

## Evidence for decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and a measurement of $\Delta\Gamma_s^{\text{CP}}/\Gamma_s$

V.M. Abazov<sup>36</sup>, B. Abbott<sup>75</sup>, M. Abolins<sup>65</sup>, B.S. Acharya<sup>29</sup>, M. Adams<sup>51</sup>, T. Adams<sup>49</sup>, E. Aguilo<sup>6</sup>, M. Ahsan<sup>59</sup>, G.D. Alexeev<sup>36</sup>, G. Alkhazov<sup>40</sup>, A. Alton<sup>64,a</sup>, G. Alverson<sup>63</sup>, G.A. Alves<sup>2</sup>, M. Anastasoiaie<sup>35</sup>, L.S. Ancu<sup>35</sup>, T. Andeen<sup>53</sup>, B. Andrieu<sup>17</sup>, M.S. Anzelc<sup>53</sup>, M. Aoki<sup>50</sup>, Y. Arnoud<sup>14</sup>, M. Arov<sup>60</sup>, M. Arthaud<sup>18</sup>, A. Askew<sup>49,b</sup>, B. Åsman<sup>41</sup>, A.C.S. Assis Jesus<sup>3</sup>, O. Atramentov<sup>49</sup>, C. Avila<sup>8</sup>, F. Badaud<sup>13</sup>, L. Bagby<sup>50</sup>, B. Baldin<sup>50</sup>, D.V. Bandurin<sup>59</sup>, P. Banerjee<sup>29</sup>, S. Banerjee<sup>29</sup>, E. Barberis<sup>63</sup>, A.-F. Barfuss<sup>15</sup>, P. Bargassa<sup>80</sup>, P. Baringer<sup>58</sup>, J. Barreto<sup>2</sup>, J.F. Bartlett<sup>50</sup>, U. Bassler<sup>18</sup>, D. Bauer<sup>43</sup>, S. Beale<sup>6</sup>, A. Bean<sup>58</sup>, M. Begalli<sup>3</sup>, M. Begel<sup>73</sup>, C. Belanger-Champagne<sup>41</sup>, L. Bellantoni<sup>50</sup>, A. Bellavance<sup>50</sup>, J.A. Benitez<sup>65</sup>, S.B. Beri<sup>27</sup>, G. Bernardi<sup>17</sup>, R. Bernhard<sup>23</sup>, I. Bertram<sup>42</sup>, M. Besançon<sup>18</sup>, R. Beuselinck<sup>43</sup>, V.A. Bezzubov<sup>39</sup>, P.C. Bhat<sup>50</sup>, V. Bhatnagar<sup>27</sup>, G. Blazey<sup>52</sup>, F. Blekman<sup>43</sup>, S. Blessing<sup>49</sup>, K. Bloom<sup>67</sup>, A. Boehnlein<sup>50</sup>, D. Boline<sup>62</sup>, T.A. Bolton<sup>59</sup>, E.E. Boos<sup>38</sup>, G. Borissov<sup>42</sup>, T. Bose<sup>77</sup>, A. Brandt<sup>78</sup>, R. Brock<sup>65</sup>, G. Brooijmans<sup>70</sup>, A. Bross<sup>50</sup>, D. Brown<sup>81</sup>, X.B. Bu<sup>7</sup>, N.J. Buchanan<sup>49</sup>, D. Buchholz<sup>53</sup>, M. Buehler<sup>81</sup>, V. Buescher<sup>22</sup>, V. Bunichev<sup>38</sup>, S. Burdin<sup>42,c</sup>, T.H. Burnett<sup>82</sup>, C.P. Buszello<sup>43</sup>, P. Calfayan<sup>25</sup>, S. Calvet<sup>16</sup>, J. Cammin<sup>71</sup>, M.A. Carrasco-Lizarraga<sup>33</sup>, E. Carrera<sup>49</sup>, W. Carvalho<sup>3</sup>, B.C.K. Casey<sup>50</sup>, H. Castilla-Valdez<sup>33</sup>, S. Chakrabarti<sup>72</sup>, D. Chakraborty<sup>52</sup>, K.M. Chan<sup>55</sup>, A. Chandra<sup>48</sup>, E. Cheu<sup>45</sup>, D.K. Cho<sup>62</sup>, S. Choi<sup>32</sup>, B. Choudhary<sup>28</sup>, L. Christofek<sup>77</sup>, T. Christoudias<sup>43</sup>, S. Cihangir<sup>50</sup>, D. Claes<sup>67</sup>, J. Clutter<sup>58</sup>, M. Cooke<sup>50</sup>, W.E. Cooper<sup>50</sup>, M. Corcoran<sup>80</sup>, F. Couderc<sup>18</sup>, M.