

## Search for Third-Generation Scalar Leptoquarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

V. M. Abazov,<sup>35</sup> B. Abbott,<sup>75</sup> M. Abolins,<sup>65</sup> B. S. Acharya,<sup>28</sup> M. Adams,<sup>51</sup> T. Adams,<sup>49</sup> E. Aguilo,<sup>5</sup> S. H. Ahn,<sup>30</sup> M. Ahsan,<sup>59</sup> G. D. Alexeev,<sup>35</sup> G. Alkhalaf,<sup>39</sup> A. Alton,<sup>64,\*</sup> G. Alverson,<sup>63</sup> G. A. Alves,<sup>2</sup> M. Anastasoiaie,<sup>34</sup> L. S. Ancu,<sup>34</sup> T. Andeen,<sup>53</sup> S. Anderson,<sup>45</sup> B. Andrieu,<sup>16</sup> M. S. Anzels,<sup>53</sup> Y. Arnoud,<sup>13</sup> M. Arov,<sup>60</sup> M. Arthaud,<sup>17</sup> A. Askew,<sup>49</sup> B. Åsman,<sup>40</sup> A. C. S. Assis Jesus,<sup>3</sup> O. Atramentov,<sup>49</sup> C. Autermann,<sup>20</sup> C. Avila,<sup>7</sup> C. Ay,<sup>23</sup> F. Badaud,<sup>12</sup> A. Baden,<sup>61</sup> L. Bagby,<sup>52</sup> B. Baldin,<sup>50</sup> D. V. Bandurin,<sup>59</sup> P. Banerjee,<sup>28</sup> S. Banerjee,<sup>28</sup> E. Barberis,<sup>63</sup> A.-F. Barfuss,<sup>14</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>16</sup> D. Bauer,<sup>43</sup> S. Beale,<sup>5</sup> A. Bean,<sup>58</sup> M. Begalli,<sup>3</sup> M. Begel,<sup>71</sup> C. Belanger-Champagne,<sup>40</sup> L. Bellantoni,<sup>50</sup> A. Bellavance,<sup>50</sup> J. A. Benitez,<sup>65</sup> S. B. Beri,<sup>26</sup> G. Bernardi,<sup>16</sup> R. Bernhard,<sup>22</sup> L. Berntzon,<sup>14</sup> I. Bertram,<sup>42</sup> M. Bessaçon,<sup>17</sup> R. Beuselinck,<sup>43</sup> V. A. Bezzubov,<sup>38</sup> P. C. Bhat,<sup>50</sup> V. Bhatnagar,<sup>26</sup> C. Biscarat,<sup>19</sup> G. Blazey,<sup>52</sup> F. Blekman,<sup>43</sup> S. Blessing,<sup>49</sup> D. Bloch,<sup>18</sup> K. Bloom,<sup>67</sup> A. Boehnlein,<sup>50</sup> D. Boline,<sup>62</sup> T. A. Bolton,<sup>59</sup> G. Borissov,<sup>42</sup> K. Bos,<sup>33</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>78</sup> N. J. Buchanan,<sup>49</sup> D. Buchholz,<sup>53</sup> M. Buehler,<sup>81</sup> V. Buescher,<sup>21</sup> S. Burdin,<sup>42,†</sup> S. Burke,<sup>45</sup> T. H. Burnett,<sup>82</sup> C. P. Buszello,<sup>43</sup> J. M. Butler,<sup>62</sup> P. Calfayan,<sup>24</sup> S. Calvet,<sup>14</sup> J. Cammin,<sup>71</sup> S. Caron,<sup>33</sup> W. Carvalho,<sup>3</sup> B. C. K. Casey,<sup>77</sup> N. M. Cason,<sup>55</sup> H. Castilla-Valdez,<sup>32</sup> S. Chakrabarti,<sup>17</sup> D. Chakraborty,<sup>52</sup> K. Chan,<sup>5</sup> K. M. Chan,<sup>55</sup> A. Chandra,<sup>48</sup> F. Charles,<sup>18</sup> E. Cheu,<sup>45</sup> F. Chevallier,<sup>13</sup> D. K. Cho,<sup>62</sup> S. Choi,<sup>31</sup> B. Choudhary,<sup>27</sup> L. Christofek,<sup>77</sup> T. Christoudias,<sup>43</sup> S. Cihangir,<sup>50</sup> D. Claes,<sup>67</sup> B. Clément,<sup>18</sup> C. Clément,<sup>40</sup> Y. Coadou,<sup>5</sup> M. Cooke,<sup>80</sup> W. E. Cooper,<sup>50</sup> M. Corcoran,<sup>80</sup> F. Couderc,<sup>17</sup> M.