

## Measurement of the $B \rightarrow \pi l \nu$ Branching Fraction and Determination of $|V_{ub}|$ with Tagged $B$ Mesons

B. Aubert,<sup>1</sup> R. Barate,<sup>1</sup> M. Bona,<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> 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> D. N. Brown,<sup>6</sup> J. Button-Shafer,<sup>6</sup> R. N. Cahn,<sup>6</sup> E. Charles,<sup>6</sup> M. S. Gill,<sup>6</sup> Y. Groyzman,<sup>6</sup> R. G. Jacobsen,<sup>6</sup> J. A. Kadyk,<sup>6</sup> L. T. Kerth,<sup>6</sup> Yu. G. Kolomensky,<sup>6</sup> G. Kukartsev,<sup>6</sup> G. Lynch,<sup>6</sup> L. M. Mir,<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> P. del Amo Sanchez,<sup>7</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> 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> W. N. Cottingham,<sup>9</sup> D. Walker,<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> D. J. Sherwood,<sup>11</sup> L. Teodorescu,<sup>11</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> A. P. Onuchin,<sup>12</sup> S. I. Serednyakov,<sup>12</sup> Yu. I. Skovpen,<sup>12</sup> E. P. Solodov,<sup>12</sup> K. Yu Todyshev,<sup>12</sup> D. S. Best,<sup>13</sup> M. Bondioli,<sup>13</sup> M. Bruinsma,<sup>13</sup> M. Chao,<sup>13</sup> S. Curry,<sup>13</sup> I. Eschrich,<sup>13</sup> D. Kirkby,<sup>13</sup> A. J. Lankford,<sup>13</sup> P. Lund,<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> S. Abachi,<sup>14</sup> C. Buchanan,<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> H. K. Hadavand,<sup>16</sup> E. J. Hill,<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> D. Kovalskyi,<sup>17</sup> J. D. Richman,<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> A. Dvoretzki,<sup>19</sup> F. Fang,<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> G. Mancinelli,<sup>20</sup> B. T. Meadows,<sup>20</sup> K. Mishra,<sup>20</sup> M. D. Sokoloff,<sup>20</sup> F. Blanc,<sup>21</sup> P. C. Bloom,<sup>21</sup> S. Chen,<sup>21</sup> W. T. Ford,<sup>21</sup> J. F. Hirschauer,<sup>21</sup> A. Kreisel,<sup>21</sup> M. Nagel,<sup>21</sup> U. Nauenberg,<sup>21</sup> A. Olivas,<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> F. Winklmeier,<sup>22</sup> Q. Zeng,<sup>22</sup> D. D. Altenburg,<sup>23</sup> E. Feltresi,<sup>23</sup> A. Hauke,<sup>23</sup> H. Jasper,<sup>23</sup> A. Petzold,<sup>23</sup> B. Spaan,<sup>23</sup> T. Brandt,<sup>24</sup> V. Klose,<sup>24</sup> H. M. Lacker,<sup>24</sup> W. F. Mader,<sup>24</sup> R. Nogowski,<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> A. Volk,<sup>24</sup> D. Bernard,<sup>25</sup> G. R. Bonneaud,<sup>25</sup> P. Grenier,<sup>25,\*</sup> E. Latour,<sup>25</sup> Ch. Thiebaux,<sup>25</sup> M. Verderi,<sup>25</sup> P. J. Clark,<sup>26</sup> W. Gradl,<sup>26</sup> F. Muheim,<sup>26</sup> S. Playfer,<sup>26</sup> A. I. Robertson,<sup>26</sup> Y. Xie,<sup>26</sup> M. Andreotti,<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> A. Petrella,<sup>27</sup> L. Piemontese,<sup>27</sup> E. Prencipe,<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> G. Finocchiaro,<sup>28</sup> S. Pacetti,<sup>28</sup> P. Patteri,<sup>28</sup> I. M. Peruzzi,<sup>28,†</sup> M. Piccolo,<sup>28</sup> M. Rama,<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. 