-C. Cousinou<sup>15</sup>, S. Crépe-Renaudin<sup>14</sup>, V. Cuplov<sup>59</sup>, D. Cutts<sup>77</sup>, M. Cwiok<sup>30</sup>, H. da Motta<sup>2</sup>, A. Das<sup>45</sup>, G. Davies<sup>43</sup>, K. De<sup>78</sup>, S.J. de Jong<sup>35</sup>, E. De La Cruz-Burelo<sup>33</sup>, C. De Oliveira Martins<sup>3</sup>, K. DeVaughan<sup>67</sup>, F. Déliot<sup>18</sup>, M. Demarteau<sup>50</sup>, R. Demina<sup>71</sup>, D. Denisov<sup>50</sup>, S.P. Denisov<sup>39</sup>, S. Desai<sup>50</sup>, H.T. Diehl<sup>50</sup>, M. Diesburg<sup>50</sup>, A. Dominguez<sup>67</sup>, T. Dorland<sup>82</sup>, A. Dubey<sup>28</sup>, L.V. Dudko<sup>38</sup>, L. Duflo<sup>16</sup>, S.R. Dugad<sup>29</sup>, D. Duggan<sup>49</sup>, A. Duperrin<sup>15</sup>, S. Dutt<sup>27</sup>, J. Dyer<sup>65</sup>, A. Dyshkant<sup>52</sup>, M. Eads<sup>67</sup>, D. Edmunds<sup>65</sup>, J. Ellison<sup>48</sup>, V.D. Elvira<sup>50</sup>, Y. Enari<sup>77</sup>, S. Eno<sup>61</sup>, P. Ermolov<sup>38,‡</sup>, H. Evans<sup>54</sup>, A. Evdokimov<sup>73</sup>, V.N. Evdokimov<sup>39</sup>, A.V. Ferapontov<sup>59</sup>, T. Ferbel<sup>61,71</sup>, F. Fiedler<sup>24</sup>, F. Filthaut<sup>35</sup>, W. Fisher<sup>50</sup>, H.E. Fisk<sup>50</sup>, M. Fortner<sup>52</sup>, H. Fox<sup>42</sup>, S. Fu<sup>50</sup>, S. Fuess<sup>50</sup>, T. Gadfort<sup>70</sup>, C.F. Galea<sup>35</sup>, C. Garcia<sup>71</sup>, A. Garcia-Bellido<sup>71</sup>, V. Gavrilov<sup>37</sup>, P. Gay<sup>13</sup>, W. Geist<sup>19</sup>, W. Geng<sup>15,65</sup>, C.E. Gerber<sup>51</sup>, Y. Gershtein<sup>49,b</sup>, D. Gillberg<sup>6</sup>, G. Ginther<sup>71</sup>, B. Gómez<sup>8</sup>, A. Goussiou<sup>82</sup>, P.D. Grannis<sup>72</sup>, H. Greenlee<sup>50</sup>, Z.D. Greenwood<sup>60</sup>, E.M. Gregores<sup>4</sup>, G. Grenier<sup>20</sup>, Ph. Gris<sup>13</sup>, J.-F. Grivaz<sup>16</sup>, A. Grohsjean<sup>25</sup>, S. Grünendahl<sup>50</sup>, M.W. Grünwald<sup>30</sup>, F. Guo<sup>72</sup>, J. Guo<sup>72</sup>, G. Gutierrez<sup>50</sup>, P. Gutierrez<sup>75</sup>, A. Haas<sup>70</sup>, N.J. Hadley<sup>61</sup>, P. Haefner<sup>25</sup>, S. Hagopian<sup>49</sup>, J. Haley<sup>68</sup>, I. Hall<sup>65</sup>, R.E. Hall<sup>47</sup>, L. Han<sup>7</sup>, K. Harder<sup>44</sup>, A. Harel<sup>71</sup>, J.M. Hauptman<sup>57</sup>, J. Hays<sup>43</sup>, T. Hebbeker<sup>21</sup>, D. Hedin<sup>52</sup>, J.G. Hegeman<sup>34</sup>, A.P. Heinson<sup>48</sup>, U. Heintz<sup>62</sup>, C. Hensel<sup>22,d</sup>, K. Herner<sup>72</sup>, G. Hesketh<sup>63</sup>, M.D. Hildreth<sup>55</sup>, R. Hirsosky<sup>81</sup>, T. Hoang<sup>49</sup>, J.D. Hobbs<sup>72</sup>, B. Hoeneisen<sup>12</sup>, M. Hohlfeld<sup>22</sup>, S. Hossain<sup>75</sup>, P. Houben<sup>34</sup>, Y. Hu<sup>72</sup>, Z. Hubacek<sup>10</sup>, V. Hynek<sup>9</sup>, I. Iashvili<sup>69</sup>, R. Illingworth<sup>50</sup>, A.S. Ito<sup>50</sup>, S. Jabeen<sup>62</sup>, M. Jaffré<sup>16</sup>, S. Jain<sup>75</sup>, K. Jakobs<sup>23</sup>, C. Jarvis<sup>61</sup>, R. Jesik<sup>43</sup>, K. Johns<sup>45</sup>, C. Johnson<sup>70</sup>, M. Johnson<sup>50</sup>, D. Johnston<sup>67</sup>, A. Jonckheere<sup>50</sup>, P. Jonsson<sup>43</sup>, A. Juste<sup>50</sup>, E. Kajfasz<sup>15</sup>, D. Karmanov<sup>38</sup>, P.A. Kasper<sup>50</sup>, I. Katsanos<sup>70</sup>, V. Kaushik<sup>78</sup>, R. Kehoe<sup>79</sup>, S. Kermiche<sup>15</sup>, N. Khalatyan<sup>50</sup>, A. Khanov<sup>76</sup>, A. Kharchilava<sup>69</sup>, Y.N. Kharzheev<sup>36</sup>, D. Khatidze<sup>70</sup>, T.J. Kim<sup>31</sup>, M.H. Kirby<sup>53</sup>, M. Kirsch<sup>21</sup>, B. Klima<sup>50</sup>, J.M. Kohli<sup>27</sup>, J.