

Search for  $CP$  violation using  $T$ -odd correlations in  $D^0 \rightarrow K^+K^-\pi^+\pi^-$  decays

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>, 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> M. Battaglia,<sup>5</sup> D. N. Brown,<sup>5</sup> B. Hooberman,<sup>5</sup> L. T. Kerth,<sup>5</sup> Yu. G. Kolomensky,<sup>5</sup> G. Lynch,<sup>5</sup> I. L. Osipenko,<sup>5</sup> T. Tanabe,<sup>5</sup> C. M. Hawkes,<sup>6</sup> N. Soni,<sup>6</sup> A. T. Watson,<sup>6</sup> H. Koch,<sup>7</sup> T. Schroeder,<sup>7</sup> D. J. Asgeirsson,<sup>8</sup> C. Hearty,<sup>8</sup> T. S. Mattison,<sup>8</sup> J. A. McKenna,<sup>8</sup> A. Khan,<sup>9</sup> A. Randle-Conde,<sup>9</sup> V. E. Blinov,<sup>10</sup> A. R. Buzykaev,<sup>10</sup> V. P. Druzhinin,<sup>10</sup> V. B. Golubev,<sup>10</sup> A. P. Onuchin,<sup>10</sup> S. I. Serednyakov,<sup>10</sup> Yu. I. Skovpen,<sup>10</sup> E. P. Solodov,<sup>10</sup> K. Yu. Todyshev,<sup>10</sup> A. N. Yushkov,<sup>10</sup> M. Bondioli,<sup>11</sup> S. Curry,<sup>11</sup> D. Kirkby,<sup>11</sup> A. J. Lankford,<sup>11</sup> M. Mandelkern,<sup>11</sup> E. C. Martin,<sup>11</sup> D. P. Stoker,<sup>11</sup> H. Atmacan,<sup>12</sup> J. W. Gary,<sup>12</sup> F. Liu,<sup>12</sup> O. Long,<sup>12</sup> G. M. Vitug,<sup>12</sup> Z. Yasin,<sup>12</sup> V. Sharma,<sup>13</sup> C. Campagnari,<sup>14</sup> T. M. Hong,<sup>14</sup> D. Kovalskyi,<sup>14</sup> J. D. Richman,<sup>14</sup> A. M. Eisner,<sup>15</sup> C. A. Heusch,<sup>15</sup> J. Kroseberg,<sup>15</sup> W. S. Lockman,<sup>15</sup> A. J. Martinez,<sup>15</sup> T. Schalk,<sup>15</sup> B. A. Schumm,<sup>15</sup> A. Seiden,<sup>15</sup> L. O. Winstrom,<sup>15</sup> C. H. Cheng,<sup>16</sup> D. A. Doll,<sup>16</sup> B. Echenard,<sup>16</sup> D. G. Hitlin,<sup>16</sup> P. Ongmongkolkul,<sup>16</sup> F. C. Porter,<sup>16</sup> A. Y. Rakitin,<sup>16</sup> R. Andreassen,<sup>17</sup> M. S. Dubrovin,<sup>17</sup> G. Mancinelli,<sup>17</sup> B. T. Meadows,<sup>17</sup> M. D. Sokoloff,<sup>17</sup> P. C. Bloom,<sup>18</sup> W. T. Ford,<sup>18</sup> A. Gaz,<sup>18</sup> J. F. Hirschauer,<sup>18</sup> M. Nagel,<sup>18</sup> U. Nauenberg,<sup>18</sup> J. G. Smith,<sup>18</sup> S. R. Wagner,<sup>18</sup> R. Ayad,<sup>19,\*</sup> W. H. Toki,<sup>19</sup> A. Hauke,<sup>20</sup> H. Jasper,<sup>20</sup> T. M. Karbach,<sup>20</sup> J. Merkel,<sup>20</sup> A. Petzold,<sup>20</sup> B. Spaan,<sup>20</sup> K. Wacker,<sup>20</sup> M. J. Kobel,<sup>21</sup> K. R. Schubert,<sup>21</sup> R. Schwierz,<sup>21</sup> D. Bernard,<sup>22</sup> M. Verderi,<sup>22</sup> P. J. Clark,<sup>23</sup> S. Playfer,<sup>23</sup> J. E. Watson,<sup>23</sup> M. Andreotti<sup>ab,24</sup>, D. Bettoni<sup>a,24</sup>, C. Bozzi<sup>a,24</sup>, R. Calabrese<sup>ab,24</sup>, A. Cecchi<sup>ab,24</sup>, G. Cibinetto<sup>ab,24</sup>, E. Fioravanti<sup>ab,24</sup>, P. Franchini<sup>ab,24</sup>, E. Luppi<sup>ab,24</sup>, M. Munerato<sup>ab,24</sup>, M. Negrini<sup>ab,24</sup>, A. Petrella<sup>ab,24</sup>, L. Piemontese<sup>a,24</sup>, R. Baldini-Ferrolì,<sup>25</sup> A. Calcaterra,<sup>25</sup> R. de Sangro,<sup>25</sup> G. Finocchiaro,<sup>25</sup> M. Nicolaci,<sup>25</sup> S. Pacetti,<sup>25</sup> P. Patteri,<sup>25</sup> I. M. Peruzzi,<sup>25,†</sup> M. Piccolo,<sup>25</sup> M. Rama,<sup>25</sup> A. Zallo,<sup>25</sup> R. Contri<sup>ab,26</sup>, E. Guido<sup>ab,26</sup>, M. Lo Vetere<sup>ab,26</sup>, M. R. Monge<sup>ab,26</sup>, S. Passaggio<sup>a,26</sup>, C. Patrignani<sup>ab,26</sup>, E. Robutti<sup>a,26</sup>, S. Tosi<sup>ab,26</sup>, B. Bhuyan,<sup>27</sup> M. Morii,<sup>28</sup> A. Adametz,<sup>29</sup> J. Marks,<sup>29</sup> S. Schenk,<sup>29</sup> U. Uwer,<sup>29</sup> F. U. Bernlochner,<sup>30</sup> H. M. Lacker,<sup>30</sup> T. Lueck,<sup>30</sup> A. Volk,<sup>30</sup> P. D. Dauncey,<sup>31</sup> M. Tibbetts,<sup>31</sup> P. K. Behera,<sup>32</sup> U. Mallik,<sup>32</sup> C. Chen,<sup>33</sup> J. Cochran,<sup>33</sup> H. B. Crawley,<sup>33</sup> L. Dong,<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> Y. Y. Gao,<sup>34</sup> A. V. Gritsan,<sup>34</sup> Z. J. Guo,<sup>34</sup> N. Arnaud,<sup>35</sup> M. Davier,<sup>35</sup> D. Derkach,<sup>35</sup> J. Firmino da Costa,<sup>35</sup> G. Grosdidier,<sup>35</sup> F. Le Diberder,<sup>35</sup> A. M. Lutz,<sup>35</sup> B. Malaescu,<sup>35</sup> A. Perez,<sup>35</sup> P. Roudeau,<sup>35</sup> M. H. Schune,<sup>35</sup> J. Serrano,<sup>35</sup> V. Sordini,<sup>35,‡</sup> A. Stocchi,<sup>35</sup> L. Wang,<sup>35</sup> G. Wormser,<sup>35</sup> D. J. Lange,<sup>36</sup> D. M. Wright,<sup>36</sup> I. Bingham,<sup>37</sup> J. P. Burke,<sup>37</sup> C. A. Chavez,<sup>37</sup> J. P. Coleman,<sup>37</sup> J. R. Fry,<sup>37</sup> E. Gabathuler,<sup>37</sup> R. Gamet,<sup>37</sup> D. E. Hutchcroft,<sup>37</sup> D. J. Payne,<sup>37</sup> C. Touramanis,<sup>37</sup> A. J. Bevan,<sup>38</sup> F. Di