

# UC Berkeley

## UC Berkeley Previously Published Works

### Title

Measurement of double charmonium production in  $e^{+}e^{-}$  annihilations at  $\sqrt{s}=10.6$  GeV

### Permalink

<https://escholarship.org/uc/item/0ks592cc>

### Journal

PHYSICAL REVIEW D, 72(3)

### ISSN

2470-0010

### Authors

Aubert, B  
Barate, R  
Boutigny, D  
[et al.](#)

### Publication Date

2005

### DOI

10.1103/PhysRevD.72.031101

### Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

## Measurement of double charmonium production in $e^+e^-$ annihilations at $\sqrt{s} = 10.6$ GeV

B. Aubert,<sup>1</sup> R. Barate,<sup>1</sup> D. Boutigny,<sup>1</sup> F. Couderc,<sup>1</sup> Y. Karyotakis,<sup>1</sup> J. P. Lees,<sup>1</sup> V. Poireau,<sup>1</sup> V. Tisserand,<sup>1</sup> A. Zghiche,<sup>1</sup> E. Grauges,<sup>2</sup> A. Palano,<sup>3</sup> M. Pappagallo,<sup>3</sup> A. Pompili,<sup>3</sup> J. C. Chen,<sup>4</sup> N. D. Qi,<sup>4</sup> G. Rong,<sup>4</sup> P. Wang,<sup>4</sup> Y. S. Zhu,<sup>4</sup> G. Eigen,<sup>5</sup> I. Ofte,<sup>5</sup> B. Stugu,<sup>5</sup> G. S. Abrams,<sup>6</sup> M. Battaglia,<sup>6</sup> A. B. Breon,<sup>6</sup> D. N. Brown,<sup>6</sup> J. Button-Shafer,<sup>6</sup> R. N. Cahn,<sup>6</sup> E. Charles,<sup>6</sup> C. T. Day,<sup>6</sup> M. S. Gill,<sup>6</sup> A. V. Gritsan,<sup>6</sup> Y. Groysman,<sup>6</sup> R. G. Jacobsen,<sup>6</sup> R. W. Kadel,<sup>6</sup> J. Kadyk,<sup>6</sup> L. T. Kerth,<sup>6</sup> Yu. G. Kolomoisky,<sup>6</sup> G. Kukartsev,<sup>6</sup> G. Lynch,<sup>6</sup> L. M. Mir,<sup>6</sup> P. J. Oddone,<sup>6</sup> T. J. Orimoto,<sup>6</sup> M. Pripstein,<sup>6</sup> N. A. Roe,<sup>6</sup> M. T. Ronan,<sup>6</sup> W. A. Wenzel,<sup>6</sup> M. Barrett,<sup>7</sup> K. E. Ford,<sup>7</sup> T. J. Harrison,<sup>7</sup> A. J. Hart,<sup>7</sup> C. M. Hawkes,<sup>7</sup> S. E. Morgan,<sup>7</sup> A. T. Watson,<sup>7</sup> M. Fritsch,<sup>8</sup> K. Goetzen,<sup>8</sup> T. Held,<sup>8</sup> H. Koch,<sup>8</sup> B. Lewandowski,<sup>8</sup> M. Pelizaeus,<sup>8</sup> K. Peters,<sup>8</sup> T. Schroeder,<sup>8</sup> M. Steinke,<sup>8</sup> J. T. Boyd,<sup>9</sup> J. P. Burke,<sup>9</sup> N. Chevalier,<sup>9</sup> W. N. Cottingham,<sup>9</sup> M. P. Kelly,<sup>9</sup> T. Cuhadar-Donszelmann,<sup>10</sup> B. G. Fulsom,<sup>10</sup> C. Hearty,<sup>10</sup> N. S. Knecht,<sup>10</sup> T. S. Mattison,<sup>10</sup> J. A. McKenna,<sup>10</sup> A. Khan,<sup>11</sup> P. Kyberd,<sup>11</sup> M. Saleem,<sup>11</sup> L. Teodorescu,<sup>11</sup> A. E. Blinov,<sup>12</sup> V. E. Blinov,<sup>12</sup> A. D. Bukin,<sup>12</sup> V. P. Druzhinin,<sup>12</sup> V. B. Golubev,<sup>12</sup> E. A. Kravchenko,<sup>12</sup> A. P. Onuchin,<sup>12</sup> S. I. Serednyakov,<sup>12</sup> Yu. I. Skovpen,<sup>12</sup> E. P. Solodov,<sup>12</sup> A. N. Yushkov,<sup>12</sup> D. Best,<sup>13</sup> M. Bondioli,<sup>13</sup> M. Bruinsma,<sup>13</sup> M. Chao,<sup>13</sup> I. Eschrich,<sup>13</sup> D. Kirkby,<sup>13</sup> A. J. Lankford,<sup>13</sup> M. Mandelkern,<sup>13</sup> R. K. Mommsen,<sup>13</sup> W. Roethel,<sup>13</sup> D. P. Stoker,<sup>13</sup> C. Buchanan,<sup>14</sup> B. L. Hartfiel,<sup>14</sup> A. J. R. Weinstein,<sup>14</sup> S. D. Foulkes,<sup>15</sup> J. W. Gary,<sup>15</sup> O. Long,<sup>15</sup> B. C. Shen,<sup>15</sup> K. Wang,<sup>15</sup> L. Zhang,<sup>15</sup> D. del