelli,<sup>19</sup> B. T. Meadows,<sup>19</sup> K. Mishra,<sup>19</sup> M. D. Sokoloff,<sup>19</sup> F. Blanc,<sup>20</sup> P. C. Bloom,<sup>20</sup> S. Chen,<sup>20</sup> W. T. Ford,<sup>20</sup> J. F. Hirschauer,<sup>20</sup> A. Kreisel,<sup>20</sup> M. Nagel,<sup>20</sup> U. Nauenberg,<sup>20</sup> A. Olivas,<sup>20</sup> J. G. Smith,<sup>20</sup> K. A. Ulmer,<sup>20</sup> S. R. Wagner,<sup>20</sup> J. Zhang,<sup>20</sup> A. Chen,<sup>21</sup> E. A. Eckhart,<sup>21</sup> A. Soffer,<sup>21</sup> W. H. Toki,<sup>21</sup> R. J. Wilson,<sup>21</sup> F. Winklmeier,<sup>21</sup> Q. Zeng,<sup>21</sup> D. D. Altenburg,<sup>22</sup> E. Feltresi,<sup>22</sup> A. Hauke,<sup>22</sup> H. Jasper,<sup>22</sup> J. Merkel,<sup>22</sup> A. Petzold,<sup>22</sup> B. Spaan,<sup>22</sup> K. Wacker,<sup>22</sup> T. Brandt,<sup>23</sup> V. Klose,<sup>23</sup> H. M. Lacker,<sup>23</sup> W. F. Mader,<sup>23</sup> R. Nogowski,<sup>23</sup> J. Schubert,<sup>23</sup> K. R. Schubert,<sup>23</sup> R. Schwierz,<sup>23</sup> J. E. Sundermann,<sup>23</sup> A. Volk,<sup>23</sup> D. Bernard,<sup>24</sup> G. R. Bonneaud,<sup>24</sup> E. Latour,<sup>24</sup> Ch. Thiebaux,<sup>24</sup> M. Verderi,<sup>24</sup> P. J. Clark,<sup>25</sup> W. Gradl,<sup>25</sup> F. Muheim,<sup>25</sup> S. Playfer,<sup>25</sup> A. I. Robertson,<sup>25</sup> Y. Xie,<sup>25</sup> M. Andreotti,<sup>26</sup> D. Bettoni,<sup>26</sup> C. Bozzi,<sup>26</sup> R. Calabrese,<sup>26</sup> A. Cecchi,<sup>26</sup> G. Cibinetto,<sup>26</sup> P. Franchini,<sup>26</sup> E. Luppi,<sup>26</sup> M. Negrini,<sup>26</sup> A. Petrella,<sup>26</sup> L. Piemontese,<sup>26</sup> E. Prencipe,<sup>26</sup> V. Santoro,<sup>26</sup> F. Anulli,<sup>27</sup> R. Baldini-Feroli,<sup>27</sup> A. Calcaterra,<sup>27</sup> R. de Sangro,<sup>27</sup> G. Finocchiaro,<sup>27</sup> S. Pacetti,<sup>27</sup> P. Patteri,<sup>27</sup> I. M. Peruzzi,<sup>27,†</sup> M. Piccolo,<sup>27</sup> M. Rama,<sup>27</sup> A. Zallo,<sup>27</sup> A. Buzzo,<sup>28</sup> R. Contri,<sup>28</sup> M. Lo Vetere,<sup>28</sup> M. M. Macri,<sup>28</sup> M. R. Monge,<sup>28</sup> S. Passaggio,<sup>28</sup> C. Patrignani,<sup>28</sup> E. Robutti,<sup>28</sup> A. Santroni,<sup>28</sup> S. Tosi,<sup>28</sup> K. S. Chaisanguanthum,<sup>29</sup> M. Morii,<sup>29</sup> J. Wu,<sup>29</sup> R. S. Dubitzky,<sup>30</sup> J. Marks,<sup>30</sup> S. Schenk,<sup>30</sup> U. Uwer,<sup>30</sup> D. J. Bard,<sup>31</sup> P. D. Dauncey,<sup>31</sup> R. L. Flack,<sup>31</sup> J. A. Nash,<sup>31</sup> M. B. Nikolich,<sup>31</sup> W. Panduro Vazquez,<sup>31</sup> P. K. Behera,<sup>32</sup> X. Chai,<sup>32</sup> M. J. Charles,<sup>32</sup> U. Mallik,<sup>32</sup> N. T. Meyer,<sup>32</sup> V. Ziegler,<sup>32</sup> J. Cochran,<sup>33</sup> H. B. Crawley,<sup>33</sup> L. Dong,<sup>33</sup> V. Eyges,<sup>33</sup> W. T. Meyer,<sup>33</sup> S. Prell,<sup>33</sup> E. I. Rosenberg,<sup>33</sup> A. E. Rubin,<sup>33</sup> A. V. Gritsan,<sup>34</sup> C. K. Lae,<sup>34</sup> A. G. Denig,<sup>35</sup> M. Fritsch,<sup>35</sup> G. Schott,<sup>35</sup> N. Arnaud,<sup>36</sup> J. Béquilleux,<sup>36</sup> M. Davier,<sup>36</sup> G. Grosdidier,<sup>36</sup> A. Höcker,<sup>36</sup> V. Lepeltier,<sup>36</sup> F. Le