-C. Cousinou,<sup>14</sup> S. Crépe-Renaudin,<sup>13</sup> D. Cutts,<sup>77</sup> M. Ćwiok,<sup>29</sup> H. da Motta,<sup>2</sup> A. Das,<sup>62</sup> G. Davies,<sup>43</sup> K. De,<sup>78</sup> P. de Jong,<sup>33</sup> S. J. de Jong,<sup>34</sup> E. De La Cruz-Burelo,<sup>64</sup> C. De Oliveira Martins,<sup>3</sup> J. D. Degenhardt,<sup>64</sup> F. Déliot,<sup>17</sup> M. Demarteau,<sup>50</sup> R. Demina,<sup>71</sup> D. Denisov,<sup>50</sup> S. P. Denisov,<sup>38</sup> S. Desai,<sup>50</sup> H. T. Diehl,<sup>50</sup> M. Diesburg,<sup>50</sup> A. Dominguez,<sup>67</sup> H. Dong,<sup>72</sup> L. V. Dudko,<sup>37</sup> L. Duflot,<sup>15</sup> S. R. Dugad,<sup>28</sup> D. Duggan,<sup>49</sup> A. Duperrin,<sup>14</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>37</sup> H. Evans,<sup>54</sup> A. Evdokimov,<sup>73</sup> V. N. Evdokimov,<sup>38</sup> A. V. Ferapontov,<sup>59</sup> T. Ferbel,<sup>71</sup> F. Fiedler,<sup>24</sup> F. Filthaut,<sup>34</sup> W. Fisher,<sup>50</sup> H. E. Fisk,<sup>50</sup> M. Ford,<sup>44</sup> M. Fortner,<sup>52</sup> H. Fox,<sup>22</sup> S. Fu,<sup>50</sup> S. Fuess,<sup>50</sup> T. Gadfort,<sup>82</sup> C. F. Galea,<sup>34</sup> E. Gallas,<sup>50</sup> E. Galyaev,<sup>55</sup> C. Garcia,<sup>71</sup> A. Garcia-Bellido,<sup>82</sup> V. Gavrilov,<sup>36</sup> P. Gay,<sup>12</sup> W. Geist,<sup>18</sup> D. Gelé,<sup>18</sup> C. E. Gerber,<sup>51</sup> Y. Gershtein,<sup>49</sup> D. Gillberg,<sup>5</sup> G. Ginter,<sup>71</sup> N. Gollub,<sup>40</sup> B. Gómez,<sup>7</sup> A. Goussiou,<sup>55</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>19</sup> Ph. Gris,<sup>12</sup> J.-F. Grivaz,<sup>15</sup> A. Grohsjean,<sup>24</sup> S. Grünendahl,<sup>50</sup> M. W. Grünwald,<sup>29</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>24</sup> S. Hagopian,<sup>49</sup> J. Haley,<sup>68</sup> I. Hall,<sup>75</sup> R. E. Hall,<sup>47</sup> L. Han,<sup>6</sup> K. Hanagaki,<sup>50</sup> P. Hansson,<sup>40</sup> K. Harder,<sup>44</sup> A. Harel,<sup>71</sup> R. Harrington,<sup>63</sup> J. M. Hauptman,<sup>57</sup> R. Hauser,<sup>65</sup> J. Hays,<sup>43</sup> T. Hebbeker,<sup>20</sup> D. Hedin,<sup>52</sup> J. G. Hegeman,<sup>33</sup> J. M. Heinmiller,<sup>51</sup> A. P. Heinson,<sup>48</sup> U. Heintz,<sup>62</sup> C. Hensel,<sup>58</sup> K. Herner,<sup>72</sup> G. Hesketh,<sup>63</sup> M. D. Hildreth,<sup>55</sup> R. Hirsch,<sup>81</sup> J. D. Hobbs,<sup>72</sup> B. Hoeneisen,<sup>11</sup> H. Hoeth,<sup>25</sup> M. Hohlfeld,<sup>21</sup> S. J. Hong,<sup>30</sup> R. Hooper,<sup>77</sup> S. Hossain,<sup>75</sup> P. Houben,<sup>33</sup> Y. Hu,<sup>72</sup> Z. Hubacek,<sup>9</sup> V. Hynek,<sup>8</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>15</sup> S. Jain,<sup>75</sup> K. Jakobs,<sup>22</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> A. Jonckheere,<sup>50</sup> P. Jonsson,<sup>43</sup> A. Juste,<sup>50</sup> D. Käfer,<sup>20</sup> S. Kahn,<sup>73</sup> E. Kajfasz,<sup>14</sup> A. M. Kalinin,<sup>35</sup> J. M. Kalk,<sup>60</sup> J. R. Kalk,<sup>65</sup> S. Kappler,<sup>20</sup> D. Karmanov,<sup>37</sup> J. Kasper,<sup>62</sup> P. Kasper,<sup>50</sup> I. Katsanos,<sup>70</sup> D. Kau,<sup>49</sup> R. Kaur,<sup>26</sup> V. Kaushik,<sup>78</sup> R. Kehoe,<sup>79</sup> S. Kermiche,<sup>14</sup> N. Khalatyan,<sup>38</sup> A. Khanov,<sup>76</sup> A. Kharchilava,<sup>69</sup> Y. M. Kharzhev,<sup>35</sup> D. Khatidze,<sup>70</sup> H. Kim,<sup>31</sup> T. J. Kim,<sup>30</sup> M. H. Kirby,<sup>34</sup> M. Kirsch,<sup>20</sup> B. Klima,<sup>50</sup> J. M. Kohli,<sup>26</sup> J.