

**Measurement of leptonic asymmetries and top-quark polarization in  $t\bar{t}$  production**

V. M. Abazov,<sup>32</sup> B. Abbott,<sup>69</sup> B. S. Acharya,<sup>26</sup> M. Adams,<sup>46</sup> T. Adams,<sup>44</sup> G. D. Alexeev,<sup>32</sup> G. Alkhazov,<sup>36</sup> A. Alton,<sup>58,\*</sup> G. Alverson,<sup>57</sup> A. Askew,<sup>44</sup> S. Atkins,<sup>55</sup> K. Augsten,<sup>7</sup> C. Avila,<sup>5</sup> F. Badaud,<sup>10</sup> L. Bagby,<sup>45</sup> B. Baldin,<sup>45</sup> D. V. Bandurin,<sup>44</sup> S. Banerjee,<sup>26</sup> E. Barberis,<sup>57</sup> P. Baringer,<sup>53</sup> J. F. Bartlett,<sup>45</sup> U. Bassler,<sup>15</sup> V. Bazterra,<sup>46</sup> A. Bean,<sup>53</sup> M. Begalli,<sup>2</sup> L. Bellantoni,<sup>45</sup> S. B. Beri,<sup>24</sup> G. Bernardi,<sup>14</sup> R. Bernhard,<sup>19</sup> I. Bertram,<sup>39</sup> M. Besançon,<sup>15</sup> R. Beuselinck,<sup>40</sup> P. C. Bhat,<sup>45</sup> S. Bhatia,<sup>60</sup> V. Bhatnagar,<sup>24</sup> G. Blazey,<sup>47</sup> S. Blessing,<sup>44</sup> K. Bloom,<sup>61</sup> A. Boehnlein,<sup>45</sup> D. Boline,<sup>66</sup> E. E. Boos,<sup>34</sup> G. Borissov,<sup>39</sup> T. Bose,<sup>56</sup> A. Brandt,<sup>72</sup> O. Brandt,<sup>20</sup> R. Brock,<sup>59</sup> A. Bross,<sup>45</sup> D. Brown,<sup>14</sup> J. Brown,<sup>14</sup> X. B. Bu,<sup>45</sup> M. Buehler,<sup>45</sup> V. Buescher,<sup>21</sup> V. Bunichev,<sup>34</sup> S. Burdin,<sup>39,†</sup> C. P. Buszello,<sup>38</sup> E. Camacho-Pérez,<sup>29</sup> B. C. K. Casey,<sup>45</sup> H. Castilla-Valdez,<sup>29</sup> S. Caughron,<sup>59</sup> S. Chakrabarti,<sup>66</sup> D. Chakraborty,<sup>47</sup> K. M. Chan,<sup>51</sup> A. Chandra,<sup>74</sup> E. Chapon,<sup>15</sup> G. Chen,<sup>53</sup> S. Chevalier-Théry,<sup>15</sup> D. K. Cho,<sup>71</sup> S. W. Cho,<sup>28</sup> S. Choi,<sup>28</sup> B. Choudhary,<sup>25</sup> S. Cihangir,<sup>45</sup> D. Claes,<sup>61</sup> J. Clutter,<sup>53</sup> M. Cooke,<sup>45</sup> W. E. Cooper,<sup>45</sup> M. Corcoran,<sup>74</sup> F. Couderc,<sup>15</sup> M.-C. Cousinou,<sup>12</sup> A. Croc,<sup>15</sup> D. Cutts,<sup>71</sup> A. Das,<sup>42</sup> G. Davies,<sup>40</sup> S. J. de Jong,<sup>30,31</sup> E. De La Cruz-Burelo,<sup>29</sup> F. Déliot,<sup>15</sup> R. Demina,<sup>65</sup> D. Denisov,<sup>45</sup> S. P. Denisov,<sup>35</sup> S. Desai,<sup>45</sup> C. Deterre,<sup>15</sup> K. DeVaughan,<sup>61</sup> H. T. Diehl,<sup>45</sup> M. Diesburg,<sup>45</sup> P. F. Ding,<sup>41</sup> A. Dominguez,<sup>61</sup> A. Dubey,<sup>25</sup> L. V. Dudko,<sup>34</sup> D. Duggan,<sup>62</sup> A. Duperrin,<sup>12</sup> S. Dutt,<sup>24</sup> A. Dyshkant,<sup>47</sup> M. Eads,<sup>61</sup> D. Edmunds,<sup>59</sup> J. Ellison,<sup>43</sup> V. D. Elvira,<sup>45</sup> Y. Enari,<sup>14</sup> H. Evans,<sup>49</sup> A. Evdokimov,<sup>67</sup> V. N. Evdokimov,<sup>35</sup> G. Facini,<sup>57</sup> L. Feng,<sup>47</sup> T. Ferbel,<sup>65</sup> F. Fiedler,<sup>21</sup> F. Filthaut,<sup>30,31</sup> W. Fisher,<sup>59</sup> H. E. Fisk,<sup>45</sup> M. Fortner,<sup>47</sup> H. Fox,<sup>39</sup> S. Fuess,<sup>45</sup> A. Garcia-Bellido,<sup>65</sup> J. A. García-González,<sup>29</sup> G. A. García-Guerra,<sup>29,‡</sup> V. Gavrilov,<sup>33</sup> P. Gay,<sup>10</sup> W. Geng,<sup>12,59</sup> D. Gerbaudo,<sup>63</sup> C. E. Gerber,<sup>46</sup> Y. Gershtein,<sup>62</sup> G. Ginther,<sup>45,65</sup> G. Golovanov,<sup>32</sup> A. Goussiou,<sup>76</sup> P. D. Grannis,<sup>66</sup> S. Greder,<sup>16</sup> H. Greenlee,<sup>45</sup> G. Grenier,<sup>17</sup> Ph. Gris,<sup>10</sup> J.