

Search for Decays of  $B^0 \rightarrow e^+e^-$ ,  $B^0 \rightarrow \mu^+\mu^-$ ,  $B^0 \rightarrow e^\pm\mu^\mp$ 

B. Aubert,<sup>1</sup> R. Barate,<sup>1</sup> D. Boutigny,<sup>1</sup> F. Couderc,<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> 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> G. Kukartsev,<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> M. T. Ronan,<sup>5</sup> V. G. Shelkov,<sup>5</sup> W. A. Wenzel,<sup>5</sup> M. Barrett,<sup>6</sup> K. E. Ford,<sup>6</sup> T. J. Harrison,<sup>6</sup> A. J. Hart,<sup>6</sup> C. M. Hawkes,<sup>6</sup> S. E. Morgan,<sup>6</sup> A. T. Watson,<sup>6</sup> M. Fritsch,<sup>7</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> 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> F. F. Wilson,<sup>8</sup> T. Cuhadar-Donszelmann,<sup>9</sup> C. Hearty,<sup>9</sup> N. S. Knecht,<sup>9</sup> T. S. Mattison,<sup>9</sup> J. A. McKenna,<sup>9</sup> D. Thiessen,<sup>9</sup> A. Khan,<sup>10</sup> P. Kyberd,<sup>10</sup> L. Teodorescu,<sup>10</sup> A. E. Blinov,<sup>11</sup> V. E. Blinov,<sup>11</sup> V. P. Druzhinin,<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. Serednyakov,<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> I. Eschrich,<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. Hartfiel,<sup>13</sup> S. D. Foulkes,<sup>14</sup> J. W. Gary,<sup>14</sup> B. C. Shen,<sup>14</sup> K. Wang,<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> V. Sharma,<sup>15</sup> J. W. Berryhill,<sup>16</sup> C. Campagnari,<sup>16</sup> B. Dahmes,<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> A. M. Eisner,<sup>17</sup> C. A. Heusch,<sup>17</sup> W. S. Lockman,<sup>17</sup> G. Nesom,<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> P. Spradlin,<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. Dvoretzky,<sup>18</sup> D. G. Hitlin,<sup>18</sup> I. Narsky,<sup>18</sup> T. Piatenko,<sup>18</sup> F. C. Porter,<sup>18</sup> 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> W. T. Ford,<sup>20</sup> U. Nauenberg,<sup>20</sup> A. Olivas,<sup>20</sup> P. Rankin,<sup>20</sup> J. G. Smith,<sup>20</sup> J. Zhang,<sup>20</sup> L. Zhang,<sup>20</sup> A. Chen,<sup>21</sup> J. L. Harton,<sup>21</sup> A. Soffer,<sup>21</sup> W. H. Toki,<sup>21</sup> R. J. Wilson,<sup>21</sup> Q. L. Zeng,<sup>21</sup> D. Altenburg,<sup>22</sup> T. Brandt,<sup>22</sup> J. Brose,<sup>22</sup> M. Dickopp,<sup>22</sup> E. Feltresi,<sup>22</sup> A. Hauke,<sup>22</sup> H. M. Lacker,<sup>22</sup> R. Müller-Pfefferkorn,<sup>22</sup> R. Nogowski,<sup>22</sup> S. Otto,<sup>22</sup> A. Petzold,<sup>22</sup> J. Schubert,<sup>22</sup> K. R. Schubert,<sup>22</sup> R. Schwierz,<sup>22</sup> B. Spaan,<sup>22</sup> J. E. Sundermann,<sup>22</sup> D. Bernard,<sup>23</sup> G. R. Bonneaud,<sup>23</sup> F. Brochard,<sup>23</sup> P. Grenier,<sup>23</sup> S. Schrenk,<sup>23</sup> Ch. Thiebaux,<sup>23</sup> G. Vasileiadis,<sup>23</sup> M. Verderi,<sup>23</sup> D. J. Bard,<sup>24</sup> P. J. Clark,<sup>24</sup> D. Lavin,<sup>24</sup> F. Muheim,<sup>24</sup> S. Playfer,<sup>24</sup> Y. Xie,<sup>24</sup> M. Andreotti,<sup>25</sup> V. Azzolini,<sup>25</sup> D. Bettoni,<sup>25</sup> C. Bozzi,<sup>25</sup> R. Calabrese,<sup>25</sup> G. Cibinetto,<sup>25</sup> E. Luppi,<sup>25</sup> M. Negrini,<sup>25</sup> L. Piemontese,<sup>25</sup> A. Sarti,<sup>25</sup> E. Treadwell,<sup>26</sup> R. Baldini-Ferroli,<sup>27</sup> A. Calcaterra,<sup>27</sup> R. de Sangro,<sup>27</sup> G. Finocchiaro,<sup>27</sup> P. Patteri,<sup>27</sup> M. Piccolo,<sup>27</sup> A. Zallo,<sup>27</sup> A. Buzzo,<sup>28</sup> R. Capra,<sup>28</sup> R. Contri,<sup>28</sup> G. Crosetti,<sup>28</sup> M. Lo