

## Search for $CP$ Violation in the Decay $D^\pm \rightarrow K_s^0 \pi^\pm$

P. del Amo Sanchez,<sup>1</sup> J. P. Lees,<sup>1</sup> V. Poireau,<sup>1</sup> E. Prencipe,<sup>1</sup> V. Tisserand,<sup>1</sup> J. Garra Tico,<sup>2</sup> E. Grauges,<sup>2</sup> M. Martinelli<sup>ab,3</sup> D. A. Milanes,<sup>3</sup> A. Palano<sup>ab,3</sup> M. Pappagallo<sup>ab,3</sup> G. Eigen,<sup>4</sup> B. Stugu,<sup>4</sup> L. Sun,<sup>4</sup> D. N. Brown,<sup>5</sup> L. T. Kerth,<sup>5</sup> Yu. G. Kolomensky,<sup>5</sup> G. Lynch,<sup>5</sup> I. L. Osipenkov,<sup>5</sup> H. Koch,<sup>6</sup> T. Schroeder,<sup>6</sup> D. J. Asgeirsson,<sup>7</sup> C. Hearty,<sup>7</sup> T. S. Mattison,<sup>7</sup> J. A. McKenna,<sup>7</sup> A. Khan,<sup>8</sup> V. E. Blinov,<sup>9</sup> A. R. Buzykaev,<sup>9</sup> V. P. Druzhinin,<sup>9</sup> V. B. Golubev,<sup>9</sup> E. A. Kravchenko,<sup>9</sup> A. P. Onuchin,<sup>9</sup> S. I. Serednyakov,<sup>9</sup> Yu. I. Skovpen,<sup>9</sup> E. P. Solodov,<sup>9</sup> K. Yu. Todyshev,<sup>9</sup> A. N. Yushkov,<sup>9</sup> M. Bondioli,<sup>10</sup> S. Curry,<sup>10</sup> D. Kirkby,<sup>10</sup> A. J. Lankford,<sup>10</sup> M. Mandelkern,<sup>10</sup> E. C. Martin,<sup>10</sup> D. P. Stoker,<sup>10</sup> H. Atmacan,<sup>11</sup> J. W. Gary,<sup>11</sup> F. Liu,<sup>11</sup> O. Long,<sup>11</sup> G. M. Vitug,<sup>11</sup> C. Campagnari,<sup>12</sup> T. M. Hong,<sup>12</sup> D. Kovalskyi,<sup>12</sup> J. D. Richman,<sup>12</sup> C. A. West,<sup>12</sup> A. M. Eisner,<sup>13</sup> C. A. Heusch,<sup>13</sup> J. Kroseberg,<sup>13</sup> W. S. Lockman,<sup>13</sup> A. J. Martinez,<sup>13</sup> T. Schalk,<sup>13</sup> B. A. Schumm,<sup>13</sup> A. Seiden,<sup>13</sup> L. O. Winstrom,<sup>13</sup> C. H. Cheng,<sup>14</sup> D. A. Doll,<sup>14</sup> B. Echenard,<sup>14</sup> D. G. Hitlin,<sup>14</sup> P. Ongmongkolkul,<sup>14</sup> F. C. Porter,<sup>14</sup> A. Y. Rakitin,<sup>14</sup> R. Andreassen,<sup>15</sup> M. S. Dubrovin,<sup>15</sup> B. T. Meadows,<sup>15</sup> M. D. Sokoloff,<sup>15</sup> P. C. Bloom,<sup>16</sup> W. T. Ford,<sup>16</sup> A. Gaz,<sup>16</sup> M. Nagel,<sup>16</sup> U. Nauenberg,<sup>16</sup> J. G. Smith,<sup>16</sup> S. R. Wagner,<sup>16</sup> R. Ayad,<sup>17,\*</sup> W. H. Toki,<sup>17</sup> H. Jasper,<sup>18</sup> A. Petzold,<sup>18</sup> B. Spaan,<sup>18</sup> M. J. Kobel,<sup>19</sup> K. R. Schubert,<sup>19</sup> R. Schwierz,<sup>19</sup> D. Bernard,<sup>20</sup> M. Verderi,<sup>20</sup> P. J. Clark,<sup>21</sup> S. Playfer,<sup>21</sup> J. E. Watson,<sup>21</sup> M. Andreotti<sup>ab,22</sup> D. Bettoni<sup>a,22</sup> C. Bozzi<sup>a,22</sup> R. Calabrese<sup>ab,22</sup> A. Cecchi<sup>ab,22</sup> G. Cibinetto<sup>ab,22</sup> E. Fioravanti<sup>ab,22</sup> P. Franchini<sup>ab,22</sup> I. Garzia<sup>ab,22</sup> E. Luppi<sup>ab,22</sup> M. Munerato<sup>ab,22</sup> M. Negrini<sup>ab,22</sup> A. Petrella<sup>ab,22</sup> L. Piemontese<sup>a,22</sup> R. Baldini-Ferroli,<sup>23</sup> A. Calcaterra,<sup>23</sup> R. de Sangro,<sup>23</sup> G. Finocchiaro,<sup>23</sup> M. Nicolaci,<sup>23</sup> S. Pacetti,<sup>23</sup> P. Patteri,<sup>23</sup> I. M. Peruzzi,<sup>23,†</sup> M. Piccolo,<sup>23</sup> M. Rama,<sup>23</sup> A. Zallo,<sup>23</sup> R. Contri<sup>ab,24</sup> E. Guido<sup>ab,24</sup> M. Lo Vetere<sup>ab,24</sup> M. R. Monge<sup>ab,24</sup> S. Passaggio<sup>a,24</sup> C. Patrignani<sup>ab,24</sup> E. Robutti<sup>a,24</sup> B. Bhuyan,<sup>25</sup> V. Prasad,<sup>25</sup> C. L. Lee,<sup>26</sup> M. Morii,<sup>26</sup> A. J. Edwards,<sup>27</sup> A. Adametz,<sup>28</sup> J. Marks,<sup>28</sup> U. Uwer,<sup>28</sup> F. U. Bernlochner,<sup>29</sup> M. Ebert,<sup>29</sup> H. M. Lacker,<sup>29</sup> T. Lueck,<sup>29</sup> A. Volk,<sup>29</sup> P. D. Dauncey,<sup>30</sup> M. Tibbetts,<sup>30</sup> P. K. Behera,<sup>31</sup> U. Mallik,<sup>31</sup> C. Chen,<sup>32</sup> J. Cochran,<sup>32</sup> H. B. Crawley,<sup>32</sup> W. T. Meyer,<sup>32</sup> S. Prell,<sup>32</sup> E. I. Rosenberg,<sup>32</sup> A. E. Rubin,<sup>32</sup> A. V. Gritsan,<sup>33</sup> Z. J. Guo,<sup>33</sup> N. Arnaud,<sup>34</sup> M. Davier,<sup>34</sup> D. Derkach,<sup>34</sup> J. Firmino da Costa,<sup>34</sup> G. Grosdidier,<sup>34</sup> F. Le