Diberder,<sup>36</sup> A. M. Lutz,<sup>36</sup> S. Pruvot,<sup>36</sup> S. Rodier,<sup>36</sup> P. Roudeau,<sup>36</sup> M. H. Schune,<sup>36</sup> J. Serrano,<sup>36</sup> V. Sordini,<sup>36</sup> A. Stocchi,<sup>36</sup> W. F. Wang,<sup>36</sup> G. Wormser,<sup>36</sup> D. J. Lange,<sup>37</sup> D. M. Wright,<sup>37</sup> C. A. Chavez,<sup>38</sup> I. J. Forster,<sup>38</sup> J. R. Fry,<sup>38</sup> E. Gabathuler,<sup>38</sup> R. Gamet,<sup>38</sup> D. E. Hutchcroft,<sup>38</sup> D. J. Payne,<sup>38</sup> K. C. Schofield,<sup>38</sup> C. Touramanis,<sup>38</sup> A. J. Bevan,<sup>39</sup> K. A. George,<sup>39</sup> F. Di Lodovico,<sup>39</sup> W. Menges,<sup>39</sup> R. Sacco,<sup>39</sup> G. Cowan,<sup>40</sup> H. U. Flaecher,<sup>40</sup> D. A. Hopkins,<sup>40</sup> P. S. Jackson,<sup>40</sup> T. R. McMahon,<sup>40</sup> F. Salvatore,<sup>40</sup> A. C. Wren,<sup>40</sup> D. N. Brown,<sup>41</sup> C. L. Davis,<sup>41</sup> J. Allison,<sup>42</sup> N. R. Barlow,<sup>42</sup> R. J. Barlow,<sup>42</sup> Y. M. Chia,<sup>42</sup> C. L. Edgar,<sup>42</sup> G. D. Lafferty,<sup>42</sup> T. J. West,<sup>42</sup> J. I. Yi,<sup>42</sup> J. Anderson,<sup>43</sup> C. Chen,<sup>43</sup> A. Jawahery,<sup>43</sup> D. A. Roberts,<sup>43</sup> G. Simi,<sup>43</sup> J. M. Tuggle,<sup>43</sup> G. Blaylock,<sup>44</sup> C. Dallapiccola,<sup>44</sup> S. S. Hertzbach,<sup>44</sup> X. Li,<sup>44</sup> T. B. Moore,<sup>44</sup> E. Salvati,<sup>44</sup> S. Saremi,<sup>44</sup> R. Cowan,<sup>45</sup> P. H. Fisher,<sup>45</sup> G. Sciolla,<sup>45</sup> S. J. Sekula,<sup>45</sup> M. Spitznagel,<sup>45</sup> F. Taylor,<sup>45</sup> R. K. Yamamoto,<sup>45</sup> H. Kim,<sup>46</sup> S. E. Mclachlin,<sup>46</sup> P. M. Patel,<sup>46</sup> S. H. Robertson,<sup>46</sup> A. Lazzaro,<sup>47</sup> V. Lombardo,<sup>47</sup> F. Palombo,<sup>47</sup> J. M. Bauer,<sup>48</sup> L. Cremaldi,<sup>48</sup> V. Eschenburg,<sup>48</sup> R. Godang,<sup>48</sup> R. Kroeger,<sup>48</sup> D. A. Sanders,<sup>48</sup> D. J. Summers,<sup>48</sup> H. W. Zhao,<sup>48</sup> S. Brunet,<sup>49</sup> D. Côté,<sup>49</sup> M. Simard,<sup>49</sup> P. Taras,<sup>49</sup> F. B. Viaud,<sup>49</sup> H. Nicholson,<sup>50</sup> G. De Nardo,<sup>51</sup> F. Fabozzi,<sup>51,‡</sup> L. Lista,<sup>51</sup> D. Monorchio,<sup>51</sup> C. Sciacca,<sup>51</sup> M. A. Baak,<sup>52</sup> G. Raven,<sup>52</sup> H. L. Snoek,<sup>52</sup> C. P. Jessop,<sup>53</sup> J. M. LoSecco,<sup>53</sup> G. Benelli,<sup>54</sup> L. A. Corwin,<sup>54</sup> K. K. Gan,<sup>54</sup> K. Honscheid,<sup>54</sup> D. Hufnagel,<sup>54</sup> H. Kagan,<sup>54</sup> R. Kass,<sup>54</sup> J. P. Morris,<sup>54</sup> A. M. Rahimi,<sup>54</sup> J. J. Regensburger,<sup>54</sup> R. Ter-Antonyan,<sup>54</sup> Q. K. Wong,<sup>54</sup> N. L. Blount,<sup>55</sup> J. Brau,<sup>55</sup> R. Frey,<sup>55</sup> O. Igonkina,<sup>55</sup> J. A. Kolb,<sup>55</sup> M. Lu,<sup>55</sup> R. Rahmat,<sup>55</sup> N. B. Sinev,<sup>55</sup> D. Strom,<sup>55</sup> J. Strube,<sup>55</sup> E. Torrence,<sup>55</sup> N. Gagliardi,<sup>56</sup> A. Gaz,<sup>56</sup> M. Margoni,<sup>56</sup> M. Morandin,<sup>56</sup> A. Pompili,<sup>56</sup> M. Posocco,<sup>56</sup> M. Rotondo,<sup>56</sup> F. Simonetto,<sup>56</sup> R. Stroili,<sup>56</sup> C. Voci,<sup>56</sup> E. Ben-Haim,<sup>57</sup> H. Briand,<sup>57</sup> J. Chauveau,<sup>57</sup> P. David,<sup>57</sup> L. Del Buono,<sup>57</sup> Ch. de la Vaissière,<sup>57</sup> O. Hamon,<sup>57</sup> B. L. Hartfiel,<sup>57</sup> Ph. Leruste,<sup>57</sup> J. Malclès,<sup>57</sup> J. Ocariz,<sup>57</sup> A. Perez,<sup>57</sup> L. Gladney,<sup>58</sup> M. Biasini,<sup>59</sup> R. Covarelli,<sup>59</sup> E. Manoni,<sup>59</sup> C. Angelini,<sup>60</sup> G. Batignani,<sup>60</sup>