Re,<sup>16</sup> H. K. Hadavand,<sup>16</sup> E. J. Hill,<sup>16</sup> D. B. MacFarlane,<sup>16</sup> H. P. Paar,<sup>16</sup> S. Rahatlou,<sup>16</sup> V. Sharma,<sup>16</sup> J. W. Berryhill,<sup>17</sup> C. Campagnari,<sup>17</sup> A. Cunha,<sup>17</sup> B. Dahmes,<sup>17</sup> T. M. Hong,<sup>17</sup> M. A. Mazur,<sup>17</sup> J. D. Richman,<sup>17</sup> W. Verkerke,<sup>17</sup> T. W. Beck,<sup>18</sup> A. M. Eisner,<sup>18</sup> C. J. Flacco,<sup>18</sup> C. A. Heusch,<sup>18</sup> J. Kroseberg,<sup>18</sup> W. S. Lockman,<sup>18</sup> G. Nesom,<sup>18</sup> T. Schalk,<sup>18</sup> B. A. Schumm,<sup>18</sup> A. Seiden,<sup>18</sup> P. Spradlin,<sup>18</sup> D. C. Williams,<sup>18</sup> M. G. Wilson,<sup>18</sup> J. Albert,<sup>19</sup> E. Chen,<sup>19</sup> G. P. Dubois-Felsmann,<sup>19</sup> A. Dvoretzki,<sup>19</sup> D. G. Hitlin,<sup>19</sup> I. Narsky,<sup>19</sup> T. Piatenko,<sup>19</sup> F. C. Porter,<sup>19</sup> A. Ryd,<sup>19</sup> A. Samuel,<sup>19</sup> R. Andreassen,<sup>20</sup> S. Jayatilake,<sup>20</sup> G. Mancinelli,<sup>20</sup> B. T. Meadows,<sup>20</sup> M. D. Sokoloff,<sup>20</sup> F. Blanc,<sup>21</sup> P. Bloom,<sup>21</sup> S. Chen,<sup>21</sup> W. T. Ford,<sup>21</sup> U. Nauenberg,<sup>21</sup> A. Olivas,<sup>21</sup> P. Rankin,<sup>21</sup> W. O. Ruddick,<sup>21</sup> J. G. Smith,<sup>21</sup> K. A. Ulmer,<sup>21</sup> S. R. Wagner,<sup>21</sup> J. Zhang,<sup>21</sup> A. Chen,<sup>22</sup> E. A. Eckhart,<sup>22</sup> A. Soffer,<sup>22</sup> W. H. Toki,<sup>22</sup> R. J. Wilson,<sup>22</sup> Q. Zeng,<sup>22</sup> D. Altenburg,<sup>23</sup> E. Feltresi,<sup>23</sup> A. Hauke,<sup>23</sup> B. Spaan,<sup>23</sup> T. Brandt,<sup>24</sup> J. Brose,<sup>24</sup> M. Dickopp,<sup>24</sup> V. Klose,<sup>24</sup> H. M. Lacker,<sup>24</sup> R. Nogowski,<sup>24</sup> S. Otto,<sup>24</sup> A. Petzold,<sup>24</sup> G. Schott,<sup>24</sup> J. Schubert,<sup>24</sup> K. R. Schubert,<sup>24</sup> R. Schwierz,<sup>24</sup> J. E. Sundermann,<sup>24</sup> D. Bernard,<sup>25</sup> G. R. Bonneaud,<sup>25</sup> P. Grenier,<sup>25</sup> S. Schrenk,<sup>25</sup> Ch. Thiebaut,<sup>25</sup> G. Vasileiadis,<sup>25</sup> M. Verderi,<sup>25</sup> D. J. Bard,<sup>26</sup> P. J. Clark,<sup>26</sup> W. Gradl,<sup>26</sup> F. Muheim,<sup>26</sup> S. Playfer,<sup>26</sup> Y. Xie,<sup>26</sup> M. Andreotti,<sup>27</sup> V. Azzolini,<sup>27</sup> D. Bettoni,<sup>27</sup> C. Bozzi,<sup>27</sup> R. Calabrese,<sup>27</sup> G. Cibinetto,<sup>27</sup> E. Luppi,<sup>27</sup> M. Negrini,<sup>27</sup> L. Piemontese,<sup>27</sup> F. Anulli,<sup>28</sup> R. Baldini-Ferrolli,<sup>28</sup> A. Calcaterra,<sup>28</sup> R. de Sangro,<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> 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> G. Brandenburg,<sup>30</sup> K. S. Chaisanguanthum,<sup>30</sup> M. Morii,<sup>30</sup> E. Won,<sup>30</sup> J. Wu,<sup>30</sup> R. S. Dubitzky,<sup>31</sup> U. Langenegger,<sup>31</sup> J. Marks,<sup>31</sup> S. Schenk,<sup>31</sup> U. Uwer,<sup>31</sup> W. Bhimji,<sup>32</sup> D. A. Bowerman,<sup>32</sup> P. D. Dauncey,<sup>32</sup> U. Egede,<sup>32</sup> R. L. Flack,<sup>32</sup> J. R. Gaillard,<sup>32</sup> G. W. Morton,<sup>32</sup> J. A. Nash