Lodovico,<sup>38</sup> R. Sacco,<sup>38</sup> M. Sigamani,<sup>38</sup> G. Cowan,<sup>39</sup> S. Paramesvaran,<sup>39</sup> A. C. Wren,<sup>39</sup> D. N. Brown,<sup>40</sup> C. L. Davis,<sup>40</sup> A. G. Denig,<sup>41</sup> M. Fritsch,<sup>41</sup> W. Gradl,<sup>41</sup> A. Hafner,<sup>41</sup> K. E. Alwyn,<sup>42</sup> D. Bailey,<sup>42</sup> R. J. Barlow,<sup>42</sup> G. Jackson,<sup>42</sup> G. D. Lafferty,<sup>42</sup> T. J. West,<sup>42</sup> J. Anderson,<sup>43</sup> R. Cenci,<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> C. Dallapiccola,<sup>44</sup> E. Salvati,<sup>44</sup> R. Cowan,<sup>45</sup> D. Dujmic,<sup>45</sup> P. H. Fisher,<sup>45</sup> G. Sciolla,<sup>45</sup> R. K. Yamamoto,<sup>45</sup> M. Zhao,<sup>45</sup> P. M. Patel,<sup>46</sup> S. H. Robertson,<sup>46</sup> M. Schram,<sup>46</sup> P. Biassoni<sup>ab,47</sup>, A. Lazzaro<sup>ab,47</sup>, V. Lombardo<sup>a,47</sup>, F. Palombo<sup>ab,47</sup>, S. Stracka<sup>ab,47</sup>, L. Cremaldi,<sup>48</sup> R. Godang,<sup>48,§</sup> R. Kroeger,<sup>48</sup> P. Sonnek,<sup>48</sup> D. J. Summers,<sup>48</sup> H. W. Zhao,<sup>48</sup> X. Nguyen,<sup>49</sup> M. Simard,<sup>49</sup> P. Taras,<sup>49</sup> G. De Nardo<sup>ab,50</sup>, D. Monorchio<sup>ab,50</sup>, G. Onorato<sup>ab,50</sup>, C. Sciacca<sup>ab,50</sup>, G. Raven,<sup>51</sup> H. L. Snoek,<sup>51</sup> C. P. Jessop,<sup>52</sup> K. J. Knoepfel,<sup>52</sup> J. M. LoSecco,<sup>52</sup> W. F. Wang,<sup>52</sup> L. A. Corwin,<sup>53</sup> K. Honscheid,<sup>53</sup> R. Kass,<sup>53</sup> J. P. Morris,<sup>53</sup> A. M. Rahimi,<sup>53</sup> N. L. Blount,<sup>54</sup> J. Brau,<sup>54</sup> R. Frey,<sup>54</sup> O. Igonkina,<sup>54</sup> J. A. Kolb,<sup>54</sup> R. Rahmat,<sup>54</sup> N. B. Sinev,<sup>54</sup> D. Strom,<sup>54</sup> J. Strube,<sup>54</sup> E. Torrence,<sup>54</sup> G. Castelli<sup>ab,55</sup>, E. Feltresi<sup>ab,55</sup>, N. Gagliardi<sup>ab,55</sup>, M. Margoni<sup>ab,55</sup>, M. Morandin<sup>a,55</sup>, M. Posocco<sup>a,55</sup>, M. Rotondo<sup>a,55</sup>, F. Simonetto<sup>ab,55</sup>, R. Stroili<sup>ab,55</sup>, E. Ben-Haim,<sup>56</sup> G. R. Bonneaud,<sup>56</sup> H. Briand,<sup>56</sup> J. Chauveau,<sup>56</sup> O. Hamon,<sup>56</sup> Ph. Leruste,<sup>56</sup> G. Marchiori,<sup>56</sup> J. Ocariz,<sup>56</sup> J. Prendki,<sup>56</sup> S. Sitt,<sup>56</sup> M. Biasini<sup>ab,57</sup>, E. Manoni<sup>ab,57</sup>, C. Angelini<sup>ab,58</sup>, G. Batignani<sup>ab,58</sup>, S. Bettarini<sup>ab,58</sup>, G. Calderini<sup>ab,58,¶</sup>, M. Carpinelli<sup>ab,58,\*\*</sup>, A. Cervelli<sup>ab,58</sup>, F. Forti<sup>ab,58</sup>, M. A. Giorgi<sup>ab,58</sup>, A. Lusiani<sup>ac,58</sup>, N. Neri<sup>ab,58</sup>, E. Paoloni<sup>ab,58</sup>, G. Rizzo<sup>ab,58</sup>, J. J. Walsh<sup>a,58</sup>, D. Lopes Pegna,<sup>59</sup> C. Lu,<sup>59</sup> J. Olsen,<sup>59</sup> A. J. S. Smith,<sup>59</sup> A. V. Telnov,<sup>59</sup> F. Anulli<sup>a,60</sup>, E. Baracchini<sup>ab,60</sup>, G. Cavoto<sup>a,60</sup>, R. Faccini<sup>ab,60</sup>, F. Ferrarotto<sup>a,60</sup>, F. Ferroni<sup>ab,60</sup>, M. Gaspero<sup>ab,60</sup>, L. Li Gioi<sup>a,60</sup>, M. A. Mazzoni<sup>a,60</sup>, G. Piredda<sup>a,60</sup>, F. Renga<sup>ab,60</sup>, M. Ebert,<sup>61</sup> T. Hartmann,<sup>61</sup> T. Leddig,<sup>61</sup> H. Schröder,<sup>61</sup> R. Waldi,<sup>61</sup> T. Adye,<sup>62</sup> B. Franek,<sup>62</sup> E. O. Olaiya,<sup>62</sup> F. F. Wilson,<sup>62</sup> S. Emery,<sup>63</sup> G. Hamel de Monchenault,<sup>63</sup> G. Vasseur,<sup>63</sup> Ch. Yèche,<sup>63</sup> M. Zito,<sup>63</sup> M. T. Allen,<sup>64</sup> D. Aston,<sup>64</sup> D. J. Bard,<sup>64</sup> R. Bartoldus,<sup>64</sup> J. F. Benitez,<sup>64</sup> C. Cartaro,<sup>64</sup> M. R. Convery,<sup>64</sup> J. Dorfan,<sup>64</sup> G. P. Dubois-Felsmann,<sup>64</sup> W. Dunwoodie,<sup>64</sup> R. C. Field,<sup>64</sup> M. Franco Sevilla,<sup>64</sup> B. G. Fulsom,<sup>64</sup> A. M. Gabareen,<sup>64</sup> M. T. Graham,<sup>64</sup> P. Grenier,<sup>64</sup> C. Hast,<sup>64</sup> W. R. Innes,<sup>64</sup> M. H. Kelsey,<sup>64</sup> H. Kim,<sup>64</sup> P. Kim,<sup>64</sup> M. L. Kocian,<sup>64</sup> D. W. G. S. Leith,<sup>64</sup> S. Li,<sup>64</sup> B. Lindquist,<sup>64</sup> S. Luitz,<sup>64</sup> V. Luth,<sup>64</sup> H. L. Lynch,<sup>64</sup>

