

# Searching the Inclusive $b\gamma E_T + b$ -quark Signature for Radiative Top Quark Decay and Non-Standard-Model Processes

T. Aaltonen,<sup>24</sup> J. Adelman,<sup>14</sup> T. Akimoto,<sup>56</sup> B. Álvarez González<sup>t,12</sup> S. Amerio<sup>z,44</sup> D. Amidei,<sup>35</sup> A. Anastassov,<sup>39</sup> A. Annovi,<sup>20</sup> J. Antos,<sup>15</sup> G. Apollinari,<sup>18</sup> A. Apresyan,<sup>49</sup> T. Arisawa,<sup>58</sup> A. Artikov,<sup>16</sup> W. Ashmanskas,<sup>18</sup> A. Attal,<sup>4</sup> A. Aurisano,<sup>54</sup> F. Azfar,<sup>43</sup> W. Badgett,<sup>18</sup> A. Barbaro-Galtieri,<sup>29</sup> V.E. Barnes,<sup>49</sup> B.A. Barnett,<sup>26</sup> P. Barria<sup>bb,47</sup> V. Bartsch,<sup>31</sup> G. Bauer,<sup>33</sup> P.-H. Beauchemin,<sup>34</sup> F. Bedeschi,<sup>47</sup> D. Beecher,<sup>31</sup> S. Behari,<sup>26</sup> G. Bellettini<sup>aa,47</sup> J. Bellinger,<sup>60</sup> D. Benjamin,<sup>17</sup> A. Beretvas,<sup>18</sup> J. Beringer,<sup>29</sup> A. Bhatti,<sup>51</sup> M. Binkley,<sup>18</sup> D. Bisello<sup>z,44</sup> I. Bizjak<sup>ff,31</sup> R.E. Blair,<sup>2</sup> C. Blocker,<sup>7</sup> B. Blumenfeld,<sup>26</sup> A. Bocci,<sup>17</sup> A. Bodek,<sup>50</sup> V. Boisvert,<sup>50</sup> G. Bolla,<sup>49</sup> D. Bortoletto,<sup>49</sup> J. Boudreau,<sup>48</sup> A. Boveia,<sup>11</sup> B. Brau<sup>a,11</sup> A. Bridgeman,<sup>25</sup> L. Brigliadori<sup>y,6</sup> C. Bromberg,<sup>36</sup> E. Brubaker,<sup>14</sup> J. Budagov,<sup>16</sup> H.S. Budd,<sup>50</sup> S. Budd,<sup>25</sup> S. Burke,<sup>18</sup> K. Burkett,<sup>18</sup> G. Busetto<sup>z,44</sup> P. Bussey,<sup>22</sup> A. Buzatu,<sup>34</sup> K. L. Byrum,<sup>2</sup> S. Cabrera<sup>v,17</sup> C. Calancha,<sup>32</sup> M. Campanelli,<sup>36</sup> M. Campbell,<sup>35</sup> F. Canelli<sup>14,18</sup> A. Canepa,<sup>46</sup> B. Carls,<sup>25</sup> D. Carlsmith,<sup>60</sup> R. Carosi,<sup>47</sup> S. Carrillo<sup>n,19</sup> S. Carron,<sup>34</sup> B. Casal,<sup>12</sup> M. Casarsa,<sup>18</sup> A. Castro<sup>y,6</sup> P. Catastini<sup>bb,47</sup> D. Cauz<sup>ee,55</sup> V. Cavaliere<sup>bb,47</sup> M. Cavalli-Sforza,<sup>4</sup> A. Cerri,<sup>29</sup> L. Cerrito<sup>p,31</sup> S.H. Chang,<sup>28</sup> Y.C. Chen,<sup>1</sup> M. Chertok,<sup>8</sup> G. Chiarelli,<sup>47</sup> G. Chlachidze,<sup>18</sup> F. Chlebana,<sup>18</sup> K. Cho,<sup>28</sup> D. Chokheli,<sup>16</sup> J.P. Chou,<sup>23</sup> G. Choudalakis,<sup>33</sup> S.H. Chuang,<sup>53</sup> K. Chung,<sup>13</sup> W.H. Chung,<sup>60</sup> Y.S. Chung,<sup>50</sup> T. Chwalek,<sup>27</sup> C.I. Ciobanu,<sup>45</sup> M.A. Ciocci<sup>bb,47</sup> A. Clark,<sup>21</sup> D. Clark,<sup>7</sup> G. Compostella,<sup>44</sup> M.E. Convery,<sup>18</sup> J. Conway,<sup>8</sup> M. Cordelli,<sup>20</sup> G. Cortiana<sup>z,44</sup> C.A. Cox,<sup>8</sup> D.J. Cox,<sup>8</sup> F. Crescioli<sup>aa,47</sup> C. Cuenca Almenar<sup>v,8</sup> J. Cuevas<sup>t,12</sup> R. Culbertson,<sup>18</sup> J.C. Cully,<sup>35</sup> D. Dagenhart,<sup>18</sup> M. Datta,<sup>18</sup> T. Davies,<sup>22</sup> P. de Barbaro,<sup>50</sup> S. De Cecco,<sup>52</sup> A. Deisher,<sup>29</sup> G. De Lorenzo,<sup>4</sup> M. Dell'Orso<sup>aa,47</sup> C. Deluca,<sup>4</sup> L. Demortier,<sup>51</sup> J. Deng,<sup>17</sup> M. Deninno,<sup>6</sup> P.F. Derwent,<sup>18</sup> A. Di Canto<sup>aa,47</sup> G.P. di Giovanni,<sup>45</sup> C. Dionisi<sup>dd,52</sup> B. Di Ruzza<sup>ee,55</sup> J.R. Dittmann,<sup>5</sup> M. D'Onofrio,<sup>4</sup> S. Donati<sup>aa,47</sup> P. Dong,<sup>9</sup> J. Donini,<sup>44</sup> T. Dorigo,<sup>44</sup> S. Dube,<sup>53</sup> J. Efron,<sup>40</sup> A. Elagin,<sup>54</sup> R. Erbacher,<sup>8</sup> D. Errede,<sup>25</sup> S. Errede,<sup>25</sup> R. Eusebi,<sup>18</sup> H.C. Fang,<sup>29</sup> S. Farrington,<sup>43</sup> W.T. Fedorko,<sup>14</sup> R.G. Feild,<sup>61</sup> M. Feindt,<sup>27</sup> J.P. Fernandez,<sup>32</sup> C. Ferrazza<sup>cc,47</sup> R. Field,<sup>19</sup> G. Flanagan,<sup>49</sup> R. Forrest,<sup>8</sup> M.J. Frank,<sup>5</sup> M. Franklin,<sup>23</sup> J.C. Freeman,<sup>18</sup> H.J. Frisch,<sup>14</sup> I. Furic,<sup>19</sup> M. Gallinaro,<sup>52</sup> J. Galyardt,<sup>13</sup> F. Garberon,<sup>11</sup> J.E. Garcia,<sup>21</sup> A.F. Garfinkel,<sup>49</sup> P. Garosi<sup>bb,47</sup> K. Genser,<sup>18</sup> H. Gerberich,<sup>25</sup> D. Gerdes,<sup>35</sup> A. Gessler,<sup>27</sup> S. Giagu<sup>dd,52</sup> V. Giakoumopoulou,<sup>3</sup> P. Giannetti,<sup>47</sup> K. Gibson,<sup>48</sup> J.L. Gimmell,<sup>50</sup> C.M. Ginsburg,<sup>18</sup> N. Giokaris,<sup>3</sup> M. Giordani<sup>ee,55</sup> P. Giromini,<sup>20</sup> M. Giunta,<sup>47</sup> G. Giurciu,<sup>26</sup> V. Glagolev,<sup>16</sup> D. Glenzinski,<sup>18</sup> M. Gold,<sup>38</sup> N. Goldschmidt,<sup>19</sup> A. Golossanov,<sup>18</sup> G. Gomez,<sup>12</sup> G. Gomez-Ceballos,<sup>33</sup> M. Goncharov,<sup>33</sup> O. González,<sup>32</sup> I. Gorelov,<sup>38</sup> A.T. Goshaw,<sup>17</sup> K. Goulianos,<sup>51</sup> A. Gresele<sup>z,44</sup> S. Grinstein,<sup>23</sup> C. Grosso-Pilcher,<sup>14</sup> R.C. Group,<sup>18</sup> U. Grundler,<sup>25</sup> J. Guimaraes da Costa,<sup>23</sup> Z. Gunay-Unalan,<sup>36</sup> C. Haber,<sup>29</sup> K. Hahn,<sup>33</sup> S.R. Hahn,<sup>18</sup> E. Halkiadakis,<sup>53</sup> B.