-F. Grivaz,<sup>13</sup> A. Grohsjean,<sup>15,§</sup> S. Grünendahl,<sup>45</sup> M. W. Grünewald,<sup>27</sup> T. Guillemin,<sup>13</sup> G. Gutierrez,<sup>45</sup> P. Gutierrez,<sup>69</sup> S. Hagopian,<sup>44</sup> J. Haley,<sup>57</sup> L. Han,<sup>4</sup> K. Harder,<sup>41</sup> A. Harel,<sup>65</sup> J. M. Hauptman,<sup>52</sup> J. Hays,<sup>40</sup> T. Head,<sup>41</sup> T. Hebbeker,<sup>18</sup> D. Hedin,<sup>47</sup> H. Hegab,<sup>70</sup> A. P. Heinson,<sup>43</sup> U. Heintz,<sup>71</sup> C. Hensel,<sup>20</sup> I. Heredia-De La Cruz,<sup>29</sup> K. Herner,<sup>58</sup> G. Hesketh,<sup>41,¶</sup> M. D. Hildreth,<sup>51</sup> R. Hirosky,<sup>75</sup> T. Hoang,<sup>44</sup> J. D. Hobbs,<sup>66</sup> B. Hoeneisen,<sup>9</sup> J. Hogan,<sup>74</sup> M. Hohlfeld,<sup>21</sup> I. Howley,<sup>72</sup> Z. Hubacek,<sup>7,15</sup> V. Hynek,<sup>7</sup> I. Iashvili,<sup>64</sup> Y. Ilchenko,<sup>73</sup> R. Illingworth,<sup>45</sup> A. S. Ito,<sup>45</sup> S. Jabeen,<sup>71</sup> M. Jaffré,<sup>13</sup> A. Jayasinghe,<sup>69</sup> M. S. Jeong,<sup>28</sup> R. Jesik,<sup>40</sup> K. Johns,<sup>42</sup> E. Johnson,<sup>59</sup> M. Johnson,<sup>45</sup> A. Jonckheere,<sup>45</sup> P. Jonsson,<sup>40</sup> J. Joshi,<sup>43</sup> A. W. Jung,<sup>45</sup> A. Juste,<sup>37</sup> K. Kaadze,<sup>54</sup> E. Kajfasz,<sup>12</sup> D. Karmanov,<sup>34</sup> P. A. Kasper,<sup>45</sup> I. Katsanos,<sup>61</sup> R. Kehoe,<sup>73</sup> S. Kermiche,<sup>12</sup> N. Khalatyan,<sup>45</sup> A. Khanov,<sup>70</sup> A. Kharchilava,<sup>64</sup> Y. N. Kharzheev,<sup>32</sup> I. Kiselevich,<sup>33</sup> J. M. Kohli,<sup>24</sup> A. V. Kozelov,<sup>35</sup> J. Kraus,<sup>60</sup> S. Kulikov,<sup>35</sup> A. Kumar,<sup>64</sup> A. Kupco,<sup>8</sup> T. Kurča,<sup>17</sup> V. A. Kuzmin,<sup>34</sup> S. Lammers,<sup>49</sup> G. Landsberg,<sup>71</sup> P. Lebrun,<sup>17</sup> H. S. Lee,<sup>28</sup> S. W. Lee,<sup>52</sup> W. M. Lee,<sup>45</sup> X. Lei,<sup>42</sup> J. Lellouch,<sup>14</sup> H. Li,<sup>11</sup> L. Li,<sup>43</sup> Q. Z. Li,<sup>45</sup> J. K. Lim,<sup>28</sup> D. Lincoln,<sup>45</sup> J. Linnemann,<sup>59</sup> V. V. Lipaev,<sup>35</sup> R. Lipton,<sup>45</sup> H. Liu,<sup>73</sup> Y. Liu,<sup>4</sup> A. Lobodenko,<sup>36</sup> M. Lokajicek,<sup>8</sup> R. Lopes de Sa,<sup>66</sup> H. J. Lubatti,<sup>76</sup> R. Luna-Garcia,<sup>29,\*\*</sup> A. L. Lyon,<sup>45</sup> A. K. A. Maciel,<sup>1</sup> R. Madar,<sup>15</sup> R. Magaña-Villalba,<sup>29</sup> S. Malik,<sup>61</sup> V. L. Malyshev,<sup>32</sup> Y. Maravin,<sup>54</sup> J. Martínez-Ortega,<sup>29</sup> R. McCarthy,<sup>66</sup> C. L. McGivern,<sup>41</sup> M. M. Meijer,<sup>30,31</sup> A. Melnitchouk,<sup>60</sup> D. Menezes,<sup>47</sup> P. G. Mercadante,<sup>3</sup> M. Merkin,<sup>34</sup> A. Meyer,<sup>18</sup> J. Meyer,<sup>20</sup> F. Miconi,<sup>16</sup> N. K. Mondal,<sup>26</sup> M. Mulhearn,<sup>75</sup> E. Nagy,<sup>12</sup> M. Naimuddin,<sup>25</sup> M. Narain,<sup>71</sup> R. Nayyar,<sup>42</sup> H. A. Neal,<sup>58</sup> J. P. Negret,<sup>5</sup> P. Neustroev,<sup>36</sup> T. Nunnemann,<sup>22</sup> D. Orbaker,<sup>65</sup> J. Orduna,<sup>74</sup> N. Osman,<sup>12</sup> J. Osta,<sup>51</sup> M. Padilla,<sup>43</sup> A. Pal,<sup>72</sup> N. Parashar,<sup>50</sup> V. Parihar,<sup>71</sup> S. K. Park,<sup>28</sup> R. Partridge,<sup>71,||</sup> N. Parua,<sup>49</sup> A. Patwa,<sup>67</sup> B. Penning,<sup>45</sup> M. Perfilov,<sup>34</sup> Y. Peters,<sup>41</sup> K. Petridis,<sup>41</sup> G. Petrillo,<sup>65</sup> P. Pétroff,<sup>13</sup> M.