Vetere,<sup>28</sup> M. Macri,<sup>28</sup> M. R. Monge,<sup>28</sup> S. Passaggio,<sup>28</sup> C. Patrignani,<sup>28</sup> E. Robutti,<sup>28</sup> A. Santroni,<sup>28</sup> S. Tosi,<sup>28</sup> S. Bailey,<sup>29</sup> G. Brandenburg,<sup>29</sup> M. Morii,<sup>29</sup> E. Won,<sup>29</sup> R. S. Dubitzky,<sup>30</sup> U. Langenegger,<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> J. R. Gaillard,<sup>31</sup> G. W. Morton,<sup>31</sup> J. A. Nash,<sup>31</sup> M. B. Nikolich,<sup>31</sup> G. P. Taylor,<sup>31</sup> M. J. Charles,<sup>32</sup> G. J. Grenier,<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. Davier,<sup>34</sup> G. Grosdidier,<sup>34</sup> A. Höcker,<sup>34</sup> S. Laplace,<sup>34</sup> F. Le Diberder,<sup>34</sup> V. Lepeltier,<sup>34</sup> A. M. Lutz,<sup>34</sup> T. C. Petersen,<sup>34</sup> S. Plaszczynski,<sup>34</sup> M. H. Schune,<sup>34</sup> L. Tantot,<sup>34</sup> G. Wormser,<sup>34</sup> C. H. Cheng,<sup>35</sup> D. J. Lange,<sup>35</sup> M. C. Simani,<sup>35</sup> D. M. Wright,<sup>35</sup> A. J. Bevan,<sup>36</sup> C. A. Chavez,<sup>36</sup> J. P. Coleman,<sup>36</sup> I. J. Forster,<sup>36</sup> J. R. Fry,<sup>36</sup> E. Gabathuler,<sup>36</sup> R. Gamet,<sup>36</sup> R. J. Parry,<sup>36</sup> D. J. Payne,<sup>36</sup> R. J. Sloane,<sup>36</sup> C. Touramanis,<sup>36</sup> J. J. Back,<sup>37,\*</sup> C. M. Cormack,<sup>37</sup> P. F. Harrison,<sup>37,\*</sup> F. Di Lodovico,<sup>37</sup> G. B. Mohanty,<sup>37,\*</sup> C. L. Brown,<sup>38</sup> G. Cowan,<sup>38</sup> R. L. Flack,<sup>38</sup> H. U. Flaecher,<sup>38</sup> M. G. Green,<sup>38</sup> P. S. Jackson,<sup>38</sup> T. R. McMahon,<sup>38</sup> S. Ricciardi,<sup>38</sup> F. Salvatore,<sup>38</sup> M. A. Winter,<sup>38</sup> D. Brown,<sup>39</sup> C. L. Davis,<sup>39</sup> J. Allison,<sup>40</sup> N. R. Barlow,<sup>40</sup> R. J. Barlow,<sup>40</sup> M. C. Hodgkinson,<sup>40</sup> G. D. Lafferty,<sup>40</sup> A. J. Lyon,<sup>40</sup> J. C. Williams,<sup>40</sup> A. Farbin,<sup>41</sup> W. D. Hulsbergen,<sup>41</sup> A. Jawahery,<sup>41</sup> D. Kovalskyi,<sup>41</sup> C. K. Lae,<sup>41</sup> V. Lillard,<sup>41</sup> D. A. Roberts,<sup>41</sup> G. Blaylock,<sup>42</sup> C. Dallapiccola,<sup>42</sup> K. T. Flood,<sup>42</sup> S. S. Hertzbach,<sup>42</sup> R. Kofler,<sup>42</sup> V. B. Koptchev,<sup>42</sup> T. B. Moore,<sup>42</sup> S. Saremi,<sup>42</sup> H. Staengle,<sup>42</sup> S. Willocq,<sup>42</sup> R. Cowan,<sup>43</sup> G. Sciolla,<sup>43</sup> F. Taylor,<sup>43</sup> R. K. Yamamoto,<sup>43</sup> D. J. J. Mangeol,<sup>44</sup> P. M. Patel,<sup>44</sup> S. H. Robertson,<sup>44</sup> A. Lazzaro,<sup>45</sup> F. Palombo,<sup>45</sup> J. M. Bauer,<sup>46</sup> L. Cremaldi,<sup>46</sup> V. Eschenburg,<sup>46</sup> R. Godang,<sup>46</sup> R. Kroeger,<sup>46</sup> J. Reidy,<sup>46</sup> D. A. Sanders,<sup>46</sup> D. J. Summers,<sup>46</sup> H. W. Zhao,<sup>46</sup> S. Brunet,<sup>47</sup> D. Côté,<sup>47</sup> P. Taras,<sup>47</sup> H. Nicholson,<sup>48</sup> F. Fabozzi,<sup>49,†</sup> C. Gatto,<sup>49</sup> L. Lista,<sup>49</sup> D. Monorchio,<sup>49</sup> P. Paolucci,<sup>49</sup> D. Piccolo,<sup>49</sup> C. Sciacca,<sup>49</sup> M. Baak,<sup>50</sup> H. Bulten,<sup>50</sup> G. Raven,<sup>50</sup> H. L. Snoek,<sup>50</sup> L. Wilden,<sup>50</sup> C. P. Jessop,<sup>51</sup> J. M. LoSecco,<sup>51</sup> T. A. Gabriel,<sup>52</sup> T. Allmendinger,<sup>53</sup> B. Brau,<sup>53</sup> K. K. Gan,<sup>53</sup> K. Honscheid,<sup>53</sup> D. Hufnagel,<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> C. T. Potter,<sup>54</sup> N. B. Sinev,<sup>54</sup> D. Strom,<sup>54</sup> E. Torrence,<sup>54</sup> F. Colecchia,<sup>55</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>

