



## Precise measurement of the top quark mass in the lepton+jets topology at CDF II

A. Abulencia,<sup>24</sup> J. Adelman,<sup>13</sup> T. Affolder,<sup>10</sup> T. Akimoto,<sup>55</sup> M.G. Albrow,<sup>17</sup> S. Amerio,<sup>43</sup> D. Amidei,<sup>35</sup>  
A. Anastassov,<sup>52</sup> K. Anikeev,<sup>17</sup> A. Annovi,<sup>19</sup> J. Antos,<sup>14</sup> M. Aoki,<sup>55</sup> G. Apollinari,<sup>17</sup> T. Arisawa,<sup>57</sup> A. Artikov,<sup>15</sup>  
W. Ashmanskas,<sup>17</sup> A. Attal,<sup>3</sup> A. Aurisano,<sup>42</sup> F. Azfar,<sup>42</sup> P. Azzi-Bacchetta,<sup>43</sup> P. Azzurri,<sup>46</sup> N. Bacchetta,<sup>43</sup>  
W. Badgett,<sup>17</sup> A. Barbaro-Galtieri,<sup>29</sup> V.E. Barnes,<sup>48</sup> B.A. Barnett,<sup>25</sup> S. Baroiant,<sup>7</sup> V. Bartsch,<sup>31</sup> G. Bauer,<sup>33</sup>  
P.-H. Beauchemin,<sup>34</sup> F. Bedeschi,<sup>46</sup> S. Behari,<sup>25</sup> G. Bellettini,<sup>46</sup> J. Bellinger,<sup>59</sup> A. Belloni,<sup>33</sup> D. Benjamin,<sup>16</sup>  
A. Beretvas,<sup>17</sup> J. Beringer,<sup>29</sup> T. Berry,<sup>30</sup> A. Bhatti,<sup>50</sup> M. Binkley,<sup>17</sup> D. Bisello,<sup>43</sup> I. Bizjak,<sup>31</sup> R.E. Blair,<sup>2</sup>  
C. Blocker,<sup>6</sup> B. Blumenfeld,<sup>25</sup> A. Bocci,<sup>16</sup> A. Bodek,<sup>49</sup> V. Boisvert,<sup>49</sup> G. Bolla,<sup>48</sup> A. Bolshov,<sup>33</sup> D. Bortoletto,<sup>48</sup>  
J. Boudreau,<sup>47</sup> A. Boveia,<sup>10</sup> B. Brau,<sup>10</sup> L. Brigliadori,<sup>5</sup> C. Bromberg,<sup>36</sup> E. Brubaker,<sup>13</sup> J. Budagov,<sup>15</sup> H.S. Budd,<sup>49</sup>  
S. Budd,<sup>24</sup> K. Burkett,<sup>17</sup> G. Busetto,<sup>43</sup> P. Bussey,<sup>21</sup> A. Buzatu,<sup>34</sup> K. L. Byrum,<sup>2</sup> S. Cabrera<sup>q</sup>,<sup>16</sup> M. Campanelli,<sup>20</sup>  
M. Campbell,<sup>35</sup> F. Canelli,<sup>17</sup> A. Canepa,<sup>45</sup> S. Carillo<sup>i</sup>,<sup>18</sup> D. Carlsmith,<sup>59</sup> R. Carosi,<sup>46</sup> S. Carron,<sup>34</sup> B. Casal,<sup>11</sup>  
M. Casarsa,<sup>54</sup> A. Castro,<sup>5</sup> P. Catastini,<sup>46</sup> D. Cauz,<sup>54</sup> M. Cavalli-Sforza,<sup>3</sup> A. Cerri,<sup>29</sup> L. Cerrito<sup>m</sup>,<sup>31</sup> S.H. Chang,<sup>28</sup>  
Y.C. Chen,<sup>1</sup> M. Chertok,<sup>7</sup> G. Chiarelli,<sup>46</sup> G. Chlachidze,<sup>17</sup> F. Chlebana,<sup>17</sup> I. Cho,<sup>28</sup> K. Cho,<sup>28</sup> D. Chokheli,<sup>15</sup>  
J.P. Chou,<sup>22</sup> G. Choudalakis,<sup>33</sup> S.H. Chuang,<sup>52</sup> K. Chung,<sup>12</sup> W.H. Chung,<sup>59</sup> Y.S. Chung,<sup>49</sup> M. Cilijak,<sup>46</sup>  
C.I. Ciobanu,<sup>24</sup> M.A. Ciocci,<sup>46</sup> A. Clark,<sup>20</sup> D. Clark,<sup>6</sup> M. Coca,<sup>16</sup> G. Compostella,<sup>43</sup> M.E. Convery,<sup>50</sup> J. Conway,<sup>7</sup>  
B. Cooper,<sup>31</sup> K. Copic,<sup>35</sup> M. Cordelli,<sup>19</sup> G. Cortiana,<sup>43</sup> F. Crescioli,<sup>46</sup> C. Cuenca Almenar<sup>q</sup>,<sup>7</sup> J. Cuevas<sup>l</sup>,<sup>11</sup>  
R. Culbertson,<sup>17</sup> J.C. Cully,<sup>35</sup> S. DaRonco,<sup>43</sup> M. Datta,<sup>17</sup> S. D'Auria,<sup>21</sup> T. Davies,<sup>21</sup> D. Dagenhart,<sup>17</sup>  
