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Measurement of the effective weak mixing angle in  $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$  events

V.M. Abazov,<sup>31</sup> B. Abbott,<sup>67</sup> B.S. Acharya,<sup>25</sup> M. Adams,<sup>46</sup> T. Adams,<sup>44</sup> J.P. Agnew,<sup>41</sup> G.D. Alexeev,<sup>31</sup> G. Alkhazov,<sup>35</sup> A. Alton<sup>a</sup>,<sup>56</sup> A. Askew,<sup>44</sup> S. Atkins,<sup>54</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>73</sup> S. Banerjee,<sup>25</sup> E. Barberis,<sup>55</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>23</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>58</sup> V. Bhatnagar,<sup>23</sup> G. Blazey,<sup>47</sup> S. Blessing,<sup>44</sup> K. Bloom,<sup>59</sup> A. Boehnlein,<sup>45</sup> D. Boline,<sup>64</sup> E.E. Boos,<sup>33</sup> G. Borissov,<sup>39</sup> M. Borysova<sup>l</sup>,<sup>38</sup> A. Brandt,<sup>70</sup> O. Brandt,<sup>20</sup> R. Brock,<sup>57</sup> A. Bross,<sup>45</sup> D. Brown,<sup>14</sup> X.B. Bu,<sup>45</sup> M. Buehler,<sup>45</sup> V. Buescher,<sup>21</sup> V. Bunichev,<sup>33</sup> S. Burdin<sup>b</sup>,<sup>39</sup> C.P. Buszello,<sup>37</sup> E. Camacho-Pérez,<sup>28</sup> B.C.K. Casey,<sup>45</sup> H. Castilla-Valdez,<sup>28</sup> S. Caughron,<sup>57</sup> S. Chakrabarti,<sup>64</sup> K.M. Chan,<sup>51</sup> A. Chandra,<sup>72</sup> E. Chapon,<sup>15</sup> G. Chen,<sup>53</sup> S.W. Cho,<sup>27</sup> S. Choi,<sup>27</sup> B. Choudhary,<sup>24</sup> S. Cihangir,<sup>45</sup> D. Claes,<sup>59</sup> J. Clutter,<sup>53</sup> M. Cooke<sup>k</sup>,<sup>45</sup> W.E. Cooper,<sup>45</sup> M. Corcoran,<sup>72</sup> F. Couderc,<sup>15</sup> M.-C. Cousinou,<sup>12</sup> D. Cutts,<sup>69</sup> A. Das,<sup>42</sup> G. Davies,<sup>40</sup> S.J. de Jong,<sup>29,30</sup> E. De La Cruz-Burelo,<sup>28</sup> F. Déliot,<sup>15</sup> R. Demina,<sup>63</sup> D. Denisov,<sup>45</sup> S.P. Denisov,<sup>34</sup> S. Desai,<sup>45</sup> C. Deterre<sup>c</sup>,<sup>20</sup> K. DeVaughan,<sup>59</sup> H.T. Diehl,<sup>45</sup> M. Diesburg,<sup>45</sup> P.F. Ding,<sup>41</sup> A. Dominguez,<sup>59</sup> A. Dubey,<sup>24</sup> L.V. Dudko,<sup>33</sup> A. Duperrin,<sup>12</sup> S. Dutt,<sup>23</sup> M. Eads,<sup>47</sup> D. Edmunds,<sup>57</sup> J. Ellison,<sup>43</sup> V.D. Elvira,<sup>45</sup> Y. Enari,<sup>14</sup> H. Evans,<sup>49</sup> V.N. Evdokimov,<sup>34</sup> A. Fauré,<sup>15</sup> L. Feng,<sup>47</sup> T. Ferbel,<sup>63</sup> F. Fiedler,<sup>21</sup> F. Filthaut,<sup>29,30</sup> W. Fisher,<sup>57</sup> H.E. Fisk,<sup>45</sup> M. Fortner,<sup>47</sup> H. Fox,<sup>39</sup> S. Fuess,<sup>45</sup> P.H. Garbincius,<sup>45</sup> A. Garcia-Bellido,<sup>63</sup> J.A. García-González,<sup>28</sup> V. Gavrilov,<sup>32</sup> W. Geng,<sup>12,57</sup> C.E. Gerber,<sup>46</sup> Y. Gershtein,<sup>60</sup> G. Ginther,<sup>45,63</sup> O. Gogota,<sup>38</sup> G. Golovanov,<sup>31</sup> P.D. Grannis,<sup>64</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>c</sup>,<sup>15</sup> S. Grünendahl,<sup>45</sup> M.W. Grünewald,<sup>26</sup> T. Guillemain,<sup>13</sup> G. Gutierrez,<sup>45</sup> P. Gutierrez,<sup>67</sup> J. Haley,<sup>68</sup> L. Han,<sup>4</sup> K. Harder,<sup>41</sup> A. Harel,<sup>63</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>68</sup> A.P. Heinson,<sup>43</sup> U. Heintz,<sup>69</sup> C. Hensel,<sup>1</sup> I. Heredia-De La Cruz<sup>d</sup>,<sup>28</sup> K. Herner,<sup>45</sup> G. Hesketh<sup>f</sup>,<sup>41</sup> M.D. Hildreth,<sup>51</sup> R. Hirosky,<sup>73</sup> T. Hoang,<sup>44</sup> J.D. Hobbs,<sup>64</sup> B. Hoeneisen,<sup>9</sup> J. Hogan,<sup>72</sup> M. Hohlfield,<sup>21</sup> J.L. Holzbauer,<sup>58</sup> I. Howley,<sup>70</sup> Z. Hubacek,<sup>7,15</sup> V. Hynek,<sup>7</sup> I. Iashvili,<sup>62</sup> Y. Ilchenko,<sup>71</sup> R. Illingworth,<sup>45</sup> A.S. Ito,<sup>45</sup> S. Jabeen<sup>m</sup>,<sup>45</sup> M. Jaffré,<sup>13</sup> A. Jayasinghe,<sup>67</sup> M.S. Jeong,<sup>27</sup> R. Jesik,<sup>40</sup> P. Jiang,<sup>4</sup> K. Johns,<sup>42</sup> E. Johnson,<sup>57</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