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> G. Brandenburg,<sup>30</sup> K. S. Chaisanguanthum,<sup>30</sup> M. Morii,<sup>30</sup> J. Wu,<sup>30</sup> R. S. Dubitzky,<sup>31</sup> J. Marks,<sup>31</sup> S. Schenk,<sup>31</sup> U. Uwer,<sup>31</sup> D. J. Bard,<sup>32</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. A. Nash,<sup>32</sup> M. B. Nikolich,<sup>32</sup> W. Panduro Vazquez,<sup>32</sup> P. K. Behera,<sup>33</sup> X. Chai,<sup>33</sup> M. J. Charles,<sup>33</sup> U. Mallik,<sup>33</sup> N. T. Meyer,<sup>33</sup> V. Ziegler,<sup>33</sup> J. Cochran,<sup>34</sup> H. B. Crawley,<sup>34</sup> L. Dong,<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> A. V. Gritsan,<sup>35</sup> A. G. Denig,<sup>36</sup> M. Fritsch,<sup>36</sup> G. Schott,<sup>36</sup> N. Arnaud,<sup>37</sup> M. Davier,<sup>37</sup> G. Grosdidier,<sup>37</sup> A. Höcker,<sup>37</sup> F. Le Diberder,<sup>37</sup> V. Lepeltier,<sup>37</sup> A. M. Lutz,<sup>37</sup> A. Oyanguren,<sup>37</sup> S. Pruvot,<sup>37</sup> S. Rodier,<sup>37</sup> P. Roudeau,<sup>37</sup> M. H. Schune,<sup>37</sup> A. Stocchi,<sup>37</sup> W. F. Wang,<sup>37</sup> G. Wormser,<sup>37</sup> C. H. Cheng,<sup>38</sup> D. J. Lange,<sup>38</sup> D. M. Wright,<sup>38</sup> C. A. Chavez,<sup>39</sup> I. J. Forster,<sup>39</sup> J. R. Fry,<sup>39</sup> E. Gabathuler,<sup>39</sup> R. Gamet,<sup>39</sup> K. A. George,<sup>39</sup> D. E. Hutchcroft,<sup>39</sup> D. J. Payne,<sup>39</sup> K. C. Schofield,<sup>39</sup> C. Touramanis,<sup>39</sup> A. J. Bevan,<sup>40</sup> F. Di Lodovico,<sup>40</sup> W. Menges,<sup>40</sup> R. Sacco,<sup>40</sup> G. Cowan,<sup>41</sup> H. U. Flaecher,<sup>41</sup> D. A. Hopkins,<sup>41</sup> P. S. Jackson,<sup>41</sup> T. R. McMahon,<sup>41</sup> S. Ricciardi,<sup>41</sup> F. Salvatore,<sup>41</sup> A. C. Wren,<sup>41</sup> D. N. Brown,<sup>42</sup> C. L. Davis,<sup>42</sup> J. Allison,<sup>43</sup> N. R. Barlow,<sup>43</sup> R. J. Barlow,<sup>43</sup> Y. M. Chia,<sup>43</sup> C. L. Edgar,<sup>43</sup> G. D. Lafferty,<sup>43</sup> M. T. Naisbit,<sup>43</sup> J. C. Williams,<sup>43</sup> J. I. Yi,<sup>43</sup> C. Chen,<sup>44</sup> W. D. Hulsbergen,<sup>44</sup> A. Jawahery,<sup>44</sup> C. K. Lae,<sup>44</sup> D. A. Roberts,<sup>44</sup> G. Simi,<sup>44</sup> G. Blaylock,<sup>45</sup> C. Dallapiccola,<sup>45</sup> S. S. Hertzbach,<sup>45</sup> X. Li,<sup>45</sup> T. B. Moore,<sup>45</sup> S. Saremi,<sup>45</sup> H. Staengle,<sup>45</sup> R. Cowan,<sup>46</sup> G. Sciolla,<sup>46</sup> S. J. Sekula,<sup>46</sup> M. Spitznagel,<sup>46</sup> F. Taylor,<sup>46</sup> R. K. Yamamoto,<sup>46</sup> H. Kim,<sup>47</sup> S. E. Mclachlin,<sup>47</sup> P. M. Patel,<sup>47</sup> S. H. Robertson,<sup>47</sup> A. Lazzaro,<sup>48</sup> V. Lombardo,<sup>48</sup> F. Palombo,<sup>48</sup> J. M. Bauer,<sup>49</sup> L. Cremaldi,<sup>49</sup> V. Eschenburg,<sup>49</sup> R. Godang,<sup>49</sup> R. Kroeger,<sup>49</sup> D. A. Sanders,<sup>49</sup> D. J. Summers,<sup>49</sup> H. W. Zhao,<sup>49</sup> S. Brunet,<sup>50</sup> D. Côté,<sup>50</sup> M. Simard,<sup>50</sup> P. Taras,<sup>50</sup> F. B. Viaud,<sup>50</sup> H. Nicholson,<sup>51</sup> N. Cavallo,<sup>52,‡</sup> G. De Nardo,<sup>52</sup> F. Fabozzi,<sup>52,‡</sup> C. Gatto,<sup>52</sup> L. Lista,<sup>52</sup> D. Monorchio,<sup>52</sup> P. Paolucci,<sup>52</sup> D. Piccolo,<sup>52</sup> C. Sciacca,<sup>52</sup> M. Baak,<sup>53</sup> G. Raven,<sup>53</sup> H. L. Snoek,<sup>53</sup> C. P. Jessop,<sup>54</sup> J. M. LoSecco,<sup>54</sup> T. Allmendinger,<sup>55</sup> G. Benelli,<sup>55</sup> K. K. Gan,<sup>55</sup> K. Honscheid,<sup>55</sup> D. Hufnagel,<sup>55</sup> P. D. Jackson,<sup>55</sup> H. Kagan,<sup>55</sup> R. Kass,<sup>55</sup> A. M. Rahimi,<sup>55</sup> R. Ter-Antonyan,<sup>55</sup> Q. K. Wong,<sup>55</sup> N. L. Blount,<sup>56</sup> J. Brau,<sup>56</sup> R. Frey,<sup>56</sup>