,<sup>32</sup> M. B. Nikolich,<sup>32</sup> G. P. Taylor,<sup>32</sup> W. P. Vazquez,<sup>32</sup> M. J. Charles,<sup>33</sup> W. F. Mader,<sup>33</sup> U. Mallik,<sup>33</sup> A. K. Mohapatra,<sup>33</sup> J. Cochran,<sup>34</sup> H. B. Crawley,<sup>34</sup> V. Eyges,<sup>34</sup> W. T. Meyer,<sup>34</sup> S. Prell,<sup>34</sup> E. I. Rosenberg,<sup>34</sup> A. E. Rubin,<sup>34</sup> J. Yi,<sup>34</sup> N. Arnaud,<sup>35</sup> M. Davier,<sup>35</sup> X. Giroux,<sup>35</sup> G. Grosdidier,<sup>35</sup> A. Höcker,<sup>35</sup> F. Le Diberder,<sup>35</sup> V. Lepeltier,<sup>35</sup> A. M. Lutz,<sup>35</sup> A. Oyanguren,<sup>35</sup> T. C. Petersen,<sup>35</sup> M. Pierini,<sup>35</sup> S. Plaszczynski,<sup>35</sup> S. Rodier,<sup>35</sup> P. Roudeau,<sup>35</sup> M. H. Schune,<sup>35</sup> A. Stocchi,<sup>35</sup> G. Wormser,<sup>35</sup> C. H. Cheng,<sup>36</sup> D. J. Lange,<sup>36</sup> M. C. Simani,<sup>36</sup> D. M. Wright,<sup>36</sup> A. J. Bevan,<sup>37</sup> C. A. Chavez,<sup>37</sup> J. P. Coleman,<sup>37</sup> I. J. Forster,<sup>37</sup> J. R. Fry,<sup>37</sup> E. Gabathuler,<sup>37</sup> R. Gamet,<sup>37</sup> K. A. George,<sup>37</sup> D. E. Hutchcroft,<sup>37</sup> R. J. Parry,<sup>37</sup> D. J. Payne,<sup>37</sup> K. C. Schofield,<sup>37</sup> C. Touramanis,<sup>37</sup> C. M. Cormack,<sup>38</sup> F. Di Lodovico,<sup>38</sup> R. Sacco,<sup>38</sup> C. L. Brown,<sup>39</sup> G. Cowan,<sup>39</sup> H. U. Flaecher,<sup>39</sup> M. G. Green,<sup>39</sup> D. A. Hopkins,<sup>39</sup> P. S. Jackson,<sup>39</sup> T. R. McMahon,<sup>39</sup> S. Ricciardi,<sup>39</sup> F. Salvatore,<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> M. C. Hodgkinson,<sup>41</sup> G. D. Lafferty,<sup>41</sup> M. T. Naisbit,<sup>41</sup> J. C. Williams,<sup>41</sup> C. Chen,<sup>42</sup> A. Farbin,<sup>42</sup> W. D. Hulsbergen,<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. Simi,<sup>42</sup> G. Blaylock,<sup>43</sup> C. Dallapiccola,<sup>43</sup> S. S. Hertzbach,<sup>43</sup> R. Kofler,<sup>43</sup> V. B. Koptchev,<sup>43</sup> X. Li,<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> K. Koeneke,<sup>44</sup> G. Sciolla,<sup>44</sup> S. J. Sekula,<sup>44</sup> M. Spitznagel,<sup>44</sup> F. Taylor,<sup>44</sup> R. K. Yamamoto,<sup>44</sup> H. Kim,<sup>45</sup> P. M. Patel,<sup>45</sup> S. H. Robertson,<sup>45</sup> A. Lazzaro,<sup>46</sup> V. Lombardo,<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. Côté,<sup>48</sup> P. Taras,<sup>48</sup> B. Viaud,<sup>48</sup> H. Nicholson,<sup>49</sup> N. Cavallo,<sup>50</sup> G. De Nardo,<sup>50</sup> F. Fabozzi,<sup>50</sup> C. Gatto,<sup>50</sup> L. Lista,<sup>50</sup> D. Monorchio,<sup>50</sup> P. Paolucci,<sup>50</sup> D. Piccolo,<sup>50</sup> C. Sciacca,<sup>50</sup> M. Baak,<sup>51</sup> H. Bulten,<sup>51</sup> G. Raven,<sup>51</sup> H. L. Snoek,<sup>51</sup> L. Wilden,<sup>51</sup> C. P. Jessop,<sup>52</sup> J. M. LoSecco,<sup>52</sup> T. Allmendinger,<sup>53</sup> G. Benelli,<sup>53</sup> K. K. Gan,<sup>53</sup> K. Honscheid,<sup>53</sup> D. Hufnagel,<sup>53</sup> P. D. Jackson,<sup>53</sup> H. Kagan,<sup>53</sup> R. Kass,<sup>53</sup> T. Pulliam,<sup>53</sup> A. M. Rahimi,<sup>53</sup> R. Ter-Antonyan,<sup>53</sup> Q. K. Wong,<sup>53</sup> J. Brau,<sup>54</sup>