>36</sup> E. Kajfasz,<sup>12</sup> D. Karmanov,<sup>33</sup> I. Katsanos,<sup>59</sup> M. Kaur,<sup>23</sup> R. Kehoe,<sup>71</sup> S. Kermiche,<sup>12</sup> N. Khalatyan,<sup>45</sup> A. Khanov,<sup>68</sup> A. Kharchilava,<sup>62</sup> Y.N. Kharzheev,<sup>31</sup> I. Kiselevich,<sup>32</sup> J.M. Kohli,<sup>23</sup> A.V. Kozelov,<sup>34</sup> J. Kraus,<sup>58</sup> A. Kumar,<sup>62</sup> A. Kupco,<sup>8</sup> T. Kurča,<sup>17</sup> V.A. Kuzmin,<sup>33</sup> S. Lammers,<sup>49</sup> P. Lebrun,<sup>17</sup> H.S. Lee,<sup>27</sup> S.W. Lee,<sup>52</sup> W.M. Lee,<sup>45</sup> X. Lei,<sup>42</sup> J. Lellouch,<sup>14</sup> D. Li,<sup>14</sup> H. Li,<sup>73</sup> L. Li,<sup>43</sup> Q.Z. Li,<sup>45</sup> J.K. Lim,<sup>27</sup> D. Lincoln,<sup>45</sup> J. Linnemann,<sup>57</sup> V.V. Lipaev,<sup>34</sup> R. Lipton,<sup>45</sup> H. Liu,<sup>71</sup> Y. Liu,<sup>4</sup> A. Lobodenko,<sup>35</sup> M. Lokajicek,<sup>8</sup> R. Lopes de Sa,<sup>45</sup> R. Luna-Garcia<sup>g</sup>,<sup>28</sup> A.L. Lyon,<sup>45</sup> A.K.A. Maciel,<sup>1</sup> R. Madar,<sup>19</sup> R. Magaña-Villalba,<sup>28</sup> S. Malik,<sup>59</sup> V.L. Malyshev,<sup>31</sup> J. Mansour,<sup>20</sup> J. Martínez-Ortega,<sup>28</sup> R. McCarthy,<sup>64</sup> C.L. McGivern,<sup>41</sup> M.M. Meijer,<sup>29,30</sup> A. Melnitchouk,<sup>45</sup> D. Menezes,<sup>47</sup> P.G. Mercadante,<sup>3</sup> M. Merkin,<sup>33</sup> A. Meyer,<sup>18</sup> J. Meyer<sup>i</sup>,<sup>20</sup> F. Miconi,<sup>16</sup> N.K. Mondal,<sup>25</sup> M. Mulhearn,<sup>73</sup> E. Nagy,<sup>12</sup> M. Narain,<sup>69</sup> R. Nayyar,<sup>42</sup> H.A. Neal,<sup>56</sup> J.P. Negret,<sup>5</sup> P. Neustroev,<sup>35</sup> H.T. Nguyen,<sup>73</sup> T. Nunnemann,<sup>22</sup> J. Orduna,<sup>72</sup> N. Osman,<sup>12</sup> J. Osta,<sup>51</sup> A. Pal,<sup>70</sup> N. Parashar,<sup>50</sup> V. Parihar,<sup>69</sup> S.K. Park,<sup>27</sup> R. Partridge<sup>e</sup>,<sup>69</sup> N. Parua,<sup>49</sup> A. Patwa<sup>j</sup>,<sup>65</sup> B. Penning,<sup>45</sup> M. Perfilov,<sup>33</sup> Y. Peters,<sup>41</sup> K. Petridis,<sup>41</sup> G. Petrillo,<sup>63</sup> P. Pétrouff,<sup>13</sup> M.-A. Pleier,<sup>65</sup> V.M. Podstavkov,<sup>45</sup> A.V. Popov,<sup>34</sup> M. Prewitt,<sup>72</sup> D. Price,<sup>41</sup> N. Prokopenko,<sup>34</sup> J. Qian,<sup>56</sup> A. Quadt,<sup>20</sup> B. Quinn,<sup>58</sup> P.N. Ratoff,<sup>39</sup> I. Razumov,<sup>34</sup> I. Ripp-Baudot,<sup>16</sup> F. Rizatdinova,<sup>68</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> A. Sánchez-Hernández,<sup>28</sup> M.P. Sanders,<sup>22</sup> A.S. Santos<sup>h</sup>,<sup>1</sup> G. Savage,<sup>45</sup> M. Savitskiy,<sup>38</sup> L. Sawyer,<sup>54</sup> T. Scanlon,<sup>40</sup> R.D. Schamberger,<sup>64</sup> Y. Scheglov,<sup>35</sup> H. Schellman,<sup>48</sup> C. Schwanenberger,<sup>41</sup> R. Schwienhorst,<sup>57</sup> J. Sekaric,<sup>53</sup> H. Severini,<sup>67</sup> E. Shabalina,<sup>20</sup> V. Shary,<sup>15</sup> S. Shaw,<sup>41</sup> A.A. Shchukin,<sup>34</sup> V. Simak,<sup>7</sup> P. Skubic,<sup>67</sup> P. Slattery,<sup>63</sup> D. Smirnov,<sup>51</sup> G.R. Snow,<sup>59</sup> J. Snow,<sup>66</sup> S. Snyder,<sup>65</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>34</sup> M. Strauss,<sup>67</sup> L. Suter,<sup>41</sup> P. Svoisky,<sup>67</sup> M. Titov,<sup>15</sup> V.V. Tokmenin,<sup>31</sup> Y.-T. Tsai,<sup>63</sup> D. Tsybychev,<sup>64</sup> B. Tuchming,<sup>15</sup> C. Tully,<sup>61</sup> L. Uvarov,<sup>35</sup> S. Uvarov,<sup>35</sup> S. Uzunyan,<sup>47</sup> R. Van Kooten,<sup>49</sup> W.M. van Leeuwen,<sup>29</sup> N. Varelas,<sup>46</sup> E.W. Varnes,<sup>42</sup> I.A. Vasilyev,<sup>34</sup> A.Y. Verkheev,<sup>31</sup> L.S. Vertogradov,<sup>31</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>51</sup> G. Watts,<sup>74</sup> M. Wayne,<sup>51</sup> J. Weichert,<sup>21</sup> L. Welty-Rieger,<sup>48</sup> M.R.J. Williams<sup>n</sup>,<sup>49</sup> G.W. Wilson,<sup>53</sup> M. Wobisch,<sup>54</sup> D.R. Wood,<sup>55</sup> T.R. Wyatt,<sup>41</sup> Y. Xie,<sup>45</sup> R. Yamada,<sup>45</sup>