-P. Konrath,<sup>22</sup> M. Kopal,<sup>75</sup> V. M. Korablev,<sup>38</sup> B. Kothari,<sup>70</sup> A. V. Kozelov,<sup>38</sup> D. Krop,<sup>54</sup> A. Kryemadhi,<sup>81</sup> T. Kuhl,<sup>23</sup> A. Kumar,<sup>69</sup> S. Kunori,<sup>61</sup> A. Kupco,<sup>10</sup> T. Kurča,<sup>19</sup> J. Kvita,<sup>8</sup> D. Lam,<sup>55</sup> S. Lammers,<sup>70</sup> G. Landsberg,<sup>77</sup> J. Lazoflores,<sup>49</sup> P. Lebrun,<sup>19</sup> W. M. Lee,<sup>50</sup> A. Leflat,<sup>37</sup> F. Lehner,<sup>41</sup> J. Lellouch,<sup>16</sup> V. Lesne,<sup>12</sup> J. Leveque,<sup>45</sup> P. Lewis,<sup>43</sup> J. Li,<sup>78</sup> L. Li,<sup>48</sup> Q. Z. Li,<sup>50</sup> S. M. Lietti,<sup>4</sup> J. G. R. Lima,<sup>52</sup> D. Lincoln,<sup>50</sup> J. Linnemann,<sup>65</sup> V. V. Lipaev,<sup>38</sup> R. Lipton,<sup>50</sup> Y. Liu,<sup>6</sup> Z. Liu,<sup>5</sup> L. Lobo,<sup>43</sup> A. Lobodenko,<sup>39</sup> M. Lokajicek,<sup>10</sup> A. Lounis,<sup>18</sup> P. Love,<sup>42</sup> H. J. Lubatti,<sup>82</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>25</sup> C. Magass,<sup>20</sup> A. Magerkurth,<sup>64</sup> N. Makovec,<sup>15</sup> P. K. Mal,<sup>55</sup> H. B. Malbouisson,<sup>3</sup> S. Malik,<sup>67</sup> V. L. Malyshev,<sup>35</sup> H. S. Mao,<sup>50</sup> Y. Maravin,<sup>59</sup> B. Martin,<sup>13</sup> R. McCarthy,<sup>72</sup> A. Melnitchouk,<sup>66</sup> A. Mendes,<sup>14</sup> L. Mendoza,<sup>7</sup> P. G. Mercadante,<sup>4</sup> M. Merkin,<sup>37</sup> K. W. Merritt,<sup>50</sup> A. Meyer,<sup>20</sup> J. Meyer,<sup>21</sup> M. Michaut,<sup>17</sup> T. Millet,<sup>19</sup> J. Mitrevski,<sup>70</sup> J. Molina,<sup>3</sup> R. K. Mommsen,<sup>44</sup> N. K. Mondal,<sup>28</sup> R. W. Moore,<sup>5</sup> T. Moulík,<sup>58</sup> G. S. Muanza,<sup>19</sup> M. Mulders,<sup>50</sup> M. Mulhearn,<sup>70</sup> O. Mundal,<sup>21</sup> L. Mundim,<sup>3</sup> E. Nagy,<sup>14</sup> M. Naimuddin,<sup>50</sup> M. Narain,<sup>77</sup> N. A. Naumann,<sup>34</sup> H. A. Neal,<sup>64</sup> J. P. Negret,<sup>7</sup> P. Neustroev,<sup>39</sup> H. Nilsen,<sup>22</sup> C. Noeding,<sup>22</sup> A. Nomerotski,<sup>50</sup> S. F. Novaes,<sup>4</sup> T. Nunnemann,<sup>24</sup> V. O'Dell,<sup>50</sup> D. C. O'Neil,<sup>5</sup> G. Obrant,<sup>39</sup> C. Ochando,<sup>15</sup> D. Onoprienko,<sup>59</sup> N. Oshima,<sup>50</sup> J. Osta,<sup>55</sup> R. Otec,<sup>9</sup> G. J. Otero y Garzón,<sup>51</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>71</sup> S. K. Park,<sup>30</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> P. M. Perea,<sup>48</sup>