D. B. MacFarlane,<sup>64</sup> H. Marsiske,<sup>64</sup> D. R. Muller,<sup>64</sup> H. Neal,<sup>64</sup> S. Nelson,<sup>64</sup> C. P. O'Grady,<sup>64</sup> I. Ofte,<sup>64</sup> M. Perl,<sup>64</sup> B. N. Ratcliff,<sup>64</sup> A. Roodman,<sup>64</sup> A. A. Salnikov,<sup>64</sup> R. H. Schindler,<sup>64</sup> J. Schwiening,<sup>64</sup> A. Snyder,<sup>64</sup> D. Su,<sup>64</sup> M. K. Sullivan,<sup>64</sup> K. Suzuki,<sup>64</sup> J. M. Thompson,<sup>64</sup> J. Va'vra,<sup>64</sup> A. P. Wagner,<sup>64</sup> M. Weaver,<sup>64</sup> C. A. West,<sup>64</sup> W. J. Wisniewski,<sup>64</sup> M. Wittgen,<sup>64</sup> D. H. Wright,<sup>64</sup> H. W. Wulsin,<sup>64</sup> A. K. Yarritu,<sup>64</sup> V. Santoro,<sup>64</sup> C. C. Young,<sup>64</sup> V. Ziegler,<sup>64</sup> X. R. Chen,<sup>65</sup> W. Park,<sup>65</sup> M. V. Purohit,<sup>65</sup> R. M. White,<sup>65</sup> J. R. Wilson,<sup>65</sup> S. J. Sekula,<sup>66</sup> M. Bellis,<sup>67</sup> P. R. Burchat,<sup>67</sup> A. J. Edwards,<sup>67</sup> T. S. Miyashita,<sup>67</sup> S. Ahmed,<sup>68</sup> M. S. Alam,<sup>68</sup> J. A. Ernst,<sup>68</sup> B. Pan,<sup>68</sup> M. A. Saeed,<sup>68</sup> S. B. Zain,<sup>68</sup> N. Guttman,<sup>69</sup> A. Soffer,<sup>69</sup> P. Lund,<sup>70</sup> S. M. Spanier,<sup>70</sup> R. Eckmann,<sup>71</sup> J. L. Ritchie,<sup>71</sup> A. M. Ruland,<sup>71</sup> C. J. Schilling,<sup>71</sup> R. F. Schwitters,<sup>71</sup> B. C. Wray,<sup>71</sup> J. M. Izen,<sup>72</sup> X. C. Lou,<sup>72</sup> F. Bianchi<sup>ab, 73</sup> D. Gamba<sup>ab, 73</sup> M. Pelliccioni<sup>ab, 73</sup> M. Bomben<sup>ab, 74</sup> G. Della Ricca<sup>ab, 74</sup> L. Lanceri<sup>ab, 74</sup> L. Vitale<sup>ab, 74</sup> V. Azzolini,<sup>75</sup> N. Lopez-March,<sup>75</sup> F. Martinez-Vidal,<sup>75</sup> D. A. Milanes,<sup>75</sup> A. Oyanguren,<sup>75</sup> J. Albert,<sup>76</sup> Sw. Banerjee,<sup>76</sup> H. H. F. Choi,<sup>76</sup> K. Hamano,<sup>76</sup> G. J. King,<sup>76</sup> R. Kowalewski,<sup>76</sup> M. J. Lewczuk,<sup>76</sup> I. M. Nugent,<sup>76</sup> J. M. Roney,<sup>76</sup> R. J. Sobie,<sup>76</sup> T. J. Gershon,<sup>77</sup> P. F. Harrison,<sup>77</sup> J. Ilic,<sup>77</sup> T. E. Latham,<sup>77</sup> G. B. Mohanty,<sup>77</sup> E. M. T. Puccio,<sup>77</sup> H. R. Band,<sup>78</sup> X. Chen,<sup>78</sup> S. Dasu,<sup>78</sup> K. T. Flood,<sup>78</sup> Y. Pan,<sup>78</sup> R. Prepost,<sup>78</sup> C. O. Vuosalo,<sup>78</sup> and S. L. Wu<sup>78</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>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 British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