P. de Barbaro,<sup>49</sup> S. De Cecco,<sup>51</sup> A. Deisher,<sup>29</sup> G. De Lentdecker<sup>c</sup>,<sup>49</sup> G. De Lorenzo,<sup>3</sup> M. Dell'Orso,<sup>46</sup> F. Delli Paoli,<sup>43</sup>  
L. Demortier,<sup>50</sup> J. Deng,<sup>16</sup> M. Deninno,<sup>5</sup> D. De Pedis,<sup>51</sup> P.F. Derwent,<sup>17</sup> G.P. Di Giovanni,<sup>44</sup> C. Dionisi,<sup>51</sup>  
B. Di Ruzza,<sup>54</sup> J.R. Dittmann,<sup>4</sup> M. D'Onofrio,<sup>3</sup> C. Dörr,<sup>26</sup> S. Donati,<sup>46</sup> P. Dong,<sup>8</sup> J. Donini,<sup>43</sup> T. Dorigo,<sup>43</sup>  
S. Dube,<sup>52</sup> J. Efron,<sup>39</sup> R. Erbacher,<sup>7</sup> D. Errede,<sup>24</sup> S. Errede,<sup>24</sup> R. Eusebi,<sup>17</sup> H.C. Fang,<sup>29</sup> S. Farrington,<sup>30</sup>  
I. Fedorko,<sup>46</sup> W.T. Fedorko,<sup>13</sup> R.G. Feild,<sup>60</sup> M. Feindt,<sup>26</sup> J.P. Fernandez,<sup>32</sup> R. Field,<sup>18</sup> G. Flanagan,<sup>48</sup> R. Forrest,<sup>7</sup>  
S. Forrester,<sup>7</sup> M. Franklin,<sup>22</sup> J.C. Freeman,<sup>29</sup> I. Furic,<sup>13</sup> M. Gallinaro,<sup>50</sup> J. Galyardt,<sup>12</sup> J.E. Garcia,<sup>46</sup>  
F. Garberson,<sup>10</sup> A.F. Garfinkel,<sup>48</sup> C. Gay,<sup>60</sup> H. Gerberich,<sup>24</sup> D. Gerdes,<sup>35</sup> S. Giagu,<sup>51</sup> P. Giannetti,<sup>46</sup> K. Gibson,<sup>47</sup>  
J.L. Gimmell,<sup>49</sup> C. Ginsburg,<sup>17</sup> N. Giokaris<sup>a</sup>,<sup>15</sup> M. Giordani,<sup>54</sup> P. Giromini,<sup>19</sup> M. Giunta,<sup>46</sup> G. Giurgiu,<sup>25</sup>  
V. Glagolev,<sup>15</sup> D. Glenzinski,<sup>17</sup> M. Gold,<sup>37</sup> N. Goldschmidt,<sup>18</sup> J. Goldstein<sup>b</sup>,<sup>42</sup> A. Golossanov,<sup>17</sup> G. Gomez,<sup>11</sup>  
G. Gomez-Ceballos,<sup>33</sup> M. Goncharov,<sup>53</sup> O. González,<sup>32</sup> I. Gorelov,<sup>37</sup> A.T. Goshaw,<sup>16</sup> K. Goulianos,<sup>50</sup> A. Gresele,<sup>43</sup>  
S. Grinstein,<sup>22</sup> C. Grosso-Pilcher,<sup>13</sup> R.C. Group,<sup>17</sup> U. Grundler,<sup>24</sup> J. Guimaraes da Costa,<sup>22</sup> Z. Gunay-Unalan,<sup>36</sup>  
C. Haber,<sup>29</sup> K. Hahn,<sup>33</sup> S.R. Hahn,<sup>17</sup> E. Halkiadakis,<sup>52</sup> A. Hamilton,<sup>20</sup> B.-Y. Han,<sup>49</sup> J.Y. Han,<sup>49</sup> R. Handler,<sup>59</sup>  
F. Happacher,<sup>19</sup> K. Hara,<sup>55</sup> D. Hare,<sup>52</sup> M. Hare,<sup>56</sup> S. Harper,<sup>42</sup> R.F. Harr,<sup>58</sup> R.M. Harris,<sup>17</sup> M. Hartz,<sup>47</sup>  
K. Hatakeyama,<sup>50</sup> J. Hauser,<sup>8</sup> C. Hays,<sup>42</sup> M. Heck,<sup>26</sup> A. Heijboer,<sup>45</sup> B. Heinemann,<sup>29</sup> J. Heinrich,<sup>45</sup> C. Henderson,<sup>33</sup>  
M. Herndon,<sup>59</sup> J. Heuser,<sup>26</sup> D. Hidas,<sup>16</sup> C.S. Hill<sup>b</sup>,<sup>10</sup> D. Hirschbuehl,<sup>26</sup> A. Hocker,<sup>17</sup> A. Holloway,<sup>22</sup> S. Hou,<sup>1</sup>  
M. Houlden,<sup>30</sup> S.-C. Hsu,<sup>9</sup> B.T. Huffman,<sup>42</sup> R.E. Hughes,<sup>39</sup> U. Husemann,<sup>60</sup> J. Huston,<sup>36</sup> J. Incandela,<sup>10</sup>  
G. Introzzi,<sup>46</sup> M. Iori,<sup>51</sup> A. Ivanov,<sup>7</sup> B. Iyutin,<sup>33</sup> E. James,<sup>17</sup> D. Jang,<sup>52</sup> B. Jayatilaka,<sup>16</sup> D. Jeans,<sup>51</sup> E.J. Jeon,<sup>28</sup>  