Diberder,<sup>34</sup> A. M. Lutz,<sup>34</sup> B. Malaescu,<sup>34</sup> A. Perez,<sup>34</sup> P. Roudeau,<sup>34</sup> M. H. Schune,<sup>34</sup> J. Serrano,<sup>34</sup> V. Sordini,<sup>34,‡</sup> A. Stocchi,<sup>34</sup> L. Wang,<sup>34</sup> G. Wormser,<sup>34</sup> D. J. Lange,<sup>35</sup> D. M. Wright,<sup>35</sup> I. Bingham,<sup>36</sup> C. A. Chavez,<sup>36</sup> J. P. Coleman,<sup>36</sup> J. R. Fry,<sup>36</sup> E. Gabathuler,<sup>36</sup> D. E. Hutchcroft,<sup>36</sup> D. J. Payne,<sup>36</sup> C. Touramanis,<sup>36</sup> A. J. Bevan,<sup>37</sup> F. Di Lodovico,<sup>37</sup> R. Sacco,<sup>37</sup> M. Sigamani,<sup>37</sup> G. Cowan,<sup>38</sup> S. Paramesvaran,<sup>38</sup> A. C. Wren,<sup>38</sup> D. N. Brown,<sup>39</sup> C. L. Davis,<sup>39</sup> A. G. Denig,<sup>40</sup> M. Fritsch,<sup>40</sup> W. Gradl,<sup>40</sup> A. Hafner,<sup>40</sup> K. E. Alwyn,<sup>41</sup> D. Bailey,<sup>41</sup> R. J. Barlow,<sup>41</sup> G. Jackson,<sup>41</sup> G. D. Lafferty,<sup>41</sup> J. Anderson,<sup>42</sup> R. Cenci,<sup>42</sup> A. Jawahery,<sup>42</sup> D. A. Roberts,<sup>42</sup> G. Simi,<sup>42</sup> J. M. Tuggle,<sup>42</sup> C. Dallapiccola,<sup>43</sup> E. Salvati,<sup>43</sup> R. Cowan,<sup>44</sup> D. Dujmic,<sup>44</sup> G. Sciolla,<sup>44</sup> M. Zhao,<sup>44</sup> D. Lindemann,<sup>45</sup> P. M. Patel,<sup>45</sup> S. H. Robertson,<sup>45</sup> M. Schram,<sup>45</sup> P. Biassoni<sup>ab,46</sup> A. Lazzaro<sup>ab,46</sup> V. Lombardo<sup>a,46</sup> F. Palombo<sup>ab,46</sup> S. Stracka<sup>ab,46</sup> L. Cremaldi,<sup>47</sup> R. Godang,<sup>47,§</sup> R. Kroeger,<sup>47</sup> P. Sonnek,<sup>47</sup> D. J. Summers,<sup>47</sup> X. Nguyen,<sup>48</sup> M. Simard,<sup>48</sup> P. Taras,<sup>48</sup> G. De Nardo<sup>ab,49</sup> D. Monorchio<sup>ab,49</sup> G. Onorato<sup>ab,49</sup> C. Sciacca<sup>ab,49</sup> G. Raven,<sup>50</sup> H. L. Snoek,<sup>50</sup> C. P. Jessop,<sup>51</sup> K. J. Knoepfel,<sup>51</sup> J. M. LoSecco,<sup>51</sup> W. F. Wang,<sup>51</sup> L. A. Corwin,<sup>52</sup> K. Honscheid,<sup>52</sup> R. Kass,<sup>52</sup> N. L. Blount,<sup>53</sup> J. Brau,<sup>53</sup> R. Frey,<sup>53</sup> O. Igonkina,<sup>53</sup> J. A. Kolb,<sup>53</sup> R. Rahmat,<sup>53</sup> N. B. Sinev,<sup>53</sup> D. Strom,<sup>53</sup> J. Strube,<sup>53</sup> E. Torrence,<sup>53</sup> G. Castelli<sup>ab,54</sup> E. Feltres<sup>ab,54</sup> N. Gagliardi<sup>ab,54</sup> M. Margoni<sup>ab,54</sup> M. Morandin<sup>a,54</sup> A. Pompili<sup>ab,54</sup> M. Posocco<sup>a,54</sup> M. Rotondo<sup>a,54</sup> F. Simonetto<sup>ab,54</sup> R. Stroili<sup>ab,54</sup> E. Ben-Haim,<sup>55</sup> M. Bomben,<sup>55</sup> G. R. Bonneaud,<sup>55</sup> H. Briand,<sup>55</sup> G. Calderini,<sup>55</sup> J. Chauveau,<sup>55</sup> O. Hamon,<sup>55</sup> Ph. Leruste,<sup>55</sup> G. Marchiori,<sup>55</sup> J. Ocariz,<sup>55</sup> J. Prendki,<sup>55</sup> S. Sitt,<sup>55</sup> M. Biasini<sup>ab,56</sup> E. Manoni<sup>ab,56</sup> A. Rossi<sup>ab,56</sup> C. Angelini<sup>ab,57</sup> G. Batignani<sup>ab,57</sup> S. Bettarini<sup>ab,57</sup> M. Carpinelli<sup>ab,57,¶</sup> G. Casarosa<sup>ab,57</sup> A. Cervelli<sup>ab,57</sup> F. Forti<sup>ab,57</sup> M. A. Giorgi<sup>ab,57</sup> A. Lusiani<sup>ac,57</sup> N. Neri<sup>ab,57</sup> E. Paoloni<sup>ab,57</sup> G. Rizzo<sup>ab,57</sup> J. J. Walsh<sup>a,57</sup> D. Lopes Pegna,<sup>58</sup> C. Lu,<sup>58</sup> J. Olsen,<sup>58</sup> A. J. S. Smith,<sup>58</sup> A. V. Telnov,<sup>58</sup> F. Anulli<sup>a,59</sup> E. Baracchini<sup>ab,59</sup> G. Cavoto<sup>a,59</sup> R. Faccini<sup>ab,59</sup> F. Ferrarotto<sup>a,59</sup> F. Ferroni<sup>ab,59</sup> M. Gaspero<sup>ab,59</sup> L. Li Gioi<sup>a,59</sup> M. A. Mazzoni<sup>a,59</sup> G. Piredda<sup>a,59</sup> F. Renga<sup>ab,59</sup> C. Buenger,<sup>60</sup> T. Hartmann,<sup>60</sup> T. Leddig,<sup>60</sup> H. Schröder,<sup>60</sup> R. Waldi,<sup>60</sup> T. Adye,<sup>61</sup> E. O. Olaiya,<sup>61</sup> F. F. Wilson,<sup>61</sup> S. Emery,<sup>62</sup> G. Hamel de Monchenault,<sup>62</sup> G. Vasseur,<sup>62</sup> Ch. Yèche,<sup>62</sup> M. T. Allen,<sup>63</sup> D. Aston,<sup>63</sup> D. J. Bard,<sup>63</sup> R. Bartoldus,<sup>63</sup> J. F. Benitez,<sup>63</sup> C. Cartaro,<sup>63</sup> M. R. Convery,<sup>63</sup> J. Dorfan,<sup>63</sup> G. P. Dubois-Felsmann,<sup>63</sup> W. Dunwoodie,<sup>63</sup> R. C. Field,<sup>63</sup> M. Franco Sevilla,<sup>63</sup> B. G. Fulsom,<sup>63</sup> A. M. Gabareen,<sup>63</sup> M. T. Graham,<sup>63</sup> P. Grenier,<sup>63</sup> C. Hast,<sup>63</sup> W. R. Innes,<sup>63</sup> M. H. Kelsey,<sup>63</sup> H. Kim,<sup>63</sup> P. Kim,<sup>63</sup> M. L. Kocian,<sup>63</sup> D. W. G. S. Leith,<sup>63</sup> P. Lewis,<sup>63</sup> S. Li,<sup>63</sup>