S. Bettarini,<sup>60</sup> G. Calderini,<sup>60</sup> M. Carpinelli,<sup>60</sup> R. Cenci,<sup>60</sup> F. Forti,<sup>60</sup> M. A. Giorgi,<sup>60</sup> A. Lusiani,<sup>60</sup> G. Marchiori,<sup>60</sup> M. A. Mazur,<sup>60</sup> M. Morganti,<sup>60</sup> N. Neri,<sup>60</sup> E. Paoloni,<sup>60</sup> G. Rizzo,<sup>60</sup> J. J. Walsh,<sup>60</sup> M. Haire,<sup>61</sup> J. Biesiada,<sup>62</sup> P. Elmer,<sup>62</sup> Y. P. Lau,<sup>62</sup> C. Lu,<sup>62</sup> J. Olsen,<sup>62</sup> A. J. S. Smith,<sup>62</sup> A. V. Telnov,<sup>62</sup> E. Baracchini,<sup>63</sup> F. Bellini,<sup>63</sup> G. Cavoto,<sup>63</sup> A. D'Orazio,<sup>63</sup> D. del Re,<sup>63</sup> E. Di Marco,<sup>63</sup> R. Faccini,<sup>63</sup> F. Ferrarotto,<sup>63</sup> F. Ferroni,<sup>63</sup> M. Gaspero,<sup>63</sup> P. D. Jackson,<sup>63</sup> L. Li Gioi,<sup>63</sup> M. A. Mazzoni,<sup>63</sup> S. Morganti,<sup>63</sup> G. Piredda,<sup>63</sup> F. Polci,<sup>63</sup> F. Renga,<sup>63</sup> C. Voena,<sup>63</sup> M. Ebert,<sup>64</sup> H. Schröder,<sup>64</sup> R. Waldi,<sup>64</sup> T. Adye,<sup>65</sup> G. Castelli,<sup>65</sup> B. Franek,<sup>65</sup> E. O. Olaiya,<sup>65</sup> S. Ricciardi,<sup>65</sup> W. Roethel,<sup>65</sup> F. F. Wilson,<sup>65</sup> R. Aleksan,<sup>66</sup> S. Emery,<sup>66</sup> M. Escalier,<sup>66</sup> A. Gaidot,<sup>66</sup> S. F. Ganzhur,<sup>66</sup> G. Hamel de Monchenault,<sup>66</sup> W. Kozanecki,<sup>66</sup> M. Legendre,<sup>66</sup> G. Vasseur,<sup>66</sup> Ch. Yèche,<sup>66</sup> M. Zito,<sup>66</sup> X. R. Chen,<sup>67</sup> H. Liu,<sup>67</sup> W. Park,<sup>67</sup> M. V. Purohit,<sup>67</sup> J. R. Wilson,<sup>67</sup> M. T. Allen,<sup>68</sup> D. Aston,<sup>68</sup> R. Bartoldus,<sup>68</sup> P. Bechtel,<sup>68</sup> N. Berger,<sup>68</sup> R. Claus,<sup>68</sup> J. P. Coleman,<sup>68</sup> M. R. Convery,<sup>68</sup> J. C. Dingfelder,<sup>68</sup> J. Dorfan,<sup>68</sup> G. P. Dubois-Felsmann,<sup>68</sup> D. Dujmic,<sup>68</sup> W. Dunwoodie,<sup>68</sup> R. C. Field,<sup>68</sup> T. Glanzman,<sup>68</sup> S. J. Gowdy,<sup>68</sup> M. T. Graham,<sup>68</sup> P. Grenier,<sup>68</sup> V. Halyo,<sup>68</sup> C. Hast,<sup>68</sup> T. Hryn'ova,<sup>68</sup> W. R. Innes,<sup>68</sup> M. H. Kelsey,<sup>68</sup> P. Kim,<sup>68</sup> D. W. G. S. Leith,<sup>68</sup> S. Li,<sup>68</sup> S. Luitz,<sup>68</sup> V. Luth,<sup>68</sup> H. L. Lynch,<sup>68</sup> D. B. MacFarlane,<sup>68</sup> H. Marsiske,<sup>68</sup> R. Messner,<sup>68</sup> D. R. Muller,<sup>68</sup> C. P. O'Grady,<sup>68</sup> V. E. Ozcan,<sup>68</sup> A. Perazzo,<sup>68</sup> M. Perl,<sup>68</sup> T. Pulliam,<sup>68</sup> B. N. Ratcliff,<sup>68</sup> A. Roodman,<sup>68</sup> A. A. Salnikov,<sup>68</sup> R. H. Schindler,<sup>68</sup> J. Schwiening,<sup>68</sup> A. Snyder,<sup>68</sup> J. Stelzer,<sup>68</sup> D. Su,<sup>68</sup> M. K. Sullivan,<sup>68</sup> K. Suzuki,<sup>68</sup> S. K. Swain,<sup>68</sup> J. M. Thompson,<sup>68</sup> J. Va'vra,<sup>68</sup> N. van Bakel,<sup>68</sup> A. P. Wagner,<sup>68</sup> M. Weaver,<sup>68</sup> W. J. Wisniewski,<sup>68</sup> M. Wittgen,<sup>68</sup> D. H. Wright,<sup>68</sup> A. K. Yarritu,<sup>68</sup> K. Yi,<sup>68</sup> C. C. Young,<sup>68</sup> P. R. Burchat,<sup>69</sup> A. J. Edwards,<sup>69</sup> S. A. Majewski,<sup>69</sup> B. A. Petersen,<sup>69</sup> L. Wilden,<sup>69</sup> S. Ahmed,<sup>70</sup> M. S. Alam,<sup>70</sup> R. Bula,<sup>70</sup> J. A. Ernst,<sup>70</sup> V. Jain,<sup>70</sup> B. Pan,<sup>70</sup> M. A. Saeed,<sup>70</sup> F. R. Wappler,<sup>70</sup> S. B. Zain,<sup>70</sup> W. Bugg,<sup>71</sup> M. Krishnamurthy,<sup>71</sup> S. M. Spanier,<sup>71</sup> R. Eckmann,<sup>72</sup> J. L. Ritchie,<sup>72</sup> A. M. Ruland,<sup>72</sup> C. J. Schilling,<sup>72</sup> R. F. Schwitters,<sup>72</sup> J. M. Izen,<sup>73</sup> X. C. Lou,<sup>73</sup> S. Ye,<sup>73</sup> F. Bianchi,<sup>74</sup> F. Gallo,<sup>74</sup> D. Gamba,<sup>74</sup> M. Pelliccioni,<sup>74</sup> M. Bomben,<sup>75</sup> L. Bosisio,<sup>75</sup> C. Cartaro,<sup>75</sup> F. Cossutti,<sup>75</sup> G. Della Ricca,<sup>75</sup> L. Lanceri,<sup>75</sup> L. Vitale,<sup>75</sup> V. Azzolini,<sup>76</sup> N. Lopez-March,<sup>76</sup> F. Martinez-Vidal,<sup>76</sup> D. A. Milanes,<sup>76</sup> A. Oyanguren,<sup>76</sup> J. Albert,<sup>77</sup> Sw. Banerjee,<sup>77</sup> B. Bhuyan,<sup>77</sup> K. Hamano,<sup>77</sup> R. Kowalewski,<sup>77</sup> I. M. Nugent,<sup>77</sup> J. M. Roney,<sup>77</sup> R. J. Sobie,<sup>77</sup> J. J. Back,<sup>78</sup> P. F. Harrison,<sup>78</sup> T. E. Latham,<sup>78</sup> G. B. Mohanty,<sup>78</sup> M. Pappagallo,<sup>78,8</sup> H. R. Band,<sup>79</sup> X. Chen,<sup>79</sup> S. Dasu,<sup>79</sup> K. T. Flood,<sup>79</sup> J. J. Hollar,<sup>79</sup> P. E. Kutter,<sup>79</sup> Y. Pan,<sup>79</sup> M. Pierini,<sup>79</sup> R. Prepost,<sup>79</sup> S. L. Wu,<sup>79</sup> Z. Yu,<sup>79</sup> and H. Neal<sup>80</sup>