-P. Konrath<sup>23</sup>, A.V. Kozelov<sup>39</sup>, J. Kraus<sup>65</sup>, T. Kuhl<sup>24</sup>, A. Kumar<sup>69</sup>, A. Kupco<sup>11</sup>, T. Kurča<sup>20</sup>, V.A. Kuzmin<sup>38</sup>, J. Kvita<sup>9</sup>, F. Lacroix<sup>13</sup>, D. Lam<sup>55</sup>, S. Lammers<sup>70</sup>, G. Landsberg<sup>77</sup>, P. Lebrun<sup>20</sup>, W.M. Lee<sup>50</sup>, A. Leflat<sup>38</sup>, J. Lellouch<sup>17</sup>, J. Li<sup>78,‡</sup>, L. Li<sup>48</sup>, Q.Z. Li<sup>50</sup>, S.M. Lietti<sup>5</sup>, J.K. Lim<sup>31</sup>, J.G.R. Lima<sup>52</sup>, D. Lincoln<sup>50</sup>, J. Linnemann<sup>65</sup>, V.V. Lipaev<sup>39</sup>, R. Lipton<sup>50</sup>, Y. Liu<sup>7</sup>, Z. Liu<sup>6</sup>, A. Lobodenko<sup>40</sup>, M. Lokajicek<sup>11</sup>, P. Love<sup>42</sup>, H.J. Lubatti<sup>82</sup>, R. Luna-Garcia<sup>33,e</sup>, A.L. Lyon<sup>50</sup>, A.K.A. Maciel<sup>2</sup>, D. Mackin<sup>80</sup>, R.J. Madaras<sup>46</sup>, P. Mättig<sup>26</sup>, A. Magerkurth<sup>64</sup>, P.K. Mal<sup>82</sup>, H.B. Malbouisson<sup>3</sup>, S. Malik<sup>67</sup>, V.L. Malyshev<sup>36</sup>, Y. Maravin<sup>59</sup>, B. Martin<sup>14</sup>, R. McCarthy<sup>72</sup>, M.M. Meijer<sup>35</sup>, A. Melnitchouk<sup>66</sup>, L. Mendoza<sup>8</sup>, P.G. Mercadante<sup>5</sup>, M. Merkin<sup>38</sup>, K.W. Merritt<sup>50</sup>, A. Meyer<sup>21</sup>, J. Meyer<sup>22,d</sup>, J. Mitrevski<sup>70</sup>, R.K. Mommsen<sup>44</sup>, N.K. Mondal<sup>29</sup>, R.W. Moore<sup>6</sup>, T. Moulik<sup>58</sup>, G.S. Muanza<sup>15</sup>, M. Mulhearn<sup>70</sup>, O. Mundal<sup>22</sup>, L. Mundim<sup>3</sup>, E. Nagy<sup>15</sup>, M. Naimuddin<sup>50</sup>, M. Narain<sup>77</sup>, H.A. Neal<sup>64</sup>, J.P. Negret<sup>8</sup>, P. Neustroev<sup>40</sup>, H. Nilsen<sup>23</sup>, H. Nogima<sup>3</sup>, S.F. Novaes<sup>5</sup>, T. Nunnemann<sup>25</sup>, D.C. O'Neil<sup>6</sup>, G. Obrant<sup>40</sup>, C. Ochando<sup>16</sup>, D. Onoprienko<sup>59</sup>, N. Oshima<sup>50</sup>, N. Osman<sup>43</sup>, J. Osta<sup>55</sup>, R. Otec<sup>10</sup>, G.J. Otero y Garzón<sup>50</sup>, M. Owen<sup>44</sup>, P. Padley<sup>80</sup>, M. Pangilinan<sup>77</sup>, N. Parashar<sup>56</sup>, S.-J. Park<sup>22,d</sup>, S.K. Park<sup>31</sup>, J. Parsons<sup>70</sup>, R. Partridge<sup>77</sup>, N. Parua<sup>54</sup>, A. Patwa<sup>73</sup>, G. Pawloski<sup>80</sup>, B. Penning<sup>23</sup>, M. Perfilov<sup>38</sup>, K. Peters<sup>44</sup>, Y. Peters<sup>26</sup>, P. Pétroff<sup>16</sup>, M. Petteni<sup>43</sup>, R. Piegaia<sup>1</sup>, J. Piper<sup>65</sup>, M.-A. Pleier<sup>22</sup>, P.L.M. Podesta-Lerma<sup>33,f</sup>, V.M. Podstavkov<sup>50</sup>, Y. Pogorelov<sup>55</sup>, M.-E. Pol<sup>2</sup>, P. Polozov<sup>37</sup>, B.G. Pope<sup>65</sup>, A.V. Popov<sup>39</sup>, C. Potter<sup>6</sup>, W.L. Prado da Silva<sup>3</sup>,