K. Peters,<sup>44</sup> Y. Peters,<sup>25</sup> P. Pétrouff,<sup>15</sup> M. Petteni,<sup>43</sup> R. Piegaia,<sup>1</sup> J. Piper,<sup>65</sup> M.-A. Pleier,<sup>21</sup> P.L. M. Podesta-Lerma,<sup>32,‡</sup>  
V.M. Podstavkov,<sup>50</sup> Y. Pogorelov,<sup>55</sup> M.-E. Pol,<sup>2</sup> A. Pompoš,<sup>75</sup> B. G. Pope,<sup>65</sup> A. V. Popov,<sup>38</sup> C. Potter,<sup>5</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>21</sup> B. Quinn,<sup>66</sup> A. Rakitine,<sup>42</sup> M. S. Rangel,<sup>2</sup>  
K. J. Rani,<sup>28</sup> K. Ranjan,<sup>27</sup> P. N. Ratoff,<sup>42</sup> P. Renkel,<sup>79</sup> S. Reucroft,<sup>63</sup> P. Rich,<sup>44</sup> M. Rijssenbeek,<sup>72</sup> I. Ripp-Baudot,<sup>18</sup>  
F. Rizatdinova,<sup>76</sup> S. Robinson,<sup>43</sup> R. F. Rodrigues,<sup>3</sup> C. Royon,<sup>17</sup> P. Rubinov,<sup>50</sup> R. Ruchti,<sup>55</sup> G. Safonov,<sup>36</sup> G. Sajot,<sup>13</sup>  
A. Sánchez-Hernández,<sup>32</sup> M. P. Sanders,<sup>16</sup> A. Santoro,<sup>3</sup> G. Savage,<sup>50</sup> L. Sawyer,<sup>60</sup> T. Scanlon,<sup>43</sup> D. Schaile,<sup>24</sup>  
R. D. Schamberger,<sup>72</sup> Y. Scheglov,<sup>39</sup> H. Schellman,<sup>53</sup> P. Schieferdecker,<sup>24</sup> T. Schleichpake,<sup>25</sup> C. Schmitt,<sup>25</sup>  
C. Schwanenberger,<sup>44</sup> A. Schwartzman,<sup>68</sup> R. Schwienhorst,<sup>65</sup> J. Sekaric,<sup>49</sup> S. Sengupta,<sup>49</sup> H. Severini,<sup>75</sup> E. Shabalina,<sup>51</sup>  
M. Shamim,<sup>59</sup> V. Shary,<sup>17</sup> A. A. Shchukin,<sup>38</sup> R. K. Shivpuri,<sup>27</sup> D. Shpakov,<sup>50</sup> V. Siccardi,<sup>18</sup> V. Simak,<sup>9</sup> V. Sirotenko,<sup>50</sup>  
P. Skubic,<sup>75</sup> P. Slattery,<sup>71</sup> D. Smirnov,<sup>55</sup> R. P. Smith,<sup>50</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>16</sup> A. Sopczak,<sup>42</sup> M. Sosebee,<sup>78</sup> K. Soustruznik,<sup>8</sup> M. Souza,<sup>2</sup> B. Spurlock,<sup>78</sup> J. Stark,<sup>13</sup> J. Steele,<sup>60</sup>  
V. Stolin,<sup>36</sup> A. Stone,<sup>51</sup> D. A. Stoyanova,<sup>38</sup> J. Strandberg,<sup>64</sup> S. Strandberg,<sup>40</sup> M. A. Strang,<sup>69</sup> M. Strauss,<sup>75</sup> R. Ströhmer,<sup>24</sup>  
D. Strom,<sup>53</sup> M. Strovink,<sup>46</sup> L. Stutte,<sup>50</sup> S. Sumowidagdo,<sup>49</sup> P. Svoisky,<sup>55</sup> A. Sznajder,<sup>3</sup> M. Talby,<sup>14</sup> P. Tamburello,<sup>45</sup>  
A. Tanasijczuk,<sup>1</sup> W. Taylor,<sup>5</sup> P. Telford,<sup>44</sup> J. Temple,<sup>45</sup> B. Tiller,<sup>24</sup> F. Tissandier,<sup>12</sup> M. Titov,<sup>17</sup> V. V. Tokmenin,<sup>35</sup>  
M. Tomoto,<sup>50</sup> T. Toole,<sup>61</sup> I. Torchiani,<sup>22</sup> T. Trefzger,<sup>23</sup> D. Tsybychev,<sup>72</sup> B. Tuchming,<sup>17</sup> C. Tully,<sup>68</sup> P. M. Tuts,<sup>70</sup>  
R. Unalan,<sup>65</sup> L. Uvarov,<sup>39</sup> S. Uvarov,<sup>39</sup> S. Uzunyan,<sup>52</sup> B. Vachon,<sup>5</sup> P. J. van den Berg,<sup>33</sup> B. van Eijk,<sup>33</sup> R. Van Kooten,<sup>54</sup>  
W. M. van Leeuwen,<sup>33</sup> N. Varelas,<sup>51</sup> E. W. Varnes,<sup>45</sup> A. Vartapetian,<sup>78</sup> I. A. Vasilyev,<sup>38</sup> M. Vaupel,<sup>25</sup> P. Verdier,<sup>19</sup>  
L. S. Vertogradov,<sup>35</sup> M. Verzocchi,<sup>50</sup> F. Villeneuve-Seguiet,<sup>43</sup> P. Vint,<sup>43</sup> E. Von Toerne,<sup>59</sup> M. Voutilainen,<sup>67,§</sup>  
M. Vreeswijk,<sup>33</sup> R. Wagner,<sup>68</sup> H. D. Wahl,<sup>49</sup> L. Wang,<sup>61</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>23</sup> M. Weber,<sup>50</sup> H. Weerts,<sup>65</sup> A. Wenger,<sup>22,||</sup> N. Wermes,<sup>21</sup> M. Wetstein,<sup>61</sup> A. White,<sup>78</sup> D. Wicke,<sup>25</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> S. Yacoob,<sup>53</sup> R. Yamada,<sup>50</sup>  
M. Yan,<sup>61</sup> T. Yasuda,<sup>50</sup> Y. A. Yatsunenko,<sup>35</sup> K. Yip,<sup>73</sup> H. D. Yoo,<sup>77</sup> S. W. Youn,<sup>53</sup> C. Yu,<sup>13</sup> J. Yu,<sup>78</sup> A. Yurkewicz,<sup>72</sup>  
A. Zatserklyaniy,<sup>52</sup> C. Zeitnitz,<sup>25</sup> D. Zhang,<sup>50</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>37</sup>