G. Tiozzo,<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> Ch. de la Vaissière,<sup>56</sup> L. Del Buono,<sup>56</sup> O. Hamon,<sup>56</sup> M. J. J. John,<sup>56</sup> Ph. Leruste,<sup>56</sup> J. Malcles,<sup>56</sup> J. Ocariz,<sup>56</sup> M. Pivk,<sup>56</sup> L. Roos,<sup>56</sup> S. T'Jampens,<sup>56</sup> G. Therin,<sup>56</sup> P. F. Manfredi,<sup>57</sup> V. Re,<sup>57</sup> P. K. Behera,<sup>58</sup> L. Gladney,<sup>58</sup> Q. H. Guo,<sup>58</sup> J. Panetta,<sup>58</sup> F. Anulli,<sup>27,59</sup> M. Biasini,<sup>59</sup> I. M. Peruzzi,<sup>27,59</sup> M. Pioppi,<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> 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> N. Danielson,<sup>62</sup> P. Elmer,<sup>62</sup> Y. P. Lau,<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> A. V. Telnov,<sup>62</sup> F. Bellini,<sup>63</sup> G. Cavoto,<sup>62,63</sup> R. Faccini,<sup>63</sup> F. Ferrarotto,<sup>63</sup> F. Ferroni,<sup>63</sup> M. Gaspero,<sup>63</sup> L. Li Gioi,<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> R. Aleksan,<sup>66</sup> S. Emery,<sup>66</sup> A. Gaidot,<sup>66</sup> S. F. Ganzhur,<sup>66</sup> P.-F. Giraud,<sup>66</sup> G. Hamel de Monchenault,<sup>66</sup> W. Kozanecki,<sup>66</sup> M. Langer,<sup>66</sup> M. Legendre,<sup>66</sup> G. W. London,<sup>66</sup> B. Mayer,<sup>66</sup> G. Schott,<sup>66</sup> G. Vasseur,<sup>66</sup> Ch. Yèche,<sup>66</sup> M. Zito,<sup>66</sup> M. V. Purohit,<sup>67</sup> A. W. Weidemann,<sup>67</sup> J. R. Wilson,<sup>67</sup> F. X. Yumiceva,<sup>67</sup> D. Aston,<sup>68</sup> R. Bartoldus,<sup>68</sup> N. Berger,<sup>68</sup> A. M. Boyarski,<sup>68</sup> O. L. Buchmueller,<sup>68</sup> R. Claus,<sup>68</sup> M. R. Convery,<sup>68</sup> M. Cristinziani,<sup>68</sup> G. De Nardo,<sup>68</sup> D. Dong,<sup>68</sup> J. Dorfan,<sup>68</sup> D. Dujmic,<sup>68</sup> W. Dunwoodie,<sup>68</sup> E. E. Elsen,<sup>68</sup> S. Fan,<sup>68</sup> R. C. Field,<sup>68</sup> T. Glanzman,<sup>68</sup> S. J. Gowdy,<sup>68</sup> T. Hadig,<sup>68</sup> V. Halyo,<sup>68</sup> C. Hast,<sup>68</sup> T. Hryn'ova,<sup>68</sup> W. R. Innes,<sup>68</sup> M. H. Kelsey,<sup>68</sup> P. Kim,<sup>68</sup> M. L. Kocian,<sup>68</sup> D. W. G. S. Leith,<sup>68</sup> J. Libby,<sup>68</sup> S. Luitz,<sup>68</sup> V. Luth,<sup>68</sup> H. L. Lynch,<sup>68</sup> H. Marsiske,<sup>68</sup> R. Messner,<sup>68</sup> D. R. Muller,<sup>68</sup> C. P. O'Grady,<sup>68</sup> V. E. Ozcan,<sup>68</sup> A. Perazzo,<sup>68</sup> M. Perl,<sup>68</sup> S. Petrak,<sup>68</sup> B. N. Ratcliff,<sup>68</sup> A. Roodman,<sup>68</sup> A. A. Salnikov,<sup>68</sup> R. H. Schindler,<sup>68</sup> J. Schwiening,<sup>68</sup> G. Simi,<sup>68</sup> A. Snyder,<sup>68</sup> A. Soha,<sup>68</sup> J. Stelzer,<sup>68</sup> D. Su,<sup>68</sup> M. K. Sullivan,<sup>68</sup> J. Va'vra,<sup>68</sup> S. R. Wagner,<sup>68</sup> M. Weaver,<sup>68</sup> A. J. R. Weinstein,<sup>68</sup> W. J. Wisniewski,<sup>68</sup> M. Wittgen,<sup>68</sup> D. H. Wright,<sup>68</sup> A. K. Yarritu,<sup>68</sup> C. C. Young,<sup>68</sup> P. R. Burchat,<sup>69</sup> A. J. Edwards,<sup>69</sup> T. I. Meyer,<sup>69</sup> B. A. Petersen,<sup>69</sup> C. Roat,<sup>69</sup> S. Ahmed,<sup>70</sup> M. S. Alam,<sup>70</sup> J. A. Ernst,<sup>70</sup> M. A. Saeed,<sup>70</sup> M. Saleem,<sup>70</sup> F. R. Wappler,<sup>70</sup> W. Bugg,<sup>71</sup> M. Krishnamurthy,<sup>71</sup> S. M. Spanier,<sup>71</sup> R. Eckmann,<sup>72</sup> H. Kim,<sup>72</sup> J. L. Ritchie,<sup>72</sup> A. Satpathy,<sup>72</sup> R. F. Schwitters,<sup>72</sup> J. M. Izen,<sup>73</sup> I. Kitayama,<sup>73</sup> X. C. Lou,<sup>73</sup> S. Ye,<sup>73</sup> F. Bianchi,<sup>74</sup> M. Bona,<sup>74</sup> F. Gallo,<sup>74</sup> D. Gamba,<sup>74</sup> C. Borean,<sup>75</sup> L. Bosisio,<sup>75</sup> C. Cartaro,<sup>75</sup> F. Cossutti,<sup>75</sup> G. Della Ricca,<sup>75</sup> S. Dittongo,<sup>75</sup> S. Grancagnolo,<sup>75</sup> L. Lanceri,<sup>75</sup> P. Propat,<sup>75,8</sup> L. Vitale,<sup>75</sup> G. Vuagnin,<sup>75</sup> R. S. Panvini,<sup>76</sup> Sw. Banerjee,<sup>77</sup> C. M. Brown,<sup>77</sup> D. Fortin,<sup>77</sup> P. D. Jackson,<sup>77</sup> R. Kowalewski,<sup>77</sup> J. M. Roney,<sup>77</sup> R. J. Sobie,<sup>77</sup> H. R. Band,<sup>78</sup> S. Dasu,<sup>78</sup> M. Datta,<sup>78</sup> A. M. Eichenbaum,<sup>78</sup> M. Graham,<sup>78</sup> J. J. Hollar,<sup>78</sup> J. R. Johnson,<sup>78</sup> P. E. Kutter,<sup>78</sup> H. Li,<sup>78</sup> R. Liu,<sup>78</sup> A. Mihalyi,<sup>78</sup> A. K. Mohapatra,<sup>78</sup> Y. Pan,<sup>78</sup> R. Prepost,<sup>78</sup> A. E. Rubin,<sup>78</sup> S. J. Sekula,<sup>78</sup> P. Tan,<sup>78</sup> J. H. von Wimmersperg-Toeller,<sup>78</sup> J. Wu,<sup>78</sup> S. L. Wu,<sup>78</sup> Z. Yu,<sup>78</sup> M. G. Greene,<sup>79</sup> and H. Neal<sup>79</sup>