<sup>9</sup>Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

<sup>10</sup>Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

<sup>11</sup>University of California at Irvine, Irvine, California 92697, USA

<sup>12</sup>University of California at Riverside, Riverside, California 92521, USA

<sup>13</sup>University of California at San Diego, La Jolla, California 92093, USA

<sup>14</sup>University of California at Santa Barbara, Santa Barbara, California 93106, USA

<sup>15</sup>University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

<sup>16</sup>California Institute of Technology, Pasadena, California 91125, USA

<sup>17</sup>University of Cincinnati, Cincinnati, Ohio 45221, USA

<sup>18</sup>University of Colorado, Boulder, Colorado 80309, USA

<sup>19</sup>Colorado State University, Fort Collins, Colorado 80523, USA

<sup>20</sup>Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany

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

<sup>22</sup>Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

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

<sup>24</sup>INFN Sezione di Ferrara<sup>a</sup>; Dipartimento di Fisica, Università di Ferrara<sup>b</sup>, I-44100 Ferrara, Italy

<sup>25</sup>INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy

<sup>26</sup>INFN Sezione di Genova<sup>a</sup>; Dipartimento di Fisica, Università di Genova<sup>b</sup>, I-16146 Genova, Italy

<sup>27</sup>Indian Institute of Technology Guwahati, Guwahati, Assam, 781 039, India

<sup>28</sup>Harvard University, Cambridge, Massachusetts 02138, USA

<sup>29</sup>Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

<sup>30</sup>Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, 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>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>36</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA

<sup>37</sup>University of Liverpool, Liverpool L69 7ZE, United Kingdom

<sup>38</sup>Queen Mary, University of London, London, E1 4NS, United Kingdom

<sup>39</sup>University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

<sup>40</sup>University of Louisville, Louisville, Kentucky 40292, USA

<sup>41</sup>Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany

<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>Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA  
<sup>46</sup>McGill University, Montréal, Québec, Canada H3A 2T8  
<sup>47</sup>INFN Sezione di Milano<sup>a</sup>; Dipartimento di Fisica, Università di Milano<sup>b</sup>, I-20133 Milano, Italy  
<sup>48</sup>University of Mississippi, University, Mississippi 38677, USA  
<sup>49</sup>Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7  
<sup>50</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>51</sup>NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands  
<sup>52</sup>University of Notre Dame, Notre Dame, Indiana 46556, USA  
<sup>53</sup>Ohio State University, Columbus, Ohio 43210, USA  
<sup>54</sup>University of Oregon, Eugene, Oregon 97403, USA  
<sup>55</sup>INFN Sezione di Padova<sup>a</sup>; Dipartimento di Fisica, Università di Padova<sup>b</sup>, I-35131 Padova, Italy  
<sup>56</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>57</sup>INFN Sezione di Perugia<sup>a</sup>; Dipartimento di Fisica, Università di Perugia<sup>b</sup>, I-06100 Perugia, Italy  
<sup>58</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>59</sup>Princeton University, Princeton, New Jersey 08544, USA  
<sup>60</sup>INFN Sezione di Roma<sup>a</sup>; Dipartimento di Fisica, Università di Roma La Sapienza<sup>b</sup>, I-00185 Roma, Italy  
<sup>61</sup>Universität Rostock, D-18051 Rostock, Germany  
<sup>62</sup>Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom  
<sup>63</sup>CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France  
<sup>64</sup>SLAC National Accelerator Laboratory, Stanford, California 94309 USA  
<sup>65</sup>University of South Carolina, Columbia, South Carolina 29208, USA  
<sup>66</sup>Southern Methodist University, Dallas, Texas 75275, USA  
<sup>67</sup>Stanford University, Stanford, California 94305-4060, USA  
<sup>68</sup>State University of New York, Albany, New York 12222, USA  
<sup>69</sup>Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel  
<sup>70</sup>University of Tennessee, Knoxville, Tennessee 37996, USA  
<sup>71</sup>University of Texas at Austin, Austin, Texas 78712, USA  
<sup>72</sup>University of Texas at Dallas, Richardson, Texas 75083, USA  
<sup>73</sup>INFN Sezione di Torino<sup>a</sup>; Dipartimento di Fisica Sperimentale, Università di Torino<sup>b</sup>, I-10125 Torino, Italy  
<sup>74</sup>INFN Sezione di Trieste<sup>a</sup>; Dipartimento di Fisica, Università di Trieste<sup>b</sup>, I-34127 Trieste, Italy  
<sup>75</sup>IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain  
<sup>76</sup>University of Victoria, Victoria, British Columbia, Canada V8W 3P6  
<sup>77</sup>Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom  
<sup>78</sup>University of Wisconsin, Madison, Wisconsin 53706, USA

(Dated: August 13, 2010)

We search for CP violation in a sample of  $4.7 \times 10^4$  Cabibbo suppressed  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  decays. We use  $470 \text{ fb}^{-1}$  of data recorded by the BABAR detector at the PEP-II asymmetric-energy  $e^+e^-$  storage rings running at center-of-mass energies near 10.6 GeV. CP violation is searched for in the difference between the  $T$ -odd asymmetries, obtained using triple product correlations, measured for  $D^0$  and  $\bar{D}^0$  decays. The measured CP violation parameter is  $\mathcal{A}_T = (1.0 \pm 5.1_{\text{stat}} \pm 4.4_{\text{syst}}) \times 10^{-3}$ .