H.B. Prosper<sup>49</sup>, S. Protopopescu<sup>73</sup>, J. Qian<sup>64</sup>, A. Quadt<sup>22,d</sup>, B. Quinn<sup>66</sup>, A. Rakitine<sup>42</sup>, M.S. Rangel<sup>2</sup>, K. Ranjan<sup>28</sup>, P.N. Ratoff<sup>42</sup>, P. Renkel<sup>79</sup>, P. Rich<sup>44</sup>, M. Rijssenbeek<sup>72</sup>, I. Ripp-Baudot<sup>19</sup>, F. Rizatdinova<sup>76</sup>, S. Robinson<sup>43</sup>, R.F. Rodrigues<sup>3</sup>, M. Rominsky<sup>75</sup>, C. Royon<sup>18</sup>, P. Rubinov<sup>50</sup>, R. Ruchti<sup>55</sup>, G. Safronov<sup>37</sup>, G. Sajot<sup>14</sup>, A. Sánchez-Hernández<sup>33</sup>, M.P. Sanders<sup>17</sup>, B. Sanghi<sup>50</sup>, G. Savage<sup>50</sup>, L. Sawyer<sup>60</sup>, T. Scanlon<sup>43</sup>, D. Schaile<sup>25</sup>, R.D. Schamberger<sup>72</sup>, Y. Scheglov<sup>40</sup>, H. Schellman<sup>53</sup>, T. Schliephake<sup>26</sup>, S. Schlobohm<sup>82</sup>, C. Schwanenberger<sup>44</sup>, A. Schwartzman<sup>68</sup>, R. Schwienhorst<sup>65</sup>, J. Sekaric<sup>49</sup>, H. Severini<sup>75</sup>, E. Shabalina<sup>51</sup>, M. Shamim<sup>59</sup>, V. Shary<sup>18</sup>, A.A. Shchukin<sup>39</sup>, R.K. Shivpuri<sup>28</sup>, V. Siccaldi<sup>19</sup>, V. Simak<sup>10</sup>, V. Sirotenko<sup>50</sup>, P. Skubic<sup>75</sup>, P. Slattey<sup>71</sup>, D. Smirnov<sup>55</sup>, G.R. Snow<sup>67</sup>, J. Snow<sup>74</sup>, S. Snyder<sup>73</sup>, S. Söldner-Rembold<sup>44</sup>, L. Sonnenschein<sup>17</sup>, A. Sopczak<sup>42</sup>, M. Sosebee<sup>78</sup>, K. Soustruznik<sup>9</sup>, B. Spurlock<sup>78</sup>, J. Stark<sup>14</sup>, V. Stolin<sup>37</sup>, D.A. Stoyanova<sup>39</sup>, J. Strandberg<sup>64</sup>, S. Strandberg<sup>41</sup>, M.A. Strang<sup>69</sup>, E. Strauss<sup>72</sup>, M. Strauss<sup>75</sup>, R. Ströhmer<sup>25</sup>, D. Strom<sup>53</sup>, L. Stutte<sup>50</sup>, S. Sumowidagdo<sup>49</sup>, P. Svoisky<sup>35</sup>, A. Sznajder<sup>3</sup>, A. Tanasijczuk<sup>1</sup>, W. Taylor<sup>6</sup>, B. Tiller<sup>25</sup>, F. Tissandier<sup>13</sup>, M. Titov<sup>18</sup>, V.V. Tokmenin<sup>36</sup>, I. Torchiani<sup>23</sup>, D. Tsybychev<sup>72</sup>, B. Tuchming<sup>18</sup>, C. Tully<sup>68</sup>, P.M. Tuts<sup>70</sup>, R. Unalan<sup>65</sup>, L. Uvarov<sup>40</sup>, S. Uvarov<sup>40</sup>, S. Uzunyan<sup>52</sup>, B. Vachon<sup>6</sup>, P.J. van den Berg<sup>34</sup>, R. Van Kooten<sup>54</sup>, W.M. van Leeuwen<sup>34</sup>, N. Varelas<sup>51</sup>, E.W. Varnes<sup>45</sup>, I.A. Vasilyev<sup>39</sup>, P. Verdier<sup>20</sup>, L.S. Vertogradov<sup>36</sup>, M. Verzocchi<sup>50</sup>, D. Vilanova<sup>18</sup>, F. Villeneuve-Seguié<sup>43</sup>, P. Vint<sup>43</sup>, P. Vokac<sup>10</sup>, M. Voutilainen<sup>67,g</sup>, R. Wagner<sup>68</sup>, H.D. Wahl<sup>49</sup>, M.H.L.S. Wang<sup>50</sup>, J. Warchol<sup>55</sup>, G. Watts<sup>82</sup>, M. Wayne<sup>55</sup>, G. Weber<sup>24</sup>, M. Weber<sup>50,h</sup>, L. Welty-Rieger<sup>54</sup>, A. Wenger<sup>23,i</sup>, N. Wermes<sup>22</sup>, M. Wetstein<sup>61</sup>, A. White<sup>78</sup>, D. Wicke<sup>26</sup>, M.R.J. Williams<sup>42</sup>, G.W. Wilson<sup>58</sup>, S.J. Wimpenny<sup>48</sup>, M. Wobisch<sup>60</sup>, D.R. Wood<sup>63</sup>, T.R. Wyatt<sup>44</sup>, Y. Xie<sup>77</sup>, C. Xu<sup>64</sup>, S. Yacoub<sup>53</sup>, R. Yamada<sup>50</sup>, W.-C. Yang<sup>44</sup>, T. Yasuda<sup>50</sup>, Y.A. Yatsunenko<sup>36</sup>, H. Yin<sup>7</sup>, K. Yip<sup>73</sup>, H.D. Yoo<sup>77</sup>, S.W. Youn<sup>53</sup>, J. Yu<sup>78</sup>, C. Zeitnitz<sup>26</sup>, S. Zelitch<sup>81</sup>, T. Zhao<sup>82</sup>, B. Zhou<sup>64</sup>, J. Zhu<sup>72</sup>, M. Zielinski<sup>71</sup>, D. Zieminska<sup>54</sup>, A. Zieminski<sup>54,‡</sup>, L. Zivkovic<sup>70</sup>, V. Zutshi<sup>52</sup>, and E.G. Zverev<sup>38</sup>

