

## Measurement of $\sin 2\beta$ with Hadronic and Previously Unused Muonic $J/\psi$ Decays

B. Aubert,<sup>1</sup> R. Barate,<sup>1</sup> D. Boutigny,<sup>1</sup> J.-M. Gaillard,<sup>1</sup> A. Hicheur,<sup>1</sup> Y. Karyotakis,<sup>1</sup> J. P. Lees,<sup>1</sup> P. Robbe,<sup>1</sup> V. Tisserand,<sup>1</sup> A. Zghiche,<sup>1</sup> A. Palano,<sup>2</sup> A. Pompili,<sup>2</sup> J. C. Chen,<sup>3</sup> N. D. Qi,<sup>3</sup> G. Rong,<sup>3</sup> P. Wang,<sup>3</sup> Y. S. Zhu,<sup>3</sup> G. Eigen,<sup>4</sup> I. Ofte,<sup>4</sup> B. Stugu,<sup>4</sup> G. S. Abrams,<sup>5</sup> A. W. Borgland,<sup>5</sup> A. B. Breon,<sup>5</sup> D. N. Brown,<sup>5</sup> J. Button-Shafer,<sup>5</sup> R. N. Cahn,<sup>5</sup> E. Charles,<sup>5</sup> C. T. Day,<sup>5</sup> M. S. Gill,<sup>5</sup> A. V. Gritsan,<sup>5</sup> Y. Groysman,<sup>5</sup> R. G. Jacobsen,<sup>5</sup> R. W. Kadel,<sup>5</sup> J. Kadyk,<sup>5</sup> L. T. Kerth,<sup>5</sup> Yu. G. Kolomensky,<sup>5</sup> J. F. Kral,<sup>5</sup> G. Kukartsev,<sup>5</sup> C. LeClerc,<sup>5</sup> M. E. Levi,<sup>5</sup> G. Lynch,<sup>5</sup> L. M. Mir,<sup>5</sup> P. J. Oddone,<sup>5</sup> T. J. Orimoto,<sup>5</sup> M. Pripstein,<sup>5</sup> N. A. Roe,<sup>5</sup> A. Romosan,<sup>5</sup> M. T. Ronan,<sup>5</sup> V. G. Shelkov,<sup>5</sup> A. V. Telnov,<sup>5</sup> W. A. Wenzel,<sup>5</sup> K. Ford,<sup>6</sup> T. J. Harrison,<sup>6</sup> C. M. Hawkes,<sup>6</sup> D. J. Knowles,<sup>6</sup> S. E. Morgan,<sup>6</sup> R. C. Penny,<sup>6</sup> A. T. Watson,<sup>6</sup> N. K. Watson,<sup>6</sup> K. Goetzen,<sup>7</sup> T. Held,<sup>7</sup> H. Koch,<sup>7</sup> B. Lewandowski,<sup>7</sup> M. Pelizaeus,<sup>7</sup> K. Peters,<sup>7</sup> H. Schmuecker,<sup>7</sup> M. Steinke,<sup>7</sup> J. T. Boyd,<sup>8</sup> N. Chevalier,<sup>8</sup> W. N. Cottingham,<sup>8</sup> M. P. Kelly,<sup>8</sup> T. E. Latham,<sup>8</sup> C. Mackay,<sup>8</sup> F. F. Wilson,<sup>8</sup> K. Abe,<sup>9</sup> T. Cuhadar-Donszelmann,<sup>9</sup> C. Hearty,<sup>9</sup> T. S. Mattison,<sup>9</sup> J. A. McKenna,<sup>9</sup> D. Thiessen,<sup>9</sup> P. Kyberd,<sup>10</sup> A. K. McKemey,<sup>10</sup> V. E. Blinov,<sup>11</sup> A. D. Bukin,<sup>11</sup> V. B. Golubev,<sup>11</sup> V. N. Ivanchenko,<sup>11</sup> E. A. Kravchenko,<sup>11</sup> A. P. Onuchin,<sup>11</sup> S. I. Serebnyakov,<sup>11</sup> Yu. I. Skovpen,<sup>11</sup> E. P. Solodov,<sup>11</sup> A. N. Yushkov,<sup>11</sup> D. Best,<sup>12</sup> M. Bruinsma,<sup>12</sup> M. Chao,<sup>12</sup> D. Kirkby,<sup>12</sup> A. J. Lankford,<sup>12</sup> M. Mandelkern,<sup>12</sup> R. K. Mommsen,<sup>12</sup> W. Roethel,<sup>12</sup> D. P. Stoker,<sup>12</sup> C. Buchanan,<sup>13</sup> B. L. Hartfel,<sup>13</sup> B. C. Shen,<sup>14</sup> D. del Re,<sup>15</sup> H. K. Hadavand,<sup>15</sup> E. J. Hill,<sup>15</sup> D. B. MacFarlane,<sup>15</sup> H. P. Paar,<sup>15</sup> Sh. Rahatlou,<sup>15</sup> U. Schwanke,<sup>15</sup> V. Sharma,<sup>15</sup> J. W. Berryhill,<sup>16</sup> C. Campagnari,<sup>16</sup> B. Dahmes,<sup>16</sup> N. Kuznetsova,<sup>16</sup> S. L. Levy,<sup>16</sup> O. Long,<sup>16</sup> A. Lu,<sup>16</sup> M. A. Mazur,<sup>16</sup> J. D. Richman,<sup>16</sup> W. Verkerke,<sup>16</sup> T. W. Beck,<sup>17</sup> J. Beringer,<sup>17</sup> A. M. Eisner,<sup>17</sup> C. A. Heusch,<sup>17</sup> W. S. Lockman,<sup>17</sup> T. Schalk,<sup>17</sup> R. E. Schmitz,<sup>17</sup> B. A. Schumm,<sup>17</sup> A. Seiden,<sup>17</sup> M. Turri,<sup>17</sup> W. Walkowiak,<sup>17</sup> D. C. Williams,<sup>17</sup> M. G. Wilson,<sup>17</sup> J. Albert,<sup>18</sup> E. Chen,<sup>18</sup> G. P. Dubois-Felsmann,<sup>18</sup> A. Dvoretzskii,<sup>18</sup> D. G. Hitlin,<sup>18</sup> I. Narsky,<sup>18</sup> F. C. Porter,<sup>18</sup> A. Ryd,<sup>18</sup> A. Samuel,<sup>18</sup> S. Yang,<sup>18</sup> S. Jayatilleke,<sup>19</sup> G. Mancinelli,<sup>19</sup> B. T. Meadows,<sup>19</sup> M. D. Sokoloff,<sup>19</sup> T. Abe,<sup>20</sup> F. Blanc,<sup>20</sup> P. Bloom,<sup>20</sup> S. Chen,<sup>20</sup> P. J. Clark,<sup>20</sup> W. T. Ford,<sup>20</sup> U. Nauenberg,<sup>20</sup> A. Olivas,<sup>20</sup> P. Rankin,<sup>20</sup> J. Roy,<sup>20</sup> J. G. Smith,<sup>20</sup> W. C. van Hoek,<sup>20</sup> L. Zhang,<sup>20</sup> J. L. Harton,<sup>21</sup> T. Hu,<sup>21</sup> A. Soffer,<sup>21</sup> W. H. Toki,<sup>21</sup> R. J. Wilson,<sup>21</sup> J. Zhang,<sup>21</sup> R. Aleksan,<sup>22</sup> S. Emery,<sup>22</sup> A. Gaidot,<sup>22</sup> S. F. Ganzhur,<sup>22</sup> P.