R. Frey,<sup>54</sup> O. Igonkina,<sup>54</sup> M. Lu,<sup>54</sup> C. T. Potter,<sup>54</sup> N. B. Sinev,<sup>54</sup> D. Strom,<sup>54</sup> J. Strube,<sup>54</sup> E. Torrence,<sup>54</sup> A. Dorigo,<sup>55</sup> F. Galeazzi,<sup>55</sup> M. Margoni,<sup>55</sup> M. Morandin,<sup>55</sup> M. Posocco,<sup>55</sup> M. Rotondo,<sup>55</sup> F. Simonetto,<sup>55</sup> R. Stroili,<sup>55</sup> C. Voci,<sup>55</sup> M. Benayoun,<sup>56</sup> H. Briand,<sup>56</sup> J. Chauveau,<sup>56</sup> P. David,<sup>56</sup> L. Del Buono,<sup>56</sup> Ch. de la Vaissière,<sup>56</sup> O. Hamon,<sup>56</sup> M. J. J. John,<sup>56</sup> Ph. Leruste,<sup>56</sup> J. Malclès,<sup>56</sup> J. Ocariz,<sup>56</sup> L. Roos,<sup>56</sup> G. Therin,<sup>56</sup> P. K. Behera,<sup>57</sup> L. Gladney,<sup>57</sup> Q. H. Guo,<sup>57</sup> J. Panetta,<sup>57</sup> M. Biasini,<sup>58</sup> R. Covarelli,<sup>58</sup> S. Pacetti,<sup>58</sup> M. Pioppi,<sup>58</sup> C. Angelini,<sup>59</sup> G. Batignani,<sup>59</sup> S. Bettarini,<sup>59</sup> F. Bucci,<sup>59</sup> G. Calderini,<sup>59</sup> M. Carpinelli,<sup>59</sup> R. Cenci,<sup>59</sup> F. Forti,<sup>59</sup> M. A. Giorgi,<sup>59</sup> A. Lusiani,<sup>59</sup> G. Marchiori,<sup>59</sup> M. Morganti,<sup>59</sup> N. Neri,<sup>59</sup> E. Paoloni,<sup>59</sup> M. Rama,<sup>59</sup> G. Rizzo,<sup>59</sup> J. Walsh,<sup>59</sup> M. Haire,<sup>60</sup> D. Judd,<sup>60</sup> D. E. Wagoner,<sup>60</sup> J. Biesiada,<sup>61</sup> N. Danielson,<sup>61</sup> P. Elmer,<sup>61</sup> Y. P. Lau,<sup>61</sup> C. Lu,<sup>61</sup> J. Olsen,<sup>61</sup> A. J. S. Smith,<sup>61</sup> A. V. Telnov,<sup>61</sup> F. Bellini,<sup>62</sup> G. Cavoto,<sup>62</sup> A. D'Orazio,<sup>62</sup> E. Di Marco,<sup>62</sup> R. Faccini,<sup>62</sup> F. Ferrarotto,<sup>62</sup> F. Ferroni,<sup>62</sup> M. Gaspero,<sup>62</sup> L. Li Gioi,<sup>62</sup> M. A. Mazzoni,<sup>62</sup> S. Morganti,<sup>62</sup> G. Piredda,<sup>62</sup> F. Polci,<sup>62</sup> F. Safai Tehrani,<sup>62</sup> C. Voena,<sup>62</sup> H. Schröder,<sup>63</sup> G. Wagner,<sup>63</sup> R. Waldi,<sup>63</sup> T. Adye,<sup>64</sup> N. De Groot,<sup>64</sup> B. Franek,<sup>64</sup> G. P. Gopal,<sup>64</sup> E. O. Olaiya,<sup>64</sup> F. F. Wilson,<sup>64</sup> R. Aleksan,<sup>65</sup> S. Emery,<sup>65</sup> A. Gaidot,<sup>65</sup> S. F. Ganzhur,<sup>65</sup> P.-F. Giraud,<sup>65</sup> G. Graziani,<sup>65</sup> G. Hamel de Monchenault,<sup>65</sup> W. Kozanecki,<sup>65</sup> M. Legendre,<sup>65</sup> G. W. London,<sup>65</sup> B. Mayer,<sup>65</sup> G. Vasseur,<sup>65</sup> Ch. Yèche,<sup>65</sup> M. Zito,<sup>65</sup> M. V. Purohit,<sup>66</sup> A. W. Weidemann,<sup>66</sup> J. R. Wilson,<sup>66</sup> F. X. Yumiceva,<sup>66</sup> T. Abe,<sup>67</sup> M. T. Allen,<sup>67</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> R. Claus,<sup>67</sup> M. R. Convery,<sup>67</sup> M. Cristinziani,<sup>67</sup> J. C. Dingfelder,<sup>67</sup> D. Dong,<sup>67</sup> J. Dorfan,<sup>67</sup> D. Dujmic,<sup>67</sup> W. Dunwoodie,<sup>67</sup> S. Fan,<sup>67</sup> R. C. Field,<sup>67</sup> T. Glanzman,<sup>67</sup> S. J. Gowdy,<sup>67</sup> T. Hadig,<sup>67</sup> V. Halyo,<sup>67</sup> C. Hast,<sup>67</sup> T. Hryn'ova,<sup>67</sup> W. R. Innes,<sup>67</sup> M. H. Kelsey,<sup>67</sup> P. Kim,<sup>67</sup> M. L. Kocian,<sup>67</sup> D. W. G. S. Leith,<sup>67</sup> J. Libby,<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> 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> A. Snyder,<sup>67</sup> J. Stelzer,<sup>67</sup> D. Su,<sup>67</sup> M. K. Sullivan,<sup>67</sup> K. Suzuki,<sup>67</sup> S. Swain,<sup>67</sup> J. M. Thompson,<sup>67</sup> J. Va'vra,<sup>67</sup> M. Weaver,<sup>67</sup> W. J. Wisniewski,<sup>67</sup> M. Wittgen,<sup>67</sup> D. H. Wright,<sup>67</sup> A. K. Yarritu,<sup>67</sup> K. Yi,<sup>67</sup> C. C. Young,<sup>67</sup> P. R. Burchat,<sup>68</sup> A. J. Edwards,<sup>68</sup> S. A. Majewski,<sup>68</sup> B. A. Petersen,<sup>68</sup> C. Roat,<sup>68</sup> M. Ahmed,<sup>69</sup> S. Ahmed,<sup>69</sup> M. S. Alam,<sup>69</sup> J. A. Ernst,<sup>69</sup> M. A. Saeed,<sup>69</sup> F. R. Wappler,<sup>69</sup> S. B. Zain,<sup>69</sup> W. Bugg,<sup>70</sup> M. Krishnamurthy,<sup>70</sup> S. M. Spanier,<sup>70</sup> R. Eckmann,<sup>71</sup> J. L. Ritchie,<sup>71</sup> A. Satpathy,<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> G. Williams,<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> M. Bomben,<sup>74</sup> L. Bosisio,<sup>74</sup> C. Cartaro,<sup>74</sup> F. Cossutti,<sup>74</sup> G. Della Ricca,<sup>74</sup> S. Dittongo,<sup>74</sup> S. Grancagnolo,<sup>74</sup> L. Lanceri,<sup>74</sup> L. Vitale,<sup>74</sup> F. Martinez-Vidal,<sup>75</sup> R. S. Panvini,<sup>76</sup> Sw. Banerjee,<sup>77</sup> B. Bhuyan,<sup>77</sup> C. M. Brown,<sup>77</sup> D. Fortin,<sup>77</sup> K. Hamano,<sup>77</sup> R. Kowalewski,<sup>77</sup> J. M. Roney,<sup>77</sup> R. J. Sobie,<sup>77</sup> J. J. Back,<sup>78</sup> P. F. Harrison,<sup>78</sup> T. E. Latham,<sup>78</sup> G. B. Mohanty,<sup>78</sup> H. R. Band,<sup>79</sup> X. Chen,<sup>79</sup> B. Cheng,<sup>79</sup> S. Dasu,<sup>79</sup> M. Datta,<sup>79</sup> A. M. Eichenbaum,<sup>79</sup> K. T. Flood,<sup>79</sup> M. Graham,<sup>79</sup> J. J. Hollar,<sup>79</sup> J. R. Johnson,<sup>79</sup> P. E. Kutter,<sup>79</sup> H. Li,<sup>79</sup> R. Liu,<sup>79</sup> B. Mellado,<sup>79</sup> A. Mihalyi,<sup>79</sup> Y. Pan,<sup>79</sup> R. Prepost,<sup>79</sup> P. Tan,<sup>79</sup> J. H. von Wimmersperg-Toeller,<sup>79</sup> S. L. Wu,<sup>79</sup> Z. Yu,<sup>79</sup> and H. Neal<sup>80</sup>