B. Lindquist,<sup>63</sup> S. Luitz,<sup>63</sup> V. Luth,<sup>63</sup> H. L. Lynch,<sup>63</sup> D. B. MacFarlane,<sup>63</sup> D. R. Muller,<sup>63</sup> H. Neal,<sup>63</sup> S. Nelson,<sup>63</sup> C. P. O'Grady,<sup>63</sup> I. Ofte,<sup>63</sup> M. Perl,<sup>63</sup> T. Pulliam,<sup>63</sup> B. N. Ratcliff,<sup>63</sup> A. Roodman,<sup>63</sup> A. A. Salnikov,<sup>63</sup> V. Santoro,<sup>63</sup> R. H. Schindler,<sup>63</sup> J. Schwiening,<sup>63</sup> A. Snyder,<sup>63</sup> D. Su,<sup>63</sup> M. K. Sullivan,<sup>63</sup> S. Sun,<sup>63</sup> K. Suzuki,<sup>63</sup> J. M. Thompson,<sup>63</sup> J. Va'vra,<sup>63</sup> A. P. Wagner,<sup>63</sup> M. Weaver,<sup>63</sup> W. J. Wisniewski,<sup>63</sup> M. Wittgen,<sup>63</sup> D. H. Wright,<sup>63</sup> H. W. Wulsin,<sup>63</sup> A. K. Yarritu,<sup>63</sup> C. C. Young,<sup>63</sup> V. Ziegler,<sup>63</sup> X. R. Chen,<sup>64</sup> W. Park,<sup>64</sup> M. V. Purohit,<sup>64</sup> R. M. White,<sup>64</sup> J. R. Wilson,<sup>64</sup> A. Randle-Conde,<sup>65</sup> S. J. Sekula,<sup>65</sup> M. Bellis,<sup>66</sup> P. R. Burchat,<sup>66</sup> T. S. Miyashita,<sup>66</sup> S. Ahmed,<sup>67</sup> M. S. Alam,<sup>67</sup> J. A. Ernst,<sup>67</sup> B. Pan,<sup>67</sup> M. A. Saeed,<sup>67</sup> S. B. Zain,<sup>67</sup> N. Guttman,<sup>68</sup> A. Soffer,<sup>68</sup> P. Lund,<sup>69</sup> S. M. Spanier,<sup>69</sup> R. Eckmann,<sup>70</sup> J. L. Ritchie,<sup>70</sup> A. M. Ruland,<sup>70</sup> C. J. Schilling,<sup>70</sup> R. F. Schwitters,<sup>70</sup> B. C. Wray,<sup>70</sup> J. M. Izen,<sup>71</sup> X. C. Lou,<sup>71</sup> F. Bianchi<sup>ab,72</sup> D. Gamba<sup>ab,72</sup> M. Pelliccioni<sup>ab,72</sup> L. Lanceri<sup>ab,73</sup> L. Vitale<sup>ab,73</sup> N. Lopez-March,<sup>74</sup> F. Martinez-Vidal,<sup>74</sup> A. Oyanguren,<sup>74</sup> H. Ahmed,<sup>75</sup> J. Albert,<sup>75</sup> Sw. Banerjee,<sup>75</sup> H. H. F. Choi,<sup>75</sup> K. Hamano,<sup>75</sup> G. J. King,<sup>75</sup> R. Kowalewski,<sup>75</sup> M. J. Lewczuk,<sup>75</sup> C. Lindsay,<sup>75</sup> I. M. Nugent,<sup>75</sup> J. M. Roney,<sup>75</sup> R. J. Sobie,<sup>75</sup> T. J. Gershon,<sup>76</sup> P. F. Harrison,<sup>76</sup> T. E. Latham,<sup>76</sup> E. M. T. Puccio,<sup>76</sup> H. R. Band,<sup>77</sup> S. Dasu,<sup>77</sup> K. T. Flood,<sup>77</sup> Y. Pan,<sup>77</sup> R. Prepost,<sup>77</sup> C. O. Vuosalo,<sup>77</sup> and S. L. Wu<sup>77</sup>