-Y. Han,<sup>50</sup> J.Y. Han,<sup>50</sup> F. Happacher,<sup>20</sup> K. Hara,<sup>56</sup> D. Hare,<sup>53</sup> M. Hare,<sup>57</sup> S. Harper,<sup>43</sup> R.F. Harr,<sup>59</sup> R.M. Harris,<sup>18</sup> M. Hartz,<sup>48</sup> K. Hatakeyama,<sup>51</sup> C. Hays,<sup>43</sup> M. Heck,<sup>27</sup> A. Heijboer,<sup>46</sup> J. Heinrich,<sup>46</sup> C. Henderson,<sup>33</sup> M. Herndon,<sup>60</sup> J. Heuser,<sup>27</sup> S. Hewamanage,<sup>5</sup> D. Hidas,<sup>17</sup> C.S. Hill<sup>c,11</sup> D. Hirschbuehl,<sup>27</sup> A. Hocker,<sup>18</sup> S. Hou,<sup>1</sup> M. Houlden,<sup>30</sup> S.-C. Hsu,<sup>29</sup> B.T. Huffman,<sup>43</sup> R.E. Hughes,<sup>40</sup> U. Husemann,<sup>61</sup> M. Hussein,<sup>36</sup> J. Huston,<sup>36</sup> J. Incandela,<sup>11</sup> G. Introzzi,<sup>47</sup> M. Iori<sup>dd,52</sup> A. Ivanov,<sup>8</sup> E. James,<sup>18</sup> D. Jang,<sup>13</sup> B. Jayatilaka,<sup>17</sup> E.J. Jeon,<sup>28</sup> M.K. Jha,<sup>6</sup> S. Jindariani,<sup>18</sup> W. Johnson,<sup>8</sup> M. Jones,<sup>49</sup> K.K. Joo,<sup>28</sup> S.Y. Jun,<sup>13</sup> J.E. Jung,<sup>28</sup> T.R. Junk,<sup>18</sup> T. Kamon,<sup>54</sup> D. Kar,<sup>19</sup> P.E. Karchin,<sup>59</sup> Y. Kato<sup>l,42</sup> R. Kephart,<sup>18</sup> W. Ketchum,<sup>14</sup> J. Keung,<sup>46</sup> V. Khotilovich,<sup>54</sup> B. Kilminster,<sup>18</sup> D.H. Kim,<sup>28</sup> H.S. Kim,<sup>28</sup> H.W. Kim,<sup>28</sup> J.E. Kim,<sup>28</sup> M.J. Kim,<sup>20</sup> S.B. Kim,<sup>28</sup> S.H. Kim,<sup>56</sup> Y.K. Kim,<sup>14</sup> N. Kimura,<sup>56</sup> L. Kirsch,<sup>7</sup> S. Klimentenko,<sup>19</sup> B. Knuteson,<sup>33</sup> B.R. Ko,<sup>17</sup> K. Kondo,<sup>58</sup> D.J. Kong,<sup>28</sup> J. Konigsberg,<sup>19</sup> A. Korytov,<sup>19</sup> A.V. Kotwal,<sup>17</sup> M. Kreps,<sup>27</sup> J. Kroll,<sup>46</sup> D. Krop,<sup>14</sup> N. Krumnack,<sup>5</sup> M. Kruse,<sup>17</sup> V. Krutelyov,<sup>11</sup> T. Kubo,<sup>56</sup> T. Kuhr,<sup>27</sup> N.P. Kulkarni,<sup>59</sup> M. Kurata,<sup>56</sup> S. Kwang,<sup>14</sup> A.T. Laasanen,<sup>49</sup> S. Lami,<sup>47</sup> S. Lammel,<sup>18</sup> M. Lancaster,<sup>31</sup> R.L. Lander,<sup>8</sup> K. Lannon<sup>s,40</sup> A. Lath,<sup>53</sup> G. Latino<sup>bb,47</sup> I. Lazzizzera<sup>z,44</sup> T. LeCompte,<sup>2</sup> E. Lee,<sup>54</sup> H.S. Lee,<sup>14</sup> S.W. Lee<sup>u,54</sup> S. Leone,<sup>47</sup> J.D. Lewis,<sup>18</sup> C.-S. Lin,<sup>29</sup> J. Linacre,<sup>43</sup> M. Lindgren,<sup>18</sup> E. Lipeles,<sup>46</sup> A. Lister,<sup>8</sup> D.O. Litvintsev,<sup>18</sup> C. Liu,<sup>48</sup> T. Liu,<sup>18</sup> N.S. Lockyer,<sup>46</sup> A. Loginov,<sup>61</sup> M. Loretiz<sup>z,44</sup> L. Lovas,<sup>15</sup> D. Lucchesi<sup>z,44</sup> C. Luci<sup>dd,52</sup> J. Lueck,<sup>27</sup> P. Lujan,<sup>29</sup> P. Lukens,<sup>18</sup> G. Lungu,<sup>51</sup> L. Lyons,<sup>43</sup> J. Lys,<sup>29</sup> R. Lysak,<sup>15</sup> D. MacQueen,<sup>34</sup> R. Madrak,<sup>18</sup> K. Maeshima,<sup>18</sup> K. Makhoul,<sup>33</sup> T. Maki,<sup>24</sup> P. Maksimovic,<sup>26</sup> S. Malde,<sup>43</sup> S. Malik,<sup>31</sup> G. Manca<sup>e,30</sup> A. Manousakis-Katsikakis,<sup>3</sup> F. Margaroli,<sup>49</sup> C. Marino,<sup>27</sup> C.P. Marino,<sup>25</sup> A. Martin,<sup>61</sup> V. Martin<sup>k,22</sup> M. Martínez,<sup>4</sup> R. Martínez-Ballarín,<sup>32</sup> T. Maruyama,<sup>56</sup> P. Mastrandrea,<sup>52</sup> T. Masubuchi,<sup>56</sup> M. Mathis,<sup>26</sup> M.E. Mattson,<sup>59</sup> P. Mazzanti,<sup>6</sup> K.S. McFarland,<sup>50</sup> P. McIntyre,<sup>54</sup> R. McNulty<sup>j,30</sup> A. Mehta,<sup>30</sup> P. Mehtala,<sup>24</sup> A. Menzione,<sup>47</sup> P. Merkel,<sup>49</sup> C. Mesropian,<sup>51</sup> T. Miao,<sup>18</sup> N. Miladinovic,<sup>7</sup> R. Miller,<sup>36</sup> C. Mills,<sup>23</sup> M. Milnik,<sup>27</sup> A. Mitra,<sup>1</sup> G. Mitselmakher,<sup>19</sup> H. Miyake,<sup>56</sup> N. Moggi,<sup>6</sup>