(BABAR Collaboration)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

<sup>22</sup>Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden, Germany

<sup>23</sup>Ecole Polytechnique, LLR, F-91128 Palaiseau, France

- <sup>24</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
- <sup>25</sup>Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
- <sup>26</sup>Florida A&M University, Tallahassee, Florida 32307, USA
- <sup>27</sup>Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
- <sup>28</sup>Dipartimento di Fisica and INFN, Università di Genova, I-16146 Genova, Italy
- <sup>29</sup>Harvard University, Cambridge, Massachusetts 02138, USA
- <sup>30</sup>Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany
- <sup>31</sup>Imperial College London, London, SW7 2AZ, United Kingdom
- <sup>32</sup>University of Iowa, Iowa City, Iowa 52242, USA
- <sup>33</sup>Iowa State University, Ames, Iowa 50011-3160, USA
- <sup>34</sup>Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
- <sup>35</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA
- <sup>36</sup>University of Liverpool, Liverpool L69 7ZE, United Kingdom
- <sup>37</sup>Queen Mary, University of London, E1 4NS, United Kingdom
- <sup>38</sup>University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
- <sup>39</sup>University of Louisville, Louisville, Kentucky 40292, USA
- <sup>40</sup>University of Manchester, Manchester M13 9PL, United Kingdom
- <sup>41</sup>University of Maryland, College Park, Maryland 20742, USA
- <sup>42</sup>University of Massachusetts, Amherst, Massachusetts 01003, USA
- <sup>43</sup>Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
- <sup>44</sup>McGill University, Montréal, QC, Canada H3A 2T8
- <sup>45</sup>Dipartimento di Fisica and INFN, Università di Milano, I-20133 Milano, Italy
- <sup>46</sup>University of Mississippi, University, Mississippi 38677, USA
- <sup>47</sup>Laboratoire René J. A. Lévesque, Université de Montréal, Montréal, QC, Canada H3C 3J7
- <sup>48</sup>Mount Holyoke College, South Hadley, Massachusetts 01075, USA
- <sup>49</sup>Dipartimento di Scienze Fisiche and INFN, Università di Napoli Federico II, I-80126, Napoli, Italy
- <sup>50</sup>NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
- <sup>51</sup>University of Notre Dame, Notre Dame, Indiana 46556, USA
- <sup>52</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
- <sup>53</sup>Ohio State University, Columbus, Ohio 43210, USA
- <sup>54</sup>University of Oregon, Eugene, Oregon 97403, USA
- <sup>55</sup>Dipartimento di Fisica and INFN, Università di Padova, I-35131 Padova, Italy
- <sup>56</sup>Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris VI et VII, F-75252 Paris, France
- <sup>57</sup>Dipartimento di Elettronica and INFN, Università di Pavia, I-27100 Pavia, Italy
- <sup>58</sup>University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
- <sup>59</sup>Dipartimento di Fisica and INFN, Università di Perugia, I-06100 Perugia, Italy
- <sup>60</sup>Dipartimento di Fisica, Scuola Normale Superiore and INFN, Università di Pisa, I-56127 Pisa, Italy
- <sup>61</sup>Prairie View A&M University, Prairie View, Texas 77446, USA
- <sup>62</sup>Princeton University, Princeton, New Jersey 08544, USA
- <sup>63</sup>Dipartimento di Fisica and INFN, Università di Roma La Sapienza, I-00185 Roma, Italy
- <sup>64</sup>Universität Rostock, D-18051 Rostock, Germany
- <sup>65</sup>Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
- <sup>66</sup>DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
- <sup>67</sup>University of South Carolina, Columbia, South Carolina 29208, USA
- <sup>68</sup>Stanford Linear Accelerator Center, Stanford, California 94309, USA
- <sup>69</sup>Stanford University, Stanford, California 94305-4060, USA
- <sup>70</sup>State University of New York, Albany, New York 12222, USA
- <sup>71</sup>University of Tennessee, Knoxville, Tennessee 37996, USA
- <sup>72</sup>University of Texas at Austin, Austin, Texas 78712, USA
- <sup>73</sup>University of Texas at Dallas, Richardson, Texas 75083, USA
- <sup>74</sup>Dipartimento di Fisica Sperimentale and INFN, Università di Torino, I-10125 Torino, Italy
- <sup>75</sup>Dipartimento di Fisica and INFN, Università di Trieste, I-34127 Trieste, Italy
- <sup>76</sup>Vanderbilt University, Nashville, Tennessee 37235, USA
- <sup>77</sup>University of Victoria, Victoria, BC, Canada V8W 3P6
- <sup>78</sup>University of Wisconsin, Madison, Wisconsin 53706, USA
- <sup>79</sup>Yale University, New Haven, Connecticut 06511, USA