S. Jindariani,<sup>18</sup> W. Johnson,<sup>7</sup> M. Jones,<sup>48</sup> K.K. Joo,<sup>28</sup> S.Y. Jun,<sup>12</sup> J.E. Jung,<sup>28</sup> T.R. Junk,<sup>24</sup> T. Kamon,<sup>53</sup>  
P.E. Karchin,<sup>58</sup> Y. Kato,<sup>41</sup> Y. Kemp,<sup>26</sup> R. Kephart,<sup>17</sup> U. Kerzel,<sup>26</sup> V. Khotilovich,<sup>53</sup> B. Kilminster,<sup>39</sup> D.H. Kim,<sup>28</sup>  
H.S. Kim,<sup>28</sup> J.E. Kim,<sup>28</sup> M.J. Kim,<sup>17</sup> S.B. Kim,<sup>28</sup> S.H. Kim,<sup>55</sup> Y.K. Kim,<sup>13</sup> N. Kimura,<sup>55</sup> L. Kirsch,<sup>6</sup> S. Klimenko,<sup>18</sup>  
M. Klute,<sup>33</sup> B. Knuteson,<sup>33</sup> B.R. Ko,<sup>16</sup> K. Kondo,<sup>57</sup> D.J. Kong,<sup>28</sup> J. Konigsberg,<sup>18</sup> A. Korytov,<sup>18</sup> A.V. Kotwal,<sup>16</sup>  
A.C. Kraan,<sup>45</sup> J. Kraus,<sup>24</sup> M. Kreps,<sup>26</sup> J. Kroll,<sup>45</sup> N. Krumnack,<sup>4</sup> M. Kruse,<sup>16</sup> V. Krutelyov,<sup>10</sup> T. Kubo,<sup>55</sup>  
S. E. Kuhlmann,<sup>2</sup> T. Kuhr,<sup>26</sup> N.P. Kulkarni,<sup>58</sup> Y. Kusakabe,<sup>57</sup> S. Kwang,<sup>13</sup> A.T. Laasanen,<sup>48</sup> S. Lai,<sup>34</sup> S. Lami,<sup>46</sup>  
S. Lammel,<sup>17</sup> M. Lancaster,<sup>31</sup> R.L. Lander,<sup>7</sup> K. Lannon,<sup>39</sup> A. Lath,<sup>52</sup> G. Latino,<sup>46</sup> I. Lazzizzera,<sup>43</sup> T. LeCompte,<sup>2</sup>  
J. Lee,<sup>49</sup> J. Lee,<sup>28</sup> Y.J. Lee,<sup>28</sup> S.W. Lee<sup>o</sup>,<sup>53</sup> R. Lefèvre,<sup>20</sup> N. Leonardo,<sup>33</sup> S. Leone,<sup>46</sup> S. Levy,<sup>13</sup> J.D. Lewis,<sup>17</sup>  
C. Lin,<sup>60</sup> C.S. Lin,<sup>17</sup> M. Lindgren,<sup>17</sup> E. Lipeles,<sup>9</sup> T.M. Liss,<sup>24</sup> A. Lister,<sup>7</sup> D.O. Litvintsev,<sup>17</sup> T. Liu,<sup>17</sup>  
N.S. Lockyer,<sup>45</sup> A. Loginov,<sup>60</sup> M. Loretì,<sup>43</sup> R.-S. Lu,<sup>1</sup> D. Lucchesi,<sup>43</sup> P. Lujan,<sup>29</sup> P. Lukens,<sup>17</sup> G. Lungu,<sup>18</sup>  
L. Lyons,<sup>42</sup> J. Lys,<sup>29</sup> R. Lysak,<sup>14</sup> E. Lytken,<sup>48</sup> P. Mack,<sup>26</sup> D. MacQueen,<sup>34</sup> R. Madrak,<sup>17</sup> K. Maeshima,<sup>17</sup>  
K. Makhoul,<sup>33</sup> T. Maki,<sup>23</sup> P. Maksimovic,<sup>25</sup> S. Malde,<sup>42</sup> S. Malik,<sup>31</sup> G. Manca,<sup>30</sup> F. Margaroli,<sup>5</sup> R. Marginean,<sup>17</sup>  
C. Marino,<sup>26</sup> C.P. Marino,<sup>24</sup> A. Martin,<sup>60</sup> M. Martin,<sup>25</sup> V. Martin<sup>g</sup>,<sup>21</sup> M. Martínez,<sup>3</sup> R. Martínez-Ballarín,<sup>32</sup>  
T. Maruyama,<sup>55</sup> P. Mastrandrea,<sup>51</sup> T. Masubuchi,<sup>55</sup> H. Matsunaga,<sup>55</sup> M.E. Mattson,<sup>58</sup> R. Mazini,<sup>34</sup> P. Mazzanti,<sup>5</sup>  
K.S. McFarland,<sup>49</sup> P. McIntyre,<sup>53</sup> R. McNulty<sup>f</sup>,<sup>30</sup> A. Mehta,<sup>30</sup> P. Mehtala,<sup>23</sup> S. Menzemer<sup>h</sup>,<sup>11</sup> A. Menzione,<sup>46</sup>  
P. Merkel,<sup>48</sup> C. Mesropian,<sup>50</sup> A. Messina,<sup>36</sup> T. Miao,<sup>17</sup> N. Miladinovic,<sup>6</sup> J. Miles,<sup>33</sup> R. Miller,<sup>36</sup> C. Mills,<sup>10</sup>  
M. Milnik,<sup>26</sup> A. Mitra,<sup>1</sup> G. Mitselmakher,<sup>18</sup> A. Miyamoto,<sup>27</sup> S. Moed,<sup>20</sup> N. Moggi,<sup>5</sup> B. Mohr,<sup>8</sup> C.S. Moon,<sup>28</sup>