-F. Giraud,<sup>22</sup> G. Hamel de Monchenault,<sup>22</sup> W. Kozanecki,<sup>22</sup> M. Langer,<sup>22</sup> M. Legendre,<sup>22</sup> G. W. London,<sup>22</sup> B. Mayer,<sup>22</sup> G. Schott,<sup>22</sup> G. Vasseur,<sup>22</sup> Ch. Yeche,<sup>22</sup> M. Zito,<sup>22</sup> D. Altenburg,<sup>23</sup> T. Brandt,<sup>23</sup> J. Brose,<sup>23</sup> T. Colberg,<sup>23</sup> M. Dickopp,<sup>23</sup> R. S. Dubitzky,<sup>23</sup> A. Hauke,<sup>23</sup> H. M. Lacker,<sup>23</sup> E. Maly,<sup>23</sup> R. Müller-Pfefferkorn,<sup>23</sup> R. Nogowski,<sup>23</sup> S. Otto,<sup>23</sup> J. Schubert,<sup>23</sup> K. R. Schubert,<sup>23</sup> R. Schwierz,<sup>23</sup> B. Spaan,<sup>23</sup> L. Wilden,<sup>23</sup> D. Bernard,<sup>24</sup> G. R. Bonneaud,<sup>24</sup> F. Brochard,<sup>24</sup> J. Cohen-Tanugi,<sup>24</sup> P. Grenier,<sup>24</sup> Ch. Thiebaux,<sup>24</sup> G. Vasileiadis,<sup>24</sup> M. Verderi,<sup>24</sup> A. Khan,<sup>25</sup> D. Lavin,<sup>25</sup> F. Muheim,<sup>25</sup> S. Playfer,<sup>25</sup> J. E. Swain,<sup>25</sup> M. Andreotti,<sup>26</sup> V. Azzolini,<sup>26</sup> D. Bettoni,<sup>26</sup> C. Bozzi,<sup>26</sup> R. Calabrese,<sup>26</sup> G. Cibinetto,<sup>26</sup> E. Luppi,<sup>26</sup> M. Negrini,<sup>26</sup> L. Piemontese,<sup>26</sup> A. Sarti,<sup>26</sup> E. Treadwell,<sup>27</sup> F. Anulli,<sup>28</sup> \* R. Baldini-Feroli,<sup>28</sup> A. Calcaterra,<sup>28</sup> R. de Sangro,<sup>28</sup> D. Falciari,<sup>28</sup> G. Finocchiaro,<sup>28</sup> P. Patteri,<sup>28</sup> I. M. Peruzzi,<sup>28</sup> \* M. Piccolo,<sup>28</sup> A. Zallo,<sup>28</sup> A. Buzzo,<sup>29</sup> R. Capra,<sup>29</sup> R. Contri,<sup>29</sup> G. Crosetti,<sup>29</sup> M. Lo Vetere,<sup>29</sup> M. Macri,<sup>29</sup> M. R. Monge,<sup>29</sup> S. Passaggio,<sup>29</sup> C. Patrignani,<sup>29</sup> E. Robutti,<sup>29</sup> A. Santroni,<sup>29</sup> S. Tosi,<sup>29</sup> S. Bailey,<sup>30</sup> M. Morii,<sup>30</sup> E. Won,<sup>30</sup> W. Bhimji,<sup>31</sup> D. A. Bowerman,<sup>31</sup> P. D. Dauncey,<sup>31</sup> U. Egede,<sup>31</sup> I. Eschrich,<sup>31</sup> J. R. Gaillard,<sup>31</sup> G. W. Morton,<sup>31</sup> J. A. Nash,<sup>31</sup> P. Sanders,<sup>31</sup> G. P. Taylor,<sup>31</sup> G. J. Grenier,<sup>32</sup> S.-J. Lee,<sup>32</sup> U. Mallik,<sup>32</sup> J. Cochran,<sup>33</sup> H. B. Crawley,<sup>33</sup> J. Lamsa,<sup>33</sup> W. T. Meyer,<sup>33</sup> S. Prell,<sup>33</sup> E. I. Rosenberg,<sup>33</sup> J. Yi,<sup>33</sup> M. Biasini,<sup>34</sup> M. Pioppi,<sup>34</sup> M. Davier,<sup>35</sup> G. Grosdidier,<sup>35</sup> A. Höcker,<sup>35</sup> S. Laplace,<sup>35</sup> F. Le Diberder,<sup>35</sup> V. Lepeltier,<sup>35</sup> A. M. Lutz,<sup>35</sup> T. C. Petersen,<sup>35</sup> S. Plaszczynski,<sup>35</sup> M. H. Schune,<sup>35</sup> L. Tantot,<sup>35</sup> G. Wormser,<sup>35</sup> V. Brigljević,<sup>36</sup> C. H. Cheng,<sup>36</sup> D. J. Lange,<sup>36</sup> D. M. Wright,<sup>36</sup> A. J. Bevan,<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> M. Kay,<sup>37</sup> R. J. Parry,<sup>37</sup> D. J. Payne,<sup>37</sup> R. J. Sloane,<sup>37</sup> C. Touramanis,<sup>37</sup> J. J. Back,<sup>38</sup> P. F. Harrison,<sup>38</sup> H. W. Shorthouse,<sup>38</sup> P. Strother,<sup>38</sup> P. B. Vidal,<sup>38</sup> C. L. Brown,<sup>39</sup> G. Cowan,<sup>39</sup> R. L. Flack,<sup>39</sup> H. U. Flaecher,<sup>39</sup> S. George,<sup>39</sup> M. G. Green,<sup>39</sup> A. Kurup,<sup>39</sup> C. E. Marker,<sup>39</sup> T. R. McMahon,<sup>39</sup> S. Ricciardi,<sup>39</sup> F. Salvatore,<sup>39</sup> G. Vaitsas,<sup>39</sup> M. A. Winter,<sup>39</sup> D. Brown,<sup>40</sup> C. L. Davis,<sup>40</sup> J. Allison,<sup>41</sup> N. R. Barlow,<sup>41</sup> R. J. Barlow,<sup>41</sup> P. A. Hart,<sup>41</sup> F. Jackson,<sup>41</sup> G. D. Lafferty,<sup>41</sup> A. J. Lyon,<sup>41</sup> J. H. Weatherall,<sup>41</sup> J. C. Williams,<sup>41</sup> A. Farbin,<sup>42</sup> A. Jawahery,<sup>42</sup> D. Kovalskyi,<sup>42</sup> C. K. Lae,<sup>42</sup> V. Lillard,<sup>42</sup> D. A. Roberts,<sup>42</sup> G. Blaylock,<sup>43</sup> C. Dallapiccola,<sup>43</sup> K. T. Flood,<sup>43</sup> S. S. Hertzbach,<sup>43</sup> R. Kofler,<sup>43</sup> V. B. Koptchev,<sup>43</sup> T. B. Moore,<sup>43</sup> S. Saremi,<sup>43</sup> H. Staengle,<sup>43</sup> S. Willocq,<sup>43</sup>