S. Yang,<sup>4</sup> T. Yasuda,<sup>45</sup> Y.A. Yatsunenko,<sup>31</sup> W. Ye,<sup>64</sup> Z. Ye,<sup>45</sup> H. Yin,<sup>45</sup> K. Yip,<sup>65</sup> S.W. Youn,<sup>45</sup> J.M. Yu,<sup>56</sup>  
 J. Zennaro,<sup>62</sup> T.G. Zhao,<sup>41</sup> B. Zhou,<sup>56</sup> J. Zhu,<sup>56</sup> M. Zielinski,<sup>63</sup> D. Zieminska,<sup>49</sup> and L. Zivkovic<sup>14</sup>

(The 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>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>Panjab University, Chandigarh, India

<sup>24</sup>Delhi University, Delhi, India

<sup>25</sup>Tata Institute of Fundamental Research, Mumbai, India

<sup>26</sup>University College Dublin, Dublin, Ireland

<sup>27</sup>Korea Detector Laboratory, Korea University, Seoul, Korea

<sup>28</sup>CINVESTAV, Mexico City, Mexico

<sup>29</sup>Nikhef, Science Park, Amsterdam, the Netherlands

<sup>30</sup>Radboud University Nijmegen, Nijmegen, the Netherlands

<sup>31</sup>Joint Institute for Nuclear Research, Dubna, Russia

<sup>32</sup>Institute for Theoretical and Experimental Physics, Moscow, Russia

<sup>33</sup>Moscow State University, Moscow, Russia

<sup>34</sup>Institute for High Energy Physics, Protvino, Russia

<sup>35</sup>Petersburg Nuclear Physics Institute, St. Petersburg, Russia

<sup>36</sup>Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain

<sup>37</sup>Uppsala University, Uppsala, Sweden

<sup>38</sup>Taras Shevchenko National University of Kyiv, Kiev, Ukraine

<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>Louisiana Tech University, Ruston, Louisiana 71272, USA