(The BABAR Collaboration)

<sup>1</sup>Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP),  
Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France

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

<sup>3</sup>INFN Sezione di Bari<sup>a</sup>; Dipartimento di Fisica, Università di Bari<sup>b</sup>, I-70126 Bari, Italy

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

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

<sup>6</sup>Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

<sup>7</sup>University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

<sup>8</sup>Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

<sup>9</sup>Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

<sup>10</sup>University of California at Irvine, Irvine, California 92697, USA

<sup>11</sup>University of California at Riverside, Riverside, California 92521, USA

<sup>12</sup>University of California at Santa Barbara, Santa Barbara, California 93106, USA

<sup>13</sup>University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

<sup>14</sup>California Institute of Technology, Pasadena, California 91125, USA

<sup>15</sup>University of Cincinnati, Cincinnati, Ohio 45221, USA

<sup>16</sup>University of Colorado, Boulder, Colorado 80309, USA

<sup>17</sup>Colorado State University, Fort Collins, Colorado 80523, USA

<sup>18</sup>Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany

<sup>19</sup>Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

<sup>20</sup>Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

<sup>21</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

<sup>22</sup>INFN Sezione di Ferrara<sup>a</sup>; Dipartimento di Fisica, Università di Ferrara<sup>b</sup>, I-44100 Ferrara, Italy

<sup>23</sup>INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy

<sup>24</sup>INFN Sezione di Genova<sup>a</sup>; Dipartimento di Fisica, Università di Genova<sup>b</sup>, I-16146 Genova, Italy

<sup>25</sup>Indian Institute of Technology Guwahati, Guwahati, Assam, 781 039, India

<sup>26</sup>Harvard University, Cambridge, Massachusetts 02138, USA

<sup>27</sup>Harvey Mudd College, Claremont, California 91711

<sup>28</sup>Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

<sup>29</sup>Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany

<sup>30</sup>Imperial College London, London, SW7 2AZ, United Kingdom

<sup>31</sup>University of Iowa, Iowa City, Iowa 52242, USA

<sup>32</sup>Iowa State University, Ames, Iowa 50011-3160, USA

<sup>33</sup>Johns Hopkins University, Baltimore, Maryland 21218, USA

<sup>34</sup>Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11,  
Centre Scientifique d'Orsay, B. P. 34, F-91898 Orsay Cedex, France

<sup>35</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA

<sup>36</sup>University of Liverpool, Liverpool L69 7ZE, United Kingdom

<sup>37</sup>Queen Mary, University of London, London, E1 4NS, United Kingdom

<sup>38</sup>University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

<sup>39</sup>University of Louisville, Louisville, Kentucky 40292, USA

<sup>40</sup>Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany

<sup>41</sup>University of Manchester, Manchester M13 9PL, United Kingdom

<sup>42</sup>University of Maryland, College Park, Maryland 20742, USA

<sup>43</sup>University of Massachusetts, Amherst, Massachusetts 01003, USA

<sup>44</sup>Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

- <sup>45</sup>McGill University, Montréal, Québec, Canada H3A 2T8
- <sup>46</sup>INFN Sezione di Milano<sup>a</sup>; Dipartimento di Fisica, Università di Milano<sup>b</sup>, I-20133 Milano, Italy
- <sup>47</sup>University of Mississippi, University, Mississippi 38677, USA
- <sup>48</sup>Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
- <sup>49</sup>INFN Sezione di Napoli<sup>a</sup>; Dipartimento di Scienze Fisiche, Università di Napoli Federico II<sup>b</sup>, I-80126 Napoli, Italy
- <sup>50</sup>NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
- <sup>51</sup>University of Notre Dame, Notre Dame, Indiana 46556, USA
- <sup>52</sup>Ohio State University, Columbus, Ohio 43210, USA
- <sup>53</sup>University of Oregon, Eugene, Oregon 97403, USA
- <sup>54</sup>INFN Sezione di Padova<sup>a</sup>; Dipartimento di Fisica, Università di Padova<sup>b</sup>, I-35131 Padova, Italy
- <sup>55</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>56</sup>INFN Sezione di Perugia<sup>a</sup>; Dipartimento di Fisica, Università di Perugia<sup>b</sup>, I-06100 Perugia, Italy
- <sup>57</sup>INFN Sezione di Pisa<sup>a</sup>; Dipartimento di Fisica, Università di Pisa<sup>b</sup>; Scuola Normale Superiore di Pisa<sup>c</sup>, I-56127 Pisa, Italy
- <sup>58</sup>Princeton University, Princeton, New Jersey 08544, USA
- <sup>59</sup>INFN Sezione di Roma<sup>a</sup>; Dipartimento di Fisica, Università di Roma La Sapienza<sup>b</sup>, 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>CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France
- <sup>63</sup>SLAC National Accelerator Laboratory, Stanford, California 94309 USA
- <sup>64</sup>University of South Carolina, Columbia, South Carolina 29208, USA
- <sup>65</sup>Southern Methodist University, Dallas, Texas 75275, USA
- <sup>66</sup>Stanford University, Stanford, California 94305-4060, USA
- <sup>67</sup>State University of New York, Albany, New York 12222, USA
- <sup>68</sup>Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel
- <sup>69</sup>University of Tennessee, Knoxville, Tennessee 37996, USA
- <sup>70</sup>University of Texas at Austin, Austin, Texas 78712, USA
- <sup>71</sup>University of Texas at Dallas, Richardson, Texas 75083, USA
- <sup>72</sup>INFN Sezione di Torino<sup>a</sup>; Dipartimento di Fisica Sperimentale, Università di Torino<sup>b</sup>, I-10125 Torino, Italy
- <sup>73</sup>INFN Sezione di Trieste<sup>a</sup>; Dipartimento di Fisica, Università di Trieste<sup>b</sup>, I-34127 Trieste, Italy
- <sup>74</sup>IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
- <sup>75</sup>University of Victoria, Victoria, British Columbia, Canada V8W 3P6
- <sup>76</sup>Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
- <sup>77</sup>University of Wisconsin, Madison, Wisconsin 53706, USA

We report on a search for  $CP$  violation in the decay  $D^\pm \rightarrow K_s^0 \pi^\pm$  using a data set corresponding to an integrated luminosity of  $469 \text{ fb}^{-1}$  collected with the BABAR detector at the PEP-II asymmetric energy  $e^+e^-$  storage rings. The  $CP$ -violating decay rate asymmetry  $A_{CP}$  is determined to be  $(-0.44 \pm 0.13(\text{stat}) \pm 0.10(\text{syst}))\%$ , consistent with predictions based on the standard model. This is currently the most precise measurement of this parameter.