(BABAR Collaboration)

<sup>1</sup>Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

<sup>2</sup>Facultat de Fisica, Departament ECM, Universitat de Barcelona, E-08028 Barcelona, Spain

<sup>3</sup>Dipartimento di Fisica and INFN, Università di Bari, I-70126 Bari, Italy

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

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

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

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

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

<sup>9</sup>University of British Columbia, Vancouver, British Columbia, 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, California 92697, USA

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

<sup>14</sup>University of California at Riverside, Riverside, California 92521, USA

<sup>15</sup>University of California at San Diego, La Jolla, California 92093, USA

<sup>16</sup>University of California at Santa Barbara, Santa Barbara, California 93106, USA

<sup>17</sup>Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA

<sup>18</sup>California Institute of Technology, Pasadena, California 91125, USA

<sup>19</sup>University of Cincinnati, Cincinnati, Ohio 45221, USA

<sup>20</sup>University of Colorado, Boulder, Colorado 80309, USA

<sup>21</sup>Colorado State University, Fort Collins, Colorado 80523, USA

<sup>22</sup>Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany

<sup>23</sup>Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden, Germany

<sup>24</sup>Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

<sup>25</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

<sup>26</sup>Dipartimento di Fisica and INFN, Università di Ferrara, I-44100 Ferrara, Italy

<sup>27</sup>Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

<sup>28</sup>Dipartimento di Fisica and INFN, Università di Genova, I-16146 Genova, Italy

<sup>29</sup>Harvard University, Cambridge, Massachusetts 02138, USA

- <sup>30</sup>*Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany*
- <sup>31</sup>*Imperial College London, London, SW7 2AZ, United Kingdom*
- <sup>32</sup>*University of Iowa, Iowa City, Iowa 52242, USA*
- <sup>33</sup>*Iowa State University, Ames, Iowa 50011-3160, USA*
- <sup>34</sup>*Johns Hopkins University, Baltimore, Maryland 21218, USA*
- <sup>35</sup>*Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany*
- <sup>36</sup>*Laboratoire de l'Accélérateur Linéaire, Centre Scientifique d'Orsay, IN2P3/CNRS et Université Paris-Sud 11, B. P. 34, F-91898 Orsay Cedex, France*
- <sup>37</sup>*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
- <sup>38</sup>*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
- <sup>39</sup>*Queen Mary, University of London, E1 4NS, United Kingdom*
- <sup>40</sup>*Royal Holloway and Bedford New College, University of London, Egham, Surrey TW20 0EX, United Kingdom*
- <sup>41</sup>*University of Louisville, Louisville, Kentucky 40292, USA*
- <sup>42</sup>*University of Manchester, Manchester M13 9PL, United Kingdom*
- <sup>43</sup>*University of Maryland, College Park, Maryland 20742, USA*
- <sup>44</sup>*University of Massachusetts, Amherst, Massachusetts 01003, USA*
- <sup>45</sup>*Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
- <sup>46</sup>*McGill University, Montréal, Québec, Canada H3A 2T8*
- <sup>47</sup>*Dipartimento di Fisica and INFN, Università di Milano, I-20133 Milano, Italy*
- <sup>48</sup>*University of Mississippi, University, Mississippi 38677, USA*
- <sup>49</sup>*Physique des Particules, Université de Montréal, Montréal, Québec, Canada H3C 3J7*
- <sup>50</sup>*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
- <sup>51</sup>*Dipartimento di Scienze Fisiche and INFN, Università di Napoli Federico II, I-80126, Napoli, Italy*
- <sup>52</sup>*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*
- <sup>53</sup>*University of Notre Dame, Notre Dame, Indiana 46556, USA*
- <sup>54</sup>*Ohio State University, Columbus, Ohio 43210, USA*
- <sup>55</sup>*University of Oregon, Eugene, Oregon 97403, USA*
- <sup>56</sup>*Dipartimento di Fisica and INFN, Università di Padova, I-35131 Padova, Italy*
- <sup>57</sup>*Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France*
- <sup>58</sup>*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
- <sup>59</sup>*Dipartimento di Fisica and INFN, Università di Perugia, Perugia, Italy*
- <sup>60</sup>*Dipartimento di Fisica, Scuola Normale Superiore and INFN, Università di Pisa, I-56127 Pisa, Italy*
- <sup>61</sup>*Prairie View A&M University, Prairie View, Texas 77446, USA*
- <sup>62</sup>*Princeton University, Princeton, New Jersey 08544, USA*
- <sup>63</sup>*Dipartimento di Fisica and INFN, Università di Roma La Sapienza, I-00185 Roma, Italy*
- <sup>64</sup>*Universität Rostock, D-18051 Rostock, Germany*
- <sup>65</sup>*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*
- <sup>66</sup>*DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France*
- <sup>67</sup>*University of South Carolina, Columbia, South Carolina 29208, USA*
- <sup>68</sup>*Stanford Linear Accelerator Center, Stanford, California 94309, USA*
- <sup>69</sup>*Stanford University, Stanford, California 94305-4060, USA*
- <sup>70</sup>*State University of New York, Albany, New York 12222, USA*
- <sup>71</sup>*University of Tennessee, Knoxville, Tennessee 37996, USA*
- <sup>72</sup>*University of Texas at Austin, Austin, Texas 78712, USA*
- <sup>73</sup>*University of Texas at Dallas, Richardson, Texas 75083, USA*
- <sup>74</sup>*Dipartimento di Fisica Sperimentale and INFN, Università di Torino, I-10125 Torino, Italy*
- <sup>75</sup>*Dipartimento di Fisica and INFN, Università di Trieste, I-34127 Trieste, Italy*
- <sup>76</sup>*IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain*
- <sup>77</sup>*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
- <sup>78</sup>*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*
- <sup>79</sup>*University of Wisconsin, Madison, Wisconsin 53706, USA*
- <sup>80</sup>*Yale University, New Haven, Connecticut 06511, USA*
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\*Deceased.