R. Cowan,<sup>44</sup> G. Sciolla,<sup>44</sup> F. Taylor,<sup>44</sup> R. K. Yamamoto,<sup>44</sup> D. J. J. Mangeol,<sup>45</sup> M. Milek,<sup>45</sup> P. M. Patel,<sup>45</sup> S. H. Robertson,<sup>45</sup> A. Lazzaro,<sup>46</sup> F. Palombo,<sup>46</sup> J. M. Bauer,<sup>47</sup> L. Cremaldi,<sup>47</sup> V. Eschenburg,<sup>47</sup> R. Godang,<sup>47</sup> R. Kroeger,<sup>47</sup> J. Reidy,<sup>47</sup> D. A. Sanders,<sup>47</sup> D. J. Summers,<sup>47</sup> H. W. Zhao,<sup>47</sup> S. Brunet,<sup>48</sup> D. Cote-Ahern,<sup>48</sup> P. Taras,<sup>48</sup> H. Nicholson,<sup>49</sup> G. Raven,<sup>50</sup> C. Cartaro,<sup>51</sup> N. Cavallo,<sup>51</sup> G. De Nardo,<sup>51</sup> F. Fabozzi,<sup>51</sup>,<sup>†</sup> C. Gatto,<sup>51</sup> L. Lista,<sup>51</sup> P. Paolucci,<sup>51</sup> D. Piccolo,<sup>51</sup> C. Sciacca,<sup>51</sup> J. M. LoSecco,<sup>52</sup> T. A. Gabriel,<sup>53</sup> B. Brau,<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> T. Pulliam,<sup>54</sup> Q. K. Wong,<sup>54</sup> J. Brau,<sup>55</sup> R. Frey,<sup>55</sup> C. T. Potter,<sup>55</sup> N. B. Sinev,<sup>55</sup> D. Strom,<sup>55</sup> E. Torrence,<sup>55</sup> F. Colecchia,<sup>56</sup> A. Dorigo,<sup>56</sup> F. Galeazzi,<sup>56</sup> M. Margoni,<sup>56</sup> M. Morandin,<sup>56</sup> M. Posocco,<sup>56</sup> M. Rotondo,<sup>56</sup> F. Simonetto,<sup>56</sup> R. Stroili,<sup>56</sup> G. Tiozzo,<sup>56</sup> C. Voci,<sup>56</sup> M. Benayoun,<sup>57</sup> H. Briand,<sup>57</sup> J. Chauveau,<sup>57</sup> P. David,<sup>57</sup> Ch. de la Vaissière,<sup>57</sup> L. Del Buono,<sup>57</sup> O. Hamon,<sup>57</sup> M. J. J. John,<sup>57</sup> Ph. Leruste,<sup>57</sup> J. Ocariz,<sup>57</sup> M. Pivk,<sup>57</sup> L. Roos,<sup>57</sup> J. Stark,<sup>57</sup> S. T'Jampens,<sup>57</sup> G. Therin,<sup>57</sup> P. F. Manfredi,<sup>58</sup> V. Re,<sup>58</sup> P. K. Behera,<sup>59</sup> L. Gladney,<sup>59</sup> Q. H. Guo,<sup>59</sup> J. Panetta,<sup>59</sup> C. Angelini,<sup>60</sup> G. Batignani,<sup>60</sup> S. Bettarini,<sup>60</sup> M. Bondioli,<sup>60</sup> F. Bucci,<sup>60</sup> G. Calderini,<sup>60</sup> M. Carpinelli,<sup>60</sup> V. Del Gamba,<sup>60</sup> F. Forti,<sup>60</sup> M. A. Giorgi,<sup>60</sup> A. Lusiani,<sup>60</sup> G. Marchiori,<sup>60</sup> F. Martinez-Vidal,<sup>60</sup> M. Morganti,<sup>60</sup> N. Neri,<sup>60</sup> E. Paoloni,<sup>60</sup> M. Rama,<sup>60</sup> G. Rizzo,<sup>60</sup> F. Sandrelli,<sup>60</sup> J. Walsh,<sup>60</sup> M. Haire,<sup>61</sup> D. Judd,<sup>61</sup> K. Paick,<sup>61</sup> D. E. Wagoner,<sup>61</sup> G. Cavoto,<sup>62</sup>,<sup>‡</sup> N. Danielson,<sup>62</sup> P. Elmer,<sup>62</sup> C. Lu,<sup>62</sup> V. Miftakov,<sup>62</sup> J. Olsen,<sup>62</sup> A. J. S. Smith,<sup>62</sup> H. A. Tanaka,<sup>62</sup> E. W. Varnes,<sup>62</sup> F. Bellini,<sup>63</sup> R. Faccini,<sup>63</sup>,<sup>§</sup> F. Ferrarotto,<sup>63</sup> F. Ferroni,<sup>63</sup> M. Gaspero,<sup>63</sup> M. A. Mazzoni,<sup>63</sup> S. Morganti,<sup>63</sup> M. Pierini,<sup>63</sup> G. Piredda,<sup>63</sup> F. Safai Tehrani,<sup>63</sup> C. Voena,<sup>63</sup> S. Christ,<sup>64</sup> G. Wagner,<sup>64</sup> R. Waldi,<sup>64</sup> T. Adye,<sup>65</sup> N. De Groot,<sup>65</sup> B. Franek,<sup>65</sup> N. I. Geddes,<sup>65</sup> G. P. Gopal,<sup>65</sup> E. O. Olaiya,<sup>65</sup> S. M. Xella,<sup>65</sup> M. V. Purohit,<sup>66</sup> A. W. Weidemann,<sup>66</sup> F. X. Yumiceva,<sup>66</sup> D. Aston,<sup>67</sup> R. Bartoldus,<sup>67</sup> N. Berger,<sup>67</sup> A. M. Boyarski,<sup>67</sup> O. L. Buchmueller,<sup>67</sup> M. R. Convery,<sup>67</sup> D. P. Coupal,<sup>67</sup> D. Dong,<sup>67</sup> J. Dorfan,<sup>67</sup> D. Dujmic,<sup>67</sup> W. Dunwoodie,<sup>67</sup> R. C. Field,<sup>67</sup> T. Glanzman,<sup>67</sup> S. J. Gowdy,<sup>67</sup> E. Grauges-Pous,<sup>67</sup> T. Hadig,<sup>67</sup> V. Halyo,<sup>67</sup> T. Hryn'ova,<sup>67</sup> W. R. Innes,<sup>67</sup> C. P. Jessop,<sup>67</sup> M. H. Kelsey,<sup>67</sup> P. Kim,<sup>67</sup> M. L. Kocian,<sup>67</sup> U. Langenegger,<sup>67</sup> D. W. G. S. Leith,<sup>67</sup> S. Luitz,<sup>67</sup> V. Luth,<sup>67</sup> H. L. Lynch,<sup>67</sup> H. Marsiske,<sup>67</sup> R. Messner,<sup>67</sup> D. R. Muller,<sup>67</sup> C. P. O'Grady,<sup>67</sup> V. E. Ozcan,<sup>67</sup> A. Perazzo,<sup>67</sup> M. Perl,<sup>67</sup> S. Petrak,<sup>67</sup> B. N. Ratcliff,<sup>67</sup> A. Roodman,<sup>67</sup> A. A. Salnikov,<sup>67</sup> R. H. Schindler,<sup>67</sup> J. Schwiening,<sup>67</sup> G. Simi,<sup>67</sup> A. Snyder,<sup>67</sup> A. Soha,<sup>67</sup> J. Stelzer,<sup>67</sup> D. Su,<sup>67</sup> M. K. Sullivan,<sup>67</sup> J. Va'vra,<sup>67</sup> S. R. Wagner,<sup>67</sup> M. Weaver,<sup>67</sup> A. J. R. Weinstein,<sup>67</sup> W. J. Wisniewski,<sup>67</sup> D. H. Wright,<sup>67</sup> C. C. Young,<sup>67</sup> P. R. Burchat,<sup>68</sup> A. J. Edwards,<sup>68</sup> T. I. Meyer,<sup>68</sup> B. A. Petersen,<sup>68</sup> C. Roat,<sup>68</sup> S. Ahmed,<sup>69</sup> M. S. Alam,<sup>69</sup> J. A. Ernst,<sup>69</sup> M. Saleem,<sup>69</sup> F. R. Wappler,<sup>69</sup> W. Bugg,<sup>70</sup> M. Krishnamurthy,<sup>70</sup> S. M. Spanier,<sup>70</sup> R. Eckmann,<sup>71</sup> H. Kim,<sup>71</sup> J. L. Ritchie,<sup>71</sup> R. F. Schwitters,<sup>71</sup> J. M. Izen,<sup>72</sup> I. Kitayama,<sup>72</sup> X. C. Lou,<sup>72</sup> S. Ye,<sup>72</sup> F. Bianchi,<sup>73</sup> M. Bona,<sup>73</sup> F. Gallo,<sup>73</sup> D. Gamba,<sup>73</sup> C. Borean,<sup>74</sup> L. Bosisio,<sup>74</sup> G. Della Ricca,<sup>74</sup> S. Dittongo,<sup>74</sup> S. Grancagnolo,<sup>74</sup> L. Lancieri,<sup>74</sup> P. Poropat,<sup>74</sup> L. Vitale,<sup>74</sup> G. Vuagnin,<sup>74</sup> R. S. Panvini,<sup>75</sup> Sw. Banerjee,<sup>76</sup> C. M. Brown,<sup>76</sup> D. Fortin,<sup>76</sup> P. D. Jackson,<sup>76</sup> R. Kowalewski,<sup>76</sup> J. M. Roney,<sup>76</sup> H. R. Band,<sup>77</sup> S. Dasu,<sup>77</sup> M. Datta,<sup>77</sup> A. M. Eichenbaum,<sup>77</sup> J. R. Johnson,<sup>77</sup> P. E. Kutter,<sup>77</sup> H. Li,<sup>77</sup> R. Liu,<sup>77</sup> F. Di Lodovico,<sup>77</sup> A. Mihalyi,<sup>77</sup> A. K. Mohapatra,<sup>77</sup> Y. Pan,<sup>77</sup> R. Prepost,<sup>77</sup> S. J. Sekula,<sup>77</sup> J. H. von Wimmersperg-Toeller,<sup>77</sup> J. Wu,<sup>77</sup> S. L. Wu,<sup>77</sup> Z. Yu,<sup>77</sup> and H. Neal<sup>78</sup>