R. Moore,<sup>17</sup> M. Morello,<sup>46</sup> P. Movilla Fernandez,<sup>29</sup> J. Mülmenstädt,<sup>29</sup> A. Mukherjee,<sup>17</sup> Th. Müller,<sup>26</sup> R. Mumford,<sup>25</sup> P. Murat,<sup>17</sup> M. Mussini,<sup>5</sup> J. Nachtman,<sup>17</sup> A. Nagano,<sup>55</sup> J. Naganoma,<sup>57</sup> K. Nakamura,<sup>55</sup> I. Nakano,<sup>40</sup> A. Napier,<sup>56</sup> V. Necula,<sup>16</sup> C. Neu,<sup>45</sup> M.S. Neubauer,<sup>9</sup> J. Nielsen,<sup>n,29</sup> L. Nodulman,<sup>2</sup> O. Norniella,<sup>3</sup> E. Nurse,<sup>31</sup> S.H. Oh,<sup>16</sup> Y.D. Oh,<sup>28</sup> I. Oksuzian,<sup>18</sup> T. Okusawa,<sup>41</sup> R. Oldeman,<sup>30</sup> R. Orava,<sup>23</sup> K. Osterberg,<sup>23</sup> C. Pagliarone,<sup>46</sup> E. Palencia,<sup>11</sup> V. Papadimitriou,<sup>17</sup> A. Papaikonomou,<sup>26</sup> A.A. Paramonov,<sup>13</sup> B. Parks,<sup>39</sup> S. Pashapour,<sup>34</sup> J. Patrick,<sup>17</sup> G. Pauletta,<sup>54</sup> M. Paulini,<sup>12</sup> C. Paus,<sup>33</sup> D.E. Pellett,<sup>7</sup> A. Penzo,<sup>54</sup> T.J. Phillips,<sup>16</sup> G. Piacentino,<sup>46</sup> J. Piedra,<sup>44</sup> L. Pinera,<sup>18</sup> K. Pitts,<sup>24</sup> C. Plager,<sup>8</sup> L. Pondrom,<sup>59</sup> X. Portell,<sup>3</sup> O. Poukhov,<sup>15</sup> N. Pounder,<sup>42</sup> F. Prakoshyn,<sup>15</sup> A. Pronko,<sup>17</sup> J. Proudfoot,<sup>2</sup> F. Ptohos<sup>e,19</sup> G. Punzi,<sup>46</sup> J. Pursley,<sup>25</sup> J. Rademacker<sup>b,42</sup> A. Rahaman,<sup>47</sup> V. Ramakrishnan,<sup>59</sup> N. Ranjan,<sup>48</sup> I. Redondo,<sup>32</sup> B. Reisert,<sup>17</sup> V. Rekovic,<sup>37</sup> P. Renton,<sup>42</sup> M. Rescigno,<sup>51</sup> S. Richter,<sup>26</sup> F. Rimondi,<sup>5</sup> L. Ristori,<sup>46</sup> A. Robson,<sup>21</sup> T. Rodrigo,<sup>11</sup> E. Rogers,<sup>24</sup> S. Rolli,<sup>56</sup> R. Roser,<sup>17</sup> M. Rossi,<sup>54</sup> R. Rossin,<sup>10</sup> P. Roy,<sup>34</sup> A. Ruiz,<sup>11</sup> J. Russ,<sup>12</sup> V. Rusu,<sup>13</sup> H. Saarikko,<sup>23</sup> A. Safonov,<sup>53</sup> W.K. Sakumoto,<sup>49</sup> G. Salamanna,<sup>51</sup> O. Saltó,<sup>3</sup> L. Santi,<sup>54</sup> S. Sarkar,<sup>51</sup> L. Sartori,<sup>46</sup> K. Sato,<sup>17</sup> P. Savard,<sup>34</sup> A. Savoy-Navarro,<sup>44</sup> T. Scheidle,<sup>26</sup> P. Schlabach,<sup>17</sup> E.E. Schmidt,<sup>17</sup> M.P. Schmidt,<sup>60</sup> M. Schmitt,<sup>38</sup> T. Schwarz,<sup>7</sup> L. Scodellaro,<sup>11</sup> A.L. Scott,<sup>10</sup> A. Scribano,<sup>46</sup> F. Scuri,<sup>46</sup> A. Sedov,<sup>48</sup> S. Seidel,<sup>37</sup> Y. Seiya,<sup>41</sup> A. Semenov,<sup>15</sup> L. Sexton-Kennedy,<sup>17</sup> A. Sfyrila,<sup>20</sup> S.Z. Shalhout,<sup>58</sup> M.D. Shapiro,<sup>29</sup> T. Shears,<sup>30</sup> P.F. Shepard,<sup>47</sup> D. Sherman,<sup>22</sup> M. Shimojima<sup>k,55</sup> M. Shochet,<sup>13</sup> Y. Shon,<sup>59</sup> I. Shreyber,<sup>20</sup> A. Sidoti,<sup>46</sup> P. Sinervo,<sup>34</sup> A. Sisakyan,<sup>15</sup> A.J. Slaughter,<sup>17</sup> J. Slaunwhite,<sup>39</sup> K. Sliwa,<sup>56</sup> J.R. Smith,<sup>7</sup> F.D. Snider,<sup>17</sup> R. Snihur,<sup>34</sup> M. Soderberg,<sup>35</sup> A. Soha,<sup>7</sup> S. Somalwar,<sup>52</sup> V. Sorin,<sup>36</sup> J. Spalding,<sup>17</sup> F. Spinella,<sup>46</sup> T. Spreitzer,<sup>34</sup> P. Squillacioti,<sup>46</sup> M. Stanitzki,<sup>60</sup> A. Staveris-Polykalas,<sup>46</sup> R. St. Denis,<sup>21</sup> B. Stelzer,<sup>8</sup> O. Stelzer-Chilton,<sup>42</sup> D. Stentz,<sup>38</sup> J. Strologas,<sup>37</sup> D. Stuart,<sup>10</sup> J.S. Suh,<sup>28</sup> A. Sukhanov,<sup>18</sup> H. Sun,<sup>56</sup> I. Suslov,<sup>15</sup> T. Suzuki,<sup>55</sup> A. Taffard<sup>p,24</sup> R. Takashima,<sup>40</sup> Y. Takeuchi,<sup>55</sup> R. Tanaka,<sup>40</sup> M. Tecchio,<sup>35</sup> P.K. Teng,<sup>1</sup> K. Terashi,<sup>50</sup> J. Thom<sup>d,17</sup> A.S. Thompson,<sup>21</sup> E. Thomson,<sup>45</sup> P. Tipton,<sup>60</sup> V. Tiwari,<sup>12</sup> S. Tkaczyk,<sup>17</sup> D. Toback,<sup>53</sup> S. Tokar,<sup>14</sup> K. Tollefson,<sup>36</sup> T. Tomura,<sup>55</sup> D. Tonelli,<sup>46</sup> S. Torre,<sup>19</sup> D. Torretta,<sup>17</sup> S. Tourneur,<sup>44</sup> W. Trischuk,<sup>34</sup> S. Tsuno,<sup>40</sup> Y. Tu,<sup>45</sup> N. Turini,<sup>46</sup> F. Ukegawa,<sup>55</sup> S. Uozumi,<sup>55</sup> S. Vallecorsa,<sup>20</sup> N. van Remortel,<sup>23</sup> A. Varganov,<sup>35</sup> E. Vataga,<sup>37</sup> F. Vazquez<sup>i,18</sup> G. Velev,<sup>17</sup> G. Veramendi,<sup>24</sup> V. Veszpremi,<sup>48</sup> M. Vidal,<sup>32</sup> R. Vidal,<sup>17</sup> I. Vila,<sup>11</sup> R. Vilar,<sup>11</sup> T. Vine,<sup>31</sup> I. Vollrath,<sup>34</sup> I. Volobouev<sup>o,29</sup> G. Volpi,<sup>46</sup> F. Würthwein,<sup>9</sup> P. Wagner,<sup>53</sup> R.G. Wagner,<sup>2</sup> R.L. Wagner,<sup>17</sup> J. Wagner,<sup>26</sup> W. Wagner,<sup>26</sup> R. Wallny,<sup>8</sup> S.M. Wang,<sup>1</sup> A. Warburton,<sup>34</sup> D. Waters,<sup>31</sup> M. Weinberger,<sup>53</sup> W.C. Wester III,<sup>17</sup> B. Whitehouse,<sup>56</sup> D. Whiteson,<sup>45</sup> A.B. Wicklund,<sup>2</sup> E. Wicklund,<sup>17</sup> G. Williams,<sup>34</sup> H.H. Williams,<sup>45</sup> P. Wilson,<sup>17</sup> B.L. Winer,<sup>39</sup> P. Wittich<sup>d,17</sup> S. Wolbers,<sup>17</sup> C. Wolfe,<sup>13</sup> T. Wright,<sup>35</sup> X. Wu,<sup>20</sup> S.M. Wynne,<sup>30</sup> A. Yagil,<sup>9</sup> K. Yamamoto,<sup>41</sup> J. Yamaoka,<sup>52</sup> T. Yamashita,<sup>40</sup> C. Yang,<sup>60</sup> U.K. Yang<sup>j,13</sup> Y.C. Yang,<sup>28</sup> W.M. Yao,<sup>29</sup> G.P. Yeh,<sup>17</sup> J. Yoh,<sup>17</sup> K. Yorita,<sup>13</sup> T. Yoshida,<sup>41</sup> G.B. Yu,<sup>49</sup> I. Yu,<sup>28</sup> S.S. Yu,<sup>17</sup> J.C. Yun,<sup>17</sup> L. Zanello,<sup>51</sup> A. Zanetti,<sup>54</sup> I. Zaw,<sup>22</sup> X. Zhang,<sup>24</sup> J. Zhou,<sup>52</sup> and S. Zucchelli<sup>5</sup>