(D0 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>Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil<sup>5</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>6</sup>University of Science and Technology of China, Hefei, People's Republic of China<sup>7</sup>Universidad de los Andes, Bogotá, Colombia<sup>8</sup>Center for Particle Physics, Charles University, Prague, Czech Republic<sup>9</sup>Czech Technical University, Prague, Czech Republic<sup>10</sup>Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic<sup>11</sup>Universidad San Francisco de Quito, Quito, Ecuador<sup>12</sup>Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France<sup>13</sup>Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Université de Grenoble 1, Grenoble, France<sup>14</sup>CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France<sup>15</sup>Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud, Orsay, France<sup>16</sup>LPNHE, IN2P3-CNRS, Universités Paris VI and VII, Paris, France<sup>17</sup>DAPNIA/Service de Physique des Particules, CEA, Saclay, France<sup>18</sup>IPHC, Université Louis Pasteur et Université de Haute Alsace, CNRS, IN2P3, Strasbourg, France<sup>19</sup>IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France

and Université de Lyon, Lyon, France

<sup>20</sup>III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany<sup>21</sup>Physikalisches Institut, Universität Bonn, Bonn, Germany<sup>22</sup>Physikalisches Institut, Universität Freiburg, Freiburg, Germany<sup>23</sup>Institut für Physik, Universität Mainz, Mainz, Germany<sup>24</sup>Ludwig-Maximilians-Universität München, München, Germany<sup>25</sup>Fachbereich Physik, University of Wuppertal, Wuppertal, Germany<sup>26</sup>Panjab University, Chandigarh, India<sup>27</sup>Delhi University, Delhi, India

- <sup>28</sup>Tata Institute of Fundamental Research, Mumbai, India  
<sup>29</sup>University College Dublin, Dublin, Ireland  
<sup>30</sup>Korea Detector Laboratory, Korea University, Seoul, Korea  
<sup>31</sup>SungKyunKwan University, Suwon, Korea  
<sup>32</sup>CINVESTAV, Mexico City, Mexico  
<sup>33</sup>FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands  
<sup>34</sup>Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands  
<sup>35</sup>Joint Institute for Nuclear Research, Dubna, Russia  
<sup>36</sup>Institute for Theoretical and Experimental Physics, Moscow, Russia  
<sup>37</sup>Moscow State University, Moscow, Russia  
<sup>38</sup>Institute for High Energy Physics, Protvino, Russia  
<sup>39</sup>Petersburg Nuclear Physics Institute, St. Petersburg, Russia  
<sup>40</sup>Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden  
<sup>41</sup>Physik Institut der Universität Zürich, Zürich, Switzerland  
<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  
<sup>82</sup>University of Washington, Seattle, Washington 98195, USA

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We report on a search for charge-1/3 third-generation leptoquarks (LQ) produced in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV using the D0 detector at Fermilab. Third-generation leptoquarks are assumed to be produced in pairs and to decay to a tau neutrino and a  $b$  quark with branching fraction  $B$ . We place upper

limits on  $\sigma(p\bar{p} \rightarrow LQ\bar{L}Q)B^2$  as a function of the leptoquark mass  $M_{LQ}$ . Assuming  $B = 1$ , we exclude at the 95% confidence level third-generation scalar leptoquarks with  $M_{LQ} < 229$  GeV.

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Leptoquarks (LQ) are bosons predicted in many extensions of the standard model (SM) [1]. They carry both nonzero lepton and color quantum numbers and decay to a lepton and quark (or antiquark). To satisfy experimental limits on lepton number violation, on flavor-changing neutral currents, and on proton decay, leptoquarks of mass accessible to current collider experiments are constrained to couple to only one generation of leptons and quarks [2]. Therefore, only leptoquarks that couple within a single generation are considered here.

This Letter reports the results of a search for charge-1/3 third-generation leptoquarks produced in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. We assume that leptoquarks are produced in pairs by  $q\bar{q}$  annihilation or  $gg$  fusion, i.e.,  $p + \bar{p} \rightarrow LQ + \bar{L}Q + X$ . These processes are independent of the unknown leptoquark-lepton-quark coupling, and the pair production cross section has been calculated including next-to-leading order terms for scalar leptoquarks [3]. Such leptoquarks would decay into either a  $\nu_\tau$  plus a  $b$  quark, or a  $\tau$  lepton plus a  $t$  quark. We search for the decay signature where both leptoquarks decay via  $LQ \rightarrow \nu_\tau + b$  with branching fraction  $B$ , resulting in a  $\nu_\tau \bar{\nu}_\tau b\bar{b}$  final state. Upper limits on the cross section times  $B^2$  as a function of leptoquark mass ( $M_{LQ}$ ) are measured and then used to determine lower limits on  $M_{LQ}$  assuming they are scalar for which the calculated cross section is lower and better determined than that for vector leptoquarks which have only been calculated to leading order [4]. Previous limits from Fermilab run I data were reported by both the D0 [5] and CDF [6,7] Collaborations based on significantly smaller integrated luminosities and at a slightly lower center-of-mass energy compared with the run II data available now.

The upgraded run II D0 detector [8] consists of layered systems surrounding the interaction point. Closest to the beam are the silicon microstrip tracker and a central fiber tracker, both immersed in the field of a 2 T solenoid. These measure the momenta of charged particles and reconstruct primary and secondary vertices. Jets and electrons are reconstructed using the pattern of energy deposited in three uranium-liquid-argon calorimeters outside the tracking system with a central section covering  $|\eta| < 1.1$  and two end calorimeters housed in separate cryostats covering the regions up to  $|\eta| \approx 4$  (where  $\eta = -\ln[\tan(\theta/2)]$  is the pseudorapidity, and  $\theta$  is the polar angle with respect to the proton beam direction). Jet reconstruction uses a cone algorithm with radius  $\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$  in pseudorapidity and azimuthal angle ( $\phi$ ) space about the jet's axis. The jet energy scale was calibrated using the transverse energy balance in photon-plus-jet events [9]. A

muon system outside the calorimeters consists of a layer of drift tubes and scintillation counters before 1.8 T iron toroids and two similar layers outside the toroids. The missing transverse energy  $\cancel{E}_T$  was determined by the vector sum of the transverse components of the energy deposited in the calorimeter and the  $p_T$  of detected muons.