(The DØ Collaboration)

<sup>1</sup>Universidad de Buenos Aires, Buenos Aires, Argentina

<sup>2</sup>LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

<sup>3</sup>Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

<sup>4</sup>Universidade Federal do ABC, Santo André, Brazil

<sup>5</sup>Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil

<sup>6</sup>University of Alberta, Edmonton, Alberta, Canada,

Simon Fraser University, Burnaby, British Columbia,

Canada, York University, Toronto, Ontario, Canada,

and McGill University, Montreal, Quebec, Canada

<sup>7</sup>University of Science and Technology of China, Hefei, People's Republic of China

<sup>8</sup>Universidad de los Andes, Bogotá, Colombia

<sup>9</sup>Center for Particle Physics, Charles University, Prague, Czech Republic

<sup>10</sup>Czech Technical University, Prague, Czech Republic

<sup>11</sup>Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

<sup>12</sup>Universidad San Francisco de Quito, Quito, Ecuador

<sup>13</sup>LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France

<sup>14</sup>LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3,

Institut National Polytechnique de Grenoble, Grenoble, France

<sup>15</sup>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

<sup>16</sup>LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France

<sup>17</sup>LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France

<sup>18</sup>CEA, Irfu, SPP, Saclay, France

<sup>19</sup>IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France

<sup>20</sup>IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

<sup>21</sup>III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany

<sup>22</sup>Physikalisches Institut, Universität Bonn, Bonn, Germany

<sup>23</sup>Physikalisches Institut, Universität Freiburg, Freiburg, Germany

<sup>24</sup>Institut für Physik, Universität Mainz, Mainz, Germany

<sup>25</sup>Ludwig-Maximilians-Universität München, München, Germany

<sup>26</sup>Fachbereich Physik, University of Wuppertal, Wuppertal, Germany

<sup>27</sup>Panjab University, Chandigarh, India

<sup>28</sup>Delhi University, Delhi, India

<sup>29</sup>Tata Institute of Fundamental Research, Mumbai, India

<sup>30</sup>University College Dublin, Dublin, Ireland

<sup>31</sup>Korea Detector Laboratory, Korea University, Seoul, Korea

<sup>32</sup>SungKyunKwan University, Suwon, Korea

- <sup>33</sup> CINVESTAV, Mexico City, Mexico
- <sup>34</sup> FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
- <sup>35</sup> Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
- <sup>36</sup> Joint Institute for Nuclear Research, Dubna, Russia
- <sup>37</sup> Institute for Theoretical and Experimental Physics, Moscow, Russia
- <sup>38</sup> Moscow State University, Moscow, Russia
- <sup>39</sup> Institute for High Energy Physics, Protvino, Russia
- <sup>40</sup> Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- <sup>41</sup> Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
- <sup>42</sup> Lancaster University, Lancaster, United Kingdom
- <sup>43</sup> Imperial College, London, United Kingdom
- <sup>44</sup> University of Manchester, Manchester, United Kingdom
- <sup>45</sup> University of Arizona, Tucson, Arizona 85721, USA
- <sup>46</sup> Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
- <sup>47</sup> California State University, Fresno, California 93740, USA
- <sup>48</sup> University of California, Riverside, California 92521, USA
- <sup>49</sup> Florida State University, Tallahassee, Florida 32306, USA
- <sup>50</sup> Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
- <sup>51</sup> University of Illinois at Chicago, Chicago, Illinois 60607, USA
- <sup>52</sup> Northern Illinois University, DeKalb, Illinois 60115, USA
- <sup>53</sup> Northwestern University, Evanston, Illinois 60208, USA
- <sup>54</sup> Indiana University, Bloomington, Indiana 47405, USA
- <sup>55</sup> University of Notre Dame, Notre Dame, Indiana 46556, USA
- <sup>56</sup> Purdue University Calumet, Hammond, Indiana 46323, USA
- <sup>57</sup> Iowa State University, Ames, Iowa 50011, USA
- <sup>58</sup> University of Kansas, Lawrence, Kansas 66045, USA
- <sup>59</sup> Kansas State University, Manhattan, Kansas 66506, USA
- <sup>60</sup> Louisiana Tech University, Ruston, Louisiana 71272, USA
- <sup>61</sup> University of Maryland, College Park, Maryland 20742, USA
- <sup>62</sup> Boston University, Boston, Massachusetts 02215, USA
- <sup>63</sup> Northeastern University, Boston, Massachusetts 02115, USA
- <sup>64</sup> University of Michigan, Ann Arbor, Michigan 48109, USA
- <sup>65</sup> Michigan State University, East Lansing, Michigan 48824, USA
- <sup>66</sup> University of Mississippi, University, Mississippi 38677, USA
- <sup>67</sup> University of Nebraska, Lincoln, Nebraska 68588, USA
- <sup>68</sup> Princeton University, Princeton, New Jersey 08544, USA
- <sup>69</sup> State University of New York, Buffalo, New York 14260, USA
- <sup>70</sup> Columbia University, New York, New York 10027, USA
- <sup>71</sup> University of Rochester, Rochester, New York 14627, USA
- <sup>72</sup> State University of New York, Stony Brook, New York 11794, USA
- <sup>73</sup> Brookhaven National Laboratory, Upton, New York 11973, USA
- <sup>74</sup> Langston University, Langston, Oklahoma 73050, USA
- <sup>75</sup> University of Oklahoma, Norman, Oklahoma 73019, USA
- <sup>76</sup> Oklahoma State University, Stillwater, Oklahoma 74078, USA
- <sup>77</sup> Brown University, Providence, Rhode Island 02912, USA
- <sup>78</sup> University of Texas, Arlington, Texas 76019, USA
- <sup>79</sup> Southern Methodist University, Dallas, Texas 75275, USA
- <sup>80</sup> Rice University, Houston, Texas 77005, USA
- <sup>81</sup> University of Virginia, Charlottesville, Virginia 22901, USA and
- <sup>82</sup> University of Washington, Seattle, Washington 98195, USA
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We search for the semi-inclusive process  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  using  $2.8 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  recorded by the D0 detector operating at the Fermilab Tevatron Collider. We observe  $26.6 \pm 8.4$  signal events with a significance above background of 3.2 standard deviations yielding a branching ratio of  $\mathcal{B}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010(\text{stat}) \pm 0.011(\text{syst})$ . Under certain theoretical assumptions, these double-charm final states saturate CP-even eigenstates in the  $B_s^0$  decays resulting in a width difference of  $\Delta\Gamma_s^{\text{CP}}/\Gamma_s = 0.072 \pm 0.021(\text{stat}) \pm 0.022(\text{syst})$ . This corresponds to the first evidence for a width difference in the  $B_s^0$  system.

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The phenomenon of CP violation is believed to be intimately tied to explaining the matter dominance in the

present day universe [1]. CP violation is expected to occur in the evolution of neutral particles that can mix between different eigenbases. For the  $B_s^0$  system, the flavor eigenstates can be decomposed into heavy ( $H$ ) and light ( $L$ ) states based on mass or into even and odd states based on CP. The width differences between these eigenstates are defined by  $\Delta\Gamma_s = \Gamma_L - \Gamma_H$  and  $\Delta\Gamma_s^{\text{CP}} = \Gamma_s^{\text{even}} - \Gamma_s^{\text{odd}}$ , respectively. These two quantities are connected with the possible presence of new physics (NP) by  $\Delta\Gamma_s = \Delta\Gamma_s^{\text{CP}} \cos \phi_s$ , where  $\phi_s$  is the CP violating mixing phase which constrains models of NP.

In the standard model (SM) a mixing parameter,  $\Gamma_{12}$ , determining the size of the width difference between CP eigenstates stems from the decays into final states common to both  $B$  and  $\bar{B}$ . Since this quantity is dominated by CKM-favored tree-level decays, it is practically insensitive to NP. Due to the hierarchy of the quark mixing matrix [2], the width difference is governed by the partial widths of  $B_s^0$  decays into final CP eigenstates through the  $b \rightarrow c\bar{c}s$  quark-level transition, such as  $B_s^0 \rightarrow D_s^+ D_s^-$  or  $B_s^0 \rightarrow J/\psi\phi$ . Topologically, the former type of decay mode is a color-allowed spectator, while the latter type is suppressed by the effective color factor. Thus, the semi-inclusive decay modes  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ , where  $D_s^{(*)}$  denotes either  $D_s^\pm$  or  $D_s^{\pm*}$ , are interesting because they give the largest contribution to the difference between the widths of the heavy and light states. The other decay modes are estimated to contribute less than 0.01 to the projected  $\sim 0.15$  value of  $\Delta\Gamma_s/\Gamma_s$  [3], where  $\Gamma_s (= 1/\tau_s) \equiv (\Gamma_L + \Gamma_H)/2$ .