-A. Pleier,<sup>67</sup> P. L. M. Podesta-Lerma,<sup>29,††</sup> V. M. Podstavkov,<sup>45</sup> A. V. Popov,<sup>35</sup> M. Prewitt,<sup>74</sup> D. Price,<sup>49</sup> N. Prokopenko,<sup>35</sup> J. Qian,<sup>58</sup> A. Quadt,<sup>20</sup> B. Quinn,<sup>60</sup> M. S. Rangel,<sup>1</sup> K. Ranjan,<sup>25</sup> P. N. Ratoff,<sup>39</sup> I. Razumov,<sup>35</sup> P. Renkel,<sup>73</sup> I. Ripp-Baudot,<sup>16</sup> F. Rizatdinova,<sup>70</sup> M. Rominsky,<sup>45</sup> A. Ross,<sup>39</sup> C. Royon,<sup>15</sup> P. Rubinov,<sup>45</sup> R. Ruchti,<sup>51</sup> G. Sajot,<sup>11</sup> P. Salcido,<sup>47</sup> A. Sánchez-Hernández,<sup>29</sup> M. P. Sanders,<sup>22</sup> A. S. Santos,<sup>1,‡‡</sup> G. Savage,<sup>45</sup> L. Sawyer,<sup>55</sup> T. Scanlon,<sup>40</sup> R. D. Schamberger,<sup>66</sup> Y. Scheglov,<sup>36</sup> H. Schellman,<sup>48</sup> S. Schlobohm,<sup>76</sup> C. Schwanenberger,<sup>41</sup> R. Schwienhorst,<sup>59</sup> J. Sekaric,<sup>53</sup> H. Severini,<sup>69</sup> E. Shabalina,<sup>20</sup> V. Shary,<sup>15</sup> S. Shaw,<sup>59</sup> A. A. Shchukin,<sup>35</sup> R. K. Shivpuri,<sup>25</sup> V. Simak,<sup>7</sup> P. Skubic,<sup>69</sup> P. Slattery,<sup>65</sup> D. Smirnov,<sup>51</sup> K. J. Smith,<sup>64</sup> G. R. Snow,<sup>61</sup> J. Snow,<sup>68</sup> S. Snyder,<sup>67</sup> S. Söldner-Rembold,<sup>41</sup> L. Sonnenschein,<sup>18</sup> K. Soustruznik,<sup>6</sup> J. Stark,<sup>11</sup> D. A. Stoyanova,<sup>35</sup> M. Strauss,<sup>69</sup> L. Suter,<sup>41</sup> P. Svoisky,<sup>69</sup> M. Takahashi,<sup>41</sup> M. Titov,<sup>15</sup> V. V. Tokmenin,<sup>32</sup> Y.-T. Tsai,<sup>65</sup> K. Tschann-Grimm,<sup>66</sup> D. Tsybychev,<sup>66</sup> B. Tuchming,<sup>15</sup> C. Tully,<sup>63</sup> L. Uvarov,<sup>36</sup> S. Uvarov,<sup>36</sup> S. Uzunyan,<sup>47</sup> R. Van Kooten,<sup>49</sup> W. M. van Leeuwen,<sup>30</sup> N. Varelas,<sup>46</sup> E. W. Varnes,<sup>42</sup> I. A. Vasilyev,<sup>35</sup> P. Verdier,<sup>17</sup> A. Y. Verkheev,<sup>32</sup> L. S. Vertogradov,<sup>32</sup> M. Verzocchi,<sup>45</sup> M. Vesterinen,<sup>41</sup> D. Vilanova,<sup>15</sup> P. Vokac,<sup>7</sup> H. D. Wahl,<sup>44</sup> M. H. L. S. Wang,<sup>45</sup> J. Warchol,<sup>76</sup> G. Watts,<sup>76</sup> M. Wayne,<sup>51</sup> J. Weichert,<sup>21</sup> L. Welty-Rieger,<sup>48</sup> A. White,<sup>72</sup> D. Wicke,<sup>23</sup> M. R. J. Williams,<sup>39</sup> G. W. Wilson,<sup>53</sup> M. Wobisch,<sup>55</sup> D. R. Wood,<sup>57</sup> T. R. Wyatt,<sup>41</sup> Y. Xie,<sup>45</sup> R. Yamada,<sup>45</sup> S. Yang,<sup>4</sup> W.-C. Yang,<sup>41</sup> T. Yasuda,<sup>45</sup> Y. A. Yatsunenko,<sup>32</sup> W. Ye,<sup>66</sup> Z. Ye,<sup>45</sup> H. Yin,<sup>45</sup> K. Yip,<sup>67</sup> S. W. Youn,<sup>45</sup> J. M. Yu,<sup>58</sup> J. Zennaro,<sup>64</sup> T. Zhao,<sup>76</sup> T. G. Zhao,<sup>41</sup> B. Zhou,<sup>58</sup> J. Zhu,<sup>58</sup> M. Zielinski,<sup>65</sup> D. Zieminska,<sup>49</sup> and L. Zivkovic<sup>71</sup>