(CDF Collaboration\*)

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

<sup>4</sup>*Baylor University, Waco, Texas 76798*

<sup>5</sup>*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*

<sup>6</sup>*Brandeis University, Waltham, Massachusetts 02254*

<sup>7</sup>*University of California, Davis, Davis, California 95616*

<sup>8</sup>*University of California, Los Angeles, Los Angeles, California 90024*

<sup>9</sup>*University of California, San Diego, La Jolla, California 92093*

<sup>10</sup>*University of California, Santa Barbara, Santa Barbara, California 93106*

<sup>11</sup>*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*

<sup>12</sup>*Carnegie Mellon University, Pittsburgh, PA 15213*

<sup>13</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*

<sup>14</sup>*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*

<sup>15</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

<sup>16</sup>*Duke University, Durham, North Carolina 27708*

<sup>17</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

<sup>18</sup>*University of Florida, Gainesville, Florida 32611*

<sup>19</sup>*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

<sup>20</sup>*University of Geneva, CH-1211 Geneva 4, Switzerland*

<sup>21</sup>*Glasgow University, Glasgow G12 8QQ, United Kingdom*

<sup>22</sup>*Harvard University, Cambridge, Massachusetts 02138*

<sup>23</sup>*Division of High Energy Physics, Department of Physics,*

*University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*

- <sup>24</sup>University of Illinois, Urbana, Illinois 61801
- <sup>25</sup>The Johns Hopkins University, Baltimore, Maryland 21218
- <sup>26</sup>Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
- <sup>27</sup>High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan
- <sup>28</sup>Center for High Energy Physics: Kyungpook National University, Taegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; SungKyunKwan University, Suwon 440-746, 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, Canada H3A 2T8; and University of Toronto, Toronto, Canada M5S 1A7
- <sup>35</sup>University of Michigan, Ann Arbor, Michigan 48109
- <sup>36</sup>Michigan State University, East Lansing, Michigan 48824
- <sup>37</sup>University of New Mexico, Albuquerque, New Mexico 87131
- <sup>38</sup>Northwestern University, Evanston, Illinois 60208
- <sup>39</sup>The Ohio State University, Columbus, Ohio 43210
- <sup>40</sup>Okayama University, Okayama 700-8530, Japan
- <sup>41</sup>Osaka City University, Osaka 588, Japan
- <sup>42</sup>University of Oxford, Oxford OX1 3RH, United Kingdom
- <sup>43</sup>University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
- <sup>44</sup>LPNHE, Université Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
- <sup>45</sup>University of Pennsylvania, Philadelphia, Pennsylvania 19104
- <sup>46</sup>Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
- <sup>47</sup>University of Pittsburgh, Pittsburgh, Pennsylvania 15260
- <sup>48</sup>Purdue University, West Lafayette, Indiana 47907
- <sup>49</sup>University of Rochester, Rochester, New York 14627
- <sup>50</sup>The Rockefeller University, New York, New York 10021
- <sup>51</sup>Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome "La Sapienza," I-00185 Roma, Italy
- <sup>52</sup>Rutgers University, Piscataway, New Jersey 08855
- <sup>53</sup>Texas A&M University, College Station, Texas 77843
- <sup>54</sup>Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy
- <sup>55</sup>University of Tsukuba, Tsukuba, Ibaraki 305, Japan
- <sup>56</sup>Tufts University, Medford, Massachusetts 02155
- <sup>57</sup>Waseda University, Tokyo 169, Japan
- <sup>58</sup>Wayne State University, Detroit, Michigan 48201
- <sup>59</sup>University of Wisconsin, Madison, Wisconsin 53706
- <sup>60</sup>Yale University, New Haven, Connecticut 06520
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We present a measurement of the mass of the top quark from proton-antiproton collisions recorded at the CDF experiment in Run II of the Fermilab Tevatron. We analyze events from the single lepton plus jets final state ( $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow l\nu b\bar{q}\bar{q}'\bar{b}$ ). The top quark mass is extracted using a direct calculation of the probability density that each event corresponds to the  $t\bar{t}$  final state. The probability is a function of both the mass of the top quark and the energy scale of the calorimeter jets, which is constrained *in situ* by the hadronic  $W$  boson mass. Using 167 events observed in  $955 \text{ pb}^{-1}$  of integrated luminosity, we achieve the single most precise measurement of the top quark mass,  $170.8 \pm 2.2$  (stat.)  $\pm 1.4$  (syst.)  $\text{GeV}/c^2$ .

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\*With visitors from <sup>a</sup>University of Athens, <sup>b</sup>University of Bristol, <sup>c</sup>University Libre de Bruxelles, <sup>d</sup>Cornell University, <sup>e</sup>University of Cyprus, <sup>f</sup>University of Dublin, <sup>g</sup>University of Edinburgh, <sup>h</sup>University of Heidelberg, <sup>i</sup>Universidad Iberoamericana,

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<sup>j</sup>University of Manchester, <sup>k</sup>Nagasaki Institute of Applied Science, <sup>l</sup>University de Oviedo, <sup>m</sup>University of London, Queen Mary College, <sup>n</sup>University of California Santa Cruz, <sup>o</sup>Texas Tech University, <sup>p</sup>University of California Irvine, <sup>q</sup>IFIC(CSIC-Universitat de Valen-

The top quark is the heaviest known elementary particle, about 40 times more massive than the next-heaviest fermion. Its large mass plays an important role in loop corrections to several electroweak observables predicted by the standard model. In conjunction with measurements of the  $W$  boson mass, a precise measurement of the top quark mass,  $m_t$ , constrains the mass of the as yet unobserved Higgs boson [1]. Moreover, by comparing precision electroweak measurements to predictions including the relevant loop corrections, a precise measurement of  $m_t$  can help constrain contributions from physics beyond the standard model. Measuring  $m_t$  to the highest achievable precision is therefore one of the main goals of the experiments operating at the Fermilab Tevatron collider.