Data collection used a three level trigger system and two trigger selections were analyzed for the results presented here. The first, called the missing energy trigger here, used missing energy plus jets elements. At level 1 it required at least three calorimeter trigger towers with  $E_T > 5$  GeV, where a trigger tower spans  $\Delta\phi \times \Delta\eta = 0.2 \times 0.2$  [10]. The vector sum of all jets' transverse momenta, defined as  $\cancel{H}_T \equiv |\sum_{\text{jets}} \vec{p}_T|$ , was required to be greater than 20 GeV at level 2 and greater than 30 GeV at level 3. For 16% of the integrated luminosity, the acoplanarity, defined as the azimuthal angle between the two leading jets, was required to be less than  $169^\circ$  and the  $H_T \equiv \sum_{\text{jets}} |\vec{p}_T|$  to be greater than 50 GeV. An integrated luminosity of  $360 \text{ pb}^{-1}$  [11] was collected with this trigger. The second trigger, called the muon trigger here, used muon and jet elements to increase the acceptance for events where one of the  $b$  jets was identified by its associated muon. At level 1 it required at least one muon candidate and at least one calorimeter trigger tower with  $E_T > 3$  GeV. Higher jet thresholds were imposed at level 2 and finally 25 GeV at level 3. An integrated luminosity of  $425 \text{ pb}^{-1}$  was collected with the muon trigger. These missing energy and muon triggers were not independent and only the  $65 \text{ pb}^{-1}$  of the muon trigger data sample which does not overlap was used for the combined result.

Signal samples for leptoquark masses between 150 and 400 GeV were generated with PYTHIA 6.202 [12]. Instrumental background comes mostly from multijet processes (referred to as ‘‘QCD’’ background in the following) with false  $\cancel{E}_T$  arising from mismeasurement, and dominates the low  $\cancel{E}_T$  region. Physics backgrounds are SM processes with real  $\cancel{E}_T$  and were estimated from Monte Carlo (MC) simulations. The most important are leptonic decays of  $W/Z$  bosons plus jets with  $Z \rightarrow \nu\bar{\nu}$  or when a lepton remains unidentified or is misidentified as a hadron, and processes which produce top quarks. For all MC samples except  $t\bar{t}$  and single top quark, the next-to-leading order cross sections were obtained from Ref. [13]. Cross sections for  $t\bar{t}$  and single top quark production were taken from Refs. [14,15], respectively. At the parton level, single top quark MC events were generated with COMPHEP 4.4 [16], and ALPGEN [17] was used for all other samples. These events were then processed with PYTHIA which performed showering and hadronization. The resulting



TABLE I. Predicted numbers of events before  $b$  tagging and after all requirements (statistical errors only).

Data sample Process	Missing energy trigger $360 \text{ pb}^{-1}$		Muon trigger $425 \text{ pb}^{-1}$	
	Pretag requirements	All requirements	Pretag requirements	All requirements
$W/Z + jj$	$1267 \pm 43$	$0.92 \pm 0.19$	$138 \pm 10$	$0.06 \pm 0.06$
$W/Z + c\bar{c}$	$18 \pm 1$	$0.46 \pm 0.11$	$3.0 \pm 1$	$0.21 \pm 0.12$
$W/Z + b\bar{b}$	$14 \pm 2$	$1.26 \pm 0.14$	$6 \pm 1$	$0.63 \pm 0.13$
$t\bar{t}$ and single top	$36 \pm 1$	$1.42 \pm 0.11$	$18 \pm 0.6$	$0.80 \pm 0.11$
Total SM expected	$1335 \pm 43$	$4.1 \pm 0.3$	$165 \pm 10$	$1.7 \pm 0.2$
QCD contribution	$40 \pm 40$	$<0.1$	$6 \pm 6$	$<0.2$
Data	1241	1	146	0
Signal (accept.) $M_{LQ} = 200 \text{ GeV}$	$34 \pm 1(0.36)$	$10.1 \pm 0.3(0.104)$	$9.6 \pm 0.4(0.084)$	$3.8 \pm 0.2(0.033)$

samples were processed using a full GEANT simulation of the D0 detector [18]. CTEQ5L [19] was used as the parton density function in all cases.

For both data samples, a set of preselection requirements was applied prior to  $b$  tagging in order to reduce the number of events from QCD multijet and  $W/Z + jets$  processes. To reject  $W \rightarrow \ell\nu$  decays, a veto was applied to events with isolated electrons or muons with  $p_T > 5 \text{ GeV}$ . Likewise, events containing a track with tighter isolation cuts and with  $p_T > 5 \text{ GeV}$  were rejected to reduce the contribution of leptons which remained unidentified. The number of events with mismeasured  $\cancel{E}_T$  was reduced by requiring that the primary vertex be within  $\pm 60 \text{ cm}$  in the beam direction from the center of the detector and by eliminating those where the  $\cancel{E}_T$  direction and a jet overlapped in  $\phi$ . For the missing energy trigger sample, events were required to have  $\cancel{E}_T > 70 \text{ GeV}$ , the leading jet was required to have  $|\eta| < 1.5$  and  $p_T > 40 \text{ GeV}$ , and, for events without muons, scalar  $H_T > 110 \text{ GeV}$ . For the muon triggered sample, the preselection required a muon with  $p_T > 4 \text{ GeV}$  and a leading jet with  $|\eta| < 1.5$  and  $p_T > 40 \text{ GeV}$  ( $> 50 \text{ GeV}$  if not associated with a muon). Additional requirements were a second jet with  $p_T > 20 \text{ GeV}$ ,  $H_T > 50 \text{ GeV}$ , and  $\cancel{E}_T > 70 \text{ GeV}$ . The numbers of preselected events in both samples and their estimated sources are given in Table I.