(The BABAR Collaboration)

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

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

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

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

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

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

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

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

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

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

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

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

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

<sup>14</sup>Univ. of California, Riverside, CA 92521

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

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

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

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

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

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

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

<sup>22</sup>DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

- <sup>23</sup>Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
- <sup>24</sup>Ecole Polytechnique, LLR, F-91128 Palaiseau, France
- <sup>25</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
- <sup>26</sup>Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
- <sup>27</sup>Florida A&M University, Tallahassee, FL 32307, USA
- <sup>28</sup>Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
- <sup>29</sup>Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
- <sup>30</sup>Harvard University, Cambridge, MA 02138, USA
- <sup>31</sup>Imperial College London, London, SW7 2BW, United Kingdom
- <sup>32</sup>University of Iowa, Iowa City, IA 52242, USA
- <sup>33</sup>Iowa State University, Ames, IA 50011-3160, USA
- <sup>34</sup>Istituto Naz. Fis. Nucleare, I-06100 Perugia, Italy
- <sup>35</sup>Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
- <sup>36</sup>Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
- <sup>37</sup>University of Liverpool, Liverpool L69 3BX, United Kingdom
- <sup>38</sup>Queen Mary, University of 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, KY 40292, USA
- <sup>41</sup>University of Manchester, Manchester M13 9PL, United Kingdom
- <sup>42</sup>University of Maryland, College Park, MD 20742, USA
- <sup>43</sup>University of Massachusetts, Amherst, MA 01003, USA
- <sup>44</sup>Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA
- <sup>45</sup>McGill University, Montréal, QC, Canada H3A 2T8
- <sup>46</sup>Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
- <sup>47</sup>University of Mississippi, University, MS 38677, USA
- <sup>48</sup>Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7
- <sup>49</sup>Mount Holyoke College, South Hadley, MA 01075, USA
- <sup>50</sup>NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
- <sup>51</sup>Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
- <sup>52</sup>University of Notre Dame, Notre Dame, IN 46556, USA
- <sup>53</sup>Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
- <sup>54</sup>Ohio State University, Columbus, OH 43210, USA
- <sup>55</sup>University of Oregon, Eugene, OR 97403, USA
- <sup>56</sup>Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
- <sup>57</sup>Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France
- <sup>58</sup>Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy
- <sup>59</sup>University of Pennsylvania, Philadelphia, PA 19104, USA
- <sup>60</sup>Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
- <sup>61</sup>Prairie View A&M University, Prairie View, TX 77446, USA
- <sup>62</sup>Princeton University, Princeton, NJ 08544, USA
- <sup>63</sup>Università di Roma La Sapienza, Dipartimento di Fisica and INFN, 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>University of South Carolina, Columbia, SC 29208, USA
- <sup>67</sup>Stanford Linear Accelerator Center, Stanford, CA 94309, USA
- <sup>68</sup>Stanford University, Stanford, CA 94305-4060, USA
- <sup>69</sup>State Univ. of New York, Albany, NY 12222, USA
- <sup>70</sup>University of Tennessee, Knoxville, TN 37996, USA
- <sup>71</sup>University of Texas at Austin, Austin, TX 78712, USA
- <sup>72</sup>University of Texas at Dallas, Richardson, TX 75083, USA
- <sup>73</sup>Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
- <sup>74</sup>Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
- <sup>75</sup>Vanderbilt University, Nashville, TN 37235, USA
- <sup>76</sup>University of Victoria, Victoria, BC, Canada V8W 3P6
- <sup>77</sup>University of Wisconsin, Madison, WI 53706, USA
- <sup>78</sup>Yale University, New Haven, CT 06511, USA

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We report a measurement of the  $CP$ -violation parameter  $\sin 2\beta$  with  $B^0 \rightarrow J/\psi K_S^0$  decays in which the  $J/\psi$  decays to hadrons or to muons that do not satisfy our standard identification criteria. With a sample of 88 million  $B\bar{B}$  events collected by the BABAR detector at the PEP-II asymmetric-energy  $B$  factory at SLAC, we reconstruct  $100 \pm 17$  such events, with  $J/\psi \rightarrow \pi^+\pi^-\pi^0$  being the most prevalent, and measure  $\sin 2\beta = 1.56 \pm 0.42(\text{stat.}) \pm 0.21(\text{syst.})$ .