At the Tevatron, top quarks are mainly produced in pairs. They decay essentially 100% of the time into a  $W$  boson and a  $b$  quark, with the  $W$  decaying into quarks or leptons. The result presented here uses the lepton+jets channel, where one  $W$  decays into two quarks, and the other decays to an electron or a muon and the corresponding neutrino. In the past, this channel has provided the most precise measurements of  $m_t$ , and recent measurements can be found in Ref. [2].

In this letter we report the single most precise measurement of the top quark mass from Tevatron proton-antiproton collisions at  $\sqrt{s}=1.96$  TeV, using  $955 \text{ pb}^{-1}$  of integrated luminosity collected with the CDF II detector from February 2002 to March 2006. The CDF II detector is a general-purpose particle detector and is described in detail elsewhere [3]. It has a solenoidal charged particle spectrometer, consisting of 7-8 layers of silicon microstrip detectors and a cylindrical drift chamber immersed in a 1.4 T magnetic field, a segmented sampling calorimeter, and a set of charged particle detectors outside the calorimeter used to identify muon candidates. We use a right-handed cylindrical coordinate system with the origin in the center of the detector, where  $\theta$  and  $\phi$  are the polar and azimuthal angles, respectively, and pseudorapidity is defined as  $\eta \equiv -\ln \tan(\theta/2)$ . Transverse energy and momentum are  $E_T=E \sin \theta$  and  $p_T=p \sin \theta$ , respectively, where  $E$  and  $p$  are energy and momentum.

Events in the lepton+jets decay channel are selected to have a single, isolated electron or muon candidate with large transverse energy, large imbalance in transverse momentum in the event (missing transverse energy [4],  $\cancel{E}_T$ ) as expected from the undetectable neutrino, and exactly four jets with large transverse energy. Jets are reconstructed using a cone algorithm with radius  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ . Of these jets, we require at least one to have originated from a  $b$  quark by using an

algorithm that identifies a long-lived  $B$  hadron through the presence of a displaced vertex ( $b$  tag) [5]. Backgrounds to the  $t\bar{t}$  signal arise from multi-jet QCD production (non- $W$ ),  $W$  production in association with jets ( $W$ +jets), and electroweak backgrounds (EWK) composed of diboson ( $WW$ ,  $WZ$ ,  $ZZ$ ) and single top production.  $W$ +jets background events include jets with real  $b$  flavor as well as light flavor jets incorrectly identified as  $b$  jets. To remove the non- $W$  backgrounds, where  $\cancel{E}_T$  is due to mis-measured jet energies, we require  $\cancel{E}_T$  not to be aligned with the highest energy jet by a suitable requirement on  $\Delta\phi$  between this jet and  $\cancel{E}_T$ . Table I summarizes the selection criteria used in this analysis, and a more detailed description can be found in Ref. [6]. We select 167 events of which we expect about 85% to be  $t\bar{t}$  events. Table II shows the expected sample composition from a previous  $t\bar{t}$  production analysis with  $318 \text{ pb}^{-1}$  [6], scaled to  $955 \text{ pb}^{-1}$  and assuming a  $t\bar{t}$  cross section of  $8.0 \text{ pb}$ .

TABLE I: Event selection criteria [6].

Lepton	$E_T > 20 \text{ GeV}$ (electron, muon), $ \eta  < 1$
Jets	exactly 4 with $E_T > 15 \text{ GeV}$ , $ \eta  < 2.0$
$\cancel{E}_T$	$> 20 \text{ GeV}$ , calculated over $ \eta  < 3.6$
$b$ tag jets	$\geq 1$ from a secondary vertex, $ \eta  < 1.5$
Non- $W$ veto	$0.5 \leq \Delta\phi \leq 2.5$ when $\cancel{E}_T < 30 \text{ GeV}$

TABLE II: Background composition and expected number of  $t\bar{t}$  candidates. All uncertainties are statistical only.

Source	Expected number of events
$W$ +jets	$14.5 \pm 5.1$
non- $W$	$5.2 \pm 2.6$
EWK	$2.2 \pm 0.5$
Total	$22.0 \pm 8.2$
$t\bar{t}$ ( $\sigma=8.0 \text{ pb}$ , $m_t=170 \text{ GeV}/c^2$ )	$145.1 \pm 16.5$
Data	167

We analyze the selected events using a likelihood technique that relies on calculations of probability densities based on matrix elements for the signal ( $t\bar{t}$ ) and dominant background ( $W$ +jets) processes [7]. The backgrounds other than  $W$ +jets are found to be adequately described by the  $W$ +jets probability density. Given a set of observed variables,  $x$ , and underlying partonic quantities,  $y$ , the signal and background probability densities are constructed by integrating over the appropriate parton-level differential cross section,  $d\sigma(y)/dy$ , convolved with parton distribution functions (PDFs) and detector reso-

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cia).

lution effects:

$$P(x) = \sum_{\text{jet perm.}} \int \frac{d\sigma(y)}{dy} f(q_1) f(q_2) dq_1 dq_2 W(x, y) dy. \quad (1)$$

The PDFs ( $f(q_1)$  and  $f(q_2)$ ) take into account the flavors of colliding quark and antiquark and are given by CTEQ5L [8]. The detector resolution effects are described by a transfer function  $W(x, y)$  relating  $x$  to  $y$ . The momenta of the leptons and the angles of jets and leptons are taken to be exactly measured, and therefore  $W(x, y)$  for these quantities is given by the product of Dirac delta functions. The non-trivial part of  $W(x, y)$  maps parton energies to measured jet energies after correction for instrumental detector effects [9]. This mapping is obtained by parameterizing the jet response in fully simulated  $t\bar{t}$  events created by the Monte Carlo (MC) generator PYTHIA [10], and including the effects of radiation, hadronization, measurement resolution, and energy omitted from the jet cone by the reconstruction algorithm. The  $t\bar{t}$  and  $W$ +jets probability densities,  $P_{t\bar{t}}$  and  $P_{W+jets}$ , include all possible permutations of matching jets with partons as well as all possible longitudinal momenta for the neutrino in the  $W$  decay. The permutations are reduced to six or two by exploiting  $b$  tagging information (single-tag or double-tag, respectively). We use different transfer functions for light quark jets and  $b$  jets, depending on the flavor of the parton assigned to the jet. In calculating  $d\sigma(y)/dy$ ,  $P_{t\bar{t}}$  uses the leading order matrix element of the  $q\bar{q} \rightarrow t\bar{t}$  process [11], and  $P_{W+jets}$  uses the sum of matrix elements of the  $W$ +4 jets sub-routines encoded in the VECBOS Monte Carlo generator [12].