O. Igonkina,<sup>56</sup> M. Lu,<sup>56</sup> R. Rahmat,<sup>56</sup> N. B. Sinev,<sup>56</sup> D. Strom,<sup>56</sup> J. Strube,<sup>56</sup> E. Torrence,<sup>56</sup> A. Gaz,<sup>57</sup> M. Margoni,<sup>57</sup> M. Morandin,<sup>57</sup> A. Pompili,<sup>57</sup> M. Posocco,<sup>57</sup> M. Rotondo,<sup>57</sup> F. Simonetto,<sup>57</sup> R. Stroili,<sup>57</sup> C. Voci,<sup>57</sup> M. Benayoun,<sup>58</sup> J. Chauveau,<sup>58</sup> H. Briand,<sup>58</sup> P. David,<sup>58</sup> L. Del Buono,<sup>58</sup> Ch. de la Vaissière,<sup>58</sup> O. Hamon,<sup>58</sup> B. L. Hartfiel,<sup>58</sup> M. J. J. John,<sup>58</sup> Ph. Leruste,<sup>58</sup> J. Malclès,<sup>58</sup> J. Ocariz,<sup>58</sup> L. Roos,<sup>58</sup> G. Therin,<sup>58</sup> L. Gladney,<sup>59</sup> J. Panetta,<sup>59</sup> M. Biasini,<sup>60</sup> R. Covarelli,<sup>60</sup> C. Angelini,<sup>61</sup> G. Batignani,<sup>61</sup> S. Bettarini,<sup>61</sup> F. Bucci,<sup>61</sup> G. Calderini,<sup>61</sup> M. Carpinelli,<sup>61</sup> R. Cenci,<sup>61</sup> F. Forti,<sup>61</sup> M. A. Giorgi,<sup>61</sup> A. Lusiani,<sup>61</sup> G. Marchiori,<sup>61</sup> M. A. Mazur,<sup>61</sup> M. Morganti,<sup>61</sup> N. Neri,<sup>61</sup> E. Paoloni,<sup>61</sup> G. Rizzo,<sup>61</sup> J. J. Walsh,<sup>61</sup> M. Haire,<sup>62</sup> D. Judd,<sup>62</sup> D. E. Wagoner,<sup>62</sup> J. Biesiada,<sup>63</sup> N. Danielson,<sup>63</sup> P. Elmer,<sup>63</sup> Y. P. Lau,<sup>63</sup> C. Lu,<sup>63</sup> J. Olsen,<sup>63</sup> A. J. S. Smith,<sup>63</sup> A. V. Telnov,<sup>63</sup> F. Bellini,<sup>64</sup> G. Cavoto,<sup>64</sup> A. D’Orazio,<sup>64</sup> D. del Re,<sup>64</sup> E. Di Marco,<sup>64</sup> R. Faccini,<sup>64</sup> F. Ferrarotto,<sup>64</sup> F. Ferroni,<sup>64</sup> M. Gaspero,<sup>64</sup> L. Li Gioi,<sup>64</sup> M. A. Mazzoni,<sup>64</sup> S. Morganti,<sup>64</sup> G. Piredda,<sup>64</sup> F. Polci,<sup>64</sup> F. Safai Tehrani,<sup>64</sup> C. Voena,<sup>64</sup> M. Ebert,<sup>65</sup> H. Schröder,<sup>65</sup> R. Waldi,<sup>65</sup> T. Adye,<sup>66</sup> N. De Groot,<sup>66</sup> B. Franek,<sup>66</sup> E. O. Olaiya,<sup>66</sup> F. F. Wilson,<sup>66</sup> R. Aleksan,<sup>67</sup> S. Emery,<sup>67</sup> A. Gaidot,<sup>67</sup> S. F. Ganzhur,<sup>67</sup> G. Hamel de Monchenault,<sup>67</sup> W. Kozanecki,<sup>67</sup> M. Legendre,<sup>67</sup> G. Vasseur,<sup>67</sup> Ch. Yèche,<sup>67</sup> M. Zito,<sup>67</sup> X. R. Chen,<sup>68</sup> H. Liu,<sup>68</sup> W. Park,<sup>68</sup> M. V. Purohit,<sup>68</sup> J. R. Wilson,<sup>68</sup> M. T. Allen,<sup>69</sup> D. Aston,<sup>69</sup> R. Bartoldus,<sup>69</sup> P. Bechtel,<sup>69</sup> N. Berger,<sup>69</sup> R. Claus,<sup>69</sup> J. P. Coleman,<sup>69</sup> M. R. Convery,<sup>69</sup> M. Cristinziani,<sup>69</sup> J. C. Dingfelder,<sup>69</sup> J. Dorfan,<sup>69</sup> G. P. Dubois-Felsmann,<sup>69</sup> D. Dujmic,<sup>69</sup> W. Dunwoodie,<sup>69</sup> R. C. Field,<sup>69</sup> T. Glanzman,<sup>69</sup> S. J. Gowdy,<sup>69</sup> M. T. Graham,<sup>69</sup> V. Halyo,<sup>69</sup> C. Hast,<sup>69</sup> T. Hryn’ova,<sup>69</sup> W. R. Innes,<sup>69</sup> M. H. Kelsey,<sup>69</sup> P. Kim,<sup>69</sup> D. W. G. S. Leith,<sup>69</sup> S. Li,<sup>69</sup> S. Luitz,<sup>69</sup> V. Luth,<sup>69</sup> H. L. Lynch,<sup>69</sup> D. B. MacFarlane,<sup>69</sup> H. Marsiske,<sup>69</sup> R. Messner,<sup>69</sup> D. R. Muller,<sup>69</sup> C. P. O’Grady,<sup>69</sup> V. E. Ozcan,<sup>69</sup> A. Perazzo,<sup>69</sup> M. Perl,<sup>69</sup> T. Pulliam,<sup>69</sup> B. N. Ratcliff,<sup>69</sup> A. Roodman,<sup>69</sup> A. A. Salnikov,<sup>69</sup> R. H. Schindler,<sup>69</sup> J. Schwiening,<sup>69</sup> A. Snyder,<sup>69</sup> J. Stelzer,<sup>69</sup> D. Su,<sup>69</sup> M. K. Sullivan,<sup>69</sup> K. Suzuki,<sup>69</sup> S. K. Swain,<sup>69</sup> J. M. Thompson,<sup>69</sup> J. Va’vra,<sup>69</sup> N. van Bakel,<sup>69</sup> M. Weaver,<sup>69</sup> A. J. R. Weinstein,<sup>69</sup> W. J. Wisniewski,<sup>69</sup> M. Wittgen,<sup>69</sup> D. H. Wright,<sup>69</sup> A. K. Yarritu,<sup>69</sup> K. Yi,<sup>69</sup> C. C. Young,<sup>69</sup> P. R. Burchat,<sup>70</sup> A. J. Edwards,<sup>70</sup> S. A. Majewski,<sup>70</sup> B. A. Petersen,<sup>70</sup> C. Roat,<sup>70</sup> L. Wilden,<sup>70</sup> S. Ahmed,<sup>71</sup> M. S. Alam,<sup>71</sup> R. Bula,<sup>71</sup> J. A. Ernst,<sup>71</sup> V. Jain,<sup>71</sup> B. Pan,<sup>71</sup> M. A. Saeed,<sup>71</sup> F. R. Wappler,<sup>71</sup> S. B. Zain,<sup>71</sup> W. Bugg,<sup>72</sup> M. Krishnamurthy,<sup>72</sup> S. M. Spanier,<sup>72</sup> R. Eckmann,<sup>73</sup> J. L. Ritchie,<sup>73</sup> A. Satpathy,<sup>73</sup> C. J. Schilling,<sup>73</sup> R. F. Schwitters,<sup>73</sup> J. M. Izen,<sup>74</sup> X. C. Lou,<sup>74</sup> S. Ye,<sup>74</sup> F. Bianchi,<sup>75</sup> F. Gallo,<sup>75</sup> D. Gamba,<sup>75</sup> M. Bomben,<sup>76</sup> L. Bosisio,<sup>76</sup> C. Cartaro,<sup>76</sup> F. Cossutti,<sup>76</sup> G. Della Ricca,<sup>76</sup> S. Dittongo,<sup>76</sup> L. Lanceri,<sup>76</sup> L. Vitale,<sup>76</sup> V. Azzolini,<sup>77</sup> F. Martinez-Vidal,<sup>77</sup> Sw. Banerjee,<sup>78</sup> B. Bhuyan,<sup>78</sup> C. M. Brown,<sup>78</sup> D. Fortin,<sup>78</sup> K. Hamano,<sup>78</sup> R. Kowalewski,<sup>78</sup> I. M. Nugent,<sup>78</sup> J. M. Roney,<sup>78</sup> R. J. Sobie,<sup>78</sup> J. J. Back,<sup>79</sup> P. F. Harrison,<sup>79</sup> T. E. Latham,<sup>79</sup> G. B. Mohanty,<sup>79</sup> M. Pappagallo,<sup>79</sup> H. R. Band,<sup>80</sup> X. Chen,<sup>80</sup> B. Cheng,<sup>80</sup> S. Dasu,<sup>80</sup> M. Datta,<sup>80</sup> K. T. Flood,<sup>80</sup> J. J. Hollar,<sup>80</sup> P. E. Kutter,<sup>80</sup> B. Mellado,<sup>80</sup> A. Mihalyi,<sup>80</sup> Y. Pan,<sup>80</sup> M. Pierini,<sup>80</sup> R. Prepost,<sup>80</sup> S. L. Wu,<sup>80</sup> Z. Yu,<sup>80</sup> and H. Neal<sup>81</sup>