PACS numbers: 11.30.Er, 13.25.Ft, 14.40.Lb

In the standard model (SM),  $CP$  violation (CPV) arises from the complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Measurements of the CPV asymmetries in the  $K$  and  $B$  meson systems are consistent with expectations based on the SM and, together with theoretical inputs, lead to the determination of the parameters of the CKM matrix. CPV has not yet been observed in the charm sector, where the theoretical predictions based on the SM for CPV asymmetries are at the level of  $10^{-3}$  or below [2].

In this Letter we present a search for CPV in the decay  $D^\pm \rightarrow K_s^0 \pi^\pm$  by measuring the CPV parameter  $A_{CP}$

defined as:

$$A_{CP} = \frac{\Gamma(D^+ \rightarrow K_s^0 \pi^+) - \Gamma(D^- \rightarrow K_s^0 \pi^-)}{\Gamma(D^+ \rightarrow K_s^0 \pi^+) + \Gamma(D^- \rightarrow K_s^0 \pi^-)}, \quad (1)$$

where  $\Gamma$  is the partial decay width for this decay. In the decay  $D^\pm \rightarrow K_s^0 \pi^\pm$ , considering only the CPV in  $K^0 - \bar{K}^0$  mixing, the predicted value for  $A_{CP}$  is  $(-0.332 \pm 0.006)\%$  [3] and contributions from non-SM processes may reduce the value of  $A_{CP}$  or enhance it up to the level of one percent [4, 5], therefore a significant deviation of the  $A_{CP}$  measurement from the expectation would be evidence for the presence of new physics beyond the SM. Due to the smallness of the predicted value, this measurement requires a large data sample

and precise control of the systematic uncertainties. The Belle collaboration has recently reported a measurement of  $A_{CP} = (-0.71 \pm 0.19(\text{stat}) \pm 0.20(\text{syst}))\%$  [6].

The data used in this analysis were recorded at or near the  $\Upsilon(4S)$  resonance by the *BABAR* detector at the PEP-II storage rings. The *BABAR* detector is described in detail elsewhere [7]. The data sample corresponds to an integrated luminosity of  $469 \text{ fb}^{-1}$ . To avoid any bias from adapting the analysis procedure to the data, we perform a “blind” analysis where all aspects of the analysis, including the statistical and systematic uncertainties, are validated with data and Monte Carlo (MC) simulation based on GEANT4 [9] before looking at the value of  $A_{CP}$ . The coordinate system defined in [7] is assumed throughout the Letter.

We select  $D^\pm \rightarrow K_s^0 \pi^\pm$  decays by combining a  $K_s^0$  candidate reconstructed in the decay mode  $K_s^0 \rightarrow \pi^+ \pi^-$  with a charged pion candidate. A  $K_s^0$  candidate is reconstructed from two oppositely charged tracks with an invariant mass within  $\pm 10 \text{ MeV}/c^2$  of the nominal  $K_s^0$  mass [3], which is equivalent to slightly more than  $\pm 2.5 \sigma$  in the measured  $K_s^0$  mass resolution. The  $\chi^2$  probability of the  $\pi^+ \pi^-$  vertex fit must be greater than 0.1%. To reduce combinatorial background, we require the measured flight length of the  $K_s^0$  candidate to be greater than 3 times its uncertainty. A reconstructed charged track that has  $p_T \geq 400 \text{ MeV}/c$  is selected as a pion candidate, where  $p_T$  is the magnitude of the momentum in the plane perpendicular to the  $z$  axis. The pion candidate is also required not to be identified as a kaon, a proton, or an electron, as determined by the Cherenkov angle and number of photons measured by the internally reflecting ring-imaging Cherenkov detector, the ionization energy loss measured by the charged-particle tracking system, and the energy deposited in the electromagnetic calorimeter [7]. These selection criteria for the pion candidate are very effective in reducing the charge asymmetry from track reconstruction and identification, as inferred from studying the large control sample described later. A kinematic fit to the parameters of the whole decay tree is then performed with no additional constraints [8]. We retain only  $D^\pm$  candidates having a  $\chi^2$  probability for this fit greater than 0.1% and an invariant mass  $m(K_s^0 \pi^\pm)$  within  $\pm 65 \text{ MeV}/c^2$  of the nominal  $D^\pm$  mass [3], which is equivalent to more than  $\pm 8 \sigma$  in the measured  $D^\pm$  mass resolution. Motivated by Monte Carlo simulation studies, we further require the magnitude of the  $D^\pm$  candidate momentum in the  $e^+e^-$  center-of-mass (CM) system,  $p^*(D^\pm)$ , to be between 2 and 5  $\text{GeV}/c$ . This criterion reduces the combinatorial background to an acceptable level, but also keeps some  $D^\pm$  mesons from  $B$  mesons decays (they are  $\approx 8\%$  of the selected sample). Additional background rejection is obtained by requiring that the impact parameter of the  $D^\pm$  candidate with respect to the beam-spot, projected onto the plane perpendicular to the  $z$  axis, be less than 0.3 cm and the  $D^\pm$

lifetime  $\tau_{xy}(D^\pm)$  be between  $-12.5$  and  $31.3$  ps. The lifetime is measured using  $L_{xy}(D^\pm)$ , defined as the distance of the  $D^\pm$  decay vertex from the beam-spot projected onto the plane perpendicular to the  $z$  axis.