C.S. Moon,<sup>28</sup> R. Moore,<sup>18</sup> M.J. Morello,<sup>47</sup> J. Morlock,<sup>27</sup> P. Movilla Fernandez,<sup>18</sup> J. Mülmenstädt,<sup>29</sup> A. Mukherjee,<sup>18</sup> Th. Muller,<sup>27</sup> R. Mumford,<sup>26</sup> P. Murat,<sup>18</sup> M. Mussini<sup>y</sup>,<sup>6</sup> J. Nachtman<sup>o</sup>,<sup>18</sup> Y. Nagai,<sup>56</sup> A. Nagano,<sup>56</sup> J. Naganoma,<sup>56</sup> K. Nakamura,<sup>56</sup> I. Nakano,<sup>41</sup> A. Napier,<sup>57</sup> V. Necula,<sup>17</sup> J. Nett,<sup>60</sup> C. Neu<sup>w</sup>,<sup>46</sup> M.S. Neubauer,<sup>25</sup> S. Neubauer,<sup>27</sup> J. Nielsen<sup>g</sup>,<sup>29</sup> L. Nodulman,<sup>2</sup> M. Norman,<sup>10</sup> O. Norriella,<sup>25</sup> E. Nurse,<sup>31</sup> L. Oakes,<sup>43</sup> S.H. Oh,<sup>17</sup> Y.D. Oh,<sup>28</sup> I. Oksuzian,<sup>19</sup> T. Okusawa,<sup>42</sup> R. Orava,<sup>24</sup> K. Osterberg,<sup>24</sup> S. Pagan Griso<sup>z</sup>,<sup>44</sup> E. Palencia,<sup>18</sup> V. Papadimitriou,<sup>18</sup> A. Papaikonomou,<sup>27</sup> A.A. Paramonov,<sup>14</sup> B. Parks,<sup>40</sup> S. Pashapour,<sup>34</sup> J. Patrick,<sup>18</sup> G. Pauletta<sup>ee</sup>,<sup>55</sup> M. Paulini,<sup>13</sup> C. Paus,<sup>33</sup> T. Peiffer,<sup>27</sup> D.E. Pellett,<sup>8</sup> A. Penzo,<sup>55</sup> T.J. Phillips,<sup>17</sup> G. Piacentino,<sup>47</sup> E. Pianori,<sup>46</sup> L. Pinera,<sup>19</sup> K. Pitts,<sup>25</sup> C. Plager,<sup>9</sup> L. Pondrom,<sup>60</sup> O. Poukhov<sup>\*</sup>,<sup>16</sup> N. Pounder,<sup>43</sup> F. Prakoshyn,<sup>16</sup> A. Pronko,<sup>18</sup> J. Proudfoot,<sup>2</sup> F. Ptohos<sup>i</sup>,<sup>18</sup> E. Pueschel,<sup>13</sup> G. Punzi<sup>aa</sup>,<sup>47</sup> J. Pursley,<sup>60</sup> J. Rademacker<sup>c</sup>,<sup>43</sup> A. Rahaman,<sup>48</sup> V. Ramakrishnan,<sup>60</sup> N. Ranjan,<sup>49</sup> I. Redondo,<sup>32</sup> P. Renton,<sup>43</sup> M. Renz,<sup>27</sup> M. Rescigno,<sup>52</sup> S. Richter,<sup>27</sup> F. Rimondi<sup>y</sup>,<sup>6</sup> L. Ristori,<sup>47</sup> A. Robson,<sup>22</sup> T. Rodrigo,<sup>12</sup> T. Rodriguez,<sup>46</sup> E. Rogers,<sup>25</sup> S. Rolli,<sup>57</sup> R. Roser,<sup>18</sup> M. Rossi,<sup>55</sup> R. Rossin,<sup>11</sup> P. Roy,<sup>34</sup> A. Ruiz,<sup>12</sup> J. Russ,<sup>13</sup> V. Rusu,<sup>18</sup> B. Rutherford,<sup>18</sup> H. Saarikko,<sup>24</sup> A. Safonov,<sup>54</sup> W.K. Sakumoto,<sup>50</sup> O. Saltó,<sup>4</sup> L. Santi<sup>ee</sup>,<sup>55</sup> S. Sarkar<sup>dd</sup>,<sup>52</sup> L. Sartori,<sup>47</sup> K. Sato,<sup>18</sup> A. Savoy-Navarro,<sup>45</sup> P. Schlabach,<sup>18</sup> A. Schmidt,<sup>27</sup> E.E. Schmidt,<sup>18</sup> M.A. Schmidt,<sup>14</sup> M.P. Schmidt<sup>\*</sup>,<sup>61</sup> M. Schmitt,<sup>39</sup> T. Schwarz,<sup>8</sup> L. Scodellaro,<sup>12</sup> A. Scribano<sup>bb</sup>,<sup>47</sup> F. Scuri,<sup>47</sup> A. Sedov,<sup>49</sup> S. Seidel,<sup>38</sup> Y. Seiya,<sup>42</sup> A. Semenov,<sup>16</sup> L. Sexton-Kennedy,<sup>18</sup> F. Sforza<sup>aa</sup>,<sup>47</sup> A. Sfyrla,<sup>25</sup> S.Z. Shalhout,<sup>59</sup> T. Shears,<sup>30</sup> P.F. Shepard,<sup>48</sup> M. Shimojima<sup>r</sup>,<sup>56</sup> S. Shiraishi,<sup>14</sup> M. Shochet,<sup>14</sup> Y. Shon,<sup>60</sup> I. Shreyber,<sup>37</sup> P. Sinervo,<sup>34</sup> A. Sisakyan,<sup>16</sup> A.J. Slaughter,<sup>18</sup> J. Slaunwhite,<sup>40</sup> K. Sliwa,<sup>57</sup> J.R. Smith,<sup>8</sup> F.D. Snider,<sup>18</sup> R. Snihur,<sup>34</sup> A. Soha,<sup>8</sup> S. Somalwar,<sup>53</sup> V. Sorin,<sup>36</sup> T. Spreitzer,<sup>34</sup> P. Squillacioti<sup>bb</sup>,<sup>47</sup> M. Stanitzki,<sup>61</sup> R. St. Denis,<sup>22</sup> B. Stelzer,<sup>34</sup> O. Stelzer-Chilton,<sup>34</sup> D. Stentz,<sup>39</sup> J. Strogas,<sup>38</sup> G.L. Strycker,<sup>35</sup> J.S. Suh,<sup>28</sup> A. Sukhanov,<sup>19</sup> I. Suslov,<sup>16</sup> T. Suzuki,<sup>56</sup> A. Taffard<sup>f</sup>,<sup>25</sup> R. Takashima,<sup>41</sup> Y. Takeuchi,<sup>56</sup> R. Tanaka,<sup>41</sup> M. Tecchio,<sup>35</sup> P.K. Teng,<sup>1</sup> K. Terashi,<sup>51</sup> J. Thom<sup>h</sup>,<sup>18</sup> A.S. Thompson,<sup>22</sup> G.A. Thompson,<sup>25</sup> E. Thomson,<sup>46</sup> P. Tipton,<sup>61</sup> P. Ttito-Guzmán,<sup>32</sup> S. Tkaczyk,<sup>18</sup> D. Toback,<sup>54</sup> S. Tokar,<sup>15</sup> K. Tollefson,<sup>36</sup> T. Tomura,<sup>56</sup> D. Tonelli,<sup>18</sup> S. Torre,<sup>20</sup> D. Torretta,<sup>18</sup> P. Totaro<sup>ee</sup>,<sup>55</sup> S. Tourneur,<sup>45</sup> M. Trovato<sup>cc</sup>,<sup>47</sup> S.-Y. Tsai,<sup>1</sup> Y. Tu,<sup>46</sup> N. Turini<sup>bb</sup>,<sup>47</sup> F. Ukegawa,<sup>56</sup> S. Vallecorsa,<sup>21</sup> N. van Remortel<sup>b</sup>,<sup>24</sup> A. Varganov,<sup>35</sup> E. Vataga<sup>cc</sup>,<sup>47</sup> F. Vázquez<sup>n</sup>,<sup>19</sup> G. Velev,<sup>18</sup> C. Vellidis,<sup>3</sup> M. Vidal,<sup>32</sup> R. Vidal,<sup>18</sup> I. Vila,<sup>12</sup> R. Vilar,<sup>12</sup> T. Vine,<sup>31</sup> M. Vogel,<sup>38</sup> I. Volobouev<sup>u</sup>,<sup>29</sup> G. Volpi<sup>aa</sup>,<sup>47</sup> P. Wagner,<sup>46</sup> R.G. Wagner,<sup>2</sup> R.L. Wagner,<sup>18</sup> W. Wagner<sup>x</sup>,<sup>27</sup> J. Wagner-Kuhr,<sup>27</sup> T. Wakisaka,<sup>42</sup> R. Wallny,<sup>9</sup> S.M. Wang,<sup>1</sup> A. Warburton,<sup>34</sup> D. Waters,<sup>31</sup> M. Weinberger,<sup>54</sup> J. Weinelt,<sup>27</sup> W.C. Wester III,<sup>18</sup> B. Whitehouse,<sup>57</sup> D. Whiteson<sup>f</sup>,<sup>46</sup> A.B. Wicklund,<sup>2</sup> E. Wicklund,<sup>18</sup> S. Wilbur,<sup>14</sup> G. Williams,<sup>34</sup> H.H. Williams,<sup>46</sup> P. Wilson,<sup>18</sup> B.L. Winer,<sup>40</sup> P. Wittich<sup>h</sup>,<sup>18</sup> S. Wolbers,<sup>18</sup> C. Wolfe,<sup>14</sup> T. Wright,<sup>35</sup> X. Wu,<sup>21</sup> F. Würthwein,<sup>10</sup> S. Xie,<sup>33</sup> A. Yagil,<sup>10</sup> K. Yamamoto,<sup>42</sup> J. Yamaoka,<sup>17</sup> U.K. Yang<sup>q</sup>,<sup>14</sup> Y.C. Yang,<sup>28</sup> W.M. Yao,<sup>29</sup> G.P. Yeh,<sup>18</sup> K. Yi<sup>o</sup>,<sup>18</sup> J. Yoh,<sup>18</sup> K. Yorita,<sup>58</sup> T. Yoshida<sup>m</sup>,<sup>42</sup> G.B. Yu,<sup>50</sup> I. Yu,<sup>28</sup> S.S. Yu,<sup>18</sup> J.C. Yun,<sup>18</sup> L. Zanello<sup>dd</sup>,<sup>52</sup> A. Zanetti,<sup>55</sup> X. Zhang,<sup>25</sup> Y. Zheng<sup>d</sup>,<sup>9</sup> and S. Zucchelli<sup>y</sup>,<sup>6</sup>