(BABAR Collaboration)

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

<sup>2</sup>Universitat de Barcelona, Facultat de Fisica Dept. ECM, E-08028 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 I, 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, Laboratoire Leprince-Ringuet, 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>*Johns Hopkins University, Baltimore, Maryland 21218, USA*
- <sup>36</sup>*Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany*
- <sup>37</sup>*Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B.P. 34, F-91898 ORSAY Cedex, France*
- <sup>38</sup>*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
- <sup>39</sup>*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
- <sup>40</sup>*Queen Mary, University of London, E1 4NS, United Kingdom*
- <sup>41</sup>*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*
- <sup>42</sup>*University of Louisville, Louisville, Kentucky 40292, USA*
- <sup>43</sup>*University of Manchester, Manchester M13 9PL, United Kingdom*
- <sup>44</sup>*University of Maryland, College Park, Maryland 20742, USA*
- <sup>45</sup>*University of Massachusetts, Amherst, Massachusetts 01003, USA*
- <sup>46</sup>*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA*
- <sup>47</sup>*McGill University, Montréal, Québec, Canada H3A 2T8*
- <sup>48</sup>*Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy*
- <sup>49</sup>*University of Mississippi, University, Mississippi 38677, USA*
- <sup>50</sup>*Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7*
- <sup>51</sup>*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
- <sup>52</sup>*Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy*
- <sup>53</sup>*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*
- <sup>54</sup>*University of Notre Dame, Notre Dame, Indiana 46556, USA*
- <sup>55</sup>*Ohio State University, Columbus, Ohio 43210, USA*
- <sup>56</sup>*University of Oregon, Eugene, Oregon 97403, USA*
- <sup>57</sup>*Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy*
- <sup>58</sup>*Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France*
- <sup>59</sup>*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
- <sup>60</sup>*Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy*
- <sup>61</sup>*Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy*
- <sup>62</sup>*Prairie View A&M University, Prairie View, Texas 77446, USA*
- <sup>63</sup>*Princeton University, Princeton, New Jersey 08544, USA*
- <sup>64</sup>*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy*
- <sup>65</sup>*Universität Rostock, D-18051 Rostock, Germany*
- <sup>66</sup>*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*
- <sup>67</sup>*DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France*
- <sup>68</sup>*University of South Carolina, Columbia, South Carolina 29208, USA*
- <sup>69</sup>*Stanford Linear Accelerator Center, Stanford, California 94309, USA*
- <sup>70</sup>*Stanford University, Stanford, California 94305-4060, USA*
- <sup>71</sup>*State University of New York, Albany, New York 12222, USA*
- <sup>72</sup>*University of Tennessee, Knoxville, Tennessee 37996, USA*
- <sup>73</sup>*University of Texas at Austin, Austin, Texas 78712, USA*
- <sup>74</sup>*University of Texas at Dallas, Richardson, Texas 75083, USA*
- <sup>75</sup>*Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy*
- <sup>76</sup>*Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy*
- <sup>77</sup>*IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain*
- <sup>78</sup>*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
- <sup>79</sup>*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*
- <sup>80</sup>*University of Wisconsin, Madison, Wisconsin 53706, USA*
- <sup>81</sup>*Yale University, New Haven, Connecticut 06511, USA*

(Received 8 August 2006; published 21 November 2006)

We report a measurement of the  $B \rightarrow \pi \ell \nu$  branching fraction based on  $211 \text{ fb}^{-1}$  of data collected with the *BABAR* detector. We use samples of  $B^0$  and  $B^+$  mesons tagged by a second  $B$  meson reconstructed in a semileptonic or hadronic decay and combine the results assuming isospin symmetry to obtain  $\mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu) = (1.33 \pm 0.17_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-4}$ . We determine the magnitude of the Cabibbo-Kobayashi-Maskawa matrix element  $|V_{ub}|$  by combining the partial branching fractions measured in ranges of the momentum transfer squared and theoretical calculations of the form factor. Using a recent lattice QCD calculation, we find  $|V_{ub}| = (4.5 \pm 0.5_{\text{stat}} \pm 0.3_{\text{syst}}^{+0.7}_{-0.5\text{FF}}) \times 10^{-3}$ , where the last error is due to the normalization of the form factor.

DOI: [10.1103/PhysRevLett.97.211801](https://doi.org/10.1103/PhysRevLett.97.211801)

PACS numbers: 13.20.He, 12.15.Hh, 12.38.Qk, 14.40.Nd

The magnitude of the Cabibbo-Kobayashi-Maskawa matrix [1] element  $V_{ub}$  is a critical constraint on the unitarity triangle. Our knowledge of  $|V_{ub}|$  comes from measurements of the  $b \rightarrow u \ell \nu$  decay rate, where the hadronic system in the final state can be reconstructed either inclusively or exclusively. The precisions are limited by the uncertainties in the nonperturbative QCD calculations that are used to extract  $|V_{ub}|$  from the measured decay rates. It is therefore crucial to pursue both the inclusive and exclusive approaches, which rely on different theoretical methods, and to test their consistency.

The rate of the exclusive decay  $B \rightarrow \pi \ell \nu$  ( $\ell = e$  or  $\mu$ ) is related to  $|V_{ub}|$  through the form factor  $f_+(q^2)$ , where  $q^2$  is the momentum transfer squared. Measurements of the  $B \rightarrow \pi \ell \nu$  branching fraction have been reported by CLEO [2], *BABAR* [3], and Belle [4]. In this Letter, we report a measurement in which  $B \rightarrow \pi \ell \nu$  decays are searched for in  $Y(4S) \rightarrow B\bar{B}$  events that are identified by reconstruction of the second  $B$  meson ( $B_{\text{tag}}$ ). The technique, which was also used in Ref. [4], allows us to constrain the kinematics, reduce the combinatorics, and determine the charge of the signal  $B$ . The result is an improved signal purity at the expense of the efficiency compared with the traditional measurements in which only the signal  $B$  meson is reconstructed. We perform two analyses in which  $B_{\text{tag}}$  is reconstructed in semileptonic and hadronic decays, respectively, and combine the measured partial branching fractions  $\Delta\mathcal{B}$  in ranges of  $q^2$  with the recent form-factor calculations [5–8] to determine  $|V_{ub}|$ .