<sup>55</sup>Northeastern University, Boston, Massachusetts 02115, USA

<sup>56</sup>University of Michigan, Ann Arbor, Michigan 48109, USA

<sup>57</sup>Michigan State University, East Lansing, Michigan 48824, USA

<sup>58</sup>University of Mississippi, University, Mississippi 38677, USA

- <sup>59</sup>University of Nebraska, Lincoln, Nebraska 68588, USA  
<sup>60</sup>Rutgers University, Piscataway, New Jersey 08855, USA  
<sup>61</sup>Princeton University, Princeton, New Jersey 08544, USA  
<sup>62</sup>State University of New York, Buffalo, New York 14260, USA  
<sup>63</sup>University of Rochester, Rochester, New York 14627, USA  
<sup>64</sup>State University of New York, Stony Brook, New York 11794, USA  
<sup>65</sup>Brookhaven National Laboratory, Upton, New York 11973, USA  
<sup>66</sup>Langston University, Langston, Oklahoma 73050, USA  
<sup>67</sup>University of Oklahoma, Norman, Oklahoma 73019, USA  
<sup>68</sup>Oklahoma State University, Stillwater, Oklahoma 74078, USA  
<sup>69</sup>Brown University, Providence, Rhode Island 02912, USA  
<sup>70</sup>University of Texas, Arlington, Texas 76019, USA  
<sup>71</sup>Southern Methodist University, Dallas, Texas 75275, USA  
<sup>72</sup>Rice University, Houston, Texas 77005, USA  
<sup>73</sup>University of Virginia, Charlottesville, Virginia 22904, USA  
<sup>74</sup>University of Washington, Seattle, Washington 98195, USA  
(Dated: August 21, 2014)

We present a measurement of the fundamental parameter of the standard model, the weak mixing angle, in  $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$  events at a center of mass energy of 1.96 TeV, using data corresponding to  $9.7 \text{ fb}^{-1}$  of integrated luminosity collected by the D0 detector at the Fermilab Tevatron. The effective weak mixing angle is extracted from the forward-backward charge asymmetry as a function of the invariant mass around the  $Z$  boson pole. The measured value of  $\sin^2 \theta_{\text{eff}}^\ell = 0.23146 \pm 0.00047$  is the most precise measurement from light quark interactions to date, with a precision close to the best LEP and SLD results.

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The weak mixing angle  $\sin^2 \theta_W$  is one of the fundamental parameters of the standard model (SM). It describes the relative strength of the axial-vector couplings  $g_A^f$  to the vector couplings  $g_V^f$  in neutral-current interactions of a  $Z$  boson to fermions  $f$  with Lagrangian

$$\mathcal{L} = -i \frac{g}{2 \cos \theta_W} \bar{f} \gamma^\mu \left( g_V^f - g_A^f \gamma_5 \right) f Z_\mu, \quad (1)$$

with  $g_V^f = I_3^f - 2Q_f \cdot \sin^2 \theta_W$ ,  $g_A^f = I_3^f$ , where  $I_3^f$  and  $Q_f$  are the weak isospin component and the charge of the fermion. At tree level and in all orders of the on-shell renormalization scheme, the weak mixing angle can be written in terms of the  $W$  and  $Z$  boson masses as  $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ . To include higher order electroweak radiative corrections, effective weak mixing an-

gles are defined as

$$\sin^2 \theta_{\text{eff}}^f = \frac{1}{4|Q_f|} \left( 1 - \frac{g_V^f}{g_A^f} \right), \quad (2)$$

for each fermion flavor.

It is customary to quote the charged lepton effective weak mixing angle  $\sin^2 \theta_{\text{eff}}^\ell$ , determined by measurements of observables around the  $Z$  boson pole. There is tension between the two most precise measurements of  $\sin^2 \theta_{\text{eff}}^\ell$ , which are  $0.23221 \pm 0.00029$  from the combined LEP measurement using the charge asymmetry  $A_{FB}^{0,b}$  for  $b$  quark production and  $0.23098 \pm 0.00026$  from the SLD measurement of the  $e^+e^-$  left-right polarization asymmetry  $A_{lr}$  [1]. An independent determination of the effective weak mixing angle is therefore an important precision test of the SM electroweak breaking mechanism.

At the Tevatron, the mixing angle can be measured in the Drell-Yan process  $p\bar{p} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ , through a forward-backward charge asymmetry in the distribution of the emission angle  $\theta^*$  of the negatively charged lepton momentum relative to the incoming quark momentum, defined in the Collins-Soper frame [2]. Events with  $\cos \theta^* > 0$  are classified as forward ( $F$ ), and those with  $\cos \theta^* < 0$  as backward ( $B$ ). The forward-backward charge asymmetry,  $A_{FB}$ , is defined by

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}, \quad (3)$$

where  $N_F$  and  $N_B$  are the numbers of forward and backward events. The asymmetry arises from the interference between vector and axial vector coupling terms.

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\*with visitors from <sup>a</sup>Augustana College, Sioux Falls, SD, USA, <sup>b</sup>The University of Liverpool, Liverpool, UK, <sup>c</sup>DESY, Hamburg, Germany, <sup>d</sup>Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico <sup>e</sup>SLAC, Menlo Park, CA, USA, <sup>f</sup>University College London, London, UK, <sup>g</sup>Centro de Investigacion en Computacion - IPN, Mexico City, Mexico, <sup>h</sup>Universidade Estadual Paulista, São Paulo, Brazil, <sup>i</sup>Karlsruher Institut für Technologie (KIT) - Steinbuch Centre for Computing (SCC), D-76128 Karlsruhe, Germany, <sup>j</sup>Office of Science, U.S. Department of Energy, Washington, D.C. 20585, USA, <sup>k</sup>American Association for the Advancement of Science, Washington, D.C. 20005, USA, <sup>l</sup>Kiev Institute for Nuclear Research, Kiev, Ukraine, <sup>m</sup>University of Maryland, College Park, Maryland 20742, USA and <sup>n</sup>European Organization for Nuclear Research (CERN), Geneva, Switzerland

The asymmetry  $A_{FB}$  can be measured as a function of the invariant mass of the dilepton pair ( $M_{ee}$ ). The presence of both vector and axial-vector couplings of the  $Z$  boson to fermions gives the most significant variation of  $A_{FB}$  in vicinity of the  $Z$  boson pole, which is sensitive to the effective weak mixing angle.