(CDF Collaboration<sup>†</sup>)

<sup>1</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*

<sup>2</sup>*Argonne National Laboratory, Argonne, Illinois 60439*

<sup>3</sup>*University of Athens, 157 71 Athens, Greece*

<sup>4</sup>*Institut de Fisica d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*

<sup>5</sup>*Baylor University, Waco, Texas 76798*

<sup>6</sup>*Istituto Nazionale di Fisica Nucleare Bologna, <sup>9</sup>University of Bologna, I-40127 Bologna, Italy*

<sup>7</sup>*Brandeis University, Waltham, Massachusetts 02254*

<sup>8</sup>*University of California, Davis, Davis, California 95616*

<sup>9</sup>*University of California, Los Angeles, Los Angeles, California 90024*

<sup>10</sup>*University of California, San Diego, La Jolla, California 92093*

<sup>11</sup>*University of California, Santa Barbara, Santa Barbara, California 93106*

<sup>12</sup>*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*

<sup>13</sup>*Carnegie Mellon University, Pittsburgh, PA 15213*

<sup>14</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*

<sup>15</sup>*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*

<sup>16</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

<sup>17</sup>*Duke University, Durham, North Carolina 27708*

<sup>18</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

<sup>19</sup>*University of Florida, Gainesville, Florida 32611*

<sup>20</sup>*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

<sup>21</sup>*University of Geneva, CH-1211 Geneva 4, Switzerland*

<sup>22</sup>*Glasgow University, Glasgow G12 8QQ, United Kingdom*

<sup>23</sup>*Harvard University, Cambridge, Massachusetts 02138*

- <sup>24</sup>*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
- <sup>25</sup>*University of Illinois, Urbana, Illinois 61801*
- <sup>26</sup>*The Johns Hopkins University, Baltimore, Maryland 21218*
- <sup>27</sup>*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
- <sup>28</sup>*Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; Sungkyunkwan University, Suwon 440-746, Korea; Korea Institute of Science and Technology Information, Daejeon, 305-806, Korea; Chonnam National University, Gwangju, 500-757, Korea*
- <sup>29</sup>*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
- <sup>30</sup>*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
- <sup>31</sup>*University College London, London WC1E 6BT, United Kingdom*
- <sup>32</sup>*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
- <sup>33</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
- <sup>34</sup>*Institute of Particle Physics: McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
- <sup>35</sup>*University of Michigan, Ann Arbor, Michigan 48109*
- <sup>36</sup>*Michigan State University, East Lansing, Michigan 48824*
- <sup>37</sup>*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
- <sup>38</sup>*University of New Mexico, Albuquerque, New Mexico 87131*
- <sup>39</sup>*Northwestern University, Evanston, Illinois 60208*
- <sup>40</sup>*The Ohio State University, Columbus, Ohio 43210*
- <sup>41</sup>*Okayama University, Okayama 700-8530, Japan*
- <sup>42</sup>*Osaka City University, Osaka 588, Japan*
- <sup>43</sup>*University of Oxford, Oxford OX1 3RH, United Kingdom*
- <sup>44</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, <sup>z</sup>University of Padova, I-35131 Padova, Italy*
- <sup>45</sup>*LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
- <sup>46</sup>*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
- <sup>47</sup>*Istituto Nazionale di Fisica Nucleare Pisa, <sup>aa</sup>University of Pisa,*
- <sup>bb</sup>*University of Siena and <sup>cc</sup>Scuola Normale Superiore, I-56127 Pisa, Italy*
- <sup>48</sup>*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
- <sup>49</sup>*Purdue University, West Lafayette, Indiana 47907*
- <sup>50</sup>*University of Rochester, Rochester, New York 14627*
- <sup>51</sup>*The Rockefeller University, New York, New York 10021*
- <sup>52</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, <sup>dd</sup>Sapienza Università di Roma, I-00185 Roma, Italy*
- <sup>53</sup>*Rutgers University, Piscataway, New Jersey 08855*
- <sup>54</sup>*Texas A&M University, College Station, Texas 77843*
- <sup>55</sup>*Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, <sup>ee</sup>University of Trieste/Udine, I-33100 Udine, Italy*
- <sup>56</sup>*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
- <sup>57</sup>*Tufts University, Medford, Massachusetts 02155*
- <sup>58</sup>*Waseda University, Tokyo 169, Japan*
- <sup>59</sup>*Wayne State University, Detroit, Michigan 48201*
- <sup>60</sup>*University of Wisconsin, Madison, Wisconsin 53706*
- <sup>61</sup>*Yale University, New Haven, Connecticut 06520*