## (D0 Collaboration)

- <sup>1</sup>LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil  
<sup>2</sup>Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil  
<sup>3</sup>Universidade Federal do ABC, Santo André, Brazil  
<sup>4</sup>University of Science and Technology of China, Hefei, People's Republic of China  
<sup>5</sup>Universidad de los Andes, Bogotá, Colombia  
<sup>6</sup>Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic  
<sup>7</sup>Czech Technical University in Prague, Prague, Czech Republic  
<sup>8</sup>Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic  
<sup>9</sup>Universidad San Francisco de Quito, Quito, Ecuador  
<sup>10</sup>LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France  
<sup>11</sup>LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France  
<sup>12</sup>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France  
<sup>13</sup>LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France  
<sup>14</sup>LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France  
<sup>15</sup>CEA, Irfu, SPP, Saclay, France  
<sup>16</sup>IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France  
<sup>17</sup>IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France  
<sup>18</sup>III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany  
<sup>19</sup>Physikalisches Institut, Universität Freiburg, Freiburg, Germany  
<sup>20</sup>II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany  
<sup>21</sup>Institut für Physik, Universität Mainz, Mainz, Germany  
<sup>22</sup>Ludwig-Maximilians-Universität München, München, Germany  
<sup>23</sup>Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany  
<sup>24</sup>Panjab University, Chandigarh, India  
<sup>25</sup>Delhi University, Delhi, India  
<sup>26</sup>Tata Institute of Fundamental Research, Mumbai, India  
<sup>27</sup>University College Dublin, Dublin, Ireland  
<sup>28</sup>Korea Detector Laboratory, Korea University, Seoul, Korea  
<sup>29</sup>CINVESTAV, Mexico City, Mexico  
<sup>30</sup>Nikhef, Science Park, Amsterdam, The Netherlands  
<sup>31</sup>Radboud University Nijmegen, Nijmegen, The Netherlands  
<sup>32</sup>Joint Institute for Nuclear Research, Dubna, Russia  
<sup>33</sup>Institute for Theoretical and Experimental Physics, Moscow, Russia  
<sup>34</sup>Moscow State University, Moscow, Russia  
<sup>35</sup>Institute for High Energy Physics, Protvino, Russia  
<sup>36</sup>Petersburg Nuclear Physics Institute, St. Petersburg, Russia  
<sup>37</sup>Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain  
<sup>38</sup>Uppsala University, Uppsala, Sweden  
<sup>39</sup>Lancaster University, Lancaster LA1 4YB, United Kingdom  
<sup>40</sup>Imperial College London, London SW7 2AZ, United Kingdom  
<sup>41</sup>The University of Manchester, Manchester M13 9PL, United Kingdom  
<sup>42</sup>University of Arizona, Tucson, Arizona 85721, USA  
<sup>43</sup>University of California Riverside, Riverside, California 92521, USA  
<sup>44</sup>Florida State University, Tallahassee, Florida 32306, USA  
<sup>45</sup>Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA  
<sup>46</sup>University of Illinois at Chicago, Chicago, Illinois 60607, USA  
<sup>47</sup>Northern Illinois University, DeKalb, Illinois 60115, USA  
<sup>48</sup>Northwestern University, Evanston, Illinois 60208, USA  
<sup>49</sup>Indiana University, Bloomington, Indiana 47405, USA  
<sup>50</sup>Purdue University Calumet, Hammond, Indiana 46323, USA  
<sup>51</sup>University of Notre Dame, Notre Dame, Indiana 46556, USA  
<sup>52</sup>Iowa State University, Ames, Iowa 50011, USA  
<sup>53</sup>University of Kansas, Lawrence, Kansas 66045, USA  
<sup>54</sup>Kansas State University, Manhattan, Kansas 66506, USA  
<sup>55</sup>Louisiana Tech University, Ruston, Louisiana 71272, USA  
<sup>56</sup>Boston University, Boston, Massachusetts 02215, USA  
<sup>57</sup>Northeastern University, Boston, Massachusetts 02115, USA

<sup>58</sup>University of Michigan, Ann Arbor, Michigan 48109, USA<sup>59</sup>Michigan State University, East Lansing, Michigan 48824, USA<sup>60</sup>University of Mississippi, University, Mississippi 38677, USA<sup>61</sup>University of Nebraska, Lincoln, Nebraska 68588, USA<sup>62</sup>Rutgers University, Piscataway, New Jersey 08855, USA<sup>63</sup>Princeton University, Princeton, New Jersey 08544, USA<sup>64</sup>State University of New York, Buffalo, New York 14260, USA<sup>65</sup>University of Rochester, Rochester, New York 14627, USA<sup>66</sup>State University of New York, Stony Brook, New York 11794, USA<sup>67</sup>Brookhaven National Laboratory, Upton, New York 11973, USA<sup>68</sup>Langston University, Langston, Oklahoma 73050, USA<sup>69</sup>University of Oklahoma, Norman, Oklahoma 73019, USA<sup>70</sup>Oklahoma State University, Stillwater, Oklahoma 74078, USA<sup>71</sup>Brown University, Providence, Rhode Island 02912, USA<sup>72</sup>University of Texas, Arlington, Texas 76019, USA<sup>73</sup>Southern Methodist University, Dallas, Texas 75275, USA<sup>74</sup>Rice University, Houston, Texas 77005, USA<sup>75</sup>University of Virginia, Charlottesville, Virginia 22901, USA<sup>76</sup>University of Washington, Seattle, Washington 98195, USA

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We present measurements of lepton ( $\ell$ ) angular distributions in top-quark ( $t$ ) pair production and  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \ell^+ \nu b \ell^- \bar{\nu} \bar{b}$  decays produced in  $p\bar{p}$  collisions at a center-of-mass energy of  $\sqrt{s} = 1.96$  TeV, where  $\ell$  is an electron or muon. Using data corresponding to an integrated luminosity of  $5.4 \text{ fb}^{-1}$ , collected with the D0 detector at the Fermilab Tevatron Collider, we measure for the first time the leptonic forward-backward asymmetry in dilepton final states and obtain  $A_{\text{FB}}^{\ell} = (5.8 \pm 5.1(\text{stat}) \pm 1.3(\text{syst}))\%$ , corrected for detector acceptance. This is compared to the standard model prediction of  $A_{\text{FB}}^{\ell}(\text{predicted}) = (4.7 \pm 0.1)\%$ . A deviation from the standard model prediction as previously seen in a D0 measurement based on the analysis of the  $\ell + \text{jets}$  final state is not observed in these dilepton final states. The two results differ from each other by 1.4 standard deviations and are combined to obtain  $A_{\text{FB}}^{\ell} = (11.8 \pm 3.2)\%$ . Furthermore, we present a first study of the top-quark polarization.

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To check the validity of the standard model (SM) of elementary particle physics and to search for possible extensions, we measure the properties of the top ( $t$ ) quark. At the Tevatron  $p\bar{p}$  collider, with  $\sqrt{s} = 1.96$  TeV,  $t\bar{t}$  production is dominated by quark-antiquark ( $q\bar{q}$ ) annihilation. At leading order (LO) in perturbative quantum chromodynamics (QCD), production of  $t\bar{t}$  pairs through  $q\bar{q}$  annihilation is expected to be forward-backward (FB) symmetric in the center-of-mass frame. At next-to-leading order (NLO) QCD, interference leads to a small positive FB asymmetry, which implies that the top (antitop) quark is emitted with higher probability in the direction of the

incoming quark (antiquark) than in the opposite direction. Top pair production through gluon-gluon fusion does not lead to such a FB asymmetry.

SM predictions for the FB asymmetry can be modified by processes beyond the SM [1,2], such as contributions from hypothesized axigluons [3],  $Z'$  or  $W'$  bosons [4], and new scalars [5]. These sources of physics beyond the SM also modify observables sensitive to the top-quark polarization [6].