Figure 1 shows distributions of  $\cancel{E}_T$  with the signal LQ and background SM events normalized to the total integrated luminosity. The contribution from QCD multijet processes is estimated from the  $\cancel{E}_T$  distribution below  $70 \text{ GeV}$  by a fit to an exponential after subtracting SM contributions. This is similar to the technique used in our search for scalar bottom quarks [20] and, for  $\cancel{E}_T > 70 \text{ GeV}$ , total  $40 \pm 40$  events and  $6 \pm 6$  events in the missing energy and muon trigger samples, respectively. After  $b$  tagging, which is described below, the contributions from this source are less than 0.1 and 0.2 events, respectively, and a value of 0 events was conservatively used for limit calculations.

Backgrounds with light flavor jets were reduced by requiring the presence of  $b$ -tagged jets. We used jets that

contained either tracks with a significant impact parameter or muons to select  $b$ -jet candidates. Events were required to have two  $b$  tags with at least one passing the impact parameter criterion. For events selected with the muon trigger, a  $b$  jet tagged using a reconstructed muon in proximity to a jet was required. Otherwise, the events from both trigger samples were treated in an identical way for the remainder of the analysis.

We assigned a  $b$  probability to a jet based on the existence of tracks with a significant impact parameter that indicated the presence of a secondary vertex. The algorithm [21] required at least two tracks in a jet, each with a hit in the silicon tracker, and the probability that each track associated with the jet originated at the primary vertex was determined. Tagging probabilities in simulated jets used parametrizations derived from data. The probability of a jet to be of light flavor was derived and required to be less than 2%, which yielded a  $b$ -tag efficiency of about 45% per  $b$  jet.

Muon-tagged jets were also considered  $b$ -jet candidates. We required  $p_T^\mu > 6 \text{ GeV}$  to suppress contributions from  $\pi/K$  decays. Remaining backgrounds from  $W$  boson decays to muons were due to accidental overlap of a muon with a nearby jet. We required that the sum of track  $p_T$  in a

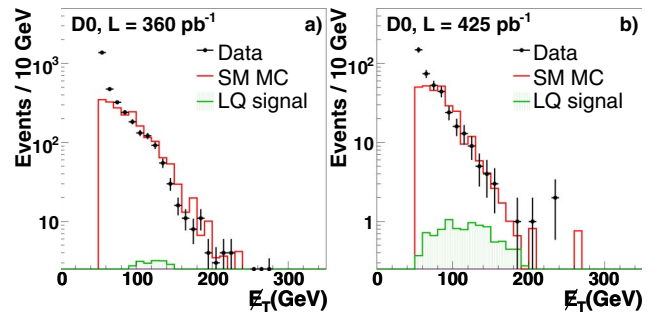


FIG. 1 (color online). The  $\cancel{E}_T$  distributions before  $b$  tagging for data (points) compared to SM background (solid histogram). The missing energy trigger sample is given in (a) and the muon trigger sample in (b). The shaded histograms are the expected contribution for a 200 GeV LQ signal.

TABLE II. Numbers of observed and predicted events after final selection, the effective signal acceptance (with total error), and the observed and expected 95% C.L. cross section limits as a function of  $M_{LQ}$ .

$M_{LQ}$ GeV	$(\cancel{E}_T, H_T)$ GeV	Data events	SM $\pm$ stat $\pm$ sys events	Signal $\pm$ stat $\pm$ sys events	Effective acceptance (%)	$\sigma$ 95% C.L. limit obs./exp. (pb)
170	(70 110)	4	$7.3 \pm 0.4 \pm 1.7$	$27.0 \pm 0.6 \pm 4.6$	$10.4 \pm 1.5$	0.163/0.232
200	(90 150)	1	$4.3 \pm 0.3 \pm 1.0$	$10.7 \pm 0.3 \pm 1.7$	$11.1 \pm 1.6$	0.101/0.163
220	(90 190)	1	$3.3 \pm 0.3 \pm 0.7$	$5.8 \pm 0.2 \pm 0.9$	$11.5 \pm 1.6$	0.097/0.142
280	(90 190)	1	$3.3 \pm 0.3 \pm 0.7$	$1.3 \pm 0.0 \pm 0.2$	$15.5 \pm 2.2$	0.071/0.105

cone of 0.5 around the muon be greater than 10 GeV, and that the approximate  $p_T$  of the muon relative to the jet's axis,  $\Delta\mathcal{R}_{\mu\text{-jet}} \times p_T^\mu$ , be less than 3.5 GeV. Muon tagging has a  $b$ -tag efficiency of about 11% with less than 0.5% of light flavored jets passing the tag criteria.