Measurement of  $CP$  violation in the  $B$ -meson system, particularly in  $b \rightarrow c\bar{c}s$  transitions, has been a primary goal of the *BABAR* experiment. In the Standard Model, these decays exhibit a  $CP$  asymmetry that is proportional to  $\sin 2\beta$ , where  $\beta$  is defined as  $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$ , with  $V_{ij}$  the elements of the CKM matrix [1]. The current world average value of  $\sin 2\beta$  is  $0.731 \pm 0.056$  [2], with the  $B$  factories (*BABAR* at SLAC and Belle at KEK) providing the most precise measurements [3, 4]. The dominant decay mode in these measurements is  $B^0 \rightarrow J/\psi K_S^0$ , where only leptonic decays of the  $J/\psi$  are considered. Leptonic decay modes have the advantage of low backgrounds, but account for only 12% of  $J/\psi$  decays [2]. Since the current measurements of  $\sin 2\beta$  are statistically limited, in this article we extend the measurement through the use of hadronic  $J/\psi$  decays, as well as previously unused muonic decays.

At the  $B$  factories,  $B^0$  mesons are produced via  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$ . For  $B^0$  mesons produced in this manner and decaying to the  $CP$  eigenstate  $J/\psi K_S^0$ ,  $\sin 2\beta$  appears as the amplitude of a time-dependent  $CP$  asymmetry. The Standard Model predicts the decay rate

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 \pm \sin 2\beta \sin(\Delta m_d \Delta t)],$$

where the plus (minus) sign indicates that the other, "tagging",  $B^0$  meson in the event decays as a  $B^0(\bar{B}^0)$ ,  $\Delta t$  is the decay time of the  $CP$ -eigenstate  $B^0$  meson minus the decay time of the tagging  $B^0$  meson,  $\tau_{B^0}$  is the  $B^0$  lifetime, and  $\Delta m_d$  is the mass difference between the two mass-eigenstate neutral  $B$  mesons ( $\Delta m_d$  is also the  $B^0 - \bar{B}^0$  oscillation frequency). The time-dependent  $CP$  asymmetry is:

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

Measurement of  $A_{CP}$  requires that a sample of  $B^0$  mesons decaying to  $J/\psi K_S^0$  be reconstructed, that the flavor of the other  $B^0$  meson in the event be determined, and that  $\Delta t$  be measured.

A sample of  $88 \pm 1$  million  $B\bar{B}$  events recorded by the *BABAR* detector [5] was used in this analysis. The innermost component of *BABAR* is a five-layer double-sided silicon microstrip vertex detector with  $90^\circ$  stereo angle, allowing precise reconstruction of the location of the  $B^0$  decay vertices along the beam direction. Since the  $\Upsilon(4S)$

is boosted along the beam direction, the difference in position between the  $B^0$  decay vertices in this direction allows one to measure  $\Delta t$ . The primary tracking device is a 40-layer drift chamber operated with a helium-based gas mixture to minimize multiple scattering. The drift chamber is surrounded by a Cherenkov particle identification device, and a CsI(Tl) calorimeter. All of the above detectors reside in a 1.5 T field generated by a superconducting solenoid. The flux is returned via layers of steel interleaved with active detectors for the identification of muons and detection of neutral hadrons.

Two types of Monte Carlo simulated events are used in the analysis. One, called "full MC", consists of events that are generated according to the known physics of  $B\bar{B}$  and continuum production, passed through a detailed model of the detector response [6], and reconstructed in the same manner as the data sample. The second, called "parametrized MC", consists of events for which the relevant parameters are randomly generated according to the distributions observed in data or in detailed simulations. For any study where an accurate model of the physics or detector response is required, full MC is used. Parametrized MC, which can be generated more quickly than full MC, is only used to explore the statistical properties of the extraction of  $\sin 2\beta$ .

While many  $J/\psi$  decays to exclusive hadronic final states have been observed [2], the sum of their measured branching fractions is less than 20%. To allow for the possibility of observing a signal in previously unmeasured decay modes, we take an inclusive approach in the first stage of event selection. Charged tracks are assigned either the electron, muon, pion, kaon, or proton mass based on particle identification information, and candidates for  $\pi^0 \rightarrow \gamma\gamma$  and  $\eta \rightarrow \gamma\gamma$  or  $\pi^+\pi^-\pi^0$  are formed. All neutral combinations of up to six tracks and neutral mesons are considered (a maximum of two neutral mesons is allowed), and those consistent with baryon number conservation, strangeness conservation, and Bose symmetry, and having invariant mass  $m_{J/\psi}$  in the range  $2.80 - 3.20$  GeV/ $c^2$ , are retained for further analysis. Decay modes of the type  $J/\psi \rightarrow KK\pi$  are excluded to ensure that the selected sample is independent of the sample used in *BABAR*'s previous measurement of  $\sin 2\beta$  [3], which included  $B^0 \rightarrow \eta_c K_S^0$  events with  $\eta_c \rightarrow KK\pi$ .

We form  $K_S^0$  candidates from a pair of oppositely-charged tracks that have invariant mass between 489 and 507 MeV and a vertex displaced by at least 1 mm from the  $J/\psi$  candidate's vertex. The selected  $J/\psi$  and  $K_S^0$  candidates are combined to form  $B^0$  candidates. Two kinematic variables are used to isolate the  $B$  meson signal: the difference  $\Delta E$  between the energy of the reconstructed  $B$  candidate and the beam energy in the center-of-mass frame, and the beam-energy substituted mass  $m_{ES} \equiv \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$ , where  $p_B^*$  is the momentum of the reconstructed  $B$  and  $E_{\text{beam}}^*$  is the beam energy,

\*Also with Università di Perugia, I-06100 Perugia, Italy

†Also with Università della Basilicata, I-85100 Potenza, Italy

‡Also with Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

§Also with University of California at San Diego, La Jolla, CA 92093, USA

both in the center-of-mass frame. The small variations of  $E_{\text{beam}}^*$  within the data sample are taken into account when calculating  $m_{\text{ES}}$ . Signal events will have  $\Delta E$  close to 0 and values of  $m_{\text{ES}}$  close to the  $B^0$  meson mass. Candidates are required to have  $m_{\text{ES}} > 5.20 \text{ GeV}/c^2$  and  $|\Delta E| < 55 \text{ MeV}$  if the  $J/\psi$  decays entirely to charged particles, and  $< 105 \text{ MeV}$  if the decay includes one or more neutral hadrons. The  $\Delta E$  selection accepts candidates within  $3\sigma$  of the distribution observed in simulated signal events. The resolution in  $m_{\text{ES}}$  is  $3 \text{ MeV}$ , so the selection admits a large region at low  $m_{\text{ES}}$  in addition to the region populated by signal candidates. Inclusion of this sideband region allows the magnitude of the combinatoric background to be measured.