(Dated: July 10, 2009)

In a search for new phenomena in a signature suppressed in the standard model of elementary particles (SM), we compare the inclusive production of events containing a lepton ( $\ell$ ), a photon ( $\gamma$ ), significant transverse momentum imbalance ( $E_T$ ), and a jet identified as containing a b-quark, to SM predictions. The search uses data produced in proton-antiproton collisions at  $\sqrt{s} = 1.96$  TeV corresponding to  $1.9 \text{ fb}^{-1}$  of integrated luminosity taken with the CDF detector at the Fermilab Tevatron. We find  $28 \ell\gamma b E_T$  events versus an expectation of  $31.0_{-3.5}^{+4.1}$  events. If we further require events to contain at least three jets and large total transverse energy, simulations predict that the largest SM source is top-quark pair production with an additional radiated photon,  $t\bar{t} + \gamma$ . In the data we observe  $16 t\bar{t}\gamma$  candidate events versus an expectation from SM sources of  $11.2_{-2.1}^{+2.3}$ . Assuming the difference between the observed number and the predicted non-top-quark total is due to SM top quark production, we estimate the  $t\bar{t}\gamma$  cross section to be  $0.15 \pm 0.08$  pb.

The unknown nature of possible new phenomena in the energy range accessible at the Tevatron collider is the motivation for a search strategy [1, 2, 3] that does not focus on current hypothetical models of new physics, but instead tests the standard model (SM) [4]. The emphasis on presenting measurements and SM predictions, rather than comparisons with arbitrarily chosen other models, allows a wide net for physics beyond the SM that can be used now by proponents of current models of ‘new physics’ as well as in the future by theorists with new ideas and facts. Here we report the results of a search for events containing a lepton ( $\ell$ ), a photon ( $\gamma$ ), significant transverse momentum imbalance ( $\cancel{E}_T$ ) [5], and a jet identified as containing a b-quark; i.e. the final state  $\ell\gamma b\cancel{E}_T + X$ . This channel, which contains a vector boson and a third-generation quark, is suppressed in the SM, and is consequently sensitive to rare new phenomena. The data correspond to an integrated luminosity of  $1.9 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$ , collected using the CDF II detector [6]. This search is an extension of a previous search in the lepton+photon+X signature, described in detail in Ref. [7].

A search for SM production of top-quark pairs with an additional photon,  $t\bar{t}\gamma$ , is a natural extension of the  $\ell\gamma b\cancel{E}_T + X$  analysis. By further requiring events to contain at least three jets and large total transverse energy ( $H_T$ ) [5], we find that the SM predicts the largest source of events will be top-quark pair production with an additional radiated photon,  $t\bar{t} + \gamma$ . The process is of interest for the direct measurement of the electric charge of the top quark [8], as well as being another low-cross-section search signature in which rare non-SM processes could appear.

The CDF II detector [6] is a cylindrically-symmetric

magnetic spectrometer designed to study  $p\bar{p}$  collisions at the Fermilab Tevatron. Here we briefly describe the detector subsystems relevant for the present analysis.

Tracking systems are used to measure the momenta of charged particles and to identify leptons with large transverse momenta [5]. A multi-layer system of silicon strip detectors [9], which identifies tracks in both the  $r$ - $\phi$  and  $r$ - $z$  views [10], and the central outer tracker (COT) [11], are contained in a superconducting solenoid that generates a magnetic field of 1.4 T. The COT is a 3.1 m long open-cell drift chamber that makes up to 96 measurements along the track of each charged particle in the region  $|\eta| < 1$ . Sense wires are arranged in 8 alternating axial and  $\pm 2^\circ$  stereo superlayers with 12 wire layers each. For high-momentum tracks, the COT transverse momentum ( $p_T$ ) resolution is  $\sigma_{p_T}/p_T^2 \simeq 0.0017 \text{ GeV}^{-1}$  [11].

Segmented calorimeters with towers arranged in a projective geometry, each tower consisting of an electromagnetic and an hadronic compartment [12, 13], cover the region  $|\eta| < 3.6$ . In this analysis we select photons and electrons in the central region,  $|\eta| < 1$ , where a system (CES) with finer spatial resolution is used to make profile measurements of electromagnetic showers at shower maximum [6]. Electrons are reconstructed in the central electromagnetic calorimeter (CEM) with an  $E_T$  resolution of  $\sigma(E_T)/E_T \simeq 13.5\%/\sqrt{E_T/\text{GeV}} \oplus 2\%$  [12]. Jets are identified in the electromagnetic and hadronic calorimeters using a cone in  $\eta - \phi$  space of radius 0.4 [14, 15]. The jet energy resolution is approximately  $\sigma \simeq 0.1 \times E_T$  (GeV) + 1.0 GeV [16].

Muons are identified using the central muon (CMU), the central muon upgrade (CMP), and the central muon extension (CMX) systems [17, 18], which cover the kinematic region  $|\eta| < 1$ . The CMU uses four layers of planar drift chambers to detect muons with  $p_T > 1.4 \text{ GeV}$  in the region of  $|\eta| < 0.6$ . The CMP consists of four additional layers of planar drift chambers located behind 0.6 m of steel outside the magnetic return yoke, and detects muons with  $p_T > 2.0 \text{ GeV}$ . The CMX detects muons in the region  $0.6 < |\eta| < 1.0$  with four to eight layers of drift chambers, depending on the polar angle.

We use identification algorithms that exploit the long lifetime ( $c\tau_0 \sim 450 \mu\text{m}$ ) of  $b$  hadrons to identify jets containing  $b$  hadrons. Candidate  $b$ -jets are identified through the presence of a secondary decay vertex displaced from the beam line in the region  $|\eta| < 2$  [19].

The beam luminosity is measured using two arrays of gas Cherenkov counters, located in the region  $3.7 < |\eta| < 4.7$ . The total uncertainty on the luminosity has been estimated to be 6%, where 4.4% comes from the acceptance and operation of the luminosity monitor and 4.0% from the calculation of the accepted inelastic  $p\bar{p}$  cross section [20].

We use events selected by the online event selection (trigger) system [6] to have a high  $p_T$  electron or muon in the central region,  $|\eta| \lesssim 1.0$ . The electron trigger

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\*Deceased

<sup>†</sup>With visitors from <sup>a</sup>University of Massachusetts Amherst, Amherst, Massachusetts 01003, <sup>b</sup>Universiteit Antwerpen, B-2610 Antwerp, Belgium, <sup>c</sup>University of Bristol, Bristol BS8 1TL, United Kingdom, <sup>d</sup>Chinese Academy of Sciences, Beijing 100864, China, <sup>e</sup>Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, <sup>f</sup>University of California Irvine, Irvine, CA 92697, <sup>g</sup>University of California Santa Cruz, Santa Cruz, CA 95064, <sup>h</sup>Cornell University, Ithaca, NY 14853, <sup>i</sup>University of Cyprus, Nicosia CY-1678, Cyprus, <sup>j</sup>University College Dublin, Dublin 4, Ireland, <sup>k</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, <sup>l</sup>University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017 <sup>m</sup>Kinki University, Higashi-Osaka City, Japan 577-8502 <sup>n</sup>Universidad Iberoamericana, Mexico D.F., Mexico, <sup>o</sup>University of Iowa, Iowa City, IA 52242, <sup>p</sup>Queen Mary, University of London, London, E1 4NS, England, <sup>q</sup>University of Manchester, Manchester M13 9PL, England, <sup>r</sup>Nagasaki Institute of Applied Science, Nagasaki, Japan, <sup>s</sup>University of Notre Dame, Notre Dame, IN 46556, <sup>t</sup>University de Oviedo, E-33007 Oviedo, Spain, <sup>u</sup>Texas Tech University, Lubbock, TX 79609, <sup>v</sup>IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain, <sup>w</sup>University of Virginia, Charlottesville, VA 22904, <sup>x</sup>Bergische Universität Wuppertal, 42097 Wuppertal, Germany, <sup>y</sup>On leave from J. Stefan Institute, Ljubljana, Slovenia,

requires a cluster of energy in the central electromagnetic calorimeter with a COT track pointing at the cluster. The muon trigger requires a COT track that extrapolates to a track segment in the muon chambers.