PACS numbers: 13.25.Ft, 11.30.Er

In the Standard Model (SM) of particle physics, CP violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa quark mixing matrix [1]. Physics beyond the SM, often referred to as New Physics (NP), can manifest itself through the production of new particles, probably at high mass, or through rare processes not consistent with SM origins. SM predictions for CP asymmetries in charm meson decays are generally of  $\mathcal{O}(10^{-3})$ , at least one order of magnitude lower than current experimental limits [2]. Thus, the observation of CP violation with current sensitivities would be a NP signal. Among all hadronic  $D$  decays, singly Cabibbo suppressed decays

are uniquely sensitive to CP violation in  $c \rightarrow u\bar{q}$  transitions, effect not expected in Cabibbo favored or doubly Cabibbo suppressed decays [3].

In this paper we report a search for CP violation in the decay  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  using a kinematic triple product correlation of the form  $C_T = \mathbf{p}_1 \cdot (\mathbf{p}_2 \times \mathbf{p}_3)$ , where each  $\mathbf{p}_i$  is a momentum vector of one of the particles in the decay. The product is odd under time-reversal ( $T$ ) and, assuming the CPT theorem,  $T$ -violation is a signal for CP-violation. Strong interaction dynamics can pro-

duce a non-zero value of the  $A_T$  asymmetry,

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad (1)$$

where  $\Gamma$  is the decay rate for the process, even if the weak phases are zero. Defining as  $\bar{A}_T$  the  $T$ -odd asymmetry measured in the  $CP$ -conjugate decay process,

$$\bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}, \quad (2)$$

we can construct:

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T), \quad (3)$$

which is a true  $T$ -violating signal [5]. At least four particles are required in the final state so that the three used to define the triple product are independent [6] of each other. Singly Cabibbo suppressed decays having relatively high branching fractions and four different particles in the final state, therefore suitable for this type of analysis, are  $D^0 \rightarrow K^+K^-\pi^+\pi^-$  (explored in this paper) and  $D^+ \rightarrow K^+K_s^0\pi^+\pi^-$ . A full angular analysis of these  $D$  decays is suggested as a method for searching for  $CP$  violation [4].

Following the suggestion by I.I. Bigi [7] to study  $CP$  violation using this technique, the FOCUS collaboration made the first measurements using approximately 800 events and reported  $\mathcal{A}_T(D^0 \rightarrow K^+K^-\pi^+\pi^-) = 0.010 \pm 0.057 \pm 0.037$  [8]. We perform a similar study using approximately  $4.7 \times 10^4$  events.

This analysis is based on a  $470 \text{ fb}^{-1}$  data sample recorded at the  $\Upsilon(4S)$  resonance and 40 MeV below the resonance by the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$  storage rings. The *BABAR* detector is described in detail elsewhere [9]. We mention here only the parts of the detector which are used in the present analysis. Charged particles are detected and their momenta measured with a combination of a cylindrical drift chamber (DCH) and a silicon vertex tracker (SVT), both operating within the 1.5 T magnetic field of a superconducting solenoid. The information from a ring-imaging Cherenkov detector combined with energy-loss measurements in the SVT and DCH provide identification of charged kaon and pion candidates.

The reaction [10]

$$e^+e^- \rightarrow X D^{*+}; D^{*+} \rightarrow \pi_s^+ D^0; D^0 \rightarrow K^+K^-\pi^+\pi^-, \quad (4)$$

where  $X$  indicates any system composed by charged and neutral particles, has been reconstructed from the sample of events having at least five charged tracks. We first reconstruct the  $D^0$  candidate. All  $K^+K^-\pi^+\pi^-$  combinations assembled from well-measured and positively identified kaons and pions are constrained to a common vertex requiring a  $\chi^2$  fit probability greater than 0.1%.

To reconstruct the  $D^{*+}$  candidate, we perform a vertex fit of the  $D^0$  candidates with all combinations of charged tracks having a laboratory momentum below  $0.65 \text{ GeV}/c$  ( $\pi_s^+$ ) with the constraint that the new vertex is located in the interaction region. We require the fit probability to be greater than 0.1%.

We require the  $D^0$  to have a center-of-mass momentum greater than  $2.5 \text{ GeV}/c$ . This requirement removes any  $D^0$  coming from  $B$  decays. We observe a contamination of the signal sample from  $D^0 \rightarrow K^+K^-K_s^0$ , where  $K_s^0 \rightarrow \pi^+\pi^-$ . The  $\pi^+\pi^-$  effective mass shows, in fact, a distinct  $K_s^0$  mass peak, which can be represented by a Gaussian distribution with  $\sigma = 4.20 \pm 0.26 \text{ MeV}/c^2$ , and which accounts for 5.2% of the selected data sample. We veto  $K_s^0$  candidates within a window of  $2.5 \sigma$ . This cut, while reducing to negligible level the background from  $D^0 \rightarrow K^+K^-K_s^0$ , removes 5.8% of the signal events.

We look for backgrounds from charm decay modes with mis-identified pions by assigning alternatively the pion mass to both kaons. Then we study the two-body, three-body, four-body and five-body mass distributions (including the  $\pi_s^+$ ). We observe a signal of  $D_s^+ \rightarrow K^+K^-\pi^+\pi^-\pi_s^+$  in the five-particle mass distribution, which is taken into account in the following fit. No other signal is observed in the resulting mass spectra.

We define the mass difference  $\Delta m$  as:

$$\Delta m \equiv m(K^+K^-\pi^+\pi^-\pi_s^+) - m(K^+K^-\pi^+\pi^-). \quad (5)$$

Figure 1(a) shows the scatter plot  $m(K^+K^-\pi^+\pi^-)$  vs.  $\Delta m$  for all the events. Figure 1(b) shows the  $m(K^+K^-\pi^+\pi^-)$  projection, Fig. 1(c) shows the  $\Delta m$  projection.