The measurement uses a sample of approximately  $232 \times 10^6 B\bar{B}$  pairs, corresponding to an integrated luminosity of  $211 \text{ fb}^{-1}$ , recorded near the  $Y(4S)$  resonance with the *BABAR* detector [9] at the PEP-II asymmetric-energy  $e^+e^-$  storage rings. We use a detailed Monte Carlo (MC) simulation to estimate the signal efficiency and the signal and background distributions.

In the first analysis, we reconstruct  $B_{\text{tag}}$  in the semileptonic decay  $B \rightarrow D^{(*)} \ell \nu$ . We reconstruct  $D^0$  mesons in  $K^- \pi^+$ ,  $K^- \pi^+ \pi^+ \pi^-$ ,  $K^- \pi^+ \pi^0$ , and  $K_S^0 \pi^+ \pi^-$  decays and  $D^+$  mesons in  $K^- \pi^+ \pi^+$  decays [10]. The  $D$  mass resolution ( $\sigma$ ) is between 4.6 and 12.9 MeV, depending on the decay channel. The mass of the  $D$  candidate is required to be within  $2.6\sigma$  and  $3.0\sigma$  of the expected value for the  $B^0$  and  $B^+$  channels, respectively. We also use a sideband

sample, in which the  $D$  candidate mass is more than  $3\sigma$  away from the nominal value, for subtracting the combinatoric background. We reconstruct  $D^{*+}$  mesons in  $D^0 \pi^+$  and  $D^+ \pi^0$  decays. The mass difference between the  $D^*$  and  $D$  is required to be within 3 MeV of the expected value [11]. The reconstructed  $D$  and  $D^*$  candidates are paired with a charged lepton with a center-of-mass (c.m.) momentum  $|\mathbf{p}_\ell| > 0.8 \text{ GeV}$  to form a  $Y = D^{(*)} \ell$  system. If the  $D$  decay contains a charged kaon, the lepton must have the same charge as the kaon. The lepton and the  $D$  meson are required to originate from a common vertex. Assuming that only a massless neutrino escaped detection, we calculate the cosine of the angle between the  $B$  and  $Y$  momenta as  $\cos\theta_{BY} = (2E_B E_Y - m_B^2 - m_Y^2)/(2|\mathbf{p}_B||\mathbf{p}_Y|)$ , where  $m_B$ ,  $m_Y$ ,  $E_B$ ,  $E_Y$ ,  $\mathbf{p}_B$ , and  $\mathbf{p}_Y$  refer to the masses, c.m. energies, and momenta of  $B$  and  $Y$ , respectively. For background events,  $\cos\theta_{BY}$  does not correspond to the cosine of a physical angle and can extend outside  $\pm 1$ . We apply a loose selection of  $|\cos\theta_{BY}| < 5$  at this stage.

After identifying the  $B_{\text{tag}}$  meson, we require the remaining particles in the event to be consistent with a  $B \rightarrow \pi \ell \nu$  decay. Charged tracks that are not identified as a lepton or a kaon are considered charged pion candidates. Neutral pion candidates are formed from pairs of photon candidates with invariant mass between 115 and 150 MeV. For the  $B^0$  channel, the lepton must have  $|\mathbf{p}_\ell| > 0.8 \text{ GeV}$ , and its charge must be opposite to that of the charged pion. The lepton charge must be opposite to that of the  $B_{\text{tag}}$  for the  $B^+$  channel. We reject the lepton candidate if, when combined with an oppositely charged track, it is consistent with a  $J/\psi \rightarrow \ell^+ \ell^-$  decay or a photon conversion. Once the signal  $B$  candidate is identified, we require that the event contain no other charged particles and a small total c.m. energy  $E_{\text{res}}$  of the residual neutral particles. In measuring  $E_{\text{res}}$ , we remove the neutral candidates that are consistent with coming from a  $D^* \rightarrow D \pi^0$  or  $D \gamma$  decay, bremsstrahlung from an electron, or beam-related background. We require  $E_{\text{res}} < 70 \text{ MeV}$  for the  $B^0$  channel and  $E_{\text{res}} < 250 \text{ MeV}$  for the  $B^+$  channel, the latter being relaxed to allow for additional photons from decays of  $D^{*0}$  and higher resonances. We calculate the cosine of the angle between the  $B$  and  $\pi \ell$  momenta as  $\cos\theta_{B\pi\ell} = (2E_B E_{\pi\ell} - m_B^2 - m_{\pi\ell}^2)/(2|\mathbf{p}_B||\mathbf{p}_{\pi\ell}|)$ , where  $m_{\pi\ell}$ ,  $E_{\pi\ell}$ , and  $\mathbf{p}_{\pi\ell}$  are the

mass, c.m. energy, and momentum of the  $\pi\ell$  system, respectively. We require  $|\cos\theta_{B\pi\ell}| < 5$ .

Ignoring the small c.m. momentum of the  $B$  meson, the invariant mass squared of the lepton-neutrino system in a  $B \rightarrow \pi\ell\nu$  decay can be inferred as  $q^2 = (m_B - E_\pi)^2 - |\mathbf{p}_\pi|^2$ , where  $E_\pi$  and  $\mathbf{p}_\pi$  are the c.m. energy and momentum of the pion, respectively. We divide the data into three bins:  $q^2 < 8 \text{ GeV}^2$ ,  $8 < q^2 < 16 \text{ GeV}^2$ , and  $q^2 > 16 \text{ GeV}^2$ . We use simulated  $B \rightarrow \pi\ell\nu$  events to estimate and to correct for the small ( $< 8\%$ ) migration between the  $q^2$  bins due to resolution, which is approximately  $0.8 \text{ GeV}^2$  at  $q^2 = 8 \text{ GeV}^2$  and improves with increasing  $q^2$ .