The CDF and D0 Collaborations have performed measurements of the  $t\bar{t}$  FB asymmetry in  $\ell + \text{jets}$  final states involving signatures with exactly one charged lepton, jets, and an imbalance in transverse momentum ( $\cancel{E}_T$ ) [7–9]. Both collaborations reported measured asymmetries significantly larger than predicted in NLO QCD. D0 finds a significant deviation from NLO QCD predictions of the order of three standard deviations (SD) [8]. The asymmetry in CDF data differs by more than three SD from the NLO QCD prediction at large values of the  $t\bar{t}$  invariant mass ( $m_{t\bar{t}} > 450$  GeV) [7]. The ATLAS and CMS Collaborations have performed measurements of the difference in angular distributions between top quarks and antiquarks in the  $\ell + \text{jets}$  final state using asymmetries based on the top-quark

\*Visitor from Augustana College, Sioux Falls, SD, USA.

†Visitor from The University of Liverpool, Liverpool, UK.

‡Visitor from UPIITA-IPN, Mexico City, Mexico.

§Visitor from DESY, Hamburg, Germany.

||Visitor from SLAC, Menlo Park, CA, USA.

¶Visitor from University College London, London, UK.

\*\*Visitor from Centro de Investigacion en Computacion—IPN, Mexico City, Mexico.

††Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacan, Mexico.

‡‡Visitor from Universidade Estadual Paulista, São Paulo, Brazil.

and antiquark rapidities [10,11] and pseudorapidities [11]. The results are consistent with the SM expectations.

In this article, we test if an excess in the FB asymmetry similar to the one seen in  $\ell + \text{jets}$  final states can also be observed in previously unexplored dilepton final states, where the  $W$  bosons from  $t$  and  $\bar{t}$  decays both decay into  $e\nu_e$ ,  $\mu\nu_\mu$ , or  $\tau\nu_\tau$ , and the  $\tau$  lepton decays leptonically ( $\tau \rightarrow \ell\nu_\ell\nu_\tau$ ). We use data corresponding to an integrated luminosity of  $5.4 \text{ fb}^{-1}$ , collected with the D0 detector in Run II of the Fermilab Tevatron Collider.

In addition to the  $t\bar{t}$  FB asymmetry, where a full reconstruction of the  $t\bar{t}$  event is required, one can also study the FB asymmetry through the  $t$  and  $\bar{t}$  decay products, for example, in the distributions of charged leptons ( $\ell = e, \mu$ ) from  $t \rightarrow W^+ b \rightarrow \ell^+ \nu b$  and  $\bar{t} \rightarrow W^- \bar{b} \rightarrow \ell^- \bar{\nu} \bar{b}$  decays. Here, we investigate such simpler leptonic asymmetries. To study the nature of a possible excess we present measurements of six different types of leptonic asymmetries based on the pseudorapidity and charge of the electrons or muons. Since these asymmetries are determined from the angles of the charged leptons, they are measured with high resolution. In addition, we combine the measurement of the leptonic FB asymmetry with the D0 measurement performed in  $\ell + \text{jets}$  final states [8]. It is important to perform measurements of both the  $t\bar{t}$  FB asymmetry and the leptonic FB asymmetry, because their correlation can be related through top-quark polarization to the underlying dynamics of top-quark production [12]. For this reason, we also present a first study of the longitudinal polarization of the top quark in this article.

A description of the D0 detector can be found in [13]. The selection criteria and object identification of the dilepton ( $ee$ ,  $e\mu$ ,  $\mu\mu$ ) decay channels follow those described in Ref. [14]. To enrich the sample in  $t\bar{t}$  events, we require two isolated, oppositely charged leptons with transverse momentum  $p_T > 15 \text{ GeV}$  and at least two jets with  $p_T > 20 \text{ GeV}$  and detector pseudorapidity  $|\eta_{\text{det}}| < 2.5$  [15]. For the  $e\mu$  channel we require that  $H_T$  (defined as the scalar sum of the larger of the two lepton- $p_T$  values and the scalar  $p_T$  of each of the two most energetic jets) be greater than  $110 \text{ GeV}$ . For  $ee$  and  $\mu\mu$  events we compute a likelihood for the significance of  $\cancel{E}_T$  [16], based on the probability distribution calculated from the value of  $\cancel{E}_T$  and the lepton and jet energy resolutions. We require this likelihood to exceed the value typical for background events. We find that only the  $\mu\mu$  channel benefits from an additional restriction on  $\cancel{E}_T$ , and to increase signal purity, we therefore require  $\cancel{E}_T > 40 \text{ GeV}$  for the  $\mu\mu$  final state. We select a  $t\bar{t}$  sample with a signal to background ratio of 3.2, 3.7, and 0.9 in the  $ee$ ,  $e\mu$ , and  $\mu\mu$  final states, respectively.

To simulate  $t\bar{t}$  production, the MC@NLO [17] generator is used assuming  $m_t = 172.5 \text{ GeV}$ . The production of top quarks is simulated at NLO, while the decay is simulated only at LO. To include full NLO QCD corrections to both production and decay as well as mixed QCD and quantum

electrodynamic corrections and mixed QCD and weak corrections to the production amplitudes (denoted by ‘‘QCD + EW’’), we simultaneously correct the normalized lepton and antilepton rapidity distributions in MC@NLO using the predictions of Ref. [18]. HERWIG [19] is used to simulate fragmentation, hadronization, and decays of short-lived particles, and the generated events are processed through a full detector simulation using GEANT [20]. The Monte Carlo (MC) events are overlaid with data from random bunch crossings to model the effect of detector noise and additional  $p\bar{p}$  interactions. The same reconstruction programs are then applied to data and MC events. The background in the dilepton channel arises from  $Z/\gamma^* \rightarrow \ell^+ \ell^-$  and diboson events ( $WW$ ,  $WZ$ , and  $ZZ$ ) with associated jets, from instrumental background where a jet is misidentified as a lepton, and from heavy quarks that decay into leptons that pass isolation requirements. A detailed description of these processes and their generation can be found in Ref. [21].