†Also at: Dipartimento di Fisica, Università di Perugia, Perugia, Italy.

‡Also at: Università della Basilicata, Potenza, Italy.

§Also at: IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom.

We present measurements of the time-dependent  $CP$ -violating asymmetries in  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  decays based on  $384 \times 10^6$   $Y(4S) \rightarrow B\bar{B}$  decays collected with the *BABAR* detector at the PEP-II asymmetric-energy  $B$  Factory at SLAC. We obtain the  $CP$  asymmetry parameters  $C = 0.02 \pm 0.21 \pm 0.05$  and  $S = -0.71 \pm 0.24 \pm 0.04$ , where the first uncertainties are statistical and the second systematic. These results are consistent with standard model expectations.

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In the standard model (SM) of particle physics, the decays  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  are dominated by the  $b \rightarrow s\bar{s}s$  gluonic penguin amplitude. A large violation of  $CP$  symmetry is predicted by the SM in the proper-time dependence of  $b \rightarrow c\bar{c}s$  decays of neutral  $B$  mesons. Recent measurements of  $CP$  violation in  $b \rightarrow c\bar{c}s$  decays [1] are in good agreement with the SM prediction [2]. The predicted amplitude of this  $CP$  violation (CPV) is  $\sin 2\beta$ , where  $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$  is defined in terms of the elements  $V_{ij}$  of the Cabibbo-Kobayashi-Maskawa (CKM) [3] quark mixing matrix. The SM also predicts that the amplitude of time-dependent CPV in  $b \rightarrow s\bar{q}q$  ( $q = d, s$ ) decays, defined as  $\sin 2\beta_{\text{eff}}$ , is approximately equal to  $\sin 2\beta$ . Contributions from loops involving non-SM particles can give large corrections to the time-dependent CPV amplitudes for these decays. The theoretical uncertainty in the SM prediction of  $\sin 2\beta_{\text{eff}}$  is particularly small, less than 4%, for the decay  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ , which is a pure  $CP$ -even eigenstate [4]. A violation of  $\sin 2\beta_{\text{eff}} \approx \sin 2\beta$  would be a clear sign of physics beyond the SM [5]. In this paper we present a measurement of the time-dependent  $CP$ -violating asymmetries in the decay  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  [6].

The results presented here are based on  $(383.6 \pm 4.2) \times 10^6$   $Y(4S) \rightarrow B\bar{B}$  decays collected with the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$  collider, located at the Stanford Linear Accelerator Center. The *BABAR* detector [7] measures the trajectories of charged particles with a five-layer double-sided silicon microstrip detector (SVT) and a 40-layer central drift chamber (DCH), both operating in a uniform 1.5 T magnetic field. Charged kaons and pions are identified using measurements of particle energy loss in the SVT and DCH, and of the Cherenkov cone angle in a detector of internally reflected Cherenkov light. A segmented CsI(Tl) electromagnetic calorimeter (EMC) provides photon detection and electron identification. Finally, the instrumented flux return of the magnet allows discrimination of muons from pions.

The time-dependent  $CP$  asymmetries are functions of the proper-time difference  $\Delta t \equiv t_{CP} - t_{\text{tag}}$  between a fully reconstructed  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  decay ( $B_{CP}$ ) and the other  $B$  meson decay in the event ( $B_{\text{tag}}$ ), which is partially reconstructed. The decay rate  $f_+$  ( $f_-$ ) when the tagging meson is a  $B^0$  ( $\bar{B}^0$ ) is given as

$$f_{\pm}(\Delta t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 \pm S \sin(\Delta m_d \Delta t) \mp C \cos(\Delta m_d \Delta t)], \quad (1)$$

where  $\tau_{B^0}$  is the  $B^0$  lifetime and  $\Delta m_d$  is the  $B^0 - \bar{B}^0$  mixing frequency. The parameters  $C$  and  $S$  describe the amount of  $CP$  violation in decay and in the interference between decays with and without mixing, respectively. Neglecting CKM-suppressed decay amplitudes, we expect  $S = -\sin 2\beta$  and  $C = 0$  in the SM.

The data are divided into two subsamples, one where all three  $K_S^0$  mesons decay into the  $\pi^+\pi^-$  channel ( $B_{CP(+)}$ ) and another where one of the  $K_S^0$  mesons decays into the  $\pi^0\pi^0$  channel, while the other two decay into the  $\pi^+\pi^-$  channel ( $B_{CP(0)}$ ).

We form  $\pi^0 \rightarrow \gamma\gamma$  candidates from pairs of photon candidates in the EMC. An energy deposit in the EMC is determined to be a photon candidate if no track intersects any of its crystals, it has a minimum energy of 50 MeV, and it has the expected lateral shower shape in the EMC. We reconstruct  $K_S^0 \rightarrow \pi^0\pi^0$  candidates from  $\pi^0$  pairs with an invariant mass in the range  $480 < m_{\pi^0\pi^0} < 520$  MeV/ $c^2$ . We reconstruct  $K_S^0 \rightarrow \pi^+\pi^-$  candidates from pairs of oppositely charged tracks, originating from a common vertex, with an invariant mass within 12 MeV/ $c^2$  (about 4 standard deviations) of the nominal  $K_S^0$  mass [2]. We also require the decay vertex to be along the expected flight path and the significance of the reconstructed flight distance  $\tau_{K_S^0}/\sigma_{\tau_{K_S^0}}$  to be larger than 5.

For each  $B_{CP(+)}$  candidate two nearly independent kinematic variables are computed; the beam-energy-substituted mass  $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$ , and the energy difference  $\Delta E = E_B^* - \sqrt{s}/2$ . Here,  $(E_i, \mathbf{p}_i) \equiv q_{e^+e^-}$  is the four-momentum of the initial  $e^+e^-$  system in the laboratory frame and  $\sqrt{s}$  is the center-of-mass energy, while  $\mathbf{p}_B$  is the reconstructed momentum of the  $B^0$  candidate in the laboratory frame and  $E_B^*$  is its energy calculated in the  $e^+e^-$  rest frame. For each  $B_{CP(0)}$  candidate we use two different kinematic variables. They are the reconstructed  $B^0$  mass  $m_B$  and the missing mass  $m_{\text{miss}} = \sqrt{(q_{e^+e^-} - \tilde{q}_B)^2}$ , where  $\tilde{q}_B$  is the four-momentum of the  $B_{CP(0)}$  candidate after a mass constraint on the  $B^0$  meson has been applied. Because of leakage effects in the EMC, which affect the photon energy measurement and therefore the  $\pi^0$  reconstruction, the shape of the  $m_B$  distribution is asymmetric around the mean value. This results in this combination of variables being less correlated than  $\Delta E$  and  $m_{\text{ES}}$ , with better background suppression [8].