(BABAR Collaboration)

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

<sup>2</sup>IFAE, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain

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

<sup>4</sup>Institute of High Energy Physics, Beijing 100039, China

<sup>5</sup>University of Bergen, Institute of Physics, N-5007 Bergen, Norway

<sup>6</sup>Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

<sup>7</sup>University of Birmingham, Birmingham, B15 2TT, United Kingdom

<sup>8</sup>Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

<sup>9</sup>University of Bristol, Bristol BS8 1TL, United Kingdom

<sup>10</sup>University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

<sup>11</sup>Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

<sup>12</sup>Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

<sup>13</sup>University of California at Irvine, Irvine, California 92697, USA

<sup>14</sup>University of California at Los Angeles, Los Angeles, California 90024, USA

<sup>15</sup>University of California at Riverside, Riverside, California 92521, USA

<sup>16</sup>University of California at San Diego, La Jolla, California 92093, USA

<sup>17</sup>University of California at Santa Barbara, Santa Barbara, California 93106, USA

<sup>18</sup>University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

<sup>19</sup>California Institute of Technology, Pasadena, California 91125, USA

- <sup>20</sup>University of Cincinnati, Cincinnati, Ohio 45221, USA  
<sup>21</sup>University of Colorado, Boulder, Colorado 80309, USA  
<sup>22</sup>Colorado State University, Fort Collins, Colorado 80523, USA  
<sup>23</sup>Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany  
<sup>24</sup>Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany  
<sup>25</sup>Ecole Polytechnique, LLR, F-91128 Palaiseau, France  
<sup>26</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom  
<sup>27</sup>Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy  
<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, Massachusetts 02138, USA  
<sup>31</sup>Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany  
<sup>32</sup>Imperial College London, London, SW7 2AZ, United Kingdom  
<sup>33</sup>University of Iowa, Iowa City, Iowa 52242, USA  
<sup>34</sup>Iowa State University, Ames, Iowa 50011-3160, USA  
<sup>35</sup>Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, 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, 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>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>Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy  
<sup>47</sup>University of Mississippi, University, Mississippi 38677, USA  
<sup>48</sup>Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Québec, Canada H3C 3J7  
<sup>49</sup>Mount Holyoke College, South Hadley, Massachusetts 01075, USA  
<sup>50</sup>Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, 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>Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy  
<sup>56</sup>Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France  
<sup>57</sup>University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA  
<sup>58</sup>Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy  
<sup>59</sup>Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy  
<sup>60</sup>Prairie View A&M University, Prairie View, Texas 77446, USA  
<sup>61</sup>Princeton University, Princeton, New Jersey 08544, USA  
<sup>62</sup>Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy  
<sup>63</sup>Universität Rostock, D-18051 Rostock, Germany  
<sup>64</sup>Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom  
<sup>65</sup>DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France  
<sup>66</sup>University of South Carolina, Columbia, South Carolina 29208, USA  
<sup>67</sup>Stanford Linear Accelerator Center, Stanford, California 94309, USA  
<sup>68</sup>Stanford University, Stanford, California 94305-4060, USA  
<sup>69</sup>State University of New York, Albany, New York 12222, USA  
<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>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>IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain  
<sup>76</sup>Vanderbilt University, Nashville, Tennessee 37235, USA  
<sup>77</sup>University of Victoria, Victoria, British Columbia, Canada V8W 3P6  
<sup>78</sup>Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom  
<sup>79</sup>University of Wisconsin, Madison, Wisconsin 53706, USA

<sup>80</sup>*Yale University, New Haven, Connecticut 06511, USA*  
(Received 25 June 2005; published 15 August 2005)

We study  $e^+e^- \rightarrow J/\psi c\bar{c}$  by measuring the invariant mass distribution recoiling against fully reconstructed  $J/\psi$  decays, using  $124 \text{ fb}^{-1}$  of data collected at a center-of-mass energy of 10.6 GeV with the *BABAR* detector. We observe signals for  $\eta_c(1S)$ ,  $\chi_{c0}$ , and  $\eta_c(2S)$  in the recoil mass distribution, thus confirming previous measurements. We measure  $\sigma(e^+e^- \rightarrow J/\psi + c\bar{c})\mathcal{B}(c\bar{c} \rightarrow >2 \text{ charged})$  to be  $17.6 \pm 2.8(\text{stat})_{-2.1}^{+1.5}(\text{syst}) \text{ fb}$ ,  $10.3 \pm 2.5(\text{stat})_{-1.8}^{+1.4}(\text{syst}) \text{ fb}$ , and  $16.4 \pm 3.7(\text{stat})_{-3.0}^{+2.4}(\text{syst}) \text{ fb}$  with  $c\bar{c} = \eta_c(1S)$ ,  $\chi_{c0}$ , and  $\eta_c(2S)$ , respectively.

DOI: [10.1103/PhysRevD.72.031101](https://doi.org/10.1103/PhysRevD.72.031101)

PACS numbers: 13.66.Bc, 12.38.Bx, 12.38.Qk, 14.40.Gx

Prompt  $J/\psi$  and  $\psi(2S)$  production in  $e^+e^-$  annihilations around  $\sqrt{s} = 10.6 \text{ GeV}$  has been observed by both the *BABAR* [1] and Belle [2] experiments. These interactions provide an opportunity to study both perturbative and non-perturbative effects in QCD and to search for new charmonium states [3,4].

Belle [5] reported the observation of  $\eta_c(1S)$ ,  $\chi_{c0}$ , and  $\eta_c(2S)$  in the mass distribution of the system recoiling against a reconstructed  $J/\psi$  in  $e^+e^-$  annihilations. The production cross sections measured by Belle are about one order of magnitude higher than those predicted by non-relativistic QCD (NRQCD) calculations [4,6,7] for  $e^+e^- \rightarrow \gamma^* \rightarrow J/\psi c\bar{c}$  reactions, where  $c\bar{c}$  is a charmonium state with even  $C$ -parity. There have been attempts [8–12] to reconcile the large discrepancy between the observed cross section and predictions, and the validity of NRQCD approximations has been questioned [9,13]. It has also been suggested that at least part of the double charmonium production might be due to two virtual-photon interactions [10], i.e.,  $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow J/\psi c\bar{c}$ , where odd- $C$ -parity states could be produced. Belle updated its observation and explored the origin of the  $J/\psi c\bar{c}$  events [14].

In this paper we present a measurement of the cross sections for  $e^+e^- \rightarrow J/\psi 2 \eta_c(1S)$ ,  $e^+e^- \rightarrow J/\psi 2 \chi_{c0}$ , and  $e^+e^- \rightarrow J/\psi \eta_c(2S)$ , and set limits on the yields for other known charmonium states produced in association with a  $J/\psi$ . We calculate the mass ( $M_{\text{rec}}$ ) of the system recoiling against a fully reconstructed  $J/\psi$  via:

$$M_{\text{rec}}^2 = (\sqrt{s} - E_{J/\psi}^*)^2 - p_{J/\psi}^{*2} \quad (1)$$

where  $\sqrt{s}$  is the  $e^+e^-$  annihilation energy in the center-of-mass (CM) system, and  $E_{J/\psi}^*$  and  $p_{J/\psi}^*$  are the energy and momentum of the  $J/\psi$  candidate in the CM system.