We perform a fit to the  $m(K^+K^-\pi^+\pi^-)$  and  $\Delta m$  distributions, using a polynomial background and a single Gaussian. The fit gives  $\sigma_{D^0} = 3.94 \pm 0.05 \text{ MeV}/c^2$  for the  $D^0$  mass and  $\sigma_{D^{*+}} = 244 \pm 20 \text{ keV}/c^2$  for the  $\Delta m$ . We define the signal region within  $\pm 2\sigma_{D^0}$  and  $\pm 3.5\sigma_{D^{*+}}$ . The total yield of tagged  $D^0$  mesons in the signal region is approximately  $4.7 \times 10^4$  events.

The  $D^0$  yields to be used in the calculation of the  $T$  asymmetry are determined using a binned, extended maximum-likelihood fit to the 2-D ( $m(K^+K^-\pi^+\pi^-)$ ,  $\Delta m$ ) distribution obtained with the two observables  $m(K^+K^-\pi^+\pi^-)$  and  $\Delta m$  in the mass regions defined in the ranges  $1.825 < m(K^+K^-\pi^+\pi^-) < 1.915 \text{ GeV}/c^2$  and  $0.1395 < \Delta m < 0.1545 \text{ GeV}/c^2$  respectively. Events having more than one slow pion candidate in this mass region are removed (1.8 % of the final sample). The final 2-D distribution contains approximately  $1.5 \times 10^5$  events and is divided into a  $100 \times 100$  grid.

The 2-D ( $m(K^+K^-\pi^+\pi^-)$ ,  $\Delta m$ ) distribution is described by five components:

1. True  $D^0$  signal originating from a  $D^{*+}$  decay. This component has characteristic peaks in both observables  $m(K^+K^-\pi^+\pi^-)$  and  $\Delta m$ .

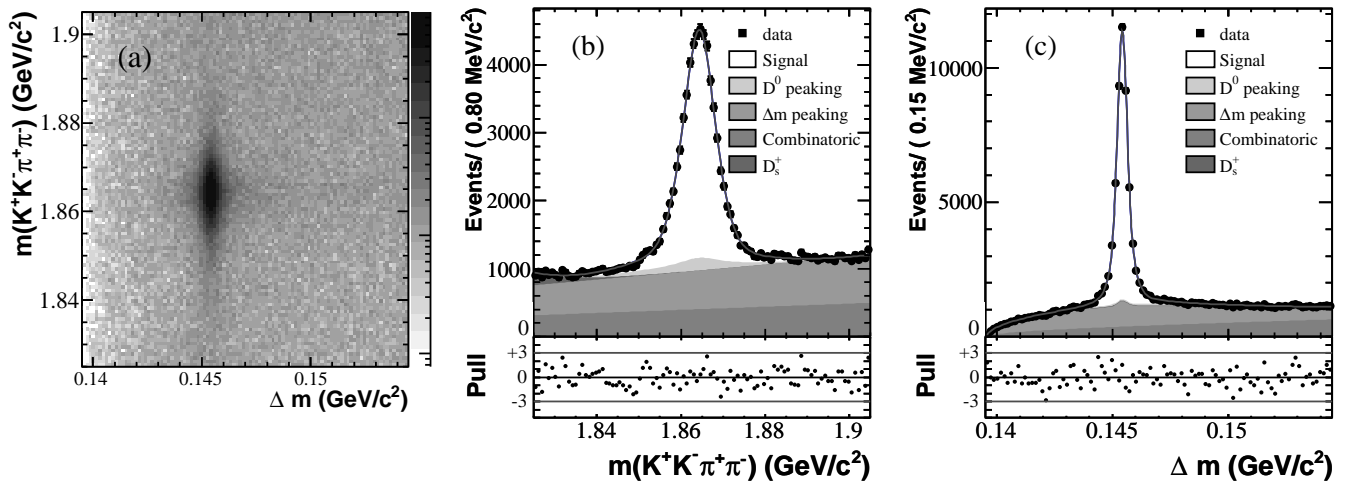


FIG. 1: (a)  $m(K^+K^-\pi^+\pi^-)$  vs.  $\Delta m$  for the total data sample. (b)  $m(K^+K^-\pi^+\pi^-)$  and (c)  $\Delta m$  projections with curves from the fit results. Shaded areas indicate the different contributions. The fit residuals, represented by the pulls, are also shown under each distribution.

2. Random  $\pi_s^+$  events where a true  $D^0$  is associated to an incorrect  $\pi_s^+$ , called  $D^0$  peaking. This contribution has the same shape in  $m(K^+K^-\pi^+\pi^-)$  as signal events, but does not peak in  $\Delta m$ .
3. Misreconstructed  $D^0$  decays where one or more of the  $D^0$  decay products are either not reconstructed or reconstructed with the wrong particle hypothesis, called  $\Delta m$  peaking. Some of these events show a peak in  $\Delta m$ , but not in  $m(K^+K^-\pi^+\pi^-)$ .
4. Combinatorial background where the  $K^+$ ,  $K^-$ ,  $\pi^+$ ,  $\pi^-$  candidates are not fragments of the same  $D^0$  decay, called combinatoric. This contribution does not exhibit any peaking structure in  $m(K^+K^-\pi^+\pi^-)$  or  $\Delta m$ .
5.  $D_s^+ \rightarrow K^+K^-\pi^+\pi^-\pi^+$  contamination, called  $D_s^+$ . This background has been studied on Monte Carlo (MC) simulations and shows a characteristic linear narrow shape in the 2-D ( $m(K^+K^-\pi^+\pi^-)$ ,  $\Delta m$ ) distribution, too small to be directly visible in Fig. 1(a).

The functional forms of the probability density functions (PDFs) for the signal and background components are based on studies of MC samples. These events are generated using the GEANT4 program [11] and are processed through the same reconstruction and analysis chain as the real events. However, all parameters related to these functions are determined from two-dimensional likelihood fits to data over the full  $m(K^+K^-\pi^+\pi^-)$  vs.  $\Delta m$  region. We make use of combinations of Gaussian and Johnson SU [12] lineshapes for peaking distributions, and we use polynomials and threshold functions for the non-peaking backgrounds.