Backgrounds arise both from continuum  $q\bar{q}$  production and from  $B$  meson decays to other modes. The continuum events tend to have a two-jet topology, in contrast to the more spherically symmetric  $B\bar{B}$  events. A set of 18 variables (described in [7]) that are sensitive to this difference are combined in a Fisher discriminant  $\mathcal{F}$ , which is defined to have an average value of 1 for signal and -1 for continuum events. The weight of each variable in the discriminant is calculated by maximizing the separation between a sample of data taken below the  $B\bar{B}$  threshold (and thus composed entirely of continuum  $q\bar{q}$  events) and a sample of simulated signal events. We place progressively tighter requirements on  $\mathcal{F}$  as the candidate  $J/\psi$  decay multiplicity increases: for two-body decays we require  $\mathcal{F} > -1.14$ , for three-body decays we require  $\mathcal{F} > -0.70$ , and for higher-multiplicity decays we require  $\mathcal{F} > -0.37$ .

For three-body  $J/\psi$  decays, which have a larger combinatoric background than two-body decays, additional separation between signal and background is attained by considering the angle  $\theta_d$  between the normal to the plane in which the momenta of the  $J/\psi$  daughter particles lie and the  $K_s^0$  direction in the  $J/\psi$  rest frame. Conservation of angular momentum requires this variable to be distributed as  $\cos^2 \theta_d$  for  $J/\psi$  decays to three pseudoscalars (the most common type of three-body decays), while it is uniformly distributed for  $B\bar{B}$  backgrounds and peaks at  $\cos \theta_d = 0$  for continuum  $q\bar{q}$  backgrounds. We require candidates to have  $|\cos \theta_d| > 0.55$ . The selection in  $\cos \theta_d$  and  $\mathcal{F}$  was chosen to maximize  $S/\sqrt{S+B}$ , where  $S$  is the expected signal and  $B$  the expected background.

There are two classes of  $B\bar{B}$  backgrounds. The first consists of candidates formed from a subset of a given  $B$  meson's decay products, or from a combination of decay products from the two  $B$  mesons in the event. This background and the continuum  $q\bar{q}$  background are henceforth referred to as ‘‘combinatoric backgrounds’’. They have a linearly falling distribution in  $\Delta E$ , and their distribution in  $m_{\text{ES}}$  may be parametrized by an empirical phase-space distribution [8] (henceforth referred to as the ARGUS function):

$$A(m_{\text{ES}}; m_0, c_{\text{arg}}) \propto m_{\text{ES}} \sqrt{1 - (m_{\text{ES}}/m_0)^2} \times \exp(c_{\text{arg}}(1 - (m_{\text{ES}}/m_0)^2)),$$

where  $m_0$  is a cutoff mass set to  $5.291 \text{ GeV}$  (a typical center-of-mass beam energy) and  $c_{\text{arg}}$  is a fitted parameter.

The second class of  $B\bar{B}$  background consists of  $B$  mesons that decay to a topology also allowed for  $J/\psi K_S^0$ , but without a  $J/\psi$  in the intermediate state. These ‘‘peaking’’ backgrounds are dominated by  $B$  decays that have a charmed meson in the intermediate state, so we remove any candidates for which a  $D$  or  $D^*$  meson within  $2\sigma$  of the nominal mass can be formed from the final-state hadrons. Since these backgrounds arise from fully reconstructed  $B^0$  mesons, they have the same distribution in  $m_{\text{ES}}$  and  $\Delta E$  as the signal.

Since the branching fractions for many of the modes that contribute to the peaking backgrounds are not well-measured, we must extract the peaking background magnitude from the data. We do this by performing a two-dimensional unbinned maximum likelihood fit to the  $m_{\text{ES}}$  and  $m_{J/\psi}$  distributions. The likelihood function used is:

$$L = (n_{\text{comb}} A(m_{\text{ES}}; m_0, c_{\text{arg}}) + (n_{\text{sig}} + n_{\text{peak}}^0) G(m_{\text{ES}})) \times ((n_{\text{comb}} + n_{\text{peak}}^0) C(m_{J/\psi}; p_1, p_2) + n_{\text{sig}} G(m_{J/\psi})),$$

where  $n_{\text{comb}}$  is the fitted combinatoric background,  $n_{\text{peak}}^0$  is the fitted peaking background,  $n_{\text{sig}}$  is the fitted signal,  $A$  is a normalized ARGUS function,  $G$  are normalized Gaussians, and  $C$  is a normalized second-order Chebyshev polynomial with parameters  $p_i$ . The mean and width of  $G(m_{\text{ES}})$  are fixed to the values observed in high-statistics hadronic  $B$ -decay samples, and the mean and width of  $G(m_{J/\psi})$  are fixed to the values observed in our  $J/\psi \rightarrow \mu^+ \mu^-$  sample for two-body decay modes, and to the values observed in full MC events for higher-multiplicity modes. The photon-energy resolution in the simulated events is degraded to match that observed in data. The additional smearing required is 3% of the measured photon energy for photons below  $100 \text{ MeV}$ , and decreases with increasing photon energy (no additional smearing is required for photons above  $1 \text{ GeV}$ ).

The  $J/\psi$  decay modes for which the measured signal magnitude is less than its statistical uncertainty are removed from the analysis. The surviving modes, and their contribution to the signal, are listed in Table I. Note that no modes including an  $\eta$  meson are observed, and also that no decays with a multiplicity of greater than three are visible above background.

The observation of 28 candidates in the  $J/\psi \rightarrow \pi^+ \pi^-$  channel is inconsistent with our expectation of observing about one event given the known branching fraction of  $(1.47 \pm 0.23) \times 10^{-4}$  [2] for this mode. We interpret the excess candidates as  $J/\psi \rightarrow \mu^+ \mu^-$  decays in which both muons fail the standard muon selection criteria. Studies using simulated events with muon identification efficiencies measured in data confirm that the observed signal magnitude is consistent with the  $J/\psi \rightarrow \mu^+ \mu^-$  hypothesis. Since these events do measure  $\sin 2\beta$ , and are independent of the events used in our previous measurements [3], we retain them for this analysis.

$J/\psi$ decay mode	Signal	Peaking Bkg.	Comb. Bkg.
$\pi^+\pi^-$	$28 \pm 8$	$84 \pm 17$	$206 \pm 12$
$K^+K^-$	$5 \pm 3$	$-1 \pm 6$	$42 \pm 5$
$p\bar{p}$	$6 \pm 3$	$1 \pm 6$	$34 \pm 5$
Total $h^+h^-$	$40 \pm 9$	$86 \pm 19$	$279 \pm 13$
After final selection	$28 \pm 8$	$13 \pm 3$	$15 \pm 3$
$\pi^+\pi^-\pi^0$	$58 \pm 17$	$104 \pm 29$	$652 \pm 23$
$p\bar{p}\pi^0$	$11 \pm 6$	$9 \pm 9$	$77 \pm 7$
Total $h^+h^-\pi^0$	$69 \pm 18$	$113 \pm 30$	$716 \pm 22$
After final selection	$72 \pm 13$	$19 \pm 5$	$74 \pm 8$

TABLE I: Observed  $B^0 \rightarrow J/\psi K_s^0$  signal and background. The combinatoric backgrounds reported are the integral of the fitted ARGUS function in the region  $m_{ES} > 5.27 \text{ GeV}/c^2$ . Except for the rows labelled “After final selection”, the numbers are measured prior to application of the final selection criteria on  $m_{J/\psi}$  and  $\Delta E$ . All uncertainties are statistical only.