The final state described by  $d\sigma(y)/dy$  contains 6 particles, which introduces 20 integration variables in Eq. 1, including the longitudinal momenta of the incoming quarks. By imposing energy-momentum conservation, in conjunction with the Dirac delta functions in  $W(x, y)$  we reduce the dimensionality of the remaining integration to five. The integration in  $P_{W+jets}$  is performed over the energies of the outgoing partons and the invariant mass of the leptonically decaying  $W$  using a Monte Carlo technique. In order to reduce the calculation time for  $P_{t\bar{t}}$ , we integrate over the following variables: the invariant masses of  $t$ ,  $\bar{t}$ ,  $W^+$ , and  $W^-$ , and the energy of one of the quarks from the hadronic  $W$  decay. Our method includes two additional integrations over the transverse momentum components of the  $t\bar{t}$  system. The integration in  $P_{t\bar{t}}$  uses the numerical integration code VEGAS [13].

The largest potential systematic uncertainty in this measurement arises from the energy scale of jets. To decrease this uncertainty, we exploit the fact that the hadronically decaying  $W$  provides an *in situ* constraint of the jet energy scale, as the two jets should form an invariant mass consistent with the precisely known mass of the  $W$  boson [1]. The jet energy scale and the mass of

the top quark are simultaneously determined from a two-dimensional likelihood that includes their correlation. A salient feature of this method is that the uncertainty due to the jet energy scale will be reduced with increasing statistics. Thus  $P_{t\bar{t}}$  is evaluated as a function of  $m_t$  and an assumed jet energy scale factor  $f_{JES} = E_{jet}^{obs}/E_{jet}$ , where  $E_{jet}^{obs}$  is the observed jet energy and  $E_{jet}$  is the true jet energy.

To extract  $m_t$  and  $f_{JES}$  from the data, we build a likelihood function for  $N$  selected events by adding  $P_{t\bar{t}}$  and  $P_{W+jets}$  for each event. The combined likelihood is minimized with respect to three variables:  $m_t$ ,  $f_{JES}$ , and  $C_s$ , the fraction of events consistent with our  $t\bar{t}$  signal hypothesis. The likelihood for  $N$  events is given by

$$\begin{aligned} \mathcal{L}(x_1, x_2, \dots, x_N; m_t, f_{JES}, C_s) = & e^{-N(C_s \langle A_{t\bar{t}}(m_t, f_{JES}) \rangle + (1-C_s) \langle A_{W+jets}(f_{JES}) \rangle)} \times \\ & \prod_{i=1}^N [C_s P_{t\bar{t}}(x_i; m_t, f_{JES}) + (1-C_s) P_{W+jets}(x_i; f_{JES})] \end{aligned} \quad (2)$$

where the first factor arises from the Poisson extension of the likelihood and normalizes the combined event probability density, and  $\langle A \rangle$  refers to the mean acceptance for  $t\bar{t}$  or  $W$ +jets events. We use fully simulated MC  $t\bar{t}$  and  $W$ +jets events to determine the functional form of  $\langle A \rangle$ .  $P_{W+jets}$  is evaluated at the central jet energy scale factor,  $f_{JES}=1$ . The  $f_{JES}$  dependence of  $P_{W+jets}$  is determined by varying the input  $f_{JES}$  in MC event samples ( $f_{JES}^{MC}$ ) and by parameterizing the average likelihood response as a function of  $f_{JES}$ . We use the  $m_t$  dependence of the theoretical leading order  $t\bar{t}$  cross section to normalize  $P_{t\bar{t}}$ . Because we use a leading order matrix element to calculate  $P_{t\bar{t}}$ , we find that  $t\bar{t}$  events where at least one of the four reconstructed jets cannot be matched to a parton from the  $t\bar{t}$  decay within  $\Delta R < 0.4$  behave like background events. As a consequence, a pure sample of  $t\bar{t}$  events yields  $C_s$  of 0.8. The quoted  $C_s$  values are corrected for this effect. For each event  $P_{t\bar{t}}$  is evaluated in increments of 2 GeV/ $c^2$  in  $m_t$  and 0.02 in  $f_{JES}$ . At each point of this grid we fit the entire sample of  $N$  events according to Eq. 2 and the most likely value of  $C_s$  is determined using MINUIT [14]. The optimal parameters  $m_t$  and  $f_{JES}$  are obtained by fitting the likelihood using a two-dimensional Gaussian. The statistical uncertainty on  $m_t$  includes the uncertainty on  $f_{JES}$ .

The performance of the analysis is tested by extracting  $m_t$  from MC pseudo-experiments containing  $t\bar{t}$  signal samples with various input top quark masses ( $m_t^{MC}$ ) and background samples described in Table II. The signal and electroweak background samples are generated using HERWIG [10]. The  $W$ +jets background is generated using ALPGEN [10] with hadronization and fragmentation done by HERWIG. The non- $W$  background is extracted from an independent data sample. All of the MC samples are

processed by the CDF detector simulation. We construct pseudo-experiments of signal and background events by fluctuating the number of events around the values shown in Table II. Figure 1(a) shows that the fitted Gaussian mean  $m_t$  extracted from 200 pseudo-experiments per point is unbiased with respect to  $m_t^{MC}$  up to the statistical uncertainty of  $0.21 \text{ GeV}/c^2$ , which is taken as a systematic uncertainty. Similar tests are performed for the output of  $f_{JES}$ . In this case, we find that a bias of +4% in  $f_{JES}$  is present, independent of  $m_t$ . We correct for this bias to properly interpret the output of  $f_{JES}$ . Figure 1(b) shows the top mass pull width, defined as the Gaussian  $\sigma$  of the top mass residual ( $m_t - m_t^{MC}$ ) divided by the uncertainty in each pseudo-experiment  $\sigma_{m_t}$ , as a function of  $m_t^{MC}$ . The pull width is  $3\% \pm 2\%$  larger than one on average, and thus, the statistical uncertainty is scaled up by 3%.