In the Shifman-Voloshin (SV) limit [4], given by  $m_b \rightarrow 2m_c \rightarrow 0$  with  $N_c \rightarrow \infty$  (where  $N_c$  is the number of colors),  $\Delta\Gamma_s^{\text{CP}}$  is saturated by  $\Gamma(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$ . Then the width difference can be related to the branching ratio of  $B_s^0$  mesons to this inclusive double-charm final state by [5, 6]

$$2\mathcal{B}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{\text{CP}} \left[ \frac{\frac{1}{1-2x_f} + \cos \phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f} - \cos \phi_s}{2\Gamma_H} \right], \quad (1)$$

where  $x_f$  is the fraction of the CP-odd component of the decay,  $\Gamma_s^{\text{odd}}/\Gamma_s^{\text{even}} = x_f/(1-x_f)$ . Therefore, given the CP structure of the final state,  $\Delta\Gamma_s^{\text{CP}}$  can be measured using the information from branching ratios without lifetime fits. The irreducible theoretical uncertainty of this approach stems from the omission of CKM-suppressed decays through the  $b \rightarrow u\bar{u}s$  transition which is of order  $2|V_{ub}V_{us}/V_{cb}V_{cs}| \sim 3 - 5\%$ .

In this Letter we report the first evidence for the decay  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ . The study uses a data sample of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV corresponding to an integrated luminosity of  $2.8 \text{ fb}^{-1}$  recorded by the D0 detector operating at the Fermilab Tevatron Collider during 2002 - 2007. This supersedes our previous study of the same

final state based on  $1.3 \text{ fb}^{-1}$  [7]. A similar study based on events containing two  $\phi$  mesons has been reported by the ALEPH collaboration at the CERN LEP Collider [8].

This analysis considers the  $B_s^0$  decay into two  $D_s^{(*)}$  mesons. No attempt is made to identify the photon or  $\pi^0$  emanating from the  $D_s^*$  decay. We search for one hadronic  $D_s$  decay to  $\phi\pi$  and one semileptonic  $D_s$  decay to  $\phi\mu\nu$ , where both  $\phi$  mesons decay to  $K^+K^-$ . The branching fraction is extracted by normalizing the  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  decay to the  $B_s^0 \rightarrow D_s^{(*)} \mu\nu$  decay.

D0 is a general purpose detector [9] consisting of a central tracking system, uranium/liquid-argon calorimeters, and an iron toroid muon spectrometer. The central tracking system allows charged particles to be reconstructed. This system is composed of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT) embedded in a 2 T solenoidal magnetic field. Muons are identified and reconstructed with a magnetic spectrometer located outside of the calorimeter. The spectrometer contains magnetized iron toroids and three super-layers of proportional drift tubes along with scintillation trigger counters. Information from the muon and tracking systems is used to form muon triggers. For the events used by this analysis, the muon from the semileptonic  $D_s$  decay satisfies the inclusive single-muon triggers.

Muons are identified by requiring segments reconstructed in at least two out of the three super-layers in the muon system and associated with a trajectory reconstructed with hits in both the SMT and the CFT. We select muon candidates with transverse momentum  $p_T > 2.0 \text{ GeV}/c$  and total momentum  $p > 3.0 \text{ GeV}/c$ .

$\phi$  mesons are formed from two opposite sign charged particles with  $p_T > 0.7 \text{ GeV}/c$  in the event assuming a kaon mass hypothesis. We require at least one kaon to have an impact parameter clearly separated from the  $p\bar{p}$  interaction point (primary vertex) with at a minimum 4 standard deviations significance. The two-kaon systems satisfying  $p_T(KK) > 2.0 \text{ GeV}/c$  and  $1.010 < m(KK) < 1.030 \text{ GeV}/c^2$  are selected as  $\phi$  candidates.

The hadronic  $D_s$  meson is reconstructed by combining the  $\phi$  candidate with a third track with  $p_T > 0.5 \text{ GeV}/c$  which is assigned the pion mass. The pion is required to have charge opposite to that of the muon. The three particles must form a well-reconstructed vertex displaced from the primary vertex [10]. We require the cosine of the angle between the  $D_s$  momentum and the direction from the primary vertex to the  $D_s$  vertex to be greater than 0.9. The study of the helicity angle  $\theta_\phi$ , the decay angle of a kaon in the  $\phi$  rest frame with respect to the direction of the  $D_s$ , reveals that  $\cos \theta_\phi$  follows a quadratic distribution for the  $D_s$  signal and a flat distribution for the background, and hence a constraint  $|\cos \theta_\phi| > 0.3$  is imposed.

The  $B_s^0 \rightarrow D_s^{(*)} \mu\nu$  decay vertex is reconstructed based on the momentum and direction of the reconstructed

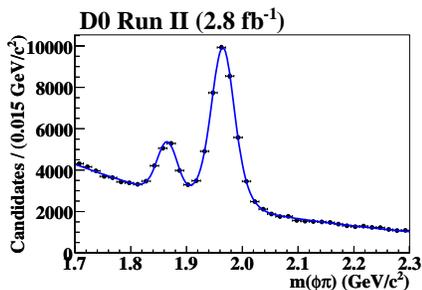


FIG. 1: Invariant mass distribution of the  $\phi\pi$  system for the  $B_s^0 \rightarrow D_s^{(*)}\mu\nu$  sample. The two peaks correspond to the  $D^\pm$  candidates (lower masses) and  $D_s$  candidates (higher masses).

hadronic  $D_s$  candidate and its intersection with the track of an oppositely charged muon. This vertex is required to be located between the primary vertex and the  $D_s$  vertex, whereby the individual  $B_s$  and  $D_s$  vertex displacements are consistent with a  $p\bar{p} \rightarrow B_s \rightarrow D_s$  decay chain. The invariant mass of the  $B_s^0$  candidate is required to be less than  $5.2 \text{ GeV}/c^2$ . We require the daughter particles of the  $B_s^0$  meson to be well isolated from other tracks. Background is further suppressed using a likelihood ratio technique [11] that combines information from the invariant masses and momenta of the reconstructed particles, vertex quality, and the  $\phi$  helicity angle.