Measurements of  $\sin^2 \theta_{\text{eff}}^\ell$  have been reported previously by the CDF Collaboration in the  $Z \rightarrow e^+e^-$  [3, 4] and  $Z \rightarrow \mu^+\mu^-$  [5] channels, and the D0 Collaboration in the  $Z \rightarrow e^+e^-$  channel [6, 7]. The angle  $\sin^2 \theta_{\text{eff}}^\ell$  has also been measured at the LHC in  $pp$  collisions by the CMS Collaboration in the  $Z \rightarrow \mu^+\mu^-$  channel at  $\sqrt{s} = 7$  TeV [8].

This letter reports a measurement of the effective weak mixing angle from the  $A_{FB}$  distribution using  $9.7 \text{ fb}^{-1}$  of integrated luminosity collected with the D0 detector at the Fermilab Tevatron collider. The precision of the previous D0 measurement using  $5 \text{ fb}^{-1}$  of data [7],  $\sin^2 \theta_{\text{eff}}^\ell = 0.2309 \pm 0.0008$  (stat.)  $\pm 0.0006$  (syst.), was dominated by available statistics and the uncertainty on the electron energy scale. The analysis of the full  $9.7 \text{ fb}^{-1}$  data set presented here features an extended acceptance and a new electron energy calibration method providing substantially improved accuracy.

The D0 detector comprises a central tracking system, a calorimeter and a muon system [9–11]. The central tracking system consists of a silicon microstrip tracker (SMT) and a scintillating central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet and optimized for tracking and vertexing capabilities at detector pseudorapidities of  $|\eta_{\text{det}}| < 3$  [12]. The solenoid and toroid polarities are reversed every two weeks on average. This helps control detector-generated asymmetries. Outside the solenoid, three liquid argon and uranium calorimeters provide coverage of  $|\eta_{\text{det}}| < 3.5$  for electrons: the central calorimeter (CC) up to  $|\eta_{\text{det}}| < 1.1$ , and two endcap calorimeters (EC) in the range  $1.5 < |\eta_{\text{det}}| < 3.5$ . Gaps between the cryostats create inefficient electron detection regions between  $1.1 < |\eta_{\text{det}}| < 1.5$  that are excluded from the analysis.

The data used in this analysis are collected by triggers requiring at least two electromagnetic (EM) clusters reconstructed in the calorimeter. The determination of their energies uses only the calorimeter information. Each EM cluster is further required to be in the CC or EC, with transverse momentum  $p_T > 25$  GeV, and have shower shapes consistent with that of an electron. For events with both EM candidates in the CC region (CC-CC), each EM object must have a spatially matched track reconstructed in the tracking system. For events with one EM cluster in the CC and the other in the EC region (CC-EC), only the CC candidate is required to have a matched track. For events with both candidates in the EC calorimeter (EC-EC), at least one EM object must have a matched track. All tracks must have  $p_T > 10$  GeV and excellent reconstruction quality. For CC-CC events, the two EM candidates are required to

have opposite charges. For CC-EC events, the determination of “forward” or “backward” is made according to the charge measured for the track-matched CC EM candidate, whereas the charge associated to the EC higher quality matched track is used for EC-EC events [13].

Events are further required to have a reconstructed dielectron invariant mass in the range  $75 < M_{ee} < 115$  GeV. A larger sample satisfying  $60 < M_{ee} < 130$  GeV is used to understand detector responses and to tune the Monte Carlo (MC) simulation.

To maximize the acceptance, previously ignored electrons reconstructed near the boundaries of CC calorimeter modules [9] ( $\phi$ -mod boundary) are included. The geometric acceptance is further extended compared with previous D0 results [7] from  $|\eta_{\text{det}}| < 1.0$  to  $|\eta_{\text{det}}| < 1.1$  for the CC, and from  $1.5 < |\eta_{\text{det}}| < 2.5$  to  $1.5 < |\eta_{\text{det}}| < 3.2$  for the EC. In addition, EC-EC events, which were excluded due to their poorer track reconstruction and calorimeter energy resolution, are now included. These extensions in  $\eta_{\text{det}}$  and  $\phi$ -mod acceptance give a 70% increase in the number of events over what would be expected from the increase in integrated luminosity. An additional 15% increase is gained from the improvements in the track reconstruction algorithm. The number of  $Z \rightarrow e^+e^-$  candidate events in the data sample is 560,267 which includes 248,380 CC-CC events, 240,593 CC-EC events and 71,294 EC-EC events.