To further improve the search sensitivity, a Boosted Decision Tree (BDT) algorithm [10] is constructed from seven discriminating variables for each  $D^\pm$  candidate:  $\tau_{xy}(D^\pm)$ ,  $L_{xy}(D^\pm)$ , the CM momentum magnitude  $p^*(D^\pm)$ , the momentum magnitudes and transverse components with respect to the beam axis for both the  $K_s^0$  and pion candidates. The final selection criteria are based on the BDT output and optimized using truth-matched signal and background candidates from the MC sample. For the optimization, we maximize the  $S/\sqrt{S+B}$  ratio, where  $S$  and  $B$  are the numbers of signal and background candidates whose invariant mass is within  $\pm 31 \text{ MeV}/c^2$  of the nominal  $D^\pm$  mass.

A binned maximum likelihood (ML) fit to the  $m(K_s^0 \pi^\pm)$  distribution for the retained  $D^\pm$  candidates is used to extract the signal yield. The total probability density function (PDF) is the sum of signal and background components. The signal PDF is modeled as a sum of three Gaussian functions, two of them with common mean. The background PDF is taken as a sum of two components: a background from  $D_s^\pm \rightarrow K_s^0 K^\pm$ , where the  $K^\pm$  is misidentified as  $\pi^\pm$ , and a combinatorial background from other sources. Based on MC studies, the yield of  $D^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm$  decays in the final data sample is estimated to be 0.02% of the signal and the estimated  $A_{CP}$  for this source to be less than 0.002%. Therefore a PDF to model this component is not included in the fit. The background from the decay  $D_s^\pm \rightarrow K_s^0 K^\pm$  is modeled using a PDF sampled from the MC histogram for this mode. The combinatorial background is described as a second-order polynomial. The fit to the  $m(K_s^0 \pi^\pm)$  distribution yields  $(807.4 \pm 0.1) \times 10^3$  signal events. The data and the fit are shown in Fig. 1. All of the fit parameters are extracted from the fit to the data sample apart from the normalization of the background due to  $D_s^\pm \rightarrow K_s^0 K^\pm$ , which is fixed to the value predicted by the MC simulation.

We determine  $A_{CP}$  by measuring the signal yield asymmetry  $A$  defined as:

$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}, \quad (2)$$

where  $N_{D^+}(N_{D^-})$  is the number of fitted  $D^+ \rightarrow K_s^0 \pi^+(D^- \rightarrow K_s^0 \pi^-)$  decays. The quantity  $A$  is the result of two other contributions in addition to  $A_{CP}$ . There is a physics component due to the forward-backward (FB) asymmetry ( $A_{FB}$ ) in  $e^+e^- \rightarrow c\bar{c}$ , arising from  $\gamma^*$ - $Z^0$  interference and high order QED processes in  $e^+e^- \rightarrow c\bar{c}$ . This asymmetry will create a difference in the number of reconstructed  $D^+$  and  $D^-$  decays due to the FB detection asymmetries arising from the boost of the CM system relative to the laboratory frame. There

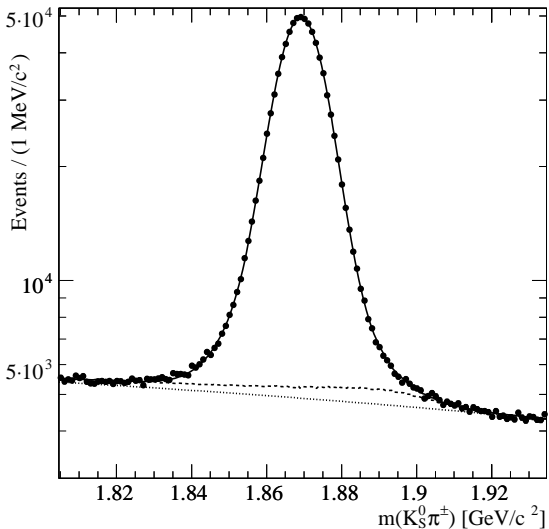


FIG. 1: Invariant mass distribution for  $K_s^0\pi^\pm$  candidates in the data (black points). The solid curve shows the fit to the data. The dashed line is the sum of all backgrounds, while the dotted line is combinatorial background only. The vertical scale of the plot is logarithmic.

is also a detector-induced component due to the difference in the reconstruction efficiencies of  $D^+ \rightarrow K_s^0\pi^+$  and  $D^- \rightarrow K_s^0\pi^-$  generated by differences in the track reconstruction and identification efficiencies for  $\pi^+$  and  $\pi^-$ . While  $A_{FB}$  is measured together with  $A_{CP}$  using the selected dataset, we correct the dataset itself for the reconstruction and identification effects using control data sets.

In this analysis we have developed a data-driven method to determine the charge asymmetry in track reconstruction as a function of the magnitude of the track momentum and its polar angle. Since  $B$  mesons are produced in the process  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  nearly at rest in the CM frame and decay isotropically in the  $B$  rest frame, these events provide a very large control sample essentially free of any physics-induced charge asymmetry. However, data recorded at the  $\Upsilon(4S)$  resonance also include continuum production  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ), where there is a non-negligible FB asymmetry due to the interference between the single virtual photon process and other production processes, as described above. The continuum contribution is estimated using the off-resonance data rescaled to the same luminosity as the on-resonance data sample. Subtracting the number of reconstructed tracks in the rescaled off-resonance sample from the number of tracks in the on-resonance one, we obtain the number of tracks corresponding to the  $B$  meson decays only. Therefore, the relative detection and identification efficiencies of the positively and negatively charged particles for given selection criteria can be determined using the numbers of positively and negatively reconstructed tracks directly from data.