Leptons are reconstructed with excellent resolution on the measurements of their angles and electric charge. In contrast, it is challenging to reconstruct the four-momenta of the  $t$  and  $\bar{t}$  quarks, since the kinematics is underconstrained because of the two neutrinos in the final state. Rather than determining the  $t$  and  $\bar{t}$  four-momenta, as in Refs. [7–9], we measure observables correlated to the FB asymmetry, which depend solely on the  $\eta$  and electric charge of the lepton  $\ell$ , as proposed in Ref. [6]. The asymmetry for leptons is defined as

$$A^\ell = \frac{N_{\ell^+}(\eta > 0) - N_{\ell^-}(\eta > 0)}{N_{\ell^+}(\eta > 0) + N_{\ell^-}(\eta > 0)}, \quad (1)$$

where  $N_{\ell^-}(\eta)$  and  $N_{\ell^+}(\eta)$  correspond to the number of leptons and antileptons as a function of  $\eta$ , respectively. If  $CP$  invariance holds in  $t\bar{t}$  production and decay, then  $N_{\ell^+}(\eta) = N_{\ell^-}(-\eta)$ , and  $A^\ell$  is equal to the leptonic FB asymmetry,  $A^\ell = A_{\text{FB}}^{\ell^+} = -A_{\text{FB}}^{\ell^-}$ , defined as

$$A_{\text{FB}}^{\ell^\pm} = \frac{N_{\ell^\pm}(\eta > 0) - N_{\ell^\pm}(\eta < 0)}{N_{\ell^\pm}(\eta > 0) + N_{\ell^\pm}(\eta < 0)}. \quad (2)$$

The asymmetries  $A_{\text{FB}}^{\ell^+}$  and  $A_{\text{FB}}^{\ell^-}$  are statistically independent and opposite. We can therefore combine the asymmetries for  $\ell^+$  and  $\ell^-$  by multiplying  $\eta$  with the charge  $Q$  of each lepton:

$$A_{\text{FB}}^\ell = \frac{N_\ell(Q \cdot \eta > 0) - N_\ell(Q \cdot \eta < 0)}{N_\ell(Q \cdot \eta > 0) + N_\ell(Q \cdot \eta < 0)}. \quad (3)$$

In analogy to the FB asymmetry for  $t$  and  $\bar{t}$  quarks, we define an angular asymmetry for leptons:

$$A^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}, \quad (4)$$

where  $\Delta\eta = \eta_{\ell^+} - \eta_{\ell^-}$ . The asymmetry  $A_{CP}^\ell$  corresponds to a longitudinal asymmetry in spin orientation relative to the proton beam direction. It is defined as

$$A_{CP}^{\ell} = \frac{N_{\ell^+}(\eta > 0) - N_{\ell^-}(\eta < 0)}{N_{\ell^+}(\eta > 0) + N_{\ell^-}(\eta < 0)}. \quad (5)$$

This asymmetry is sensitive to  $s$ -channel exchanges of heavy nonscalar resonances with  $CP$ -violating couplings to quarks, but not to possible  $P$ - and  $CP$ -violating effects from an  $s$ -channel exchange of Higgs bosons [6].

The asymmetries are measured in four ways using  $\eta$  and  $Q$  of the leptons: separate  $\eta$  distributions for (i)  $\ell^+$  and (ii)  $\ell^-$ , (iii) the charge-signed pseudorapidity,  $Q \cdot \eta$ , and (iv)  $\Delta\eta$ . They are presented in Fig. 1. To extract the asymmetries for  $t\bar{t}$  events from the distributions shown in Fig. 1, we subtract the background and then correct for effects from event reconstruction and acceptance. The correction for detector acceptance is performed by multiplying the background-subtracted number of events with the inverse of the selection efficiency. This is calculated using  $t\bar{t}$  MC events, where we evaluate the selection efficiency separately for 20 bins in lepton  $\eta$ , to reduce the model dependence of our acceptance correction and to provide sufficient MC statistics.

The resolution of the measurement of lepton  $\eta$  is obtained from studies of  $t\bar{t}$  MC events by comparing the generated value of  $\eta$  with the value measured following the event reconstruction. For electrons and muons, we use the  $\eta$  of tracks measured in the tracking system and find this resolution to be the same for both types of leptons. This resolution is also investigated using cosmic-ray muons that appear as dimuon events and is found to be  $\approx 0.0026$ , consistent with the MC expectation. For  $\approx 99.8\%$  of the electrons or muons in  $t\bar{t}$  MC events, the sign of lepton  $\eta$  is correctly reconstructed. Migration of events within the

“forward” or “backward” regions does not affect the reconstructed angular asymmetry except for negligible acceptance corrections. The reconstruction effects on the measurement of  $\eta$  can therefore be neglected for charged leptons.

The  $Z$  + jets background, which is predicted through MC simulation [21], contributes to the asymmetry. To study the influence of the  $Z$  + jets background, we perform measurements of all six asymmetries in a sample dominated by  $Z$  + jets production in final states with two electrons or two muons. Applying the same event selections as for the final  $t\bar{t}$  enriched sample, except for the  $\cancel{E}_T$  significance likelihood and  $\cancel{E}_T$  requirements, all asymmetries are measured using the same procedure as for the measurement of  $t\bar{t}$  asymmetries, but treating  $Z$  + jets as “signal” and  $t\bar{t}$  as “background.” In this control sample, all other background contributions are negligible. The data and MC predictions for the  $\eta$  distribution of positively and negatively charged leptons, for  $Q \cdot \eta$ , and  $\Delta\eta$ , are in good agreement, as presented in [22].

To verify that the measurement of the  $t\bar{t}$  asymmetries is unbiased and correctly estimates the statistical uncertainty of the result, we perform the measurement using ensembles of MC pseudoexperiments. To obtain samples with different asymmetries, we mix a  $t\bar{t}$  MC event sample weighted to have no asymmetry with different fractions of  $t\bar{t}$  MC events with a SM asymmetry. We fluctuate the expected number of events in the “forward” and “backward” direction for each pseudoexperiment assuming Poisson statistics and apply the same procedure as for data to extract the asymmetry. This test shows that the measurement is unbiased and that the statistical uncertainties are estimated correctly.