The  $\phi\pi$  invariant mass distribution for  $B_s^0$  candidates is shown in Fig 1. Maxima corresponding to the  $D_s \rightarrow \phi\pi$  decay and the  $D^\pm \rightarrow \phi\pi$  decay are clearly observed. The  $D_s$  signal originates from  $\sim 90\%$  semileptonic  $B_s^0$  decays and  $\sim 10\%$  decays of the type  $B \rightarrow D_s D$  followed by semileptonic  $D$  decay. These fractions are determined from Monte Carlo (MC) simulation using the known or estimated branching fractions from the PDG [12] or EVTGEN [13]. Approximately 2% of the events are due to direct charm production  $p\bar{p} \rightarrow DD$ , determined by using full simulation and reconstruction of  $DD^*$  candidates. The overall sample composition is verified using studies of the  $B$  lifetime and mixing parameters [14, 15].

For the second  $\phi$  candidate, we search for an additional pair of oppositely charged particles in the event imposing the same criteria as for the first  $\phi$  meson. The two kaon tracks are combined with the muon track to produce a common vertex for the semileptonic  $D_s$  candidate. We require the  $D_s$  candidate to originate from a common vertex to the hadronic  $D_s$  candidate to complete the  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  decay. By applying the same selection criteria as in the normalization  $B_s^0 \rightarrow D_s^{(*)}\mu\nu$  decay sample, many detector related systematic effects cancel. The total invariant mass is required to lie between  $4.30$  and  $5.20 \text{ GeV}/c^2$ .

Correlated production of this double-charm decay is then determined by examining the two-dimensional dis-

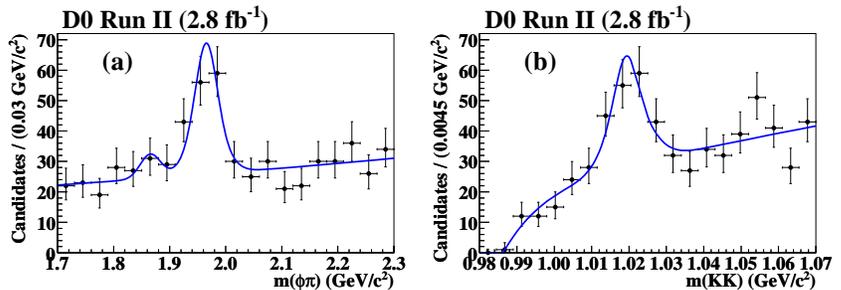


FIG. 2: Projections of the two-dimensional maximum likelihood fit onto invariant mass spectra of the (a)  $\phi\pi$  system from hadronic  $D_s$  decays and (b)  $KK$  system from semileptonic  $D_s$  decays. The peaks in both distributions are explored to search for the correlation between the two systems.

tribution of  $m(\phi\pi)$  from hadronic  $D_s$  candidates versus  $m(KK)$  from semileptonic candidates. We perform a maximum likelihood fit to this distribution with four components: the correlated  $D_s D_s$  component is modeled as the product of signal terms in both dimensions, the uncorrelated components are modeled as the product of the signal term in one dimension and the background term in the other dimension, and the background correlation is modeled as the combination of the background terms in both dimensions. Signal and background models are expected to be identical with those for the  $B_s^0 \rightarrow D_s^{(*)}\mu\nu$  sample, from which the parameters of the signal models are determined. Projections of the two-dimensional likelihood fit onto both axes are displayed in Fig. 2. The fit returns a yield of  $31.0 \pm 9.4$  correlated events.

Three possible sources of background are considered in the correlated sample. Direct charm production from  $p\bar{p}$  is estimated based on the fraction of prompt charm measured directly in the inclusive  $D_s^{(*)}\mu\nu$  sample,  $(10.3 \pm 2.5)\%$ , along with the decay fraction of the second charm quark to a  $D_s$  meson and the reconstruction efficiency for this decay. Due to a shorter decay length of the charm decay, the lifetime requirement reduces its contribution significantly leading to an estimate of  $(1.9 \pm 0.5)\%$ .

The second background source arises from the semileptonic  $B_s^0 \rightarrow D_s^{(*)}\phi\mu\nu$  decay. This can be extracted by studying the  $m(\phi\mu)$  spectrum. In this variable,  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  events tend towards lower values, while  $B_s^0 \rightarrow D_s^{(*)}\phi\mu\nu$  events tend towards higher values.

The third source consists of  $B^{\pm,0} \rightarrow D_s^{(*)} D_s^{(*)} KX$  events. This background can be extracted by studying the visible mass of all reconstructed daughter particles,  $m(D_s\phi\mu)$ . The mass tends to have higher values for  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  than for  $B^{\pm,0} \rightarrow D_s^{(*)} D_s^{(*)} KX$ .

These backgrounds are estimated with MC samples by repeating the fit in three separate regions chosen so that mainly one source contributes to each region in the  $m(\phi\mu) - m(D_s\phi\mu)$  plane. The separate components, the

signal and the two latter backgrounds, are then extracted based on the expected distribution over the three regions of the three components. We find a signal yield of  $26.6 \pm 8.4$  events originating from the  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  process after subtracting the correlated background events.