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We present a search for the decays  $B^0 \rightarrow e^+e^-$ ,  $B^0 \rightarrow \mu^+\mu^-$ , and  $B^0 \rightarrow e^\pm\mu^\mp$  in data collected at the  $\Upsilon(4S)$  resonance with the BABAR detector at the SLAC B Factory. Using a data set of  $111 \text{ fb}^{-1}$ , we find no evidence for a signal in any of the three channels investigated and set the following branching fraction

upper limits at the 90% confidence level:  $\mathcal{B}(B^0 \rightarrow e^+e^-) < 6.1 \times 10^{-8}$ ,  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 8.3 \times 10^{-8}$ , and  $\mathcal{B}(B^0 \rightarrow e^\pm\mu^\mp) < 18 \times 10^{-8}$ .

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In the standard model (SM), rare  $B$  decays such as  $B^0 \rightarrow \ell^+\ell^-$ , where  $\ell$  refers to  $e$  or  $\mu$ , are expected to proceed through diagrams such as those shown in Fig. 1 (charge conjugate processes are included implicitly throughout). These decays are highly suppressed since they involve a  $b \rightarrow d$  transition and require an internal quark annihilation within the  $B$  meson. In addition, the decays are helicity suppressed by factors of  $(m_\ell/m_B)^2$ , where  $m_\ell$  is the mass of the lepton  $\ell$  and  $m_B$  is the mass of the  $B$  meson.  $B^0$  decays to leptons of two different flavors violate lepton flavor conservation and are therefore forbidden in the SM, although permitted in extensions to the SM with nonzero neutrino mass [1]. The SM expectations are given in Table I.

Since these processes are highly suppressed in the SM, they are potentially sensitive probes of physics beyond the SM. In the minimally supersymmetric standard model (MSSM) the branching fraction for these decays can be enhanced by orders of magnitude [2]. In particular, for MSSM models with modified minimal flavor violation (MFV) and large  $\tan\beta$  [3], the branching fraction can be increased by up to 4 orders of magnitude. Experimental bounds can restrict allowed regions of parameter space, specifically the mass of the charged Higgs boson. In models with two Higgs doublets and natural flavor conservation at large  $\tan\beta$ , an increase in the branching fraction of several orders of magnitude is expected [4].  $B^0 \rightarrow \ell^+\ell^-$  decays are also allowed in specific models containing leptoquarks [5] and supersymmetric (SUSY) models without  $R$  parity [6]. The branching fractions for the flavor violating channels  $B^0 \rightarrow \ell_i^+\ell_j^-$  ( $i \neq j$ ) are expected to be exceedingly small but can be enhanced by leptoquarks or  $R$  parity violating operators in SUSY models.

To date,  $B^0 \rightarrow \ell^+\ell^-$  decays have not been observed. As shown in Table I, experimental limits are approaching a level of sensitivity that will restrict the allowed parameter space of models that produce  $B^0 \rightarrow \ell^+\ell^-$  branching fraction enhancements of a few orders of magnitude with respect to the SM rates.

The data used in these analyses were collected with the *BABAR* detector at the PEP-II  $e^+e^-$  storage ring and correspond to an integrated luminosity of  $111 \text{ fb}^{-1}$  accumulated at the  $Y(4S)$  resonance (“on resonance”) and  $11.9 \text{ fb}^{-1}$  accumulated at a center-of-mass (c.m.) energy about 40 MeV below the  $Y(4S)$  resonance (“off resonance”). The latter sample is used for nonresonant  $q\bar{q}$  ( $q = u, d, s$ , and  $c$ ) background studies. The collider is operated with asymmetric beam energies, producing a boost ( $\beta\gamma = 0.55$ ) of the  $Y(4S)$  along the collision axis.

The *BABAR* detector is optimized for the asymmetric beam configuration at PEP-II and is described in detail in

[7]. The 1.5-T superconducting solenoidal magnet, whose cylindrical volume is 1.4 m in radius and 3 m long, contains a charged-particle tracking system, a Cherenkov detector dedicated to charged-particle identification, and central and forward electromagnetic CsI calorimeters (EMC). The segmented flux return, including end caps, is instrumented with resistive plate chambers for muon and  $K_L^0$  identification.

The presence of two charged high-momentum leptons provides a very clean signature for the three decay modes under consideration. We require two oppositely-charged high-momentum leptons (i.e.,  $|p_\ell^*| \sim m_B/2$  where  $p_\ell^*$  is the c.m. momentum of lepton  $\ell$ ) from a common vertex consistent with the decay of a  $B^0$  meson. Since the signal events contain two  $B^0$  mesons and no additional particles, the total energy of each  $B^0$  in the c.m. must be equal to half of the total beam energy. We define

$$m_{\text{ES}} = \sqrt{(E_{\text{beam}}^*)^2 - \left(\sum_i \mathbf{p}_i^*\right)^2} \quad (1)$$

$$\Delta E = \sum_i \sqrt{m_i^2 + (\mathbf{p}_i^*)^2} - E_{\text{beam}}^*, \quad (2)$$

where  $E_{\text{beam}}^*$  is the ( $e^+$  or  $e^-$ ) beam energy in the c.m. frame,  $\mathbf{p}_i^*$  is the momentum of lepton  $i$  in the c.m. frame, and  $m_i$  is the mass of lepton  $i$ . In Eq. (1),  $E_{\text{beam}}^*$  is used as opposed to  $E_B^*$  because  $E_{\text{beam}}^*$  is known with much greater precision. For correctly reconstructed  $B^0$  mesons,  $m_{\text{ES}}$  peaks at the mass of the  $B^0$  meson with a resolution of about  $2.8 \text{ MeV}/c^2$  and  $\Delta E$  peaks near zero.