The MC Drell-Yan  $Z/\gamma^* \rightarrow e^+e^-$  sample is generated by using the D0 simulation software, based on the leading-order PYTHIA generator [14] with the NNPDF2.3 [15] parton distribution functions (PDFs), followed by a GEANT-based simulation [16] of the D0 detector. The PYTHIA MC samples, with data events from random beam crossings overlaid, are mainly used to understand the geometric acceptance, and the energy scale and resolution of electrons in the calorimeter.

A new method of electron energy calibration is developed and applied to both the data and MC, which significantly reduces the systematic uncertainty due to the electron energy measurement. The weak mixing angle, which is extracted from  $A_{FB}$  as a function of  $M_{ee}$ , depends strongly on the position of the peak value of  $M_{ee}$ . Therefore, it is critical to have a precise electron energy measurement and a consistent measured peak value of  $M_{ee}$  from different regions of the detector across various Tevatron running conditions. In Ref. [7], an overall scale factor is applied to simulations to model the detector response for electron energy depositions, where the scale factor is determined by comparing the  $M_{ee}$  spectrum in data and MC, yielding a large uncertainty due to background estimation and detector resolution. In this analysis, a new energy calibration method is applied to the data and the MC separately. For CC electrons, an instantaneous luminosity-dependent scale factor ( $\alpha_L^{\text{CC}}$ ) and an  $\eta_{\text{det}}$ -dependent scale factor ( $\alpha_\eta^{\text{CC}}$ ) are applied to the electron energy. For EC electrons in addition to the scale

factors  $\alpha_L^{\text{EC}}$  and  $\alpha_\eta^{\text{EC}}$ , an  $\eta_{\text{det}}$ -dependent offset  $\beta_\eta^{\text{EC}}$  is introduced to model the  $\eta_{\text{det}}$  dependence of the electron energy. All correction factors are determined by scaling the peak of the  $M_{ee}$  distribution as a function of instantaneous luminosity and  $\eta_{\text{det}}$  to the  $Z$  boson mass measured by LEP ( $M_Z = 91.1875$  GeV) [1]. The CC correction factors are tuned with the CC-CC events. To remove one degree of freedom,  $\beta_\eta^{\text{EC}}$  is expressed as a function of  $\alpha_\eta^{\text{EC}}$ , and the relationship is measured with the CC-EC events. The values of  $\alpha_\eta^{\text{EC}}$  and  $\beta_\eta^{\text{EC}}(\alpha_\eta^{\text{EC}})$  are fitted with the EC-EC events. After the calibration, the standard deviation  $\delta M$  of the  $M_{ee}$  peak value from the LEP  $M_Z$  value is  $\approx 20$  MeV. Various closure tests are performed to check the validity of the calibration procedure. For example, an extra  $\eta_{\text{det}}$ -dependent offset is applied to the corrected energy and fixed by performing the calibration again. The extra offset is found to be consistent with  $\delta M$ . The ratio of  $\delta M$  to  $M_Z$  is propagated into the uncertainty of the  $\sin^2 \theta_{\text{eff}}^\ell$  measurement to estimate the systematic uncertainty arising from the energy calibration.

After the electron energy calibration, an additional electron energy resolution smearing is derived and applied to the MC to achieve agreement of the width of the  $M_{ee}$  distribution in data. For the CC  $\phi$ -mod boundary electrons, the resolution smearing is modeled with a Crystal Ball function [17]. For other electrons, the smearing is modeled with a Gaussian function.

Additional corrections and reweightings are applied to the MC simulation to improve the agreement with data. The scale factors of the electron identification efficiency between the MC and the data are measured using the tag-probe method [18] and applied to the MC distribution as functions of  $p_T$  and  $\eta_{\text{det}}$ . The simulation is further corrected for higher-order effects not included in PYTHIA by reweighting the MC events at the generator level in two dimensions ( $p_T$  and rapidity  $y$  of the  $Z$  boson) to match RESBOS [19] predictions. In addition, next-to-next-leading order QCD corrections are applied as a function of  $M_Z$  [19, 20]. The distribution of the instantaneous luminosity and the  $z$  coordinate of the  $p\bar{p}$  collision vertices are also weighted to match those in the data. Since  $A_{FB}$  is defined as a ratio of numbers of events, many small uncertainties cancel out. Only the electron selection efficiency scale factor in these additional corrections contributes significantly to the final uncertainty.

The charge of the particle track matched to the EM cluster is used to determine if the EM cluster is associated to an electron or positron and to classify the event as forward or backward. The charge misidentification probability  $f_q$  is given by

$$f_q = \frac{1}{2} N_{SS} / (N_{SS} + N_{OS}), \quad (4)$$

where  $N_{SS}(N_{OS})$  is the total number of  $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$  events reconstructed with same-sign (opposite-sign) electrons. The probabilities are measured in data

and MC using tag-and-probe method. The charge of electrons and positrons reconstructed in the MC is randomly changed to match the misidentification probability in the data averaged over  $p_T$  spectrum of electrons. In the CC region the average charge misidentification rate in data is about 0.3%, whereas in the EC region it varies from 1% at  $|\eta_{\text{det}}| = 1.5$  to 10% at  $|\eta_{\text{det}}| = 3.0$ . The statistical uncertainty of the measured charge misidentification rate is included as a systematic uncertainty.