The signal is normalized to the total  $B_s^0 \rightarrow D_s^{(*)} \mu \nu$  yield taking into account the composition of the sample as discussed earlier. The reconstruction efficiency ratio between the two samples is estimated from MC to be  $0.082 \pm 0.015$ . This small value results from the softer muon momentum spectrum in charm decays as compared to bottom decays. The systematic uncertainty in the ratio contains uncertainties from the modeling of the  $B_s^0$  momentum spectrum, the decay form factors and sample composition, and the trigger and reconstruction efficiencies. Our efficiency model is verified by comparing the expected and measured  $D_s$  yield and the relative  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  to  $B_s^0 \rightarrow D_s^{(*)} \mu \nu$  yields as a function of muon  $p_T$ .

Using all the above inputs, the branching ratio is measured as

$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) \\ = 0.035 \pm 0.010(\text{stat}) \pm 0.008(\text{exp syst}) \pm 0.007(\text{ext}), \end{aligned}$$

where the ‘‘ext’’ uncertainty arises from the external input branching ratios taken from the PDG [12]. This uncertainty contributes  $\sim 45\%$  to the total systematic uncertainty (exp syst  $\oplus$  ext), which leaves room for further improvements in the result. The experimental systematic uncertainty accounts for the rest of the total systematic uncertainty, containing a 37% component from the reconstruction efficiency ratio, 11% from the background estimation, and 4% from the fitting procedure. All other uncertainties are  $\leq 1\%$ .

The probability that the total background would fluctuate to the measured event yield or higher is evaluated to be  $1.2 \times 10^{-3}$  through pseudo-experiments including systematic uncertainties. This corresponds to a significance of 3.2 standard deviations.

Information on the mixing-induced CP asymmetry in the  $B_s^0$  system can be extracted from the branching fraction measurement through Eq. (1). Since the CP structure of the decay is presently not accessible either in theory or experiment, several scenarios for different  $x_f$  values can be considered. In the heavy quark hypothesis [3] along with the SV limit, the CP-odd component of the decay vanishes, leaving the inclusive final state to be CP-even, i.e.  $x_f = 0$ , with a theoretical uncertainty of  $\sim 5\%$  [18]. This scenario is illustrated in Fig. 3, presenting the constraint in the  $\Delta\Gamma_s - \phi_s$  plane from this measurement assuming the relation  $\Delta\Gamma_s = \Delta\Gamma_s^{\text{CP}} \cos \phi_s$ . We take the mean lifetime of  $B_s^0$  meson from Ref. [12].

Furthermore, within the SM framework, the mass eigenstates coincide with the CP eigenstates and the expression used in the previous studies [7, 8] is recovered

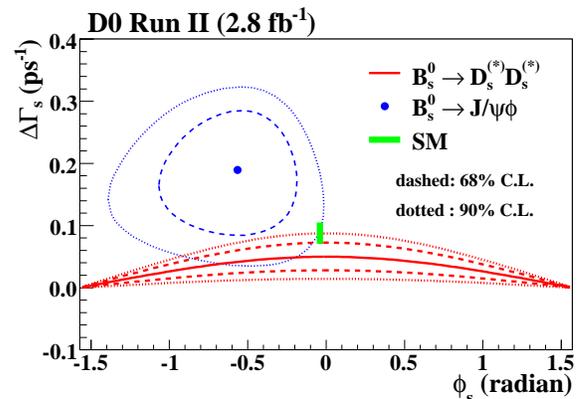


FIG. 3: Constraints in the  $\Delta\Gamma_s - \phi_s$  plane. The solid line represents this measurement under the theoretical assumptions stated in the text and with  $x_f = 0$ . Confidence-level (C.L.) contours from the flavor-tagged decay  $B_s^0 \rightarrow J/\psi\phi$  at D0 [16] are superimposed. Two pairs of lines are 68% (dashed) and 90% (dotted) C.L. intervals of  $\Delta\Gamma_s$  for a given assumed value of  $\phi_s$ , while the contours are the equivalent C.L. regions of  $(\Delta\Gamma_s, \phi_s)$  when measuring simultaneously both parameters. No theoretical uncertainties are reflected in the plot. The SM prediction is represented by the thick vertical line.

and our measurement gives

$$\begin{aligned} \frac{\Delta\Gamma_s^{\text{CP}}}{\Gamma_s} &\simeq \frac{2\mathcal{B}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})}{1 - \mathcal{B}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})} \\ &= 0.072 \pm 0.021(\text{stat}) \pm 0.022(\text{syst}). \end{aligned} \quad (2)$$

This result is consistent with the SM prediction [17] as well as with the current world average value [18]. Therefore, if the CP structure of the final state can be disentangled and the theoretical errors can be controlled, this approach can provide a powerful constraint on mixing and CP violation in the  $B_s^0$  system.

In summary, we performed a study of  $B_s^0$  decays into the semi-inclusive double-charm final state using an integrated luminosity of  $2.8 \text{ fb}^{-1}$  at the D0 experiment. We see evidence of this process and measure the branching ratio as  $\mathcal{B}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010(\text{stat}) \pm 0.011(\text{syst})$ . Based on this measurement and under certain theoretical assumptions, mixing and CP violation information in the  $B_s^0$  meson system are extracted. Due to the one-to-one correspondence between  $\mathcal{B}$  and  $\Delta\Gamma_s^{\text{CP}}$  as in Eq. (2), this represents the first evidence for a width difference in the  $B_s^0$  system. In particular, in the absence of NP, the fractional width difference is derived as  $\Delta\Gamma_s^{\text{CP}}/\Gamma_s = 0.072 \pm 0.021(\text{stat}) \pm 0.022(\text{syst})$ .

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- [a] Visitor from Augustana College, Sioux Falls, SD, USA.
  - [b] Visitor from Rutgers University, Piscataway, NJ, USA.
  - [c] Visitor from The University of Liverpool, Liverpool, UK.
  - [d] Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
  - [e] Visitor from Centro de Investigacion en Computacion - IPN, Mexico City, Mexico.
  - [f] Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.
  - [g] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
  - [h] Visitor from Universität Bern, Bern, Switzerland.
  - [i] Visitor from Universität Zürich, Zürich, Switzerland.
  - [‡] Deceased.
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