In this paper, we analyze  $112 \text{ fb}^{-1}$  of data collected at the peak of the  $Y(4S)$  resonance and  $12 \text{ fb}^{-1}$  at  $\sqrt{s} = 10.54 \text{ GeV}$ , just below the  $Y(4S)$ , with the *BABAR* detector

\*Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy.

†Also with Università della Basilicata, Potenza, Italy.

‡Also with Università della Basilicata, Potenza, Italy.

[15] operating at the asymmetric energy PEP-II  $e^+e^-$  storage ring. The *BABAR* detector includes a five-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) in a 1.5 T solenoidal magnetic field, which detects charged particles and measures their momenta and specific ionizations (dE/dx). Photons and electrons are detected with a CsI(Tl)-crystal electromagnetic calorimeter (EMC). An internally reflecting ring-imaging Cherenkov (DIRC) is used for particle identification. Penetrating muons are identified by an array of resistive-plate chambers (RPC) embedded in the steel of the flux return (IFR).

We select events with at least five well reconstructed charged tracks in the DCH, within the fiducial volume  $0.41 < \theta < 2.54$ , where  $\theta$  is the polar angle. Electron candidates have a pattern of specific ionization (dE/dx) in the DCH, a Cherenkov cone angle, an EMC shower energy divided by momentum, and a number of EMC crystals that are consistent with an electron hypothesis. A muon candidate is selected on the basis of energy deposited in the EMC, the number and distribution of hits in the IFR, and the match between the IFR hits and the extrapolation of the DCH track into the IFR. A more detailed explanation of particle identification is given elsewhere [1].

A pair of oppositely charged lepton candidates originating from a common vertex is selected as a  $J/\psi$  candidate if its mass ( $m(\ell^+\ell^-)$ ) falls within  $[-50, 30] \text{ MeV}/c^2$  (for  $e^+e^-$ ) or  $[-30, 30] \text{ MeV}/c^2$  (for  $\mu^+\mu^-$ ), of the nominal  $J/\psi$  mass of  $3.097 \text{ MeV}/c^2$  [16]. In the calculation of  $m(e^+e^-)$ , electron candidates are combined with nearby photon candidates in order to recover some of the energy lost through bremsstrahlung radiation. These mass intervals are referred to as the  $J/\psi$  mass windows. In order to improve the  $p_{J/\psi}^*$  resolution, we perform a kinematic fit where the  $J/\psi$  candidate is constrained to have the nominal  $J/\psi$  mass.

There are two main background sources in this analysis: events with genuine  $J/\psi$  mesons and combinatorial background. The region  $60 \text{ MeV}/c^2 < |M(\ell^+\ell^-) - M(J/\psi)| < 200 \text{ MeV}/c^2$ , defined as the  $J/\psi$  mass sidebands, where  $M(J/\psi)$  is the nominal  $J/\psi$  mass, is used to estimate the combinatorial background due to random tracks. This background is largely rejected by particle identification, and by a requirement on the lepton helicity

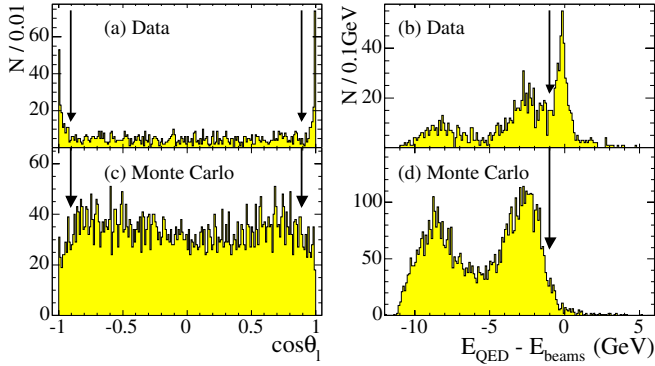


FIG. 1 (color online). Distributions of (a)  $\cos\theta_l$  and (b)  $E_{\text{QED}} - E_{\text{beams}}$  in the data, (c)  $\cos\theta_l$  and (d)  $E_{\text{QED}} - E_{\text{beams}}$  in the signal Monte Carlo. The arrows point to where the selection criteria are applied.

angle in the  $J/\psi$  decay,  $|\cos\theta_l| < 0.9$ , as shown in Fig. 1(a) and 1(c).

The largest backgrounds are due to real  $J/\psi$  mesons from QED processes such as  $J/\psi$  or  $\psi(2S)$  mesons produced via initial state radiation (ISR).  $J/\psi$  mesons from  $B$  meson decay have  $p^* < 2 \text{ GeV}/c$  and do not constitute a background for recoil masses below  $6.6 \text{ GeV}/c^2$ . Most QED backgrounds have low multiplicity, and may have electrons or photons escaping detection along the beam line. These backgrounds are suppressed by the requirement of at least five charged tracks and the following requirement: for each event we calculate the energy deposited in the EMC plus the energy that can be attributed to an undetected electron or photon,

$$E_{\text{QED}} = E_{\text{EMC}} + p_{\text{miss}}, \quad (2)$$

where  $E_{\text{EMC}}$  is the total energy deposited in the EMC, and  $p_{\text{miss}}$  is the missing momentum in the lab frame in the event. We require  $E_{\text{QED}} - E_{\text{beams}} < -1.0 \text{ GeV}$  as shown in Fig. 1(b) and 1(d), where  $E_{\text{beams}}$  is the sum of the  $e^+e^-$  beam energies calculated in the lab frame. We reject the  $J/\psi$  background from  $\psi(2S)$  events by vetoing events if the invariant mass of the  $J/\psi$  candidates combined with any pair of oppositely charged tracks with pion mass hypothesis is within  $15 \text{ MeV}/c^2$  of the  $\psi(2S)$  mass.

The recoil mass distribution for events in the  $J/\psi$  mass window is shown as points with error bars in Fig. 2. The ISR  $\psi(2S)$  background is estimated using a Monte Carlo sample of ISR  $\psi(2S)$  events. The  $\psi(2S)$  feeddown background from continuum production is estimated using continuum  $\psi(2S)$  events selected in the data.