The background is suppressed by the strict requirements on the quality of the matched track. The main contribution is from multijet events, in which jets are misreconstructed as electrons, and is estimated from data. Multijet events are selected by reversing part of the electron selections to study the differential distributions of the multijet background, which are different from the real multijet background that passes all the electron selections. Therefore, a correction factor is applied as a function of electron  $p_T$ , given by the ratios of the efficiencies for EM-like jets (which are selected in a multijet-enriched data sample and pass all the electron selections) and “reverse-selected” jets. The normalization of the multijet background is determined by fitting the sum of the  $M_{ee}$  distributions of multijet events and the signal MC events to the distribution from the selected data events. The  $W$ +jets,  $Z/\gamma^* \rightarrow \tau\tau$ , di-boson ( $WW$  and  $WZ$ ) and  $t\bar{t}$  backgrounds are estimated using the PYTHIA MC simulation and found to be negligible around the  $Z$  boson pole. The total number of background events is found to be less than 1% in CC-CC events and 4% in CC-EC and EC-EC events. The  $M_{ee}$  and  $\cos\theta^*$  distributions of data and of the sum of signal MC and background expectations are in good agreement with the SM predictions.

The weak mixing angle is extracted from the background-subtracted raw  $A_{FB}$  spectrum in the regions  $75 < M_{ee} < 115$  GeV for CC-CC and CC-EC events, and  $81 < M_{ee} < 97$  GeV for EC-EC events by comparing the data to simulated  $A_{FB}$  templates corresponding to different input values of  $\sin^2 \theta_W$ . The mass window for EC-EC events is narrower to take into account the different track reconstruction and energy measurement. The templates are obtained by reweighting  $M_Z$  and  $\cos\theta^*$  distributions at the generator level to different Born-level  $\sin^2 \theta_W$  predictions. The  $A_{FB}$  distribution is negligibly sensitive to the effect of QED final state radiation because most of these radiated photons are emitted co-linearly with the electron and are reconstructed as one single EM object by the detector. The background-subtracted raw  $A_{FB}$  distribution and the PYTHIA prediction with the fitted  $\sin^2 \theta_W$  are shown in Fig. 1.

The results of the fits for different event categories, with statistical and systematic uncertainties, are listed in Table I. The uncertainties on  $\sin^2 \theta_W$  are dominated by the data statistics. The systematic uncertainties due to the electron energy calibration and resolution smearing, the estimation of the backgrounds, the charge misidenti-

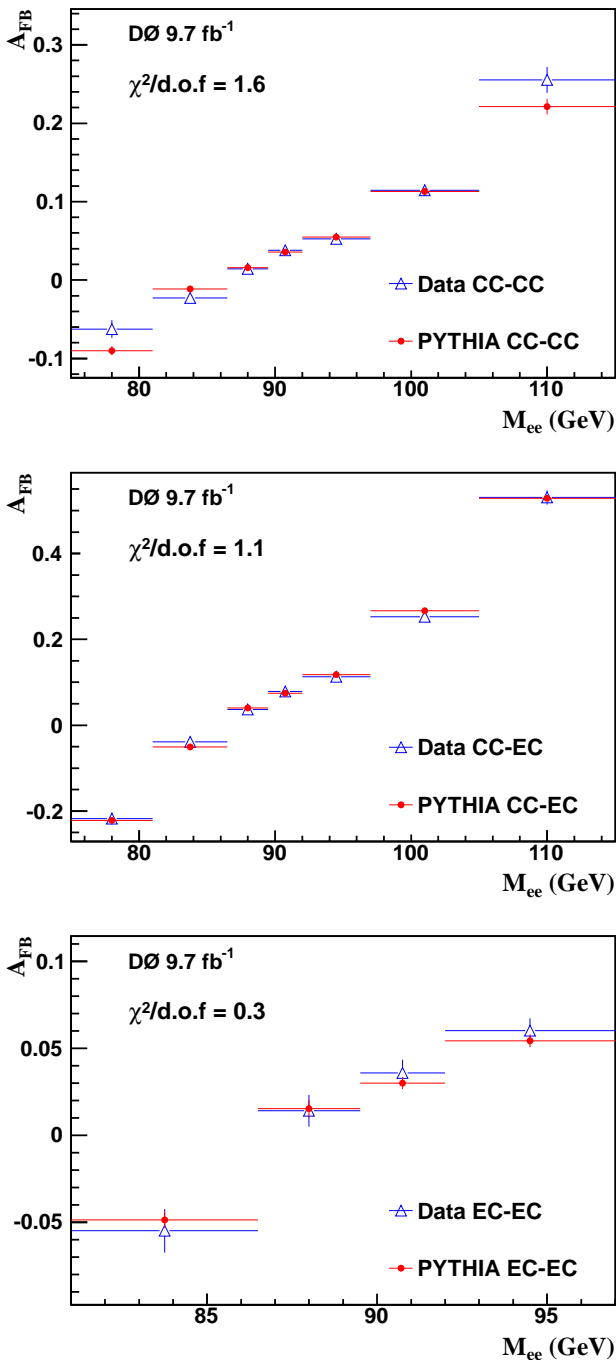


FIG. 1: (color online). Comparison between the raw  $A_{FB}$  distributions measured in the background-subtracted data and the MC, with the corresponding  $\chi^2$  per degree of freedom.  $\sin^2 \theta_W$  in the MC is 0.23138. The error bars are statistical only.

fication rate and the identification efficiency of electrons measured in the data and the MC are also dominated by the data statistics.