Since signal events are dominated by high energy  $b$  jets, the quantity  $X_{jj} \equiv (p_T^{\text{tag}1} + p_T^{\text{tag}2})/(\sum_{\text{jets}} p_T)$  was defined, with the muon  $p_T$  included in the  $p_T$  of the tagged jet, where applicable. We required  $X_{jj} > 0.8$  which was found to significantly reduce the contribution from top quark pair events. Since  $\cancel{E}_T$  and  $H_T$  increase for higher values of  $M_{LQ}$ , we optimized the requirements on these parameters as a function of leptoquark mass by maximizing  $S/\sqrt{B}$ , where  $S$  and  $B$  are estimated signal and background rates. The values used for the minimum  $H_T$  and  $\cancel{E}_T$  are given in Table II and were applied only to the double  $b$  vertex tagged sample. For the muon-tagged events, the  $H_T > 140$  GeV requirement was applied, and the  $\cancel{E}_T$  cut remained at 70 GeV as these events have a smaller contribution from light flavor jets.

Results of the final event selection along with predicted numbers for signal ( $M_{LQ} = 200$  GeV) and SM backgrounds are listed in Table I. The latter originate mostly from  $W/Z + b\bar{b}$  production and top quark events.

Sources of systematic uncertainties include errors in the determination of the integrated luminosity (6.1%) [11] and SM cross sections (15%). Trigger and jet selection efficiencies were measured with data and their contribution to the systematic errors is small. Jet energies and  $\cancel{E}_T$  were varied within the energy scale correction uncertainty, and the impact on signal acceptance and background rates was determined with MC calculations to be 3% and 10%, respectively. Jet  $b$ -tagging efficiency uncertainties are 12% for signal and 11% for background.

One event remains in the combined data sample for the selection criteria used for all points with  $M_{LQ} \geq 200$  GeV. This is consistent with the  $3.3 \pm 0.3 \pm 0.7$  expected events from SM processes. The probability of the observed deficit is 16%. The 95% C.L. upper limits on the  $\sigma(p\bar{p} \rightarrow LQL\bar{Q} \rightarrow \nu\bar{\nu}b\bar{b}) \times B^2$  were obtained using the techniques in Ref. [22]. The effective signal acceptances of the combined sample (normalized to  $360 \text{ pb}^{-1}$ ), numbers of events, and the resulting limits as functions of  $M_{LQ}$  are summarized in Table II.

Figure 2 shows the cross section limit as a function of  $M_{LQ}$ . Limits on the scalar leptoquark mass were obtained by the intersections of the observed 95% C.L. cross section limits with the lower bounds of a next-to-leading order calculation for which variation of the renormalization scale  $\mu$  from  $0.5M_{LQ}$  to  $2M_{LQ}$  and the PDF uncertainties [23] were included. If  $B(LQ \rightarrow \nu_\tau b) = 1$  is assumed, our limit is  $M_{LQ} > 229$  GeV. We can also consider the case where  $LQ \rightarrow t\tau$  decays occur. If we assume that the leptoquark couplings to  $\nu_\tau b$  and  $t\tau$  are the same, the branching fraction for  $LQ \rightarrow \nu_\tau b$  is then  $1 - 0.5 \times F_{sp}$  where  $F_{sp}$  is the phase space suppression factor for the  $t\tau$  channel [24]. This is shown on the figure as a displacement from the lower edge of the theory band. With this assumption, the 95% C.L. lower mass limit for scalar leptoquarks is 221 GeV.

In conclusion, we observe one event with the topology  $b\bar{b} + \cancel{E}_T$  consistent with that expected from top quark and  $W$  and  $Z$  boson production and set limits on the cross section times branching fraction squared to the  $b\nu$  final state as a function of leptoquark mass for charge-1/3 leptoquarks. These limits are interpreted as mass limits

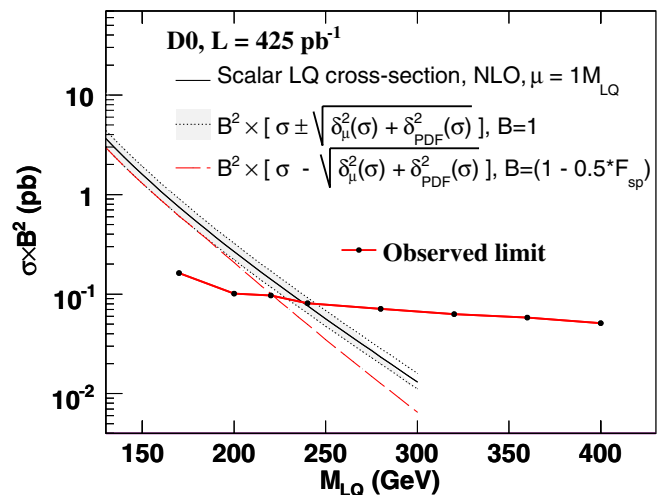


FIG. 2 (color online). The 95% C.L. limit on  $\sigma \times B^2$  (points plus solid line) as a function of  $M_{LQ}$ . The prediction for scalar leptoquarks (solid line) include an error range (in gray) of  $\mu$  between  $0.5M_{LQ}$  and  $2M_{LQ}$ . The long-dashed line below the theory band indicates the threshold effect for the  $\tau\tau$  channel.

for third-generation scalar leptoquarks and increase the excluded value by 81 GeV compared to previous results.

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

†Visitor from The University of Liverpool, Liverpool, U.K.

‡Visitor from ICN-UNAM, Mexico City, Mexico.

§Visitor from Helsinki Institute of Physics, Helsinki, Finland.

||Visitor from Universität Zürich, Zürich, Switzerland.

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