Using samples of  $8.5 \text{ fb}^{-1}$  on-resonance and  $9.5 \text{ fb}^{-1}$

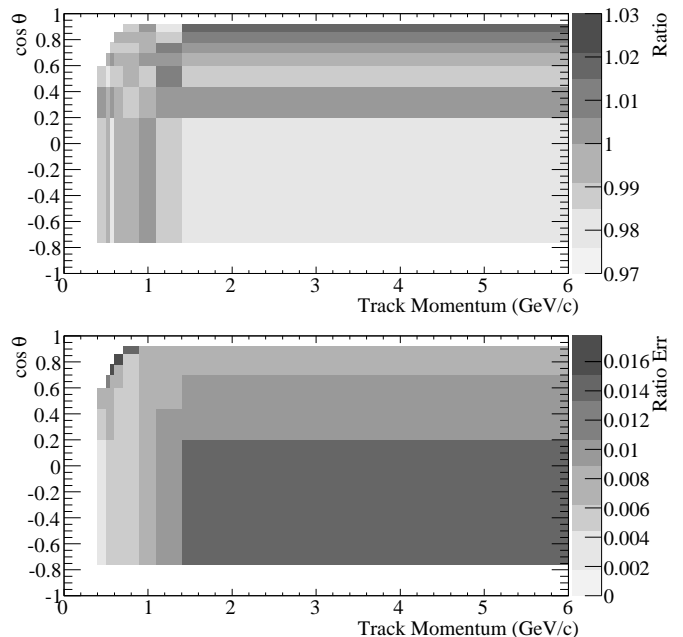


FIG. 2: Map of the ratio between detection efficiency for  $\pi^+$  and  $\pi^-$  (top) plus the corresponding statistical errors (bottom). The map is produced using the numbers of  $\pi^-$  and  $\pi^+$  tracks in the selected control sample.

off-resonance data, applying the same charged pion track selection criteria used in the reconstruction of  $D^\pm \rightarrow K_s^0\pi^\pm$  decays, and subtracting the off-resonance sample from the on-resonance sample, we obtain a sample of more than 20 million tracks. We use this sample to produce a map for the ratio of detection efficiencies for  $\pi^+$  and  $\pi^-$  as a function of the track-momentum magnitude and  $\cos\theta$ , where  $\theta$  is the polar angle of the track in the laboratory frame. The map and associated statistical errors are shown in Fig. 2. Since the charm meson production is azimuthally uniform, the  $\phi$  dependence of this ratio is found to be very small and uncorrelated with momentum magnitude and polar angle. Therefore, the ratio of detection efficiencies is averaged over the  $\phi$  coordinate. The statistical uncertainties can be reduced by increasing the control sample size, but this would bring a negligible reduction in the final systematic error. In the fit procedure described below, the  $D^-$  yields, in intervals of pion-momentum and  $\cos\theta$ , are weighted with this relative efficiency map to correct for the detection efficiency differences between  $\pi^+$  and  $\pi^-$ , leaving only FB and CP asymmetries.

Neglecting the second-order terms that contain the product of  $A_{CP}$  and  $A_{FB}$ , the resulting asymmetry can be expressed simply as the sum of the two. The parameter  $A_{CP}$  is independent of kinematic variables, while  $A_{FB}$  is an odd function of  $\cos\theta_D^*$ , where  $\theta_D^*$  is the polar angle of the  $D^\pm$  candidate momentum in the  $e^+e^-$  CM frame. If we compute  $A(+|\cos\theta_D^*|)$  for the  $D^\pm$  candidates in a positive  $\cos\theta_D^*$  bin and  $A(-|\cos\theta_D^*|)$  for the candidates

in its negative counterpart, the contribution to the two asymmetries from  $A_{CP}$  is the same, while the contribution from  $A_{FB}$  has the same magnitude but opposite sign. Therefore  $A_{CP}$  and  $A_{FB}$  can be written as a function of  $|\cos\theta_D^*|$  as follows:

$$A_{FB}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) - A(-|\cos\theta_D^*|)}{2} \quad (3)$$

and

$$A_{CP}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) + A(-|\cos\theta_D^*|)}{2}. \quad (4)$$

Furthermore, the small fraction of the  $D^\pm$  signal yields produced from  $B$  meson decays have zero FB asymmetry. As a result, the measured  $A_{FB}$  from the  $e^+e^- \rightarrow c\bar{c}$  production is slightly diluted.

The selected sample is divided into ten subsamples corresponding to ten  $\cos\theta_D^*$  bins of equal width and a simultaneous binned ML fit is performed on the invariant mass distributions of  $D^+$  and  $D^-$  candidates for each subsample to extract the signal yield asymmetries. The total PDF that describes the distribution is the same as the one used in the fit to the full sample, but some of the parameters (e.g., the signal yields and the asymmetries) can differ between the subsamples. The fit involves a total of 78 free parameters. Using the asymmetry measurements in five positive and in five negative  $\cos\theta_D^*$  bins, we obtain five  $A_{FB}$  and five  $A_{CP}$  values. As  $A_{CP}$  does not depend upon  $\cos\theta_D^*$ , we compute a central value of this parameter using a  $\chi^2$  minimization to a constant:  $A_{CP} = (-0.39 \pm 0.13)\%$ , where the error is statistical only. The  $A_{CP}$  and  $A_{FB}$  values are shown in Fig. 3, together with the central value and  $\pm 1\sigma$  confidence interval for  $A_{CP}$ .

We perform two tests to validate the analysis procedure. The first involves generating ensembles of toy MC experiments and extracting  $A_{CP}$  for each experiment. We determine that the fitted value of the  $A_{CP}$  parameter is unbiased, and that the fit returns an accurate estimate of the statistical uncertainty. The second test involves fitting a large number of MC events from the full *BABAR* detector simulation. We measure  $A_{CP}$  from this MC sample to be within  $\pm 1\sigma$  from the generated value of zero.