Having identified the two  $B$  mesons that decayed semileptonically, conservation of the total momentum determines the angle  $\phi_B$  between the direction of the  $B$  momenta and the plane defined by the  $Y$  and  $\pi\ell$  momenta:

$$\cos^2\phi_B = \frac{\cos^2\theta_{BY} + \cos^2\theta_{B\pi\ell} + 2\cos\theta_{BY}\cos\theta_{B\pi\ell}\cos\gamma}{\sin^2\gamma}, \quad (1)$$

where  $\gamma$  is the angle between the  $Y$  and  $\pi\ell$  momenta. The variable  $\cos^2\phi_B$  satisfies  $\cos^2\phi_B \leq 1$  for correctly reconstructed signal events and is broadly distributed for the background (see Fig. 1). We use the  $\cos^2\phi_B$  distributions to extract the signal yield in the data in each  $q^2$  bin. We did not require stringent cuts on  $\cos\theta_{BY}$  and  $\cos\theta_{B\pi\ell}$  because they are incorporated in  $\cos^2\phi_B$ .

We express the data distribution as a sum of three contributions:  $dN/d\cos^2\phi_B = N_{\text{sig}}\mathcal{P}_{\text{sig}} + N_{\text{bkg}}\mathcal{P}_{\text{bkg}} + N_{\text{cmb}}\mathcal{P}_{\text{cmb}}$ , where  $N_c$  and  $\mathcal{P}_c$  are the number of events and the probability density function (PDF) for each category  $c$ , defined as the signal (sig), background with correctly reconstructed  $D$  mesons (bkg), and other backgrounds (cmb). The events in the  $D$  mass sideband are also used in the fit to constrain the  $N_{\text{cmb}}\mathcal{P}_{\text{cmb}}$  term. The PDF shapes are determined from the MC simulation. The signal PDF is a combination of a smeared step function and

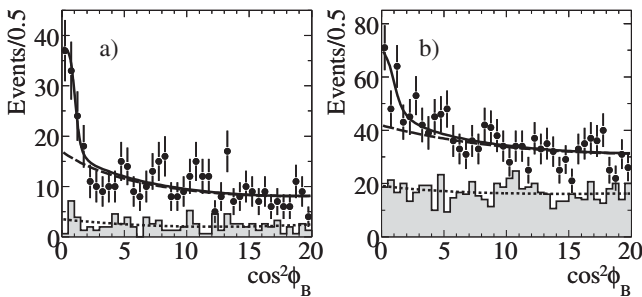


FIG. 1. Distributions of  $\cos^2\phi_B$  of the (a)  $B^0 \rightarrow \pi^-\ell^+\nu$  and (b)  $B^+ \rightarrow \pi^0\ell^+\nu$  candidates. The points with error bars and the shaded histograms are the data in the  $D$  mass peak and sideband, respectively. The curves are the fit results representing the total (solid), background (dashed), and “cmb” (dotted) components defined in the text. The fits were performed in bins of  $q^2$ , but the results shown are for the complete  $q^2$  range.

an exponential tail. The background PDFs are either an exponential plus a constant or a second order polynomial. The two data samples ( $D$  mass peak and sideband) and the MC samples are used in an unbinned maximum likelihood fit that determines  $N_{\text{sig}}$ ,  $N_{\text{bkg}}$ ,  $N_{\text{cmb}}$ , and the PDF parameters simultaneously. Figure 1 shows the fit results summed over the  $q^2$  bins. We find the signal yields and their statistical errors to be  $57^{+13}_{-12}$  and  $92^{+26}_{-24}$  events for the  $B^0$  and  $B^+$  channels, respectively.

We use simulated  $B \rightarrow \pi\ell\nu$  events to estimate the signal efficiencies. Control samples are used to derive corrections for the data-MC differences in the  $B_{\text{tag}}$  reconstruction, charged and neutral particle reconstruction, and lepton identification. The largest uncertainty comes from the  $B_{\text{tag}}$  reconstruction efficiency, which is determined from a sample of events in which two nonoverlapping  $B_{\text{tag}}$  candidates are reconstructed. The efficiency correction factors for the  $B_{\text{tag}}$  reconstruction are found to be  $1.00 \pm 0.07$  and  $0.99 \pm 0.02$  for the  $B^0$  and  $B^+$  channels, respectively. The average signal efficiencies after the correction are  $1.1 \times 10^{-3}$  for the  $B^0$  channel and  $3.0 \times 10^{-3}$  for the  $B^+$  channel. The latter is larger mainly because of the higher efficiency of reconstructing a  $D^0$  meson compared with a  $D^+$  or  $D^{*+}$  meson.

The measured branching fractions are summarized in Table I. The largest sources of systematic error [12] are the  $B_{\text{tag}}$  reconstruction efficiency (discussed above), the shape of the background  $\cos^2\phi_B$  distribution (studied with control samples that fail the signal selection criteria), and the branching fractions of the  $B$  semileptonic decays other than  $B \rightarrow \pi\ell\nu$  (varied within the current knowledge [11]).

In the second analysis, we reconstruct the  $B_{\text{tag}}$  meson in a set of purely hadronic final states  $B \rightarrow D^{(*)}X$ . We reconstruct  $D^0$  mesons in  $K^-\pi^+$ ,  $K^-\pi^+\pi^0$ ,  $K^-\pi^+\pi^+\pi^-$ , and  $K_S^0\pi^+\pi^-$  decays and  $D^+$  mesons in  $K^-\pi^+\pi^+$ ,  $K^-\pi^+\pi^+\pi^0$ ,  $K_S^0\pi^+$ ,  $K_S^0\pi^+\pi^0$ , and  $K_S^0\pi^+\pi^+\pi^-$  decays. The  $D^*$  mesons are reconstructed in  $D^0\pi^+$ ,  $D^0\pi^0$ , and  $D^0\gamma$  decays. The hadronic system  $X$  has a total charge  $\pm 1$  and is composed of  $n_1\pi^\pm + n_2K^\pm + n_3\pi^0 + n_4K_S^0$ , where  $n_1 + n_2 < 6$ ,  $n_3 < 3$ , and  $n_4 < 3$ . The total reconstruction efficiency for a  $B^0$  ( $B^+$ ) meson is 0.3% (0.5%).

We separate correctly reconstructed  $B_{\text{tag}}$  mesons from the background using two kinematic variables: the beam-energy substituted mass  $m_{\text{ES}} = \sqrt{s/4 - |\mathbf{p}_B|^2}$  and the energy difference  $\Delta E = E_B - \sqrt{s}/2$ , where  $\sqrt{s}$  is the c.m. energy of the  $e^+e^-$  system. We select signal candidates in mode-dependent  $\Delta E$  windows around zero. We apply a loose selection  $5.2 < m_{\text{ES}} < 5.3 \text{ GeV}$  and fit the  $m_{\text{ES}}$  distribution at a later stage to extract the signal yield.