After  $n_{\text{peak}}^0$  is determined, the following final selection criteria are imposed to improve the purity of the sample: We recalculate  $\Delta E$  with the  $J/\psi$  candidate constrained to the nominal mass, and define the result as  $\Delta E_c$ . The resolution in  $\Delta E_c$  is 11 MeV for two-body  $J/\psi$  decay candidates, and 12 MeV for three-body candidates. For two-body  $J/\psi$  decay candidates we require  $3.06 < m_{J/\psi} < 3.12 \text{ GeV}/c^2$  and  $|\Delta E_c| < 33 \text{ MeV}$ , and for three-body  $J/\psi$  decay candidates we require  $3.05 < m_{J/\psi} < 3.15 \text{ GeV}/c^2$  and  $|\Delta E_c| < 35 \text{ MeV}$ .

The efficiency of this selection for peaking backgrounds ( $\varepsilon_{\text{peak}}$ ) is estimated using full MC events. We define  $\varepsilon_{\text{peak}}$  as the ratio of the area of the fitted Gaussian in  $m_{ES}$  after the final selection to the area before the final selection. For two-body decay candidates  $\varepsilon_{\text{peak}} = 0.15 \pm 0.01(\text{stat.})$  and for three-body decay candidates  $\varepsilon_{\text{peak}} = 0.17 \pm 0.02(\text{stat.})$ . An unbinned maximum likelihood fit to the sum of a Gaussian distribution and an ARGUS function is performed on the  $m_{ES}$  distributions of the surviving candidates. The integral of the ARGUS function measures the combinatoric background, while the integral of the Gaussian measures the sum of the signal and peaking background. Subtracting  $n_{\text{peak}} \equiv \varepsilon_{\text{peak}} n_{\text{peak}}^0$  from the latter provides an estimate of the signal. The  $m_{ES}$  distributions are shown in Fig. 1, and the signal and background magnitudes in the final sample are reported in Table I.

Once the sample of  $B^0 \rightarrow J/\psi K_s^0$  candidates has been isolated, the extraction of  $\sin 2\beta$  proceeds in the same manner as for BABAR’s other recent measurements [3]. Information from the final-state particles recoiling against the  $J/\psi K_s^0$  meson candidate is used to determine whether the other  $B$  meson in the event was a  $B^0$  or  $\bar{B}^0$  at the time of its decay. This is referred to as the flavor “tag”. The variables used for tagging include the charge of any high-momentum identified electron or muon, the charge of any identified kaon, and the charge of a slow pion consistent with arising from  $D^*$  meson decay. The efficiency  $\varepsilon$  and mistag rate  $w$  are measured using

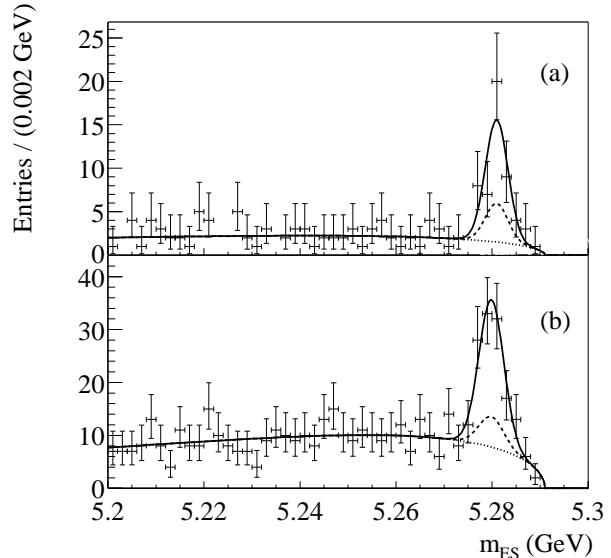


FIG. 1:  $m_{ES}$  distributions for candidates for  $B^0 \rightarrow J/\psi K_s^0$  with the  $J/\psi$  decaying to (a) two and (b) three particles. The dotted line represents the fitted combinatoric background distribution. The dashed line represents the total background distribution, while the solid line represents the signal plus background distribution.

the data as described below, and reported in Ref. [3]; the overall figure of merit for the flavor-tagging performance,  $\varepsilon(1 - 2w)^2$ , is  $(28.1 \pm 0.7)\%$ .

The extraction of  $\sin 2\beta$  is done using an unbinned maximum likelihood fit to the  $\Delta t$  distribution of the candidate events, where the assumed functional form is  $f_{\pm}(\Delta t)$  convolved with the resolution of the  $\Delta t$  measurement, with the mistag probability taken into account. The input to the fit consists of both the signal sample and a large sample of fully reconstructed  $B^0$  decays to  $D^{(*)+}\pi^-$ ,  $D^{(*)+}\rho^-$ ,  $D^{(*)+}a^-$  and  $J/\psi K^{0*}$  with  $K^{0*} \rightarrow K^+\pi^-$ . The  $B^0$  flavor is known for these modes, so this sample constrains a set of parameters describing the flavor-tagging performance and vertex resolution. The simultaneous fit takes into account any correlations between these parameters and the value of  $\sin 2\beta$ . The result is:

$$\sin 2\beta = 1.56 \pm 0.42 (\text{stat.})$$

The  $\Delta t$  distribution for flavor-tagged signal events is shown in Fig. 2, and the  $CP$  asymmetry observed before correction for backgrounds and mistag probability is shown in Fig. 3. In each case a projection of the best-fit model is superimposed.

As a cross-check, the analysis was repeated using a sample of  $B^{\pm} \rightarrow J/\psi K^{\pm}$  events selected in a manner analogous to the  $CP$  sample, and with the same  $J/\psi$  decay modes considered. This sample yields an apparent

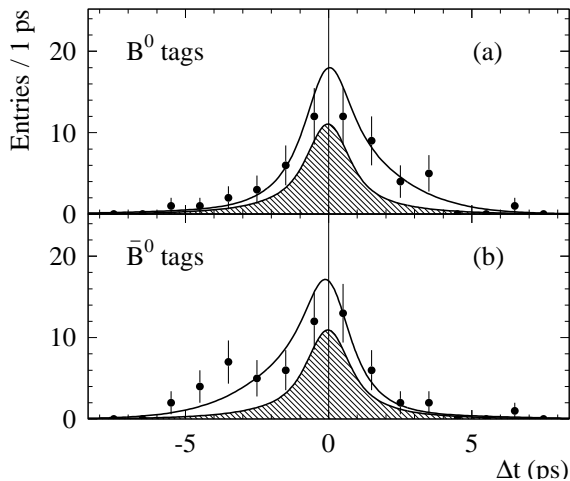


FIG. 2:  $\Delta t$  values observed in the  $B^0 \rightarrow J/\psi K_S^0$  candidates. The plots show the distribution for events in which the recoiling  $B$  meson is tagged as (a)  $B^0$  and (b)  $\bar{B}^0$ . In each plot the solid line represents the result of the maximum likelihood fit, and the shaded area the contribution of background.