Since the systematic and statistical uncertainties in

	CC-CC	CC-EC	EC-EC	Combined
$\sin^2 \theta_W$	0.23140	0.23142	0.22986	0.23138
Statistical	0.00116	0.00047	0.00276	0.00043
Systematic	0.00009	0.00009	0.00019	0.00008
Energy Calibration	0.00003	0.00001	0.00004	0.00001
Energy Smearing	0.00001	0.00002	0.00013	0.00002
Background	0.00002	0.00001	0.00002	0.00001
Charge Misidentification	0.00002	0.00004	0.00012	0.00003
Electron Identification	0.00008	0.00008	0.00005	0.00007
Total	0.00116	0.00048	0.00277	0.00044

TABLE I: Measured  $\sin^2 \theta_W$  values and corresponding uncertainties. Uncertainties from higher-order corrections and the PDFs are not included.

different categories are uncorrelated, the results are combined by using the corresponding uncertainties as weights, giving

$$\begin{aligned} \sin^2 \theta_W = & \\ & 0.23138 \pm 0.00043 \text{ (stat.)} \pm \\ & 0.00008 \text{ (syst.)} \pm 0.00017 \text{ (PDF)}. \end{aligned}$$

The PDF uncertainty is estimated by reweighting the PDF set in the MC simulations to different sets of the NNPDF2.3 parameterization [15].

To have a consistent SM definition and make our result comparable with previous measurements, the PYTHIA interpretation of the weak mixing angle is compared to the predictions from modified RESBOS with CTEQ6.6 PDF set [21], which uses different values of effective weak mixing angle for leptons and up or down quarks [22]. A constant 0.00008 positive shift in  $\sin^2 \theta_W$  in the prediction from RESBOS relative to the LO prediction from PYTHIA changes the measured leptonic effective weak mixing angle to  $\sin^2 \theta_{\text{eff}}^\ell = 0.23146 \pm 0.00047$ , with the same breakdown of uncertainties as above. The comparison between our measurement and other experimental results is shown in Fig. 2. Our measurement is consistent with the current world average.

In conclusion, we have measured the effective weak mixing angle  $\sin^2 \theta_{\text{eff}}^\ell$  from the distribution of the forward-backward charge asymmetry  $A_{FB}$  in the process  $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$  at the Tevatron. This measurement, which supersedes that reported in [7], uses nearly twice the integrated luminosity and significantly extends the electron acceptance. The primary systematic uncertainty is reduced by introducing a new electron energy calibration method. The final result from 9.7 fb<sup>-1</sup> of integrated luminosity is  $\sin^2 \theta_{\text{eff}}^\ell = 0.23146 \pm 0.00047$ , and is the most precise measurement from light quark interactions, and is close to the precision of the world's best measurements performed by the LEP and SLD Collaborations.

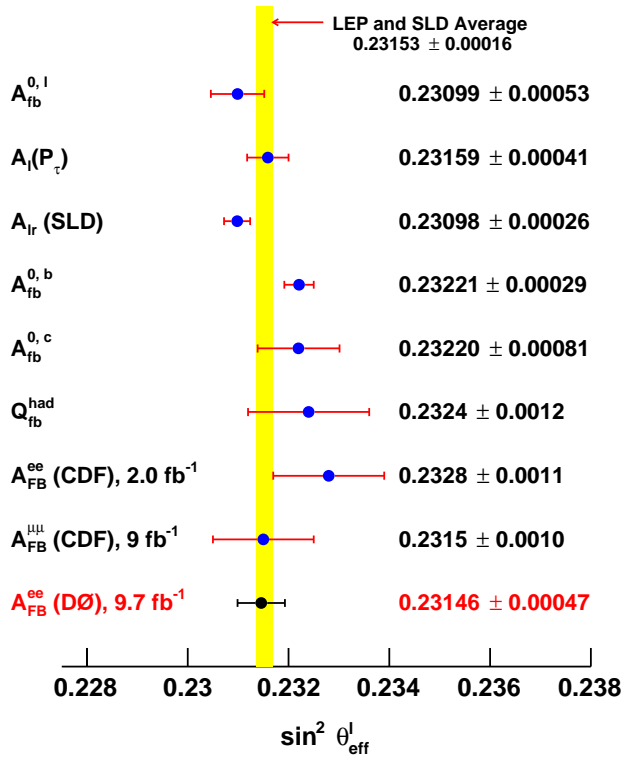


FIG. 2: (color online). Comparison of measured  $\sin^2 \theta_{eff}^l$  with results from other experiments. The average is a combination of  $A_{FB}^{0,\ell}$ ,  $A_l(P_\tau)$ ,  $A_{lr}(SLD)$ ,  $A_{FB}^{0,b}$ ,  $A_{FB}^{0,c}$ , and  $Q_{FB}^{had}$  measurements from the LEP and SLD Collaborations [1].

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