For  $B_{CP}$  signal decays, the  $m_{\text{ES}}$ ,  $m_{\text{miss}}$ , and  $m_B$  distributions peak near the  $B^0$  mass, while the  $\Delta E$  distribu-

tion peaks near zero. For  $B_{CP(+-)}$  candidates, we require  $5.22 < m_{ES} < 5.30 \text{ GeV}/c^2$  and  $|\Delta E| < 120 \text{ MeV}$ . For  $B_{CP(00)}$  candidates, we require  $5.11 < m_{\text{miss}} < 5.31 \text{ GeV}/c^2$  and  $|m_B - m_B^{PDG}| < 150 \text{ MeV}/c^2$ , where  $m_B^{PDG}$  represents the world-average  $B^0$  mass [2]. These selection windows include the signal peak and a ‘‘sideband’’ region which is used for characterization of the background.

The sample of  $B_{CP}$  candidates is dominated by random  $K_S^0 K_S^0 K_S^0$  combinations from  $e^+ e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) fragmentation (the  $q\bar{q}$  continuum). We use topological observables to discriminate jetlike  $e^+ e^- \rightarrow q\bar{q}$  events from the more spherical  $B\bar{B}$  events. In the  $e^+ e^-$  rest frame we compute the angle  $\theta_T^*$  between the thrust axis of the  $B_{CP(+-)}$  ( $B_{CP(00)}$ ) candidate’s decay products and that of the remaining particles in the event. We require  $|\cos\theta_T^*| < 0.90(0.95)$ , which reduces the number of background events by 1 order of magnitude. We also use the Legendre monomials  $L_0$  and  $L_2$ , for the characterization of the event shape [8]. The monomials are combined in a Fisher discriminant  $\mathcal{F}$  [8] (ratio  $l_2 = L_2/L_0$ ) for  $B_{CP(+-)}$  ( $B_{CP(00)}$ ) candidates, and it is used in the maximum-likelihood fit described below.

The average  $B_{CP}$  candidate multiplicity in the  $B_{CP(00)}$  sample is approximately 1.7, coming from multiple  $K_S^0 \rightarrow \pi^0 \pi^0$  combinations. In these events, we select the combination with the smallest  $\chi^2 = \sum_i (m_i - m_{K_S^0})^2 / \sigma_{m_i}^2$ , where  $m_i$  ( $m_{K_S^0}$ ) is the measured (world-average)  $K_S^0$  mass [2] and  $\sigma_{m_i}$  is its estimated uncertainty. We use the same method in the  $B_{CP(+-)}$  sample, where only 1.4% of events have more than one  $B_{CP(+-)}$  candidate.

Since  $B^0 \rightarrow \chi_{c0,2} K_S^0$  decays proceed through a  $b \rightarrow c\bar{c}s$  transition, we remove all  $B_{CP(+-)}$  ( $B_{CP(00)}$ ) candidates with a  $K_S^0 K_S^0$  mass combination within  $3\sigma$  ( $2\sigma$ ) of the  $\chi_{c0}$  or  $\chi_{c2}$  mass. After these vetoes, the total reconstruction efficiency, including  $K_S^0$  branching fractions, is about 6% (3%) for  $B_{CP(+-)}$  ( $B_{CP(00)}$ ) candidates, assuming a uniform Dalitz distribution.

The remaining background from  $B\bar{B}$  events is estimated to be negligible for the  $B_{CP(+-)}$  sample and is absorbed into the  $q\bar{q}$  continuum component. For the  $B_{CP(00)}$  sample, we extract the yield of  $B\bar{B}$  background events simultaneously with the signal and  $q\bar{q}$  event yields.

A multivariate tagging algorithm determines the flavor of the  $B_{\text{tag}}$  meson and classifies it in one of seven mutually exclusive tagging categories [1,9]. They rely upon the presence of prompt leptons, or one or more charged kaons and pions in the event, and have different purities. We measure the performance of this algorithm with a data sample ( $B_{\text{flav}}$ ) of fully reconstructed  $B^0 \rightarrow D^{(*)-} \pi^+ / \rho^+ / a_1^+$  decays. The effective tagging efficiency is  $Q \equiv \sum_c \varepsilon^c (1 - 2w^c)^2 = 0.304 \pm 0.003$ , where  $\varepsilon^c$  ( $w^c$ ) is the efficiency (mistag probability) for events tagged in category  $c$ .

We compute the proper-time difference  $\Delta t = \Delta z / \gamma \beta c$  using the known boost of the  $e^+ e^-$  system and the measured separation between the  $B_{CP}$  and  $B_{\text{tag}}$  decay vertices along the boost direction ( $\Delta z = z_{CP} - z_{\text{tag}}$ ) [9]. For the  $B_{CP}$  decay, where no charged particles are produced at the decay vertex, we determine the decay point by constraining the  $B$  production vertex to the interaction point (IP) in the plane orthogonal to the beam axis using only the  $K_S^0 \rightarrow \pi^+ \pi^-$  trajectories. The IP position is determined on a run-by-run basis from two-track events. We compute  $\Delta t$  and its uncertainty  $\sigma_{\Delta t}$  from a geometric fit to the  $Y(4S) \rightarrow B^0 \bar{B}^0$  system that takes into account this IP constraint and a Gaussian constraint on the sum of the two  $B$  decay times ( $t_{CP} + t_{\text{tag}}$ ) to be equal to  $2\tau_{B^0}$  with an uncertainty of  $\sqrt{2}\tau_{B^0}$  [8,10]. In order to ensure a well-determined vertex separation between  $B_{\text{rec}}$  and  $B_{\text{tag}}$ , we exclude events that have the error on  $\Delta t$ , determined from the vertex fit,  $\sigma_{\Delta t} > 2.5 \text{ ps}$  and events with  $|\Delta t| > 20 \text{ ps}$ . The mean uncertainty in  $z_{CP}$ , a convolution of the uncertainty in the interaction region position and the  $z_{\text{tag}}$  resolution, is  $75 \mu\text{m}$ . The mean uncertainty on  $z_{\text{tag}}$  is about  $200 \mu\text{m}$ , which dominates the  $\Delta z$  uncertainty. The resulting  $\Delta z$  resolution is comparable to that in  $B^0 \rightarrow J/\psi K_S^0$  decays [8]. Simulation studies and a  $B^0 \rightarrow J/\psi K_S^0$  data control sample show that the procedure we use to determine the vertex for a  $B_{CP}$  decay provides an unbiased estimate of  $z_{CP}$  [8].