Inclusive  $\ell\gamma$  events are selected by requiring a central high-energy  $\gamma$  candidate and a central high-energy  $e$  or  $\mu$  candidate originating less than 60 cm along the beam-line from the detector center and passing the selection criteria listed below. To reduce background from the decays of hadrons produced in jets, both the photon and the lepton in each event are required to be isolated [21].

An electron candidate must meet the following selection criteria: a) a high-quality track [22] with  $p_T > 0.5 E_T$ , unless  $E_T > 100$  GeV, in which case the  $p_T$  threshold is set to 20 GeV; b) a good transverse shower profile that matches the extrapolated track position; c) a lateral sharing of energy in the calorimeter towers containing the electron shower consistent with that expected; and d) minimal leakage into the hadron calorimeter [23].

A muon candidate must have: a) a well-measured track in the COT; b) energy deposited in the calorimeter consistent with expectations; c) a muon track segment in both the CMU and CMP, or in the CMX, consistent with the extrapolated COT track; and d) COT timing consistent with a track from a  $p\bar{p}$  collision.

Photon candidates are required to have no track with  $p_T > 1$  GeV, and at most one track with  $p_T < 1$  GeV, pointing at the calorimeter cluster, good profiles in both transverse dimensions at shower maximum, and minimal leakage into the hadron calorimeter [23].

Missing transverse energy ( $E_T$ ) is calculated from the calorimeter tower energies in the region  $|\eta| < 3.6$ . Corrections are then made to the  $E_T$  for the position of the reconstructed primary vertex, and for non-uniform calorimeter response [24] for jets with uncorrected  $E_T > 15$  GeV and  $|\eta| < 2.0$ , and for muons with  $P_T^\mu > 20$  GeV.

The inclusive  $\ell\gamma b E_T$  search is defined by requiring that an event contain a central electron (or muon) with  $E_T^e(P_T^\mu) > 20$  GeV [5], a central photon with  $E_T^\gamma > 10$  GeV, a  $b$ -tagged jet with  $E_T^{\text{jet}} > 15$  GeV, and  $E_T > 20$  GeV [25]. Figures 1 and 2 show kinematic distributions for events in the  $\ell\gamma b E_T$  sample.

The dominant SM sources of  $\ell\gamma b E_T$  events at the Tevatron are  $t\bar{t}\gamma$  production and  $W\gamma$ +heavy flavour (HF) ( $Wc\gamma$ ,  $Wc\bar{c}\gamma$ ,  $Wbb\gamma$ ) in which a  $W$  boson decays leptonically ( $\ell\nu$ ) and a photon is radiated from an initial-state quark, the  $W$ , or a charged final-state lepton [26]. We use the MADGRAPH matrix-element event generator [27] to estimate these contributions. Initial state radiation and parton showering are simulated by the PYTHIA shower code [28] tuned to reproduce the underlying event [29]. The generated particles are then passed through a full simulation of the detector, and these events are then reconstructed with the same reconstruction code used for the data. The expected contributions from  $t\bar{t}\gamma$  and

TABLE I: Summary for the  $\ell\gamma b E_T$  search. Backgrounds from  $WW$ ,  $ZZ$ , and single top quark with an additional radiated photon are found to be negligible.

Lepton + Photon + $E_T$ + $b$ Events			
SM Source	$e\gamma b E_T$	$\mu\gamma b E_T$	$(e + \mu)\gamma b E_T$
$t\bar{t}\gamma$ semileptonic	$2.06 \pm 0.38$	$1.52 \pm 0.28$	$3.58 \pm 0.65$
$t\bar{t}\gamma$ dileptonic	$1.30 \pm 0.23$	$1.02 \pm 0.18$	$2.32 \pm 0.41$
$W^\pm c\gamma$	$1.58 \pm 0.83$	$1.51 \pm 0.80$	$3.09 \pm 1.59$
$W^\pm cc\gamma$	$0.17 \pm 0.12$	$0.46 \pm 0.26$	$0.63 \pm 0.35$
$W^\pm bb\gamma$	$1.30 \pm 0.67$	$0.88 \pm 0.46$	$2.18 \pm 1.11$
$Z(\tau\tau)\gamma$	$0.13 \pm 0.09$	$0.11 \pm 0.08$	$0.24 \pm 0.12$
$WZ$	$0.08 \pm 0.04$	$0.01 \pm 0.01$	$0.09 \pm 0.04$
$\tau \rightarrow \gamma$ fake	$0.12 \pm 0.04$	$0.10 \pm 0.03$	$0.22 \pm 0.05$
Jet faking $\gamma$	$4.56 \pm 1.92$	$3.02 \pm 1.19$	$7.58 \pm 3.11$
Mistagged $b$ -jets	$4.11 \pm 0.41$	$3.54 \pm 0.37$	$7.65 \pm 0.70$
QCD	$1.5 \pm 0.8$	$0.0_{-0.0}^{+1.0}$	$1.5_{-0.8}^{+1.3}$
$ee E_T b$ , $e \rightarrow \gamma$	$1.50 \pm 0.28$	–	$1.50 \pm 0.28$
$\mu e E_T b$ , $e \rightarrow \gamma$	–	$0.45 \pm 0.10$	$0.45 \pm 0.10$
Predicted	$18.4 \pm 2.4$ (tot)	$12.6_{-1.6}^{+1.9}$ (tot)	$31.0_{-3.9}^{+4.1}$ (tot)
Observed	16	12	28

$W\gamma + HF$  production to the  $\ell\gamma b E_T$  and  $t\bar{t}\gamma$  searches are given in Tables I and II. A correction for higher-order processes (K-factor) of  $1.10 \pm 0.15$  for the  $t\bar{t}\gamma$  [25] has been applied to the LO MC estimates. We have also applied a K-factor of  $2.10 \pm 1.05$  for the  $W\gamma + HF$  [30]. Backgrounds from  $WW$ ,  $ZZ$ , and the production of a single top quark plus a photon are estimated to be negligible.