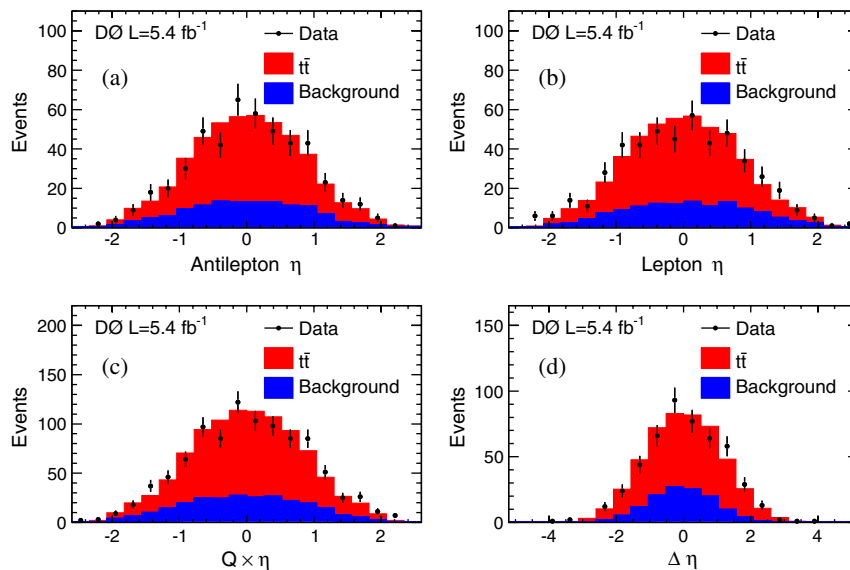


FIG. 1 (color online). Pseudorapidity distributions of the charged leptons for the combination of the  $ee$ ,  $e\mu$ , and  $\mu\mu$  final states after the selection criteria have been applied. The  $\eta$  distribution of positively (a) and negatively (b) charged leptons, the distribution of  $Q \cdot \eta$  (c), and the distribution of  $\Delta\eta = \eta_{\ell^+} - \eta_{\ell^-}$  (d) are shown. The vertical error bars indicate the statistical uncertainty. The  $t\bar{t}$  contribution is normalized to the data after background subtraction.

Systematic uncertainties can affect the distributions in lepton  $\eta$ . In particular, the energy scale for jets, the jet energy resolution, the jet reconstruction, the normalization of background, the MC-derived acceptance, and the finite number of MC events can shift the measured asymmetry. The normalization of the background has uncertainties from diboson and  $Z + \text{jets}$  cross sections, as well as a 6.1% uncertainty on the data sample's integrated luminosity. The systematic uncertainties on the light- and heavy-flavor jet energy scales, the jet energy resolution, and the jet reconstruction can affect the acceptance. We evaluate the size of these uncertainties by applying the variation in acceptance corrections and in the differential distribution of lepton  $\eta$  in deriving the  $t\bar{t}$  asymmetry.

In addition, we compare the acceptance from single leptons obtained from simulated  $t\bar{t}$  events with the acceptance obtained from  $Z \rightarrow \ell^+ \ell^-$  data. We select a data sample enriched in  $Z \rightarrow \ell^+ \ell^-$  events, where one lepton is required to pass tight lepton-selection criteria to function as a ‘‘tag’’ and the other ‘‘probe’’ lepton to pass a loose lepton selection. The acceptance is evaluated as a function of  $\eta$  by applying a tight-lepton identification requirement on the probe. No significant difference is observed between the acceptance for positive or negative pseudorapidities, or between positively and negatively charged leptons. A systematic uncertainty on the acceptance is defined for each lepton charge by the difference in acceptance between the forward and backward hemisphere of the detector. This study is performed separately for electrons and muons. The systematic uncertainties are added in quadrature to yield the total systematic uncertainties given in Table I.

Using the distributions in Fig. 1, the lepton asymmetries of Eqs. (1)–(5) are measured. The raw asymmetries are corrected for acceptance effects (‘‘unfolded’’) and compared to the predictions from MC@NLO including QCD + EW corrections [6]. All values are listed in Table II. The unfolded asymmetries are in agreement with the SM predictions within errors.

The asymmetry  $A_{\text{FB}}^\ell$  defined in Eq. (2) is also measured in  $\ell + \text{jets}$  final states [8]. The result for  $A_{\text{FB}}^\ell = (15.2 \pm 4.0)\%$  is compared to a predicted value from MC@NLO of  $(2.1 \pm 0.1)\%$  in Ref. [17]. We checked that our current predicted asymmetry of  $(4.7 \pm 0.1)\%$  is independent of the final state and that the difference from the prediction given

TABLE I. Systematic uncertainties for the six unfolded asymmetries defined in Eqs. (1)–(5) for the combination of all dilepton final states. All values are given in %.

Source	$A^\ell$	$A_{\text{FB}}^{\ell^+}$	$A_{\text{FB}}^{\ell^-}$	$A_{\text{FB}}^\ell$	$A^{\ell\ell}$	$A_{\text{CP}}^\ell$
Jets	1.1	0.8	1.7	1.0	1.5	1.2
MC statistics	0.4	0.4	0.4	0.3	0.5	0.3
Background normalization	0.3	0.3	0.6	0.3	0.7	0.3
Acceptance	0.7	0.2	1.5	0.7	2.3	0.9
Total	1.4	1.1	2.4	1.3	2.9	1.6

in Ref. [17], which should be considered superseded, is only due to the additional QCD + EW corrections as described previously. The dominant systematic uncertainty on the prediction and on our measurement in dilepton final states is given by jet reconstruction related systematics. The total uncertainty of the measurement is dominated by the statistical component.

Since the  $\ell + \text{jets}$  and dilepton final states are selected to be statistically independent, we can combine the two asymmetries  $A_{\text{FB}}^\ell$  using the BLUE method [23,24]. All systematic uncertainties evaluated in both measurements are treated as fully correlated. The difference between the two individual measurements is 1.4 SD. The combination yields a leptonic FB asymmetry of  $A_{\text{FB}}^\ell = (11.8 \pm 3.2)\%$ , where the  $\ell + \text{jets}$  channel contributes 64% and the dilepton channel 36% of the information. This represents an improvement of about 20% relative to the uncertainty in the  $\ell + \text{jets}$  channel alone. Comparing the combined result to the predicted leptonic FB asymmetry from MC@NLO plus higher order QCD + EW corrections,  $A_{\text{FB}}^\ell(\text{predicted}) = (4.7 \pm 0.1)\%$ , we observe a disagreement at the level of 2.2 SD.