After reconstructing  $B_{\text{tag}}$ , we look for the signature of a  $B \rightarrow \pi\ell\nu$  decay in the recoiling system. The selection criteria for the pion and lepton candidates are similar to the first analysis, except (a) the minimum  $|\mathbf{p}_\ell|$  for electrons is 0.5 GeV, and (b) the  $\pi^0$  mass window is 110–160 MeV.

TABLE I. Partial and total branching fractions, in units of  $10^{-4}$ , measured with the semileptonic and hadronic tag analyses. The  $q^2$  ranges are in  $\text{GeV}^2$ . The errors are statistical and systematic. The combined results are expressed as  $B^0 \rightarrow \pi^- \ell^+ \nu$  branching fractions.

		$q^2 < 8$	$8 < q^2 < 16$	$q^2 > 16$	$q^2 < 16$	Total
$B^0$	Semileptonic	$0.50 \pm 0.16 \pm 0.05$	$0.33 \pm 0.14 \pm 0.04$	$0.29 \pm 0.15 \pm 0.04$	$0.83 \pm 0.22 \pm 0.08$	$1.12 \pm 0.25 \pm 0.10$
	Hadronic	$0.09 \pm 0.10 \pm 0.02$	$0.33 \pm 0.15 \pm 0.05$	$0.65 \pm 0.20 \pm 0.13$	$0.42 \pm 0.18 \pm 0.05$	$1.07 \pm 0.27 \pm 0.15$
	Average	$0.38 \pm 0.12 \pm 0.04$	$0.33 \pm 0.10 \pm 0.03$	$0.47 \pm 0.13 \pm 0.06$	$0.72 \pm 0.16 \pm 0.06$	$1.19 \pm 0.20 \pm 0.10$
$B^+$	Semileptonic	$0.18 \pm 0.08 \pm 0.02$	$0.45 \pm 0.13 \pm 0.05$	$0.10 \pm 0.12 \pm 0.04$	$0.63 \pm 0.16 \pm 0.06$	$0.73 \pm 0.18 \pm 0.08$
	Hadronic	$0.16 \pm 0.11 \pm 0.03$	$0.39 \pm 0.16 \pm 0.06$	$0.26 \pm 0.12 \pm 0.06$	$0.56 \pm 0.19 \pm 0.08$	$0.82 \pm 0.22 \pm 0.11$
	Average	$0.18 \pm 0.07 \pm 0.02$	$0.43 \pm 0.10 \pm 0.04$	$0.22 \pm 0.09 \pm 0.05$	$0.61 \pm 0.12 \pm 0.05$	$0.82 \pm 0.15 \pm 0.09$
Combined	$0.36 \pm 0.09 \pm 0.03$	$0.52 \pm 0.10 \pm 0.04$	$0.46 \pm 0.10 \pm 0.06$	$0.87 \pm 0.13 \pm 0.06$	$1.33 \pm 0.17 \pm 0.11$	

We require  $E_{\text{res}} < 450$  MeV for the  $B^0$  channel to reduce the  $B^0 \rightarrow \rho^- \ell^+ \nu$  background, and no requirement is made for the  $B^+$  channel.

The full reconstruction of  $B_{\text{tag}}$  allows us to determine the neutrino four-momentum precisely from the missing four-momentum  $p_{\text{miss}} = p_{Y(4S)} - p_{B_{\text{tag}}} - p_{\pi} - p_{\ell}$ . The missing mass squared  $m_{\text{miss}}^2$  peaks near zero for the signal and extends above zero for the background (see Fig. 2). We require  $|m_{\text{miss}}^2| < 0.3$   $\text{GeV}^2$  for the  $B^0$  channel and  $-0.5 < m_{\text{miss}}^2 < 0.7$   $\text{GeV}^2$  for the  $B^+$  channel, with the latter being broader and asymmetric due to the resolution of the  $\pi^0$  energy measurement.

Precise knowledge of  $p_{\text{miss}}$  allows us to calculate  $q^2$  with small uncertainties. We divide the signal candidates into the same three  $q^2$  bins as before and subtract the small bin-to-bin migration as background. In each  $q^2$  bin, we obtain the number of correctly tagged events by an unbinned maximum likelihood fit to the  $m_{\text{ES}}$  distribution. The PDF for the signal is determined from MC simulation as a Gaussian function joined to an exponential tail. For the background, we use a threshold function of the form  $x\sqrt{1-x^2}\exp(-\xi(1-x^2))$ , where  $x = 2m_{\text{ES}}/\sqrt{s}$  and the parameter  $\xi$  is allowed to float in the fit. Figure 2 shows the  $m_{\text{miss}}^2$  distribution obtained by splitting the data samples in bins of  $m_{\text{miss}}^2$  and repeating the  $m_{\text{ES}}$  fit.

The signal side of the correctly tagged events may not be a  $B \rightarrow \pi \ell \nu$  decay. Contributions from this type of background are estimated with the MC simulation, as indicated by shaded histograms in Fig. 2, which are scaled to match the data in the sideband region  $1 < m_{\text{miss}}^2 < 4$   $\text{GeV}^2$ . After background subtraction, we find signal yields of  $31 \pm 7$  and  $26 \pm 7$  events for the  $B^0$  and  $B^+$  channels, respectively, where the errors are statistical.

Instead of estimating the absolute signal efficiency, we normalize the signal yield to the number of inclusive  $B$  semileptonic decays,  $B \rightarrow X \ell \nu$ , in the recoil of  $B_{\text{tag}}$ . The reconstruction efficiencies of  $B_{\text{tag}}$  and of the lepton cancel to first order in the ratio between the yields of the signal and normalization samples. The inclusive branching fraction  $\mathcal{B}(B \rightarrow X \ell \nu)$  is taken as  $10.73 \pm 0.28\%$  [11]. The yield of the normalization sample is extracted by a fit to the  $m_{\text{ES}}$  distribution. The component of the background

that peaks in the  $m_{\text{ES}}$  distribution is estimated from the MC simulation and subtracted. Efficiency differences between the signal and normalization samples are estimated with the MC simulation, and the corresponding corrections are applied to the result.