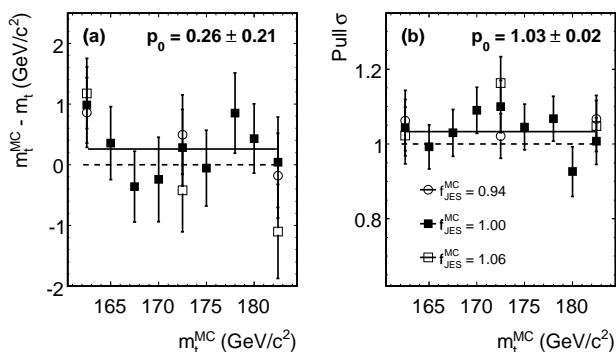


FIG. 1: Results of pseudo-experiment tests. (a) Difference between the measured  $m_t$  and the input top quark mass in the MC event sample ( $m_t^{MC}$ ), as a function of  $m_t^{MC}$ . (b) Gaussian  $\sigma$  of pull distributions (see text), as a function of  $m_t^{MC}$ . The plots include results using MC event samples with different values of  $f_{JES}$  ( $f_{JES}^{MC}$ ). The weighted average  $p_0$  is indicated by the solid horizontal line. The dashed line indicates an example of an unbiased result.

Applying this method to data, we measure the top quark mass to be  $m_t = 170.8 \pm 2.2$  (stat.), and the  $f_{JES}$  scale to be  $f_{JES} = 0.99 \pm 0.02$  (stat.) in good agreement with the reference scale from the default CDF calibration [9]. Figure 2 shows the fitted two-dimensional likelihood with  $\Delta \ln L$  contours. The statistical uncertainty is taken from the maximum and minimum  $m_t$  values on the  $\Delta \ln L = 0.5$  contour. We find a correlation coefficient of 0.32 between  $m_t$  and  $f_{JES}$ . The fit yields a signal fraction  $C_s = 0.84 \pm 0.10$  (stat.), which corresponds to  $140 \pm 17$   $t\bar{t}$  events and is consistent with the expectation shown in Table II. Monte Carlo tests have shown that the resulting  $m_t$  is stable over a wide range of sample purities. Figure 3 shows comparisons of two representative kinematic quantities between data and simulation using  $f_{JES}^{MC} = 0.99$  and  $m_t^{MC} = 170 \text{ GeV}/c^2$ ; the agreement is good.

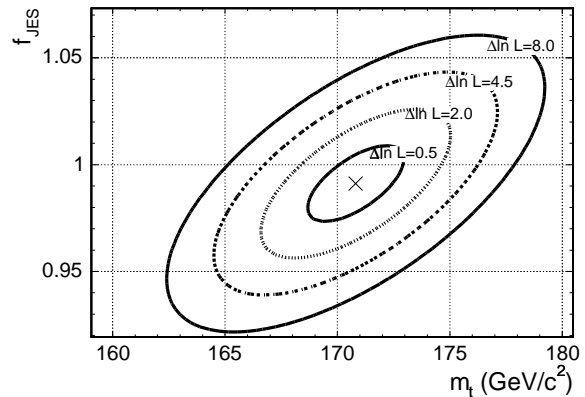


FIG. 2: Contours of likelihood evaluated over the 955  $\text{pb}^{-1}$  event sample. Our measurement is indicated by the X.

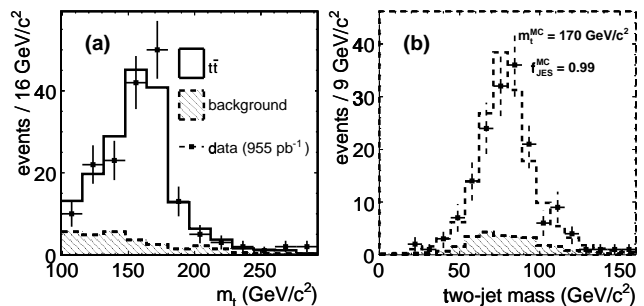


FIG. 3: Comparison of two kinematic variables for data and MC using  $f_{JES}^{MC} = 0.99$  and  $m_t^{MC} = 170 \text{ GeV}/c^2$ . (a) Most probable value of  $m_t$  for each event extracted from evaluating  $P_{t\bar{t}}$  at  $f_{JES} = 1$ . (b) Invariant mass of the pair of jets assigned as  $W$  decay products calculated using the most probable permutation at the most probable value of  $m_t$  and  $f_{JES}$  in each event evaluated from  $P_{t\bar{t}}$ . The backgrounds contain all contributions shown in Table II.

The sources of systematic uncertainty are listed in Table III. To first order,  $f_{JES}$  is already included in the statistical uncertainty, but we also consider a dependence of  $f_{JES}$  on the  $p_T$  and  $\eta$  of the jets (residual jet energy scale) using the dependence found in other studies [9]. Another uncertainty is calculated from possible differences in  $f_{JES}$  between  $b$  jets and light quark jets. The generator uncertainty takes into account differences in parton showering and jet fragmentation between two different MC programs used to generate  $t\bar{t}$  events, PYTHIA and HERWIG. Variations in initial- and final-state radiation (ISR, FSR), constrained by studies using Drell-Yan data, are also considered [2]. PDF uncertainties are evaluated using MC samples generated with MRST [15] and the full set of eigenvectors from CTEQ6M [8]. Systematic effects on the modeling of the background samples include fluctuations in the total background contribution, relative contributions from individual background pro-

cesses, and variations due to the  $Q^2$  scale used in  $W$ +jets simulation. We also include effects from the uncertainties in the simulated lepton  $p_T$ , the dependence of  $b$  tagging with jet  $p_T$ , and the effect of the limited MC event samples used in the analysis. Finally, we include possible mis-modeling of multiple interactions in the simulation at high luminosity. The sum in quadrature of all systematic uncertainties is  $1.4 \text{ GeV}/c^2$ .

TABLE III: Summary of systematic uncertainties.

Source	Uncertainty ( $\text{GeV}/c^2$ )
Residual jet energy scale	0.4
$b$ jet energy scale	0.6
Generator	0.2
ISR/FSR	1.1
PDFs	0.1
Background composition	0.2
Lepton $p_T$	0.2
$b$ tag $p_T$ dependence	0.3
Monte Carlo statistics	0.2
Multiple interactions	0.1
Total	1.4

In summary, we present a measurement of the top quark mass in the lepton+jets channel using  $955 \text{ pb}^{-1}$  of data collected by the CDF experiment. A matrix element analysis was used with an *in situ* measurement of the jet energy scale. We measure

$$m_t = 170.8 \pm 2.2 \text{ (stat.)} \pm 1.4 \text{ (syst.) GeV}/c^2 \quad (3)$$

where the statistical uncertainty includes the uncertainty of  $1.5 \text{ GeV}/c^2$  due to the jet energy scale. With a total uncertainty of 1.5%, this result is the most precise measurement of the top quark mass to date and is a 35% improvement over the previous best measurement [2].

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