The spectrum in Fig. 2 is fit to the sum of signal functions representing the  $\eta_c(1S)$ ,  $\chi_{c0}$ , and  $\eta_c(2S)$  line-shapes, plus a second-order polynomial background function. The signal line shapes are obtained by convoluting the Breit-Wigner line shape of each resonance with a fixed-width Gaussian representing the recoil mass resolution

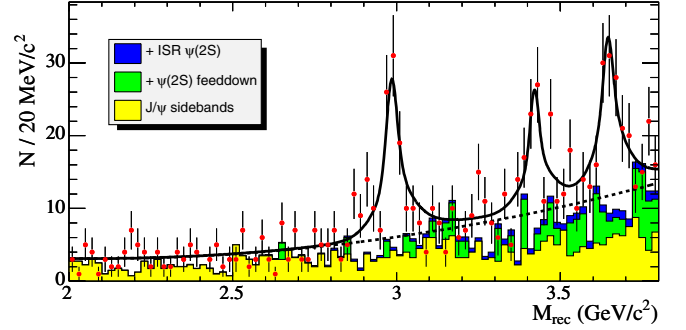


FIG. 2 (color online). The fit to the recoil mass distribution is represented by the solid curve. The dashed curve is a second-order polynomial representing the background. The points with error bars refer to the events in the  $J/\psi$  mass window. The histograms represent different sources of backgrounds.

function. The widths of the Gaussians are determined from a Monte Carlo simulation of the momentum of the reconstructed  $J/\psi$ ; the  $J/\psi$  momentum resolution is different for the  $J/\psi \rightarrow e^+e^-$  and  $J/\psi \rightarrow \mu^+\mu^-$  samples, but independent of the recoiling system. This shape in turn is convolved with a long radiative tail that is calculated to  $\mathcal{O}(\alpha^2)$  [17] for ISR photons that carry off an energy greater than  $10 \text{ MeV}$ . The free parameters in the data fit are the coefficients for the background parameterization, the event yields for each resonance, the masses of the resonances, and the  $\eta_c(2S)$  total width. The total widths for the  $\eta_c(1S)$  and the  $\chi_{c0}$  are fixed to their world average values [16] of  $17.3 \text{ MeV}/c^2$  and  $10.1 \text{ MeV}/c^2$ , respectively. The fit is performed simultaneously to the recoil mass spectra in the  $J/\psi \rightarrow e^+e^-$  and  $J/\psi \rightarrow \mu^+\mu^-$  samples, and the total event yield for each resonance is given by the sum of the yields in each mode.

The fit result is given in Table I and is shown as the solid curve in Fig. 2. Other known charmonium states may also be produced in association with the  $J/\psi$  via two virtual-

TABLE I. Result of the fits to the recoil-mass spectrum. The errors are statistical only. Where indicated, the value of the corresponding parameter is fixed to the current world average [16]. The primary fit is obtained including signals of  $\eta_c(1S)$ ,  $\chi_{c0}$ , and  $\eta_c(2S)$ . The event yield for the other resonances is determined by including each resonance in the primary fit.

Recoil system	Number of Events	Mass ( $\text{MeV}/c^2$ )	Total width ( $\text{MeV}/c^2$ )
$\eta_c(1S)$	$126 \pm 20$	$2984.8 \pm 4.0$	fixed
$\chi_{c0}$	$81 \pm 20$	$3420.5 \pm 4.8$	fixed
$\eta_c(2S)$	$121 \pm 27$	$3645.0 \pm 5.5$	$22 \pm 14$
$J/\psi$	$-26 \pm 13$	fixed	fixed
$\chi_{c1}$	$-5 \pm 16$	fixed	fixed
$\chi_{c2}$	$-12 \pm 16$	fixed	fixed
$\psi(2S)$	$30 \pm 27$	fixed	fixed

TABLE II. Summary of systematic errors: variations of cross sections and masses due to the selection and fitting procedure (Fit), particle identification (PID) efficiency, and recoil-mass scale uncertainty.  $\Delta M$  refers to the mass difference between the  $\eta_c(2S)$  and  $\eta_c(1S)$ .

Source	Variations(%) in cross section			Variations (MeV/ $c^2$ ) in mass			
	$\eta_c(1S)$	$\chi_{c0}$	$\eta_c(2S)$	$\eta_c(1S)$	$\chi_{c0}$	$\eta_c(2S)$	$\Delta M$
Selection	+3.5 -8.3	+0.3 -9.2	+12.6 -15.6	+3.0 -0.2	+1.2 -0.7	+1.0 -5.1	-7.2
Fit	+6.7	+13.5	+6.8	+0.1	+9.9	+3.3	+7.1
PID	-8.1	-14.2	-8.3	-3.4	-8.0	-3.7	-2.3
	$\pm 3.5$	$\pm 3.5$	$\pm 3.5$	...	...	...	...
Mass scale	...	...	...	$\pm 1.5$	$\pm 1.5$	$\pm 1.5$	0
Sum	+8 -12	+14 -17	+15 -18	+4.5 -5.0	+11.5 -9.5	+4.9 -7.8	+7.1 -7.6

photon interactions. We therefore attempt to include in our primary fit each one of the other known charmonium resonances in turn to determine their event yields, which are presented in Table I. We find no evidence for  $J/\psi$ ,  $\chi_{c1}$ ,  $\chi_{c2}$ , or  $\psi(2S)$  in the mass spectrum of the system recoiling against a  $J/\psi$ .

The topological branching fraction is unknown for the  $\eta_c(1S)$ ,  $\chi_{c0}$ , and  $\eta_c(2S)$ , so we report the product of the branching fraction for final states with more than two charged tracks ( $\mathcal{B}_{>2}(c\bar{c} \rightarrow >2 \text{ charged})$ ) times the double charmonium production cross section. In order to include the effect of ISR, the yields reported in Table I are calculated with a line shape based on a model of the  $\sqrt{s}$  dependence of double charmonium production model. To allow a direct comparison of experimental results, we follow the same method used by Belle [14] to remove this model dependence by determining cross section values that correspond to the non-tail fraction of the fit shape ( $f_{\text{rad}} = 0.61$ ) [17] where no ISR photon with an energy greater than 10 MeV is radiated. We use

$$\sigma(e^+e^- \rightarrow J/\psi c\bar{c})\mathcal{B}_{>2} = \frac{N_{c\bar{c}}f_{\text{rad}}}{\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-)\mathcal{L}\varepsilon}, \quad (3)$$

where  $N_{c\bar{c}}$  is the event yield,  $\mathcal{L}$  is the integrated luminosity,  $\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-)$  is the  $J/\psi$  branching fraction, and  $\varepsilon$  is the detection efficiency. The value of  $\varepsilon$  is determined using a Monte Carlo simulation with the assumption that exclusive  $J/\psi\eta_c(nS)$  production is  $P$  wave and that exclusive  $J/\psi\chi_{c0}$  production is  $S$  wave, as expected for a single virtual-photon process. The efficiency is determined to be

(28.8  $\pm$  0.7)% for the  $\eta_c(1S)$ , (31.5  $\pm$  0.7)% for the  $\chi_{c0}$ , and (28.9  $\pm$  0.8)% for the  $\eta_c(2S)$ .