The event yields and fractions of the different components arising from the fit are given in Table I and shown in Fig. 1. The fit residuals shown under each distribution are represented by  $Pull = (N_{data} - N_{fit})/\sqrt{N_{data}}$ .

TABLE I: Fitted number of events for each category.

Category	Events	Fraction (%)
1. Signal	$46691 \pm 241$	$30.8 \pm 0.3$
2. $D^0$ peaking	$5178 \pm 331$	$3.4 \pm 0.2$
3. $\Delta m$ peaking	$57099 \pm 797$	$37.7 \pm 0.6$
4. Combinatoric	$40512 \pm 818$	$26.7 \pm 0.6$
5. $D_s^+$	$2023 \pm 156$	$1.3 \pm 0.1$
Total	$151503 \pm 1223$	

Using momenta of the decay particles calculated in the  $D^0$  rest frame, we define the triple product correlations  $C_T$  and  $\overline{C}_T$  as

$$\begin{aligned} C_T &\equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}), \\ \overline{C}_T &\equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}). \end{aligned} \quad (6)$$

According to the  $D^{*+}$  tag and the  $C_T$  variable, we divide the total data sample into four subsamples, defined in Table II. These four data samples are fit with fixed PDFs from the total sample. The signal event yields are given in Table II. Fig. 2 shows the  $K^+K^-\pi^+\pi^-$  mass distributions for the four different  $C_T$  subsamples with fit projections in the  $\Delta m$  signal region previously defined.

We validate the method using  $e^+e^- \rightarrow c\bar{c}$  MC simulations, where  $D^0$  decays through the intermediate resonances with the branching fractions reported in the PDG [13]. We obtain a T asymmetry  $\mathcal{A}_T = (2.3 \pm 3.3) \times 10^{-3}$ , consistent with the generated value of  $1.0 \times 10^{-3}$ .

TABLE II: Definition of the four subsamples and the event yields from the fit.

Subsample	Events
(a) $D^0, C_T > 0$	$10974 \pm 117$
(b) $D^0, C_T < 0$	$12587 \pm 125$
(c) $\bar{D}^0, \bar{C}_T > 0$	$10749 \pm 116$
(d) $\bar{D}^0, \bar{C}_T < 0$	$12380 \pm 124$

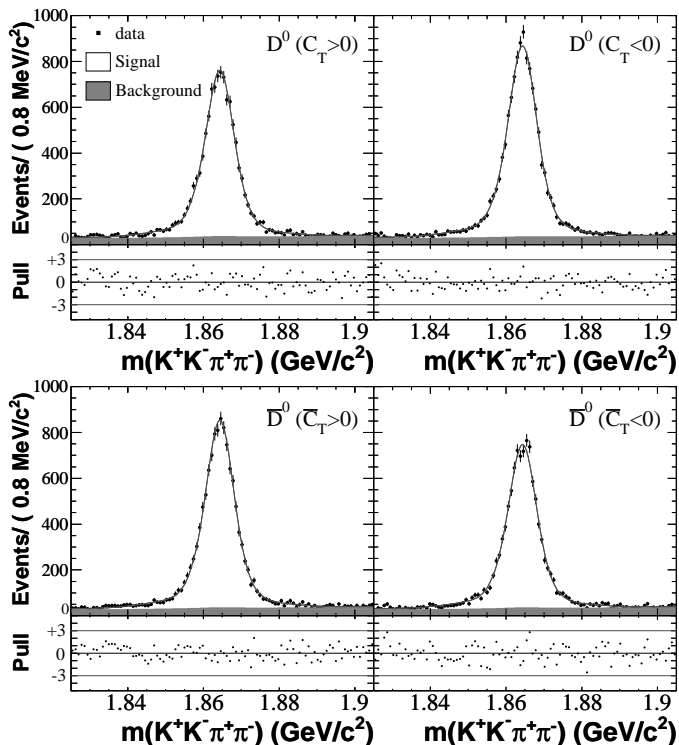


FIG. 2: Fit projections onto the  $m(K^+K^-\pi^+\pi^-)$  for the four different  $C_T$  subsamples with cut on  $\Delta m$ . The shaded areas indicate the total backgrounds. The fit residuals, represented by the pulls are also shown under each distribution.

To test the effect of possible asymmetries generated by the detector, we use signal MC in which the  $D^0$  decays uniformly over phase space. In this case possible asymmetries are generated only by the detector efficiency. These reconstructed events give an asymmetry  $\mathcal{A}_T = (1.1 \pm 1.1) \times 10^{-3}$ , again consistent with zero.

To avoid potential bias, all event selection criteria are determined before separating the data into the four subsamples of Table II. Systematic uncertainties are obtained directly from the data. In these studies the true  $\mathcal{A}_T$  and  $\bar{\mathcal{A}}_T$  central values are masked by adding unknown random offsets.

After removing the offsets, we measure the following

asymmetries:

$$\begin{aligned} \mathcal{A}_T &= (-68.5 \pm 7.3_{\text{stat}} \pm 5.8_{\text{syst}}) \times 10^{-3}, \\ \bar{\mathcal{A}}_T &= (-70.5 \pm 7.3_{\text{stat}} \pm 3.9_{\text{syst}}) \times 10^{-3}. \end{aligned} \quad (7)$$

We observe non-zero values of  $\mathcal{A}_T$  and  $\bar{\mathcal{A}}_T$  indicating that final state interaction effects are significant in this  $D^0$  decay. No effect is found, on the other hand, in the analysis of MC samples. Final state interactions effects are common in hadronic  $D$  decays because of the complex interference patterns between intermediate resonances formed between hadrons in the final states [14].