The primary sources of systematic uncertainty are the contamination in the composition of particles for the data control sample used to determine the charge asymmetry in track reconstruction efficiencies and statistical uncertainties in the detection efficiency ratios used to weight the  $D^-$  yields. The charged pion sample selected to determine the ratio of detection efficiencies for  $\pi^-$  and  $\pi^+$  contains a contamination of kaons, electrons, muons, and protons at the percent level due to particle misidentification and inefficiencies. This contamination introduces a small bias in the  $A_{CP}$  measurement due to the slightly different particle identification efficiencies between positively and negatively charged non-pion particles. The

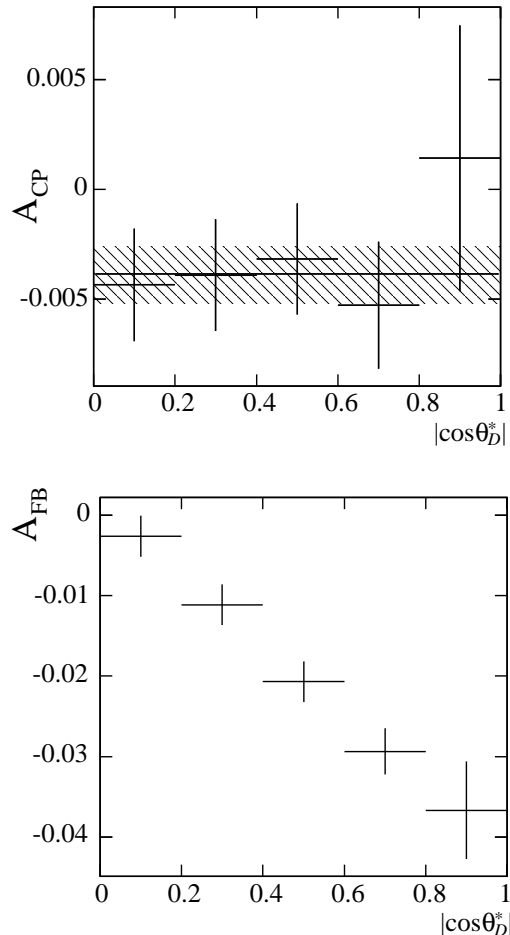


FIG. 3:  $A_{CP}$  (top) and  $A_{FB}$  (bottom) asymmetries for  $D^\pm \rightarrow K_S^0 \pi^\pm$  candidates as a function of  $|\cos\theta_D^*|$  in the data sample. The solid line represents the central value of  $A_{CP}$  and the hatched region is the  $\pm 1\sigma$  interval, both obtained from a  $\chi^2$  minimization assuming no dependence on  $|\cos\theta_D^*|$ .

particle identification efficiencies are separately measured in the data for positively and negatively charged tracks. They are found to be in a good agreement with the MC simulation. We therefore study this bias using the MC simulated events and determine the bias to be  $+0.05\%$ . As a result, we shift the measured  $A_{CP}$  by  $-0.05\%$  to correct for the bias and then, conservatively, include the same value as a contribution to the systematic uncertainty. Therefore the bias-corrected value of  $A_{CP}$  is  $(-0.44 \pm 0.13)\%$ .

The technique used here to remove the charge asymmetry from detector-induced effects produces a small systematic uncertainty in the measurement of  $A_{CP}$  due to the statistical error in the relative efficiency map ( $\pm 0.06\%$ ). Using MC simulation, we evaluate an additional systematic uncertainty of  $\pm 0.01\%$  due to a possible charge asymmetry present in the control sample before applying the selection criteria. Combining these two contributions with the systematic contribution from the

difference in the composition of the control sample compared to the signal sample ( $\pm 0.05\%$ ), as described earlier, the total contribution from the correction technique is  $\pm 0.08\%$ , which is the dominant source of systematic error. We also consider a possible systematic uncertainty due to the regeneration of  $K^0$  and  $\bar{K}^0$  mesons in the material of the detector.  $K^0$  and  $\bar{K}^0$  mesons produced in the decay process can interact with the material around the interaction point before they decay. Following a method similar to that described in [11], we compute the probability for  $K^0$  and  $\bar{K}^0$  to interact inside the *BABAR* tracking system. We numerically integrate the interaction probability distribution, which depends on the measured nuclear cross-section for  $K^\pm$  (assuming isospin symmetry), the amount of material in the *BABAR* beam-pipe and tracking detectors, the  $K^0/\bar{K}^0$  time evolutions, and the  $K_S^0$  kinematic distribution and reconstruction efficiency as determined from simulation studies. From the difference between the interaction probabilities for  $K^0$  and  $\bar{K}^0$ , we estimate a systematic uncertainty of  $\pm 0.06\%$ . Minor systematic uncertainties from the simultaneous ML fit are also considered: the choice of the signal and background PDF, the limited data set in the MC signal sample, and the choice of binning in  $\cos\theta_D^*$ , for a total contribution of  $\pm 0.01\%$ . The combined systematic uncertainty in the  $CP$  asymmetry measurement including all the contributions is calculated as the quadrature sum and is found to be  $\pm 0.10\%$ .

In conclusion, we measure the direct  $CP$  asymmetry,  $A_{CP}$ , in the  $D^\pm \rightarrow K_S^0 \pi^\pm$  decay using approximately 800,000  $D^\pm$  signal candidates. We obtain

$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\%, \quad (5)$$

where the first error is statistical and the second is systematic. The result is consistent with the prediction of  $(-0.332 \pm 0.006)\%$  for this mode based on the SM.

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), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MICIIN (Spain), STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union), the A. P. Sloan Foundation (USA) and the Binational Science Foundation (USA-Israel).

---

\* Now at Temple University, Philadelphia, Pennsylvania 19122, USA

† Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

‡ Also with Università di Roma La Sapienza, I-00185 Roma, Italy

§ Now at University of South Alabama, Mobile, Alabama 36688, USA

¶ Also with Università di Sassari, Sassari, Italy

- [1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
- [2] F. Buccella *et al.*, Phys. Rev. D **51**, 3478 (1995).
- [3] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
- [4] I. I. Bigi and H. Yamamoto, Phys. Lett. B **349**, 363 (1995).
- [5] H. J. Lipkin and Z. Xing, Phys. Lett. B **450**, 405 (1999).
- [6] B. R. Ko *et al.* (Belle collaboration), Phys. Rev. Lett. **104**, 181602 (2010).
- [7] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instr. Methods Phys. Res., Sect. A **479**, 1 (2002).
- [8] W. D. Hulsbergen, Nucl. Instrum. Meth. A **552**, 566 (2005).
- [9] S. Agostinelli *et al.* (GEANT4 Collaboration), Nucl. Instr. Methods Phys. Res., Sect. A **506**, 250 (2003).
- [10] P. Speckmayer, A. Hocker, J. Stelzer and H. Voss, J. Phys. Conf. Ser. **219**, 032057 (2010).
- [11] B. R. Ko *et al.*, arXiv:1006.1938 [hep-ex] (2010).