Most events have at least one  $K_S^0$  candidate for which both tracks have at least one hit in the inner three SVT layers. We have verified on simulation and on data control samples that the parameters of the signal  $\Delta t$  resolution function for these  $B_{CP}$  signal decays are similar to those obtained from the  $B_{\text{flav}}$  sample [9]. When at least one  $K_S^0$  has tracks with hits in the outer two SVT layers but not in the inner three layers, the resolution is nearly two times worse and the  $\Delta t$  information is not used.

We extract the event yields and  $CP$  parameters with an unbinned extended maximum-likelihood fit to the kinematic, event shape, and  $\Delta t$  variables. For each of the subsamples  $k = 1, 2$  ( $B_{CP(+-)}$ ,  $B_{CP(00)}$ ) we use

$$\mathcal{L}_k = e^{-(\sum_j N_j)} \prod_i^{N_T} \sum_j^n N_j \mathcal{P}_j^i,$$

where  $\mathcal{P}_j$  is the probability density function (PDF) for the  $j$ th fit component.  $N_j$  is the event yield of each of the  $n$  components:  $N_S$  signal events,  $N_{q\bar{q}}$  continuum  $q\bar{q}$  events and, for  $B_{CP(00)}$  only,  $N_{B\bar{B}}$   $B\bar{B}$  background events;  $N_T$  is the total number of events selected. For  $B_{CP(+-)}$  ( $B_{CP(00)}$ ) candidates, the PDF  $\mathcal{P}_j$  is given by the product of  $\mathcal{P}_j(m_{ES}) \mathcal{P}_j(\Delta E) \mathcal{P}_j(\mathcal{F})$  ( $\mathcal{P}_j(m_{\text{miss}}) \mathcal{P}_j(m_B) \mathcal{P}_j(l_2)$ )  $\mathcal{P}_j^c(\Delta t, \sigma_{\Delta t}) \varepsilon^c$ , summed over the tagging categories  $c$ . The product  $\mathcal{L}_1 \mathcal{L}_2$  is maximized to determine the common  $CP$  asymmetry parameters  $S$  and  $C$  and the values of  $N_j$ , which are specific to each subsample.

B. AUBERT *et al.*PHYSICAL REVIEW D **76**, 091101(R) (2007)TABLE I. Event yields and  $CP$  asymmetry parameters obtained in the fit. The errors are statistical only.

	$B_{CP(+-)}$	$B_{CP(00)}$	Combined
$N_S$	$125 \pm 13$	$64 \pm 12$	...
$N_{q\bar{q}}$	$732 \pm 28$	$4942 \pm 77$	...
$N_{B\bar{B}}$	...	$-14 \pm 32$	...
$S$	$-1.06^{+0.25}_{-0.16}$	$0.24 \pm 0.52$	$-0.71 \pm 0.24$
$C$	$-0.08^{+0.23}_{-0.22}$	$0.23 \pm 0.38$	$0.02 \pm 0.21$

Along with  $S$  and  $C$ , the fit extracts  $\varepsilon^c$  and parameters describing the background.

A fit to 857  $B_{CP(+-)}$  and 4992  $B_{CP(00)}$  candidates returns the event yields reported in Table I. Figure 1 shows the  $m_{ES}$  and  $\Delta E$  ( $m_{miss}$  and  $m_B$ ) distributions for signal and background  $B_{CP(+-)}$  ( $B_{CP(00)}$ ) candidates. The extracted  $CP$  parameters for the two separate subsamples and the combined ones are shown in Table I. Using a Monte Carlo (MC) technique, in which we assume that the measured values for the  $CP$  parameters on the combined data sample are the true values, we find that the two subsamples agree within  $1.6\sigma$ . The statistical significance of the  $CP$  violation is evaluated as  $\sqrt{2 \cdot \Delta \ln(\mathcal{L}_1 \mathcal{L}_2)}$ , where  $\Delta \ln(\mathcal{L}_1 \mathcal{L}_2)$  is the

change in the natural log of the combined likelihood for the no  $CP$ -violation hypothesis with respect to the maximum value. We estimate it to be 2.9 standard deviations.

Figure 2 shows distributions of  $\Delta t$  for  $B^0$  and  $\bar{B}^0$ -tagged events, and the asymmetry  $\mathcal{A}(\Delta t) = (N_{B^0} - N_{\bar{B}^0}) / (N_{B^0} + N_{\bar{B}^0})$ .

Systematic uncertainties on the  $CP$  parameters are given in Table II. The systematic errors are evaluated using large samples of simulated  $B_{CP}$  decays and the  $B_{flav}$  data sample. We perform fits to the simulated  $B_{CP}$  signal with parameters obtained either from signal or  $B_{flav}$  events to account for possible differences in the  $\Delta t$  resolution function. We use the differences in the resolution function and tagging parameters extracted from these samples to vary the signal parameters. We account for possible biases due to the vertexing technique by comparing fits to a large simulated sample of IP-constrained (neglecting the  $J/\psi$  contribution to the vertex and using the  $K_S^0$  trajectory only) and nominal  $B^0 \rightarrow J/\psi K_S^0$  events. Several SVT misalignment scenarios are applied to the simulated  $B_{CP}$  events to estimate detector effects. We consider variations of 20  $\mu\text{m}$  in the direction orthogonal to the beam axis for the IP position and resolution and find they have a negligible impact. The systematic error due to correlations between the variables used in