To further investigate this deviation of the asymmetry from the SM prediction, we analyze the longitudinal polarization of the top quark. While in the SM top quarks are expected to be produced unpolarized in  $t\bar{t}$  events, there are many beyond the SM models that would enhance the  $t\bar{t}$  FB asymmetry [1] and therefore the leptonic asymmetries defined in Eqs. (1)–(5), and would also lead to a nonvanishing longitudinal polarization of the top quark. Examples are models with new parity-violating interactions. In the absence of effects from acceptance, the distribution of  $\cos\theta^-$  and  $\cos\theta^+$  should be isotropic [6] for unpolarized top quarks, where  $\theta^+$  ( $\theta^-$ ) is the angle between the direction of the  $\ell^+$  ( $\ell^-$ ) in the  $t$  ( $\bar{t}$ ) rest frame and the  $t$  ( $\bar{t}$ ) direction in the  $t\bar{t}$  rest frame. A longitudinal

TABLE II. Measured asymmetries for leptons, as defined in Eqs. (1)–(5), including statistical and systematic uncertainties for the combined dilepton final states using raw and unfolded distributions are compared to predictions from MC@NLO including QCD + EW corrections. Our predictions are calculated using the NLO QCD + EW distributions in both numerator and denominator of Eqs. (1)–(5). This is different from the calculations in Refs. [6,18] where the denominator is calculated in LO QCD to derive expressions for the asymmetries of  $\mathcal{O}(\alpha_s)$ . All values are given in %.

	Raw	Unfolded	Predicted
$A^\ell$	$2.9 \pm 6.1 \pm 0.9$	$2.5 \pm 7.1 \pm 1.4$	$4.7 \pm 0.1$
$A_{\text{FB}}^{\ell^+}$	$4.5 \pm 6.1 \pm 1.1$	$4.1 \pm 6.8 \pm 1.1$	$4.4 \pm 0.2$
$A_{\text{FB}}^{\ell^-}$	$-1.2 \pm 6.1 \pm 1.3$	$-8.4 \pm 7.4 \pm 2.4$	$-5.0 \pm 0.2$
$A_{\text{FB}}^\ell$	$3.1 \pm 4.3 \pm 0.8$	$5.8 \pm 5.1 \pm 1.3$	$4.7 \pm 0.1$
$A^{\ell\ell}$	$3.3 \pm 6.0 \pm 1.1$	$5.3 \pm 7.9 \pm 2.9$	$6.2 \pm 0.2$
$A_{\text{CP}}^\ell$	$1.8 \pm 4.3 \pm 1.0$	$-1.8 \pm 5.1 \pm 1.6$	$-0.3 \pm 0.1$

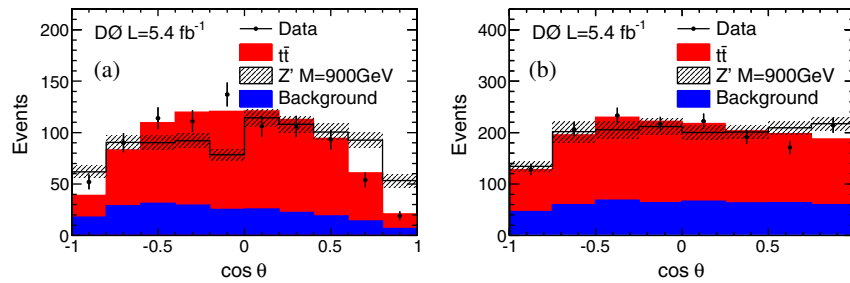


FIG. 2 (color online). The distribution of  $\cos\theta$  is shown for the combination of the dilepton channels (a) and the  $\ell + \text{jets}$  channels (b). The data are compared to the SM predictions. The vertical error bars on the data points indicate the statistical uncertainty of the data. The distribution of  $t\bar{t}$  pairs produced via a hypothetical  $Z'$  boson is also shown; the uncertainty due to the limited size of the MC sample is shown by the shaded band. The same  $Z'$  model as in [26,27] is used.

polarization of the top quark would cause asymmetric  $\cos\theta^\pm$  distributions.

Assuming  $CP$  invariance, i.e. that the distributions of  $\cos\theta^+$  and  $\cos\theta^-$  are equal, we measure the distribution of  $\cos\theta$ , defined by the sum of the  $\cos\theta^\pm$  distributions. The calculation of the angles  $\theta^\pm$  requires a transformation of the momenta of the charged leptons into the  $t$  and  $\bar{t}$  quark rest frames. Every event must therefore be fully reconstructed. This is performed using the neutrino weighting method, devised originally to measure the top-quark mass in the dilepton channel [25] and recently applied to measure  $t\bar{t}$  spin correlations [21].

In Fig. 2, the  $\cos\theta$  distribution is shown separately for the dilepton and  $\ell + \text{jets}$  final states. The distribution for  $t\bar{t}$  events produced via a leptophobic topcolor  $Z'$  boson, with the same parity-violating couplings to quarks as the SM  $Z$  boson and a width  $\Gamma = 0.012M_Z$  [26,27], is also shown to illustrate the effect of producing  $t$  and  $\bar{t}$  quarks with longitudinal polarization. The agreement between the data and the SM prediction in both distributions is good, yielding a Kolmogorov-Smirnov test probability of 14% in the dilepton channel and 58% in the  $\ell + \text{jets}$  channel. There is no significant hint of new sources of parity violation leading to a longitudinal polarization in  $t\bar{t}$  production.

In conclusion, we measured angular asymmetries in  $t\bar{t}$  production based on  $\eta$  distributions of charged leptons in dilepton final states for the first time. We find the leptonic

FB asymmetry  $A_{\text{FB}}^\ell$  and the lepton asymmetry  $A^{\ell\ell}$  in agreement with zero and with the SM prediction and do not observe an excess such as previously reported in  $\ell + \text{jets}$  final states. Combining our measurement of  $A_{\text{FB}}^\ell$  with the measurement performed using leptons in  $\ell + \text{jets}$  final states yields  $A_{\text{FB}}^\ell = (11.8 \pm 3.2)\%$ , which is 2.2 SD above the calculated value including higher order QCD + EW corrections of  $A_{\text{FB}}^\ell(\text{predicted}) = (4.7 \pm 0.1)\%$ . To explore the nature of this deviation, the top-quark polarization in the dilepton and  $\ell + \text{jets}$  final states has been studied for the first time and shows good agreement between the data and the SM prediction in both channels.

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