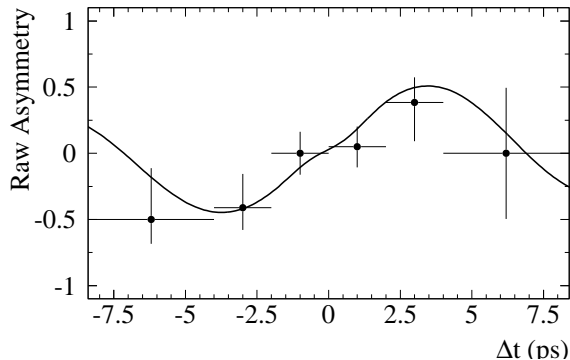


FIG. 3:  $\Delta t$  asymmetry observed before correction for backgrounds and mistag probability in  $B^0 \rightarrow J/\psi K_S^0$  candidates, with best-fit asymmetry displayed.

$\sin 2\beta$  of  $-0.13 \pm 0.20$  (stat.), consistent with the expected null result.

Systematic uncertainties arise from several sources. In performing the fit for  $\sin 2\beta$  it is assumed that the background has no  $CP$  asymmetry. Since some of the background is composed of real  $B^0$  mesons this may not be true. Fitting for  $\sin 2\beta$  on a sample composed of candidates in the  $m_{J/\psi}$  or  $\Delta E_c$  sidebands yields  $0.18 \pm 0.46$ . The signal sample is then refit with the  $CP$  asymmetry of the peaking background fixed to the  $\pm 1\sigma$  limits of the measured asymmetry, and the observed variation of  $\pm 0.15$  in  $\sin 2\beta$  is taken as a systematic uncertainty.

The next most significant systematic uncertainty arises from the estimation of the background magnitudes. When the  $\sin 2\beta$  fit is performed, the parameter  $c_{\text{arg}}$  of the ARGUS distribution describing the combinatoric background is fixed to the central value determined from fitting the  $m_{\text{ES}}$  distribution. The  $\sin 2\beta$  fit is repeated with

this value fixed to its  $\pm 1\sigma$  limits, and the observed variation in  $\sin 2\beta$  of  $\pm 0.13$  is taken as a systematic uncertainty.

The uncertainty on the peaking background arises from several sources, the largest of which is the statistical uncertainty on  $n_{\text{peak}}^0$ . The next most significant source is uncertainty in  $\varepsilon_{\text{peak}}$ . We estimate the magnitude of this uncertainty by observing the variations in  $\varepsilon_{\text{peak}}$  among samples of different simulated  $B^0$  decay modes. In addition, one could define  $\varepsilon_{\text{peak}}$  as the efficiency for any candidate with  $m_{\text{ES}} > 5.27 \text{ GeV}$  to pass the final selection, rather than defining it as the ratio of fitted Gaussian areas. We take the difference between the two definitions as a systematic. The estimate of  $n_{\text{peak}}^0$  is also subject to uncertainty in the distribution of peaking backgrounds in  $m_{J/\psi}$ , which is modeled as a second-order Chebyshev polynomial. The variation in  $n_{\text{peak}}^0$  when the order is changed by  $\pm 1$  is propagated to the systematic uncertainty. The accuracy of the fit used to extract the signal is verified using background-only samples, such as data recorded below the  $B\bar{B}$  threshold or samples of candidates reconstructed in modes not accessible to the  $J/\psi$ . No statistically-significant signal yields are reported in fits to these samples. We assign the largest artificial signal yield consistent with these tests as a systematic uncertainty. The final source is the uncertainty on the resolution of the  $J/\psi$  peak (which is held fixed in the fit that determines  $n_{\text{peak}}^0$ ). Variation of this assumed width between values observed in different decay modes yields a variation in  $n_{\text{peak}}^0$ . The sum in quadrature of all these effects totals 25% of the magnitude of  $n_{\text{peak}}$ . Repeating the fit on many samples of parametrized MC events, each of which has the same size and background as the sample observed in data, shows that the variation in  $\sin 2\beta$  resulting from a 25% uncertainty in the peaking background is  $\pm 0.07$ .

There are potentially differences in the flavor-tagging performance and vertex resolution between events with hadronic  $J/\psi$  decays and the other fully-reconstructed  $B$  decays used to measure these parameters. Performing a  $\sin 2\beta$  fit to a large sample of full MC signal events with  $J/\psi \rightarrow \pi^+\pi^-\pi^0$  with the flavor tagging and vertex resolution fixed to the measured values yields a result consistent with the generated value. The statistical uncertainty of the result ( $\pm 0.04$ ) is taken as a systematic uncertainty.

Another systematic uncertainty arises from events in which one or more of the final state particles assigned to the reconstructed  $B^0$  in fact originated from the other  $B^0$  in the event. The fraction of such events is negligible for two-body  $J/\psi$  decays, and about 5% for three-body decays. Performing  $\sin 2\beta$  fits on full MC samples with and without including the incorrectly reconstructed candidates yields a variation of  $\pm 0.01$  in  $\sin 2\beta$ .

Finally we take into account all the sources of systematic uncertainty that apply to BABAR's previous measurements of  $\sin 2\beta$  [3], except for those specific to the  $B^0 \rightarrow J/\psi K_L^0$  mode, that have not already been specifi-

Source	Uncertainty
Peaking background CP	0.15
Combinatoric background magnitude	0.13
Peaking background magnitude	0.07
Tagging and vertexing differences	0.04
Common to leptonic modes	0.03
Misreconstructed signal	0.01
Total	0.21

TABLE II: Summary of systematic uncertainties on the measurement of  $\sin 2\beta$ .

cally addressed here. These uncertainties primarily arise from limits on our understanding of flavor-tagging and vertex reconstruction performance, and yield a variation of  $\pm 0.03$  in  $\sin 2\beta$ .

The systematic uncertainties are summarized in Table II. The sum in quadrature of all contributions is 0.21.

The value of  $\sin 2\beta$  reported in this analysis is higher than the world average value of  $0.731 \pm 0.056$ . To estimate the consistency of this result with the world average, 10,000 parametrized MC samples with the same signal and background magnitudes as observed in the data were generated with a true  $\sin 2\beta$  of 0.731. To simulate the systematic uncertainty in this analysis and the total uncertainty on the world average, a random number with Gaussian distribution and  $\sigma = 0.22$  is added to the  $\sin 2\beta$  result for each sample. Of the 10,000 samples, 629 fluctuated to a value of 1.56 or greater, indicating that the probability of such a fluctuation is 6.3%.

In summary, we have extended *BABAR*'s previous  $\sin 2\beta$  measurement by including  $J/\psi K_s^0$  modes where the  $J/\psi$

decays to hadronic final states. The result is

$$\sin 2\beta = 1.56 \pm 0.42 \text{ (stat.)} \pm 0.21 \text{ (syst.)}.$$

Although we searched for many hadronic  $J/\psi$  decay modes, signals were observed only in modes that have been previously seen [2]. Further, only in hadron multiplicities of two and three was it possible to observe a signal above background. Extending the analysis to the  $\chi_c$  and  $\psi(2S)$  mass regions does not yield additional significant signals, nor is an  $\eta_c$  signal observed after elimination of  $KK\pi$  modes.

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