The measured branching fractions are summarized in Table I. The largest source of systematic error is the limited statistics of the signal MC sample. Other significant sources include the modeling of the signal PDF (studied with alternative fitting methods), photon-energy measurement,  $\pi^0$  reconstruction, muon identification, and the branching fractions of nonsignal  $B \rightarrow X_{\ell} \ell \nu$  decays.

We take weighted averages of the measured partial branching fractions in each  $q^2$  bin. The results for the  $B^0$  and  $B^+$  channels are consistent with the isospin relation  $\Gamma(B^0 \rightarrow \pi^- \ell^+ \nu) = 2\Gamma(B^+ \rightarrow \pi^0 \ell^+ \nu)$  and the lifetime ratio  $\tau_{B^+}/\tau_{B^0} = 1.081 \pm 0.015$  [11], with  $\chi^2 = 5.2$  for 3 degrees of freedom. Assuming isospin symmetry, we combine the  $B^0$  and  $B^+$  channels and express the results as the  $B^0$  branching fraction in the last row in Table I. The overall  $\chi^2$  is 10.2 for 9 degrees of freedom.

We extract  $|V_{ub}|$  from the partial branching fractions  $\Delta\mathcal{B}$  using  $|V_{ub}| = \sqrt{\Delta\mathcal{B}/(\tau_{B^0}\Delta\zeta)}$ , where  $\tau_{B^0} = (1.536 \pm 0.014)$  ps [11] is the  $B^0$  lifetime and  $\Delta\zeta = \Delta\Gamma/|V_{ub}|^2$  is the normalized partial decay rate predicted by the form-factor calculations. We use the light-cone sum rules calcu-

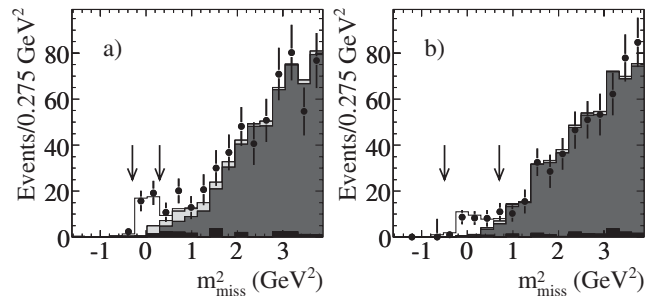


FIG. 2. Distributions of  $m_{\text{miss}}^2$  of the (a)  $B^0 \rightarrow \pi^- \ell^+ \nu$  and (b)  $B^+ \rightarrow \pi^0 \ell^+ \nu$  candidates. The points with error bars are the data. The histograms represent, from the lightest to the darkest, the MC simulation of the  $B \rightarrow \pi \ell \nu$  signal,  $b \rightarrow u \ell \nu$ ,  $b \rightarrow c \ell \nu$ , and other backgrounds. The arrows indicate the regions in which the signals are extracted.

TABLE II. Values of  $|V_{ub}|$  derived using the form-factor calculations. The first two errors on  $|V_{ub}|$  come from the statistical and systematic uncertainties of the partial branching fractions. The third errors correspond to the uncertainties on  $\Delta\zeta$  due to the form-factor calculations and are taken from Refs. [5–8].

	$q^2$ (GeV <sup>2</sup> )	$\Delta\zeta$ (ps <sup>-1</sup> )	$ V_{ub} $ (10 <sup>-3</sup> )
Ball-Zwicky [5]	<16	$5.44 \pm 1.43$	$3.2 \pm 0.2 \pm 0.1_{-0.4}^{+0.5}$
Gulez <i>et al.</i> [6]	>16	$1.46 \pm 0.35$	$4.5 \pm 0.5 \pm 0.3_{-0.5}^{+0.7}$
Okamoto <i>et al.</i> [7]	>16	$1.83 \pm 0.50$	$4.0 \pm 0.5 \pm 0.3_{-0.5}^{+0.7}$
Abada <i>et al.</i> [8]	>16	$1.80 \pm 0.86$	$4.1 \pm 0.5 \pm 0.3_{-0.7}^{+1.6}$

lation [5] for  $q^2 < 16$  GeV<sup>2</sup> and the lattice QCD calculations [6–8] for  $q^2 > 16$  GeV<sup>2</sup>. The results are shown in Table II.

In conclusion, we have measured the  $B \rightarrow \pi\ell\nu$  branching fraction as a function of  $q^2$  using tagged  $B$  meson samples and have extracted  $|V_{ub}|$ . The measured total branching fraction  $\mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu) = (1.33 \pm 0.17_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-4}$  has the smallest systematic uncertainty among the existing measurements [2–4] thanks to the superior signal purity, and the overall precision is comparable to the best. Using theoretical calculations of the form factor, we obtain values of  $|V_{ub}|$  ranging between  $3.2 \times 10^{-3}$  and  $4.5 \times 10^{-3}$ . As an example, the recently published unquenched lattice QCD calculation [6] gives  $|V_{ub}| = (4.5 \pm 0.5_{\text{stat}} \pm 0.3_{\text{syst}-0.5\text{FF}}^{+0.7}) \times 10^{-3}$ . Improvement will be possible with additional data combined with more precise form-factor calculations.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions

thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), MEC (Spain), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

\*Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France.

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

\*Also with Università della Basilicata, Potenza, Italy.

- [1] M. Kobayahi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
- [2] S. B. Athar *et al.* (CLEO Collaboration), *Phys. Rev. D* **68**, 072003 (2003).
- [3] B. Aubert *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **72**, 051102 (2005).
- [4] T. Hokuue *et al.* (Belle Collaboration), hep-ex/0604024.
- [5] P. Ball and R. Zwicky, *Phys. Rev. D* **71**, 014015 (2005).
- [6] E. Gulez *et al.* (HPQCD Collaboration), *Phys. Rev. D* **73**, 074502 (2006).
- [7] M. Okamoto *et al.*, hep-lat/0409116.
- [8] A. Abada *et al.*, *Nucl. Phys.* **B619**, 565 (2001).
- [9] B. Aubert *et al.* (*BABAR* Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **479**, 1 (2002).
- [10] Charge conjugate states are implied throughout this Letter.
- [11] S. Eidelman *et al.* (Particle Data Group), *Phys. Lett. B* **592**, 1 (2004).
- [12] See EPAPS Document No. E-PRLTAO-97-050647 for two tables containing (i) the systematic errors of the measured partial branching fractions ( $B \rightarrow \pi\ell\nu$ ) and (ii) the error matrices. For more information on EPAPS, see <http://www.aip.org/pubservs/epaps.html>.