The result for the  $CP$  violation parameter,  $\mathcal{A}_T$ , is

$$\mathcal{A}_T = (1.0 \pm 5.1_{\text{stat}} \pm 4.4_{\text{syst}}) \times 10^{-3}. \quad (8)$$

The sources of systematic uncertainties considered in this analysis are listed in Table III. The estimates of their values are derived as follows:

1. The PDFs used to describe the signal are modified, replacing the Johnson SU function by a Crystal Ball function [15], obtaining fits of similar quality.
2. As in 1., for the peaking background.
3. We increase the number of bins of the 2-D ( $m(K^+K^-\pi^+\pi^-)$ ,  $\Delta m$ ) distribution to a  $(120 \times 120)$  grid and decrease to a grid of  $(80 \times 80)$ .
4. The particle identification algorithms used to identify kaons and pions are modified to more stringent conditions in different combinations. We notice that the difference between different selection efficiencies is significantly larger than the uncertainties on efficiency of the default selection. On the other hand, the use of the discrepancy between data and MC obtained using high statistics control samples, gives a much lower contribution.
5. The  $p^*(D^0)$  cut is increased to  $2.6 \text{ GeV}/c$  and  $2.7 \text{ GeV}/c$ .
6. We study possible intrinsic asymmetries due to the interference between the electromagnetic  $e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$  and weak neutral current  $e^+e^- \rightarrow Z^0 \rightarrow c\bar{c}$  amplitudes. This interference produces a  $D^0/\bar{D}^0$  production asymmetry that varies linearly with the quark production angle with respect to the  $e^-$  direction. Since *BABAR* is an asymmetric detector, the final yields of  $D^0$  and  $\bar{D}^0$  are not equal. We constrain the possible systematics by measuring  $\mathcal{A}_T$  in three regions of the center-of-mass  $D^0$  production angle  $\theta^*$ : forward ( $0.3 < \cos(\theta^*)_{D^0}$ ), central ( $-0.3 < \cos(\theta^*)_{D^0} \leq 0.3$ ), and backward ( $\cos(\theta^*)_{D^0} < -0.3$ ). We observe that the  $\mathcal{A}_T$  angular variation is, within the large statistical errors, consistent with zero as expected from the MC

7. Fit bias: we use MC simulations to compute the difference between the generated and reconstructed  $\mathcal{A}_T$ .
8. Mistag: there are a few ambiguous cases with more than one  $D^*$  in the event. We use MC simulations where these events are included or excluded from the analysis. This effect has a negligible contribution to the systematic uncertainty.
9. Detector asymmetry: we use the value obtained from the MC simulation where  $D^0$  decays uniformly over the phase space.

In the evaluation of the systematic uncertainties, we keep, for a given category, the largest deviation from the reference value and assume symmetric uncertainties. Thus, most systematic uncertainties have a statistical component, and are conservatively estimated. In con-

TABLE III: Systematic uncertainty evaluation on  $\mathcal{A}_T$ ,  $A_T$ , and  $\overline{A}_T$  in units of  $10^{-3}$ .

Effect	$\mathcal{A}_T$	$A_T$	$\overline{A}_T$
1. Alternative signal PDF	0.2	0.3	0.2
2. Alternative misreconstructed $D^0$ PDF	0.5	0.1	0.9
3. Bin size	0.2	0.4	0.3
4. Particle identification	3.5	4.2	2.9
5. $p^*(D^0)$ cut	1.7	1.6	2.4
6. $\cos\theta^*$ dependence	0.9	0.0	0.2
7. Fit bias	1.4	3.0	0.3
8. Mistag	0.0	0.0	0.0
9. Detector asymmetry	1.1	2.1	0.0
Total	4.4	5.8	3.9

clusion, we search for  $CP$  violation using  $T$ -odd correlations in a high statistics sample of Cabibbo suppressed  $D^0 \rightarrow K^+K^-\pi^+\pi^-$  decays. We obtain a  $T$ -violating asymmetry consistent with zero with a sensitivity of  $\approx 0.5\%$ .

The study of triple product correlations in  $B$  decays shows evidence for final state interaction but also give asymmetries consistent with zero, in agreement with SM expectations [16]. These results constrain the possible effects of New Physics in this observable [3]. The results from this analysis fix a reference point, since the study of  $T$ -odd correlations play an important role in the Physics program of present and future charm and  $B$ -factories.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing 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), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

\* 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 Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France

\*\* 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] A.J. Schwartz (representing the HFAG charm group), arXiv:0911.1464.
- [3] Y. Grossman, A.L. Kagan, and Y. Nir, Phys. Rev. **D75**, 036008 (2007).
- [4] X.W. Kang and H.B. Li, Phys. Lett. **B684**, 165 (2010).
- [5] W. Bensalem, A. Datta and D. London, Phys. Rev. **D66**, 094004 (2002). W. Bensalem and D. London, Phys. Rev. **D64**, 116003 (2001). W. Bensalem, A. Datta and D. London, Phys. Lett. **B538**, 309 (2002).
- [6] E. Golowich and G. Valencia, Phys. Rev. **D40**, 112 (1989).
- [7] I.I. Bigi, in Proceedings of KAON2001: International Conference on  $CP$  Violation, Pisa, Italy, 12-17 Jun 2001, p.417 (hep-ph/0107102).
- [8] J.M. Link *et al.* (FOCUS Collaboration), Phys. Lett. **B622**, 239 (2005).
- [9] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instr. Meth. **A479**, 1 (2002).
- [10] Charge-conjugate reactions are implied throughout.
- [11] S. Agostinelli *et al.* (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect A **506**, 250 (2003).
- [12] N.L. Johnson, Biometrika **36**, 149 (1949).
- [13] C. Amsler *et al.* (Review of Particle Physics), Phys. Lett. **B667**, 1 (2008).
- [14] J.A. Oller, Phys. Rev. **D71**, 054030 (2005).
- [15] J.E. Gaiser, Appendix-F Charmonium Spectroscopy from Radiative Decays of the  $J/\psi$  and  $\psi'$ , Ph.D. Thesis, SLAC-R-255 (1982).
- [16] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **93**, 231804 (2004); K.F. Chen *et al.* (Belle Collaboration), Phys. Rev. Lett. **94**, 221804 (2005); R. Itoh, *et al.* (Belle Collaboration), Phys. Rev. Lett. **95**, 091601 (2005).