The background from top decays in which tau leptons are misidentified as photons is estimated from a

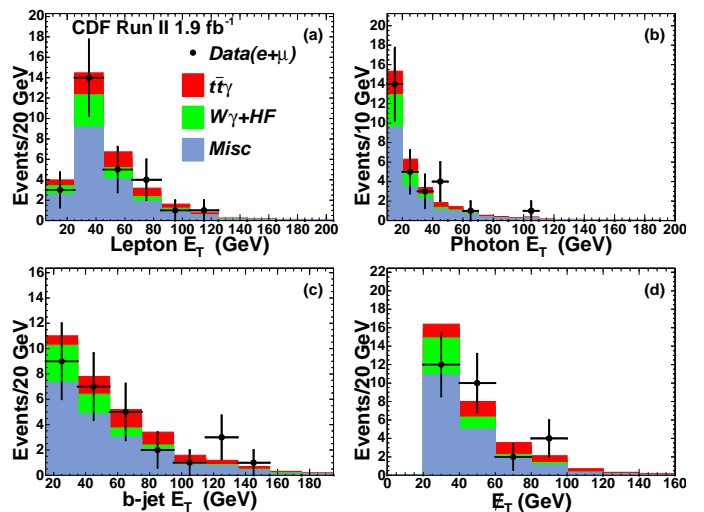


FIG. 1: The distributions for events in the  $\ell\gamma b E_T$  sample (points) in a) the  $E_T$  of the lepton; b) the  $E_T$  of the photon; c) the  $E_T$  of the most energetic  $b$ -jet in an event; and d) the missing transverse energy. The histograms show the estimated SM contributions from radiative top quark decay ( $t\bar{t}\gamma$ ),  $WZ$  production,  $W\gamma$  production with heavy flavor (HF),  $\tau$  leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

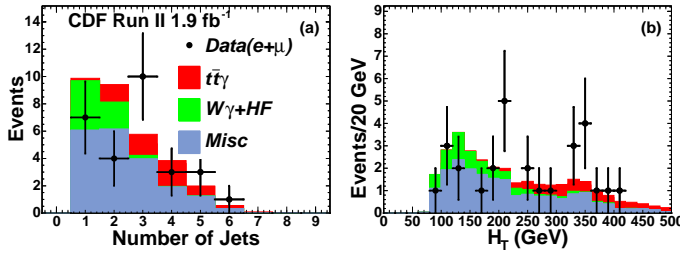


FIG. 2: The distributions for events in the  $l\gamma bE_T$  sample (points) in a) the total number of jets; b) the total transverse energy  $H_T$  for the  $l\gamma bE_T$  events. The histograms show the estimated SM contributions from radiative top quark decay ( $t\bar{t}\gamma$ ), WZ production,  $W\gamma$  production with heavy flavor (HF),  $\tau$  leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

$t\bar{t}$  PYTHIA [28] sample using simulation information to identify tau leptons and then applying the same analysis selection criteria as for data.

High- $p_T$  photons are copiously created from hadron decays in jets initiated by a scattered quark or gluon. In particular, mesons such as the  $\pi^0$  or  $\eta$  decay to multiple photons which may pass the photon selection criteria. To estimate the number of events with a jet misidentified as a photon, we first measure the probability for a jet to be misidentified as a photon,  $P_\gamma^{\text{jet}}(E_T)$ , as a function of the measured  $E_T^{\text{jet}}$ , in data samples triggered on jets. We then measure the jet  $E_T$  in  $lE_T b + \text{jet}$  and  $lE_T + > 3$  jets ( $H_T > 200$  GeV) samples, respectively, and multiply by

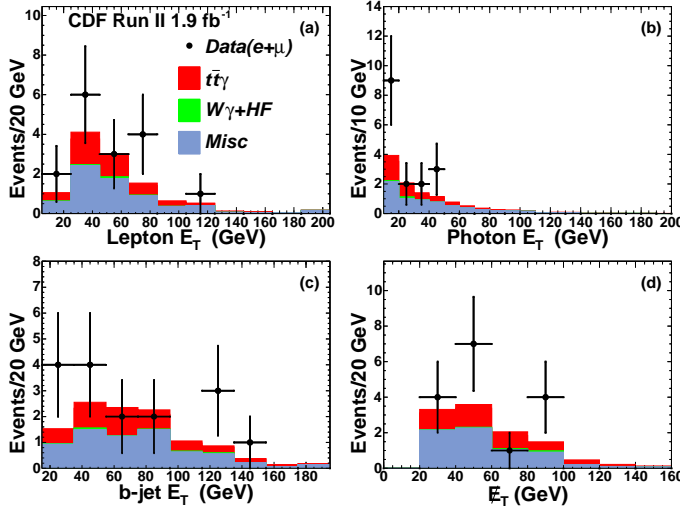


FIG. 3: The distributions for events in the  $t\bar{t}\gamma$  sample (points) in a) the  $E_T$  of the lepton; b) the  $E_T$  of the photon; c) the  $E_T$  of the most energetic  $b$ -jet in an event; and d) the missing transverse energy,  $E_T$ . The histograms show the estimated SM contributions from radiative top quark decay ( $t\bar{t}\gamma$ ), WZ production,  $W\gamma$  production with heavy flavor (HF),  $\tau$  leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

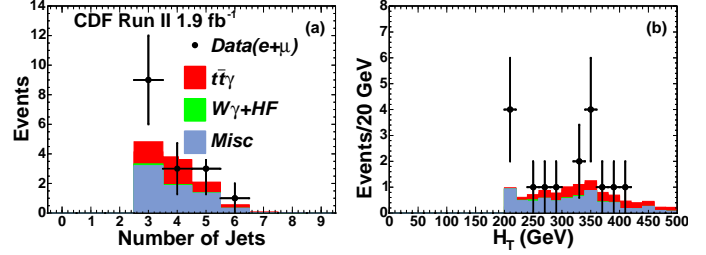


FIG. 4: The distributions for events in the  $t\bar{t}\gamma$  sample (points) in a) the total number of jets; b) the total transverse energy  $H_T$  for the  $l\gamma bE_T$  events. The histograms show the estimated SM contributions from radiative top quark decay ( $t\bar{t}\gamma$ ), WZ production,  $W\gamma$  production with heavy flavor (HF),  $\tau$  leptons, electrons, and jets misidentified as photons, mistagged light-quark and gluon jets, and jets misidentified as leptons (QCD).

$P_\gamma^{\text{jet}}(E_T)$ . An uncertainty of 50% on the number of such events is calculated by using the measured jet spectrum and the upper and lower bounds on the  $E_T$ -dependent misidentification rate [26].

To estimate the probability to mistakenly b-tag a light jet (a mistag), each jet in the  $l\gamma E_T + \text{pretagged jet}$  sample is weighted by its mistag rate that is obtained from tagged events in which the  $b$ -hadron decay vertex is measured to be on the opposite side of the primary vertex from the direction of the jet, an unphysical geometry. The mistag rate derived from these ‘negative’ tags provides an estimate of the number of false positive tags after a correction for interactions in material in the inner tracking volume and long-lived light-flavor particles. The mistag rate per jet is measured using a large inclusive-jet data sample.

We have estimated the background due to events with jets misidentified as high- $p_T$  leptons by studying the total  $p_T$  of tracks in a cone in  $\eta - \varphi$  space of radius  $R=0.4$

TABLE II: Summary of the expected SM contributions to the  $t\bar{t}\gamma$  search. Backgrounds from  $WW$ ,  $ZZ$ , single top quark with an additional radiated photon are found to be negligible.