To reduce background from lepton misidentification, we require the leptons to satisfy stringent electron and muon identification criteria [8]. The electron identification efficiency is greater than 93% with a misidentification rate of less than 0.3%. The muon identification efficiency ranges from (55–70)% (depending on run period) with a misidentification rate of 3%. Electron energy lost through bremsstrahlung is partially recovered by adding the energy of photons that lie within a 3 degree cone about the electron direction.

Suppression of background from nonresonant  $q\bar{q}$  production is provided by a series of topological requirements.

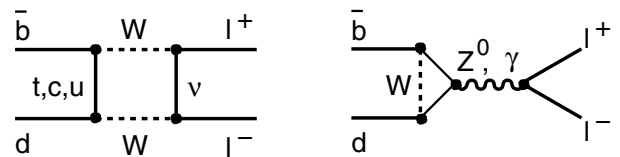


FIG. 1. Representative Feynman diagrams for  $B^0 \rightarrow \ell^+\ell^-$  in the standard model.

TABLE I. The expected branching fractions in the standard model [13] and the current best upper limits (U.L.) at the 90% C.L.

| Decay Mode     | SM Expectation        | CLEO [14]<br>9.1 fb <sup>-1</sup> | Belle [15]<br>78 fb <sup>-1</sup> | CDF [16]<br>0.17 fb <sup>-1</sup> |
|----------------|-----------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $e^+e^-$       | $2.4 \times 10^{-15}$ | $8.3 \times 10^{-7}$              | $1.9 \times 10^{-7}$              | ...                               |
| $\mu^+\mu^-$   | $1.0 \times 10^{-10}$ | $6.1 \times 10^{-7}$              | $1.6 \times 10^{-7}$              | $1.5 \times 10^{-7}$              |
| $e^\pm\mu^\mp$ | ...                   | $15 \times 10^{-7}$               | $1.7 \times 10^{-7}$              | ...                               |

In particular, we require  $|\cos\theta_T| < 0.8$ , where  $\theta_T$  is the angle in the c.m. frame between the thrust axis of the particles that form the reconstructed  $B^0$  candidate and the thrust axis of the remaining tracks and neutral clusters in the event. In addition, we employ cuts on the invariant mass of the “rest of the event” (ROE) (all tracks not associated with the  $B^0$  candidate where all nonleptonic tracks are assumed to be pions) of  $m_{\text{ROE}} > 0.5$  GeV and on the second normalized Fox-Wolfram moment of  $R_2 < 0.8$  [9]. We also cut on the total multiplicity of both charged tracks and neutral particles by means of the variable  $N_{\text{mult}}$  defined as  $N_{\text{mult}} = N_{\text{trk}} + N_\gamma/2$ , where  $N_{\text{trk}}$  is the total number of tracks in the event and  $N_\gamma$  is the number of photons found with an energy  $E_\gamma > 80$  MeV. We require  $N_{\text{mult}} \geq 5.5$  for the  $ee$  and  $e\mu$  channels and  $N_{\text{mult}} \geq 5.0$  for the  $\mu\mu$  channel. This variable is especially useful in the rejection of radiative Bhabha events. We also require that the total energy in the EMC ( $E_{\text{EMC}}$ ) be less than 11 GeV. This cut is effective in reducing background from QED  $e^+e^-$  events, including radiative Bhabhas with many conversions.

Four of the selection criteria given above ( $|\cos\theta_T|$ ,  $m_{\text{ROE}}$ ,  $N_{\text{mult}}$ , and  $E_{\text{EMC}}$ ) were simultaneously optimized for the best upper limit on  $\mathcal{B}(B^0 \rightarrow \ell^+\ell^-)$  where the assumed number of observed events is determined from a Poisson distribution with the mean equal to the expected background. Sideband data are compared with signal Monte Carlo (MC) for the  $e^+e^-$  channel for four of these variables,  $|\cos\theta_T|$ ,  $m_{\text{ROE}}$ ,  $R_2$ , and  $N_{\text{mult}}$  in Fig. 2.

The  $B^0 \rightarrow \ell^+\ell^-$  candidates are selected by simultaneous requirements on the energy difference  $\Delta E$  and the energy-substituted mass  $m_{\text{ES}}$ . For the  $B^0 \rightarrow \mu^+\mu^-$  decay mode, the size of this “signal box” is chosen to be  $[+2, -2]\sigma$  of the  $m_{\text{ES}}$  distribution and  $[+2, -2]\sigma$  for the  $\Delta E$ . In the cases of the  $B^0 \rightarrow e^+e^-$  and  $B^0 \rightarrow e^\pm\mu^\mp$  decay modes, the signal box sizes in  $m_{\text{ES}}$  are also  $[+2, -2]\sigma$  but in  $\Delta E$  are relaxed to  $[+2, -3]\sigma$  and  $[+2, -2.5]\sigma$ , respectively, to accommodate the tail in the distribution resulting from uncorrected bremsstrahlung and final state radiation. The resolution in  $m_{\text{ES}}$  is obtained from a fit to a Gaussian distribution, whereas the resolution in  $\Delta E$  is obtained from a fit to an empirical function [10] that gives a good description of this tail.