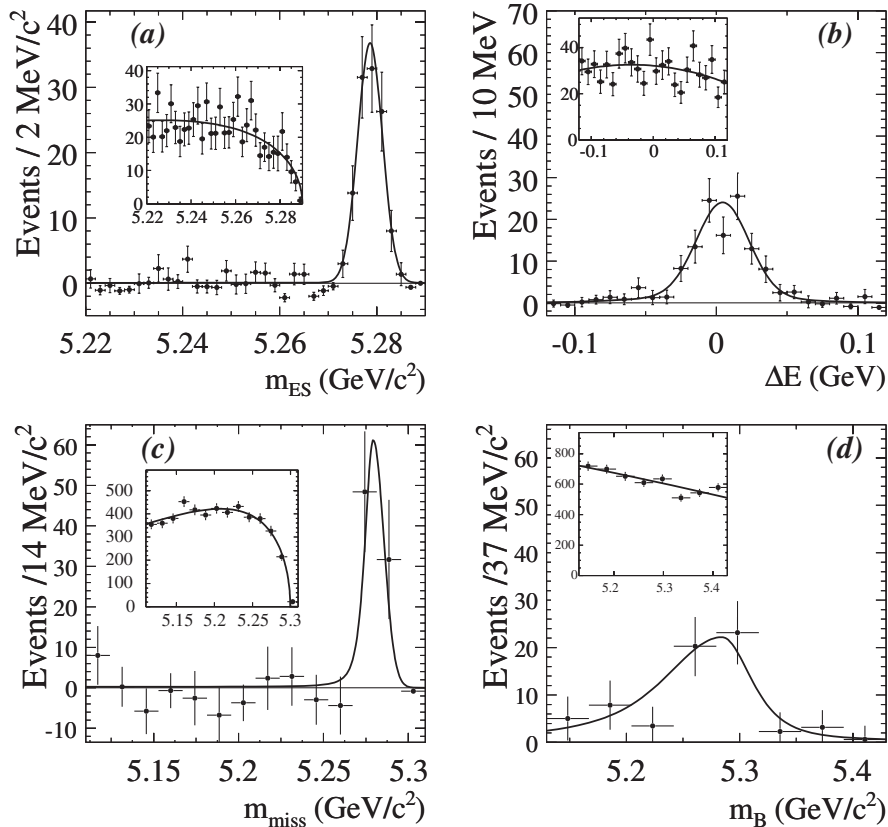


FIG. 1. Signal and background distributions of (a)  $m_{ES}$  and (b)  $\Delta E$  for  $B_{CP(+-)}$  candidates and of (c)  $m_{miss}$  and (d)  $m_B$  for  $B_{CP(00)}$  candidates. The signal and background distributions have been separated using the technique described in [13]. The curves represent the PDF projections. The background distributions are shown in the insets.

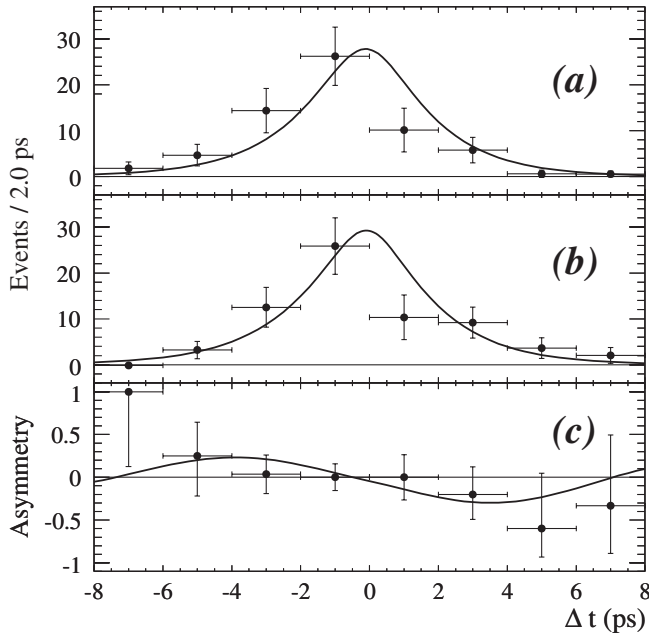


FIG. 2. Distributions of  $\Delta t$  for events weighted using the technique described in [13] for  $B_{\text{tag}}$  tagged as (a)  $B^0$  or (b)  $\bar{B}^0$ , and (c) the asymmetry  $\mathcal{A}(\Delta t)$ . The points are the weighted data and the curves are PDF projections.

the fit is determined from a fit to a sample of randomly selected signal MC events added to background events generated from the background PDFs used in the fit. The values of the effective  $CP$  parameters for the  $B\bar{B}$  background, which are fixed to zero in the nominal fit, are varied over the whole physically allowed range. The largest deviations in  $S$  and  $C$  resulting from this variation are used as systematic uncertainties. The world-average values of  $\Delta m_d$  and of the  $B^0$  mean lifetime,  $\tau_{B^0}$ , held fixed in the fit, are varied by their uncertainties [2]. We account for the possible interference between the suppressed  $\bar{b} \rightarrow \bar{u}c\bar{d}$  and the favored  $b \rightarrow c\bar{u}d$  amplitudes for some  $B_{\text{tag}}$  decays [11]. Finally, we include a systematic uncertainty to account for imperfect knowledge of the PDFs used in the fit. Most of this uncertainty is due to MC statistics, the rest to differences between data control samples and MC simulation.

TABLE II. Systematic uncertainties on  $S$  and  $C$ .

	$\sigma(S)$	$\sigma(C)$
Vertex reconstruction	0.016	0.003
Resolution function	0.005	0.007
Flavor tagging	0.009	0.015
SVT alignment and IP position	0.016	0.008
Fit correlation	0.004	0.025
$B\bar{B}$ $CP$ , $\Delta m_d$ , and $\tau_{B^0}$	0.008	0.009
Tag-side interference	0.001	0.011
PDFs	0.026	0.031
Total	0.037	0.046

In summary, we measured the  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  time-dependent  $CP$  asymmetries,  $S = -0.71 \pm 0.24 \pm 0.04$  and  $C = 0.02 \pm 0.21 \pm 0.05$  where the first errors are statistical and the second systematic. The statistical correlation between  $S$  and  $C$  is  $-14.1\%$ . These results agree well with the SM expectation. This measurement, which is limited by the small statistics of the sample, constrains, but does not exclude contributions from physics beyond the SM, such as the low-energy supersymmetry [5]. These results supersede our previously published  $CP$  asymmetry results for  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  [12] and are consistent with the measurements performed by the Belle Collaboration reported in [1].

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