The systematic error is estimated taking into account contributions from the event selection, the fitting procedure, the particle identification efficiency, and the recoil-mass scale uncertainty. The contributions from uncertainties in the integrated luminosity and the  $J/\psi$  branching fraction are negligible. The contributions from individual sources (listed in Table II) are added in quadrature, except for the systematic errors due to the mass-scale uncertainty, which are added linearly, to determine the total systematic errors.

We obtain  $\sigma(e^+e^- \rightarrow J/\psi c\bar{c})\mathcal{B}(c\bar{c} \rightarrow >2 \text{ charged})$  to be  $17.6 \pm 2.8^{+1.5}_{-2.1}$  fb for  $J/\psi\eta_c(1S)$ ,  $10.3 \pm 2.5^{+1.4}_{-1.8}$  fb for  $J/\psi\chi_{c0}$ , and  $16.4 \pm 3.7^{+2.4}_{-3.0}$  fb for  $J/\psi\eta_c(2S)$ . Throughout this paper, the first error is statistical and the second systematic. Our values of the cross sections are consistent with Belle's measurements [14] for all three resonances. The cross sections measured by both experiments are much larger than those predicted by many NRQCD calculations.

From the fit to the recoil mass spectrum we determine the  $\eta_c(2S)$  mass to be  $3645.0 \pm 5.5^{+4.9}_{-7.8}$  MeV/ $c^2$ , and the total width to be  $22 \pm 14$  MeV/ $c^2$ . The systematic errors are mainly due to the uncertainty on the  $J/\psi$  momentum measurement. We use ISR  $J/\psi$  and ISR  $\psi(2S)$  data samples to determine the momentum shifts away from the expectations for ISR events. Assuming a constant momentum shift, we obtain the recoil mass uncertainty for  $J/\psi c\bar{c}$  processes due to the  $J/\psi$  momentum uncertainty. The mass difference ( $\Delta M$ ) between the  $\eta_c(2S)$  and  $\eta_c(1S)$  does not significantly depend on the absolute mo-

TABLE III. Comparison of cross sections ( $\sigma \times \mathcal{B}_{>2}$  in fb) with Belle's results [14], and with theoretical expectations that do not include the  $\mathcal{B}_{>2}$  factor.

$J/\psi c\bar{c}$	$\eta_c(1S)$	$\chi_{c0}$	$\eta_c(2S)$
BABAR	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
Belle [14]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
NRQCD [6]	$2.31 \pm 1.09$	$2.28 \pm 1.03$	$0.96 \pm 0.45$
NRQCD [4]	5.5	6.9	3.7

momentum scale and common systematic errors mostly cancel. We measure  $\Delta M = 660.2 \pm 6.8_{-7.6}^{+7.1} \text{ MeV}/c^2$ , which is in good agreement with the mass difference previously reported by this experiment [18] and by other experiments [14,19].

In summary, we have measured the cross section for double charmonium production  $\sigma(e^+e^- \rightarrow J/\psi c\bar{c})\mathcal{B}(c\bar{c} \rightarrow >2 \text{ charged})$  for  $J/\psi \eta_c(1S)$ ,  $J/\psi \chi_{c0}$ , and  $J/\psi \eta_c(2S)$ . We confirm the unexpectedly large cross sections previously reported by the Belle experiment for these processes. No evidence is found for  $e^+e^- \rightarrow J/\psi$ ,  $J/\psi \chi_{c1}$ ,  $J/\psi \chi_{c2}$ , or  $J/\psi \psi(2S)$ . We also measure the mass difference between the  $\eta_c(2S)$  and the  $\eta_c(1S)$ .

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions

wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Énergie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from CONACyT (Mexico), the A.P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

- 
- [1] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **87**, 162002 (2001).  
 [2] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **88**, 052001 (2002).  
 [3] Y. Iwasaki, Phys. Rev. D **16**, 220 (1977).  
 [4] Kui-Yong Liu, Zhi-Guo He, and Kuang-Ta Chao, hep-ph/0408141.  
 [5] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 142001 (2002).  
 [6] E. Braaten and J. Lee, Phys. Rev. D **67**, 054007 (2003).  
 [7] Kui-Yong Liu, Zhi-Guo He, and Kuang-Ta Chao, Phys. Lett. B **557**, 45 (2003).  
 [8] Y.J. Zhang, Y.J. Gao, and K. T. Chao, hep-ph/0506076.  
 [9] A. E. Bondar and V. L. Chernyak, Phys. Lett. B **612**, 215 (2005).  
 [10] G. T. Bodwin, J. Lee, and E. Braaten, Phys. Rev. D **67**, 054023 (2003).  
 [11] G. T. Bodwin, J. Lee, and E. Braaten, Phys. Rev. Lett. **90**, 162001 (2003).  
 [12] S. J. Brodsky, A. S. Goldhaber, and J. Lee, Phys. Rev. Lett. **91**, 112001 (2003).  
 [13] N. Brambilla *et al.*, hep-ph/0412158.  
 [14] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **70**, 071102 (2004).  
 [15] B. Aubert *et al.* (*BABAR* Collaboration), Nucl. Instrum. Methods A **479**, 1 (2002).  
 [16] S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004).  
 [17] S. Jadach, B. F. L. Ward, and Z. Was, Comput. Phys. Commun. **130**, 260 (2000).  
 [18] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **92**, 142002 (2004).  
 [19] D. M. Asner *et al.* (CLEO Collaboration), Phys. Rev. Lett. **92**, 142001 (2004).