Comparisons between data and MC indicate that two-photon processes result in substantial electron backgrounds

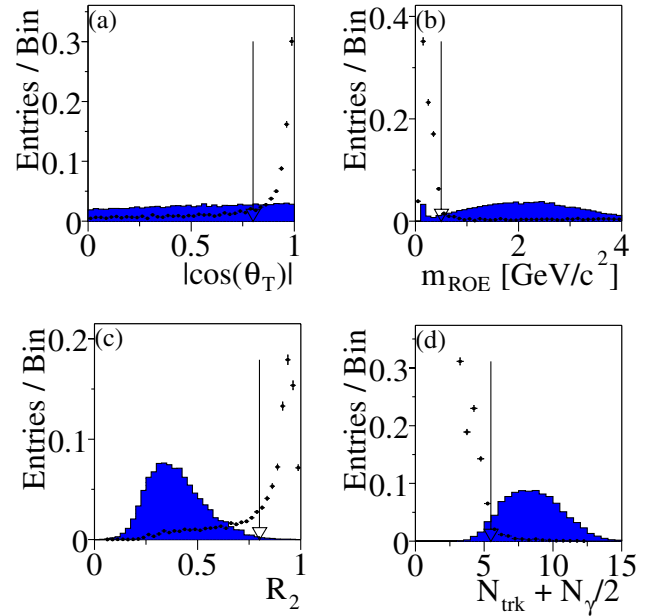


FIG. 2 (color online). Distributions of signal MC (hatched) and sideband data (points) for the  $e^+e^-$  channel after the initial selection cuts for (a)  $|\cos\theta_T|$ , (b)  $m_{\text{ROE}}$ , (c)  $R_2$ , and (d)  $N_{\text{mult}}$ . Arrows indicate final cut values. All distributions are normalized to unit area.

which are not modeled in the generic MC. We thus parametrize the background level in the signal box from the data sidebands with the ARGUS function [11] in  $m_{\text{ES}}$  and an exponential function in  $\Delta E$ . We use these parametrizations to extrapolate the background level found in the sidebands into the signal box. As indicated in Table II, three different sideband boxes are used. The grand sideband boxes are used to estimate the functional form of the  $\Delta E$  distributions. The  $\chi^2/\text{d.o.f.}$  for these fits are 24.5/38, 28.6/38, and 27.0/38 for the  $ee$ ,  $\mu\mu$ , and  $e\mu$  channels, respectively. The upper and lower  $m_{\text{ES}}$  sideband boxes are used to estimate the functional form of the  $m_{\text{ES}}$  distribution. The  $\chi^2/\text{d.o.f.}$  for these fits are 27.1/34, 39.3/34, and 29.8/34 for the  $ee$ ,  $\mu\mu$ , and  $e\mu$  channels, respectively. The remaining background is dominated by pairs of real leptons ( $e^+e^-$ ,  $\mu^+\mu^-$ ,  $e^\pm\mu^\mp$ ) from  $c\bar{c}$  decay, resulting in a proportionately larger background in the  $e\mu$  channel (appearing almost entirely in the lower  $m_{\text{ES}}$  sideband box). Peaking backgrounds from misidentified two-body

TABLE II. Definition of the three different sideband boxes used for all three decay modes and the observed number of events in each.

| Sideband box          | span in          |                               | # events |          |        |
|-----------------------|------------------|-------------------------------|----------|----------|--------|
|                       | $\Delta E$ [GeV] | $m_{\text{ES}}$ [GeV/ $c^2$ ] | $ee$     | $\mu\mu$ | $e\mu$ |
| Grand                 | (-0.40, 0.40)    | (5.20, 5.26)                  | 46       | 56       | 57     |
| Upper $m_{\text{ES}}$ | (0.20, 0.50)     | (5.20, 5.29)                  | 12       | 13       | 13     |
| Lower $m_{\text{ES}}$ | (-0.50, -0.20)   | (5.20, 5.29)                  | 33       | 40       | 52     |

TABLE III. Summary of the analyses where  $N_{\text{obs}}$  and  $N_{\text{exp}}^{\text{bg}}$  are the observed and expected number of events in the signal box,  $\varepsilon$  is the efficiency, and  $\mathcal{B}_{\text{U.L.}}(B^0 \rightarrow \ell^+ \ell^-)$  is the upper limit on the branching fraction at the 90% C.L. Uncertainties on  $N_{\text{exp}}^{\text{bg}}$  and  $\varepsilon$  are statistical and systematic added in quadrature.

| Decay mode      | $N_{\text{obs}}$ | $N_{\text{exp}}^{\text{bg}}$ | $\varepsilon[\%]$ | $\mathcal{B}_{\text{U.L.}}(B^0 \rightarrow \ell^+ \ell^-)$ |
|-----------------|------------------|------------------------------|-------------------|--|
| $e^+ e^-$       | 0                | $0.71 \pm 0.31$              | $21.8 \pm 1.2$    | $6.1 \times 10^{-8}$                                       |
| $\mu^+ \mu^-$   | 0                | $0.72 \pm 0.26$              | $15.9 \pm 1.1$    | $8.3 \times 10^{-8}$                                       |
| $e^\pm \mu^\mp$ | 2                | $1.29 \pm 0.44$              | $18.1 \pm 1.2$    | $18 \times 10^{-8}$  |

$B$  decay modes were estimated using an MC sample equivalent to more than 20 times the data luminosity and found to be negligible. The total background expectations and signal efficiencies are given in Table III.