SM Source	$t\bar{t}\gamma$		
	$e\gamma bE_T$	$\mu\gamma bE_T$	$(e + \mu)\gamma bE_T$
$t\bar{t}\gamma$ semileptonic	$1.97 \pm 0.36$	$1.47 \pm 0.27$	$3.44 \pm 0.62$
$t\bar{t}\gamma$ dileptonic	$0.52 \pm 0.10$	$0.43 \pm 0.08$	$0.95 \pm 0.17$
$W^\pm c\gamma$	$0.0_{-0}^{+0.05}$	$0.0_{-0}^{+0.05}$	$0_{-0}^{+0.07}$
$W^\pm cc\gamma$	$0.0_{-0}^{+0.04}$	$0.03 \pm 0.03$	$0.03_{-0.03}^{+0.05}$
$W^\pm bb\gamma$	$0.13 \pm 0.08$	$0.02 \pm 0.02$	$0.15 \pm 0.09$
WZ	$0.02 \pm 0.02$	$0.0_{-0}^{+0.02}$	$0.02 \pm 0.02$
$\tau \rightarrow \gamma$ fake	$0.08 \pm 0.01$	$0.02 \pm 0.01$	$0.10 \pm 0.01$
Jet faking $\gamma$	$2.37 \pm 1.22$	$1.42 \pm 0.70$	$3.79 \pm 1.92$
Mistagged $b$ -jets	$0.78 \pm 0.20$	$0.83 \pm 0.22$	$1.61 \pm 0.31$
QCD	$0.5 \pm 0.5$	$0.0_{-0.0}^{+1.0}$	$0.5_{-0.5}^{+1.1}$
$eeE_T b, e \rightarrow \gamma$	$0.34 \pm 0.11$	–	$0.34 \pm 0.11$
$\mu eE_T b, e \rightarrow \gamma$	–	$0.20 \pm 0.06$	$0.20 \pm 0.06$
Predicted	$6.7 \pm 1.4(\text{tot})$	$4.4_{-0.8}^{+1.3}(\text{tot})$	$11.2_{-2.1}^{+2.3}(\text{tot})$
Observed	8	8	16

around the lepton track (track isolation) [7]. We compared the distribution of track isolation in the signal sample to that of the  $Z^0 \rightarrow e^+e^-$  and  $Z^0 \rightarrow \mu^+\mu^-$  data samples, and to that of the QCD background data sample, which is dominated by light-flavor and gluon jets.

The number of events with an electron misidentified as a photon expected in the  $\ell\gamma b\cancel{E}_T$  sample is determined by measuring the electron  $E_T$  spectrum in  $\ell e\cancel{E}_T b$  samples, and then multiplying by  $P_{e\rightarrow\gamma}$ , the probability of an electron being misidentified as a photon. We determine  $P_{e\rightarrow\gamma}$  from  $Z^0 \rightarrow e^+e^-$  events in which one of the electrons radiates a high- $E_T$  photon, resulting in an electron-photon system with an invariant mass consistent with that of the Z-boson.

The uncertainties on the numbers of expected events for the  $\ell\gamma b\cancel{E}_T$  search listed in Tables I and II include systematic and statistical uncertainties. A total uncertainty of 6% is quoted for the luminosity measurements [20]. The systematics relevant to the  $\ell\gamma b\cancel{E}_T$  and  $t\bar{t}\gamma$  analyses also include a 5% uncertainty on the  $b$ -tagging efficiency, and uncertainties on the K-factors of 15% for the  $t\bar{t}\gamma$  MC samples and 50% for the  $W\gamma + HF$  samples. The largest experimental systematic uncertainty comes from the rate of misidentifying jets as photons, which we estimate to be uncertain to approximately 50%.

We find 28  $\ell\gamma b\cancel{E}_T$  events versus an expectation of  $31.0^{+4.1}_{-3.5}$  events. The data agree well with the SM predictions, with the precision of the comparison being limited by statistics for the present integrated luminosity.

A second search, for  $t\bar{t}\gamma$  events, is constructed by further requiring  $H_T > 200$  GeV [31] and  $N_{jets} > 2$ , where  $N_{jets}$  is the number of jets in the event [15]. We observe 16  $t\bar{t}\gamma$  candidate events. Figures 3 and 4 show the corresponding kinematic distributions for events in the  $t\bar{t}\gamma$  subsample. An event display of a  $t\bar{t}\gamma$  candidate event is shown in Fig. 5.

For the  $t\bar{t}\gamma$  search, the detection efficiency and acceptance are calculated using MADGRAPH to generate  $t\bar{t}\gamma$

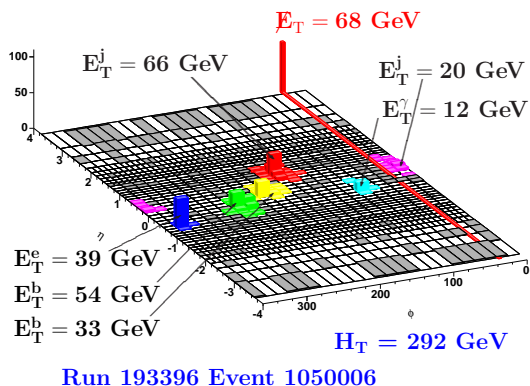


FIG. 5: The  $\eta - \phi$  plot of a  $t\bar{t}\gamma$  candidate event, in which the energies deposited in the calorimeter towers are displayed in the  $\eta - \phi$  plane. The reconstructed top quark mass is 167 GeV; the photon  $E_T$  is 12 GeV.

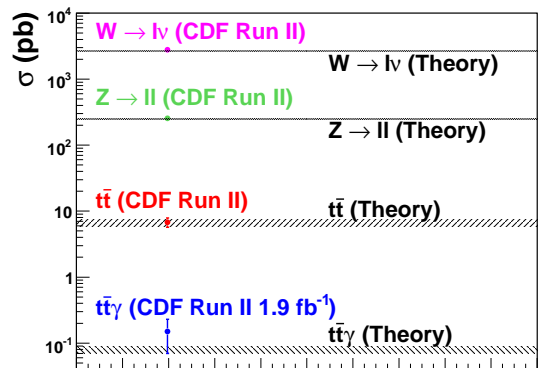


FIG. 6: Estimate of  $\sigma_{t\bar{t}\gamma}$  compared with SM expectations and other SM cross sections  $\sigma_{W\pm\rightarrow\ell\pm\nu}$ ,  $\sigma_{Z\rightarrow\ell+\ell-}$  and  $\sigma_{t\bar{t}}$  [32].

events with one leptonic  $W$  decay. As in the  $\ell\gamma b\cancel{E}_T$  search, the generated particles are then passed through a full detector simulation of the detector and are then reconstructed with the same reconstruction code used for the data. We find a SM expectation of  $11.2^{+2.3}_{-2.1}$  events.

The probability that the backgrounds alone (i.e. assuming that there is no SM production of the  $t\bar{t}\gamma$  final state) will produce 16 or more events, is 1% (2.3 standard deviations). Assuming that the difference between the non-top background estimate and the number of observed events is due to  $t\bar{t}\gamma$  SM production, we estimate the  $t\bar{t}\gamma$  cross section to be  $0.15 \pm 0.08$  pb (see Fig. 6). An estimate of the expected semileptonic cross section  $\sigma(SM) = 0.080 \pm 0.011$  pb is obtained from the LO MADGRAPH cross section of 0.073 pb, multiplied by a K-factor ( $\sigma_{NLO}/\sigma_{LO}$ ) of  $1.10 \pm 0.15$  [25]. The uncertainty on the cross section is dominated by the statistical uncertainties associated with the small number of events observed.

In conclusion, we have performed a search for events containing a lepton, photon,  $b$ -quark production, and missing  $E_T$ , a channel which contains a vector boson and a third-generation quark and is suppressed in the SM. We find no evidence for non-SM production. As an extension of this search we have also performed a search for the SM process  $p\bar{p} \rightarrow t\bar{t}\gamma$ , which is predicted to be the dominant process that produces this signature with at least 3 jets and large total transverse energy  $H_T$ . Here too we find good agreement with the SM expectations. Although not statistically significant, the number of observed  $t\bar{t}\gamma$  events is larger than the SM prediction not including  $t\bar{t}\gamma$  production. Assuming the difference between the observed number and the predicted non-top-quark SM total is due to top quark production, we estimate the  $t\bar{t}\gamma$  cross section to be  $0.15 \pm 0.08$  pb.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. Uli Baur, Johan Alwall, Fabio Maltoni, Michel Herquet, Zack Sullivan, Stephen Mrenna, Frank Pietrello, and Tim Stelzer were extraordinarily helpful with the SM predic-

tions. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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