The systematic uncertainties on the signal efficiency  $\varepsilon$ , the number of  $B^0$  mesons produced in the data, and the background estimate are incorporated into the determination of the upper limit on  $\mathcal{B}(B^0 \rightarrow \ell^+ \ell^-)$ . Since the signal efficiency is determined from MC simulation only, differences between data and the simulation would result in an error in our normalization. To estimate this uncertainty we perform comparisons of data and MC using high statistics control samples that have similar characteristics to our  $B^0 \rightarrow \ell^+ \ell^-$  signal. The optimal control samples are  $B^0 \rightarrow J/\psi K_S^0$ , with  $J/\psi \rightarrow e^+ e^-$  for  $B^0 \rightarrow e^+ e^-$  and  $J/\psi \rightarrow \mu^+ \mu^-$  for  $B^0 \rightarrow \mu^+ \mu^-$ , respectively. Since there exists no appropriate control sample for the  $e^\pm \mu^\mp$  mode, we use the larger of the systematic errors derived from either the  $ee$  or  $\mu\mu$  modes. In performing these comparisons we found a substantial uncertainty on the signal efficiency to be due to differences between data and the MC simulation in the mean and resolutions of various quantities, depend-

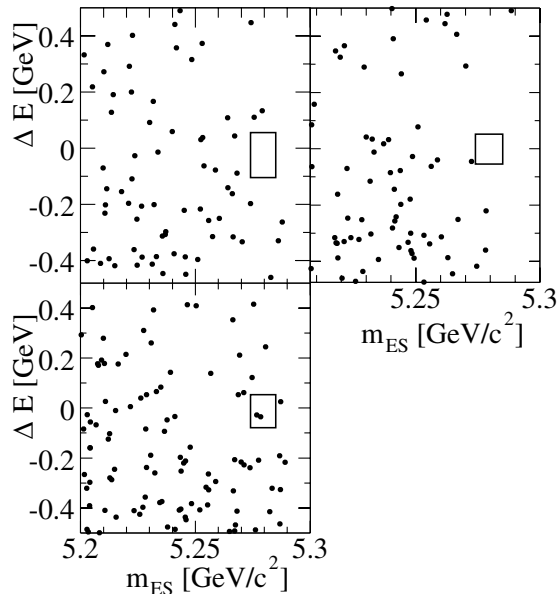


FIG. 3. Distribution of events in  $m_{\text{ES}}$  and  $\Delta E$  for  $B^0 \rightarrow e^+ e^-$  (top left),  $B^0 \rightarrow \mu^+ \mu^-$  (top right), and  $B^0 \rightarrow e^\pm \mu^\mp$  (bottom).

ing on the channel. For the electron channels, the dominant quantities are  $\Delta E$  and  $m_{\text{ROE}}$ , whereas for the muon channels, they are  $|\cos\theta_T|$ ,  $N_{\text{mult}}$ , and  $m_{\text{ROE}}$ . When combined with the uncertainties on tracking efficiency of 2.6% and that for particle identification (1.0% per electron, 3.0% per muon), the total systematic uncertainty on the efficiency is estimated to be 5.7%, 7.1%, and 6.8% for the  $ee$ ,  $\mu\mu$ , and  $e\mu$  modes, respectively.

The background estimate is obtained from a fit to sideband data, so the primary uncertainty is due to fluctuations in the fit procedure as events fall in or out of the sideband box. We have studied the stability of the fit and the background estimate when adding or removing events from the  $m_{\text{ES}}$  and  $\Delta E$  histograms. We find that the fit is unbiased and stable to a level significantly less than the statistical uncertainty on the background estimate.

As shown in Fig. 3 and Table III, when the contents of the signal box were revealed, 0, 0, and 2 events were found in the  $ee$ ,  $\mu\mu$ , and  $e\mu$  channels, respectively. As can be seen in Table III, the numbers of events found in the signal boxes are compatible with the expected background for each mode.

An upper limit (U.L.) on the branching fraction is computed using

$$\mathcal{B}(B^0 \rightarrow \ell^+ \ell^-) = \frac{N_{\text{UL}}(N_{\text{obs}})}{(N_{B^0} + N_{\overline{B}^0}) \cdot \varepsilon}, \quad (3)$$

where  $N_{\text{UL}}(N_{\text{obs}})$  is the Poisson 90% U.L. on the number of events for  $N_{\text{obs}}$  events having been observed,  $N_{B^0}(N_{\overline{B}^0})$  is the number of  $B^0(\overline{B}^0)$  mesons produced in the data, and  $\varepsilon$  is the signal efficiency. We have  $N_{B^0} + N_{\overline{B}^0} = N_{B\overline{B}}$  under the assumption of equal production of  $B^0\overline{B}^0$  and  $B^+B^-$  in  $Y(4S)$  decays. For our data set,  $N_{B\overline{B}} = (122.5 \pm 1.2) \times 10^6$ .

We follow the technique of [12] in order to account for the presence of background and to include our systematic uncertainties in the determination of the upper limit. As summarized in Table III, the resulting upper limits at the 90% confidence level (C.L.) for  $\mathcal{B}(B^0 \rightarrow e^+ e^-)$ ,  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ , and  $\mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp)$  are  $6.1 \times 10^{-8}$ ,  $8.3 \times 10^{-8}$ , and  $18 \times 10^{-8}$ , respectively. The corresponding non-background-subtracted upper limits are  $8.6 \times 10^{-8}$ ,  $1.2 \times 10^{-7}$ , and  $2.4 \times 10^{-7}$  respectively.

These bounds are stringent enough to place interesting constraints on popular models. For example, for the MSSM ( $\overline{\text{MFV}}$ ) models, the relation between  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$  and the mass of the charged Higgs boson  $m_H$  is given as a function of  $\tan\beta$  in [7]. We find that for  $\tan\beta = 60$ ,  $m_H > 138 \text{ GeV}/c^2$  (90% C.L.).

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\*Now at Department of Physics, University of Warwick, Coventry, United Kingdom.

†Also with Università della Basilicata, Potenza, Italy.

‡Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain.

§Deceased.

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