FERMILAB-PUB-08-089-E

Measurement of the polarization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ states in $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV

V.M. Abazov[36], B. Abbott[75], M. Abolins[65], B.S. Acharya[29], M. Adams[51], T. Adams[49], E. Aguilo[6], S.H. Ahn[31], M. Ahsan[59], G.D. Alexeev[36], G. Alkhazov[40], A. Alton[64,a], G. Alverson[63], G.A. Alves[2], M. Anastasoaie[35], L.S. Ancu[35], T. Andeen[53], S. Anderson[45], B. Andrieu[17], M.S. Anzelc[53], M. Aoki[50], Y. Arnoud[14], M. Arov[60], M. Arthaud[18], A. Askew[49], B. Åsman[41], A.C.S. Assis Jesus[3], O. Atramentov[49], C. Avila[8], F. Badaud[13], A. Baden[61], L. Bagby[50], B. Baldin[50], D.V. Bandurin[59], P. Banerjee[29], S. Banerjee[29], E. Barberis[63], A.-F. Barfuss[15], P. Bargassa[80], P. Baringer[58], J. Barreto[2], J.F. Bartlett[50], U. Bassler[18], D. Bauer[43], S. Beale[6], A. Bean[58], M. Begalli[3], M. Begel[73], C. Belanger-Champagne[41], L. Bellantoni[50], A. Bellavance[50], J.A. Benitez[65], S.B. Beri[27], G. Bernardi[17], R. Bernhard[23], I. Bertram[42], M. Besançon[18], R. Beuselinck[43], V.A. Bezzubov[39], P.C. Bhat[50], V. Bhatnagar[27], C. Biscarat[20], G. Blazey[52], F. Blekman[43], S. Blessing[49], D. Bloch[19], K. Bloom[67], A. Boehnlein[50], D. Boline[62], T.A. Bolton[59], E.E. Boos[38], G. Borissov[42], T. Bose[77], A. Brandt[78], R. Brock[65], G. Brooijmans[70], A. Bross[50], D. Brown[81], N.J. Buchanan[49], D. Buchholz[53], M. Buehler[81], V. Buescher[22], V. Bunichev[38], S. Burdin[42,b], S. Burke[45], T.H. Burnett[82], C.P. Buszello[43], J.M. Butler[62], P. Calfayan[25], S. Calvet[16], J. Cammin[71], W. Carvalho[3], B.C.K. Casey[50], H. Castilla-Valdez[33], S. Chakrabarti[18], D. Chakraborty[52], K. Chan[6], K.M. Chan[55], A. Chandra[48], F. Charles[19,‡], E. Cheu[45], F. Chevallier[14], D.K. Cho[62], S. Choi[32], B. Choudhary[28], L. Christofek[77], T. Christoudias[43], S. Cihangir[50], D. Claes[67], J. Clutter[58], M. Cooke[80], W.E. Cooper[50], M. Corcoran[80], F. Couderc[18], M.-C. Cousinou[15], S. Crépé-Renaudin[14], D. Cutts[77], M. Ćwiok[30], H. da Motta[2], A. Das[45], G. Davies[43], K. De[78], S.J. de Jong[35], E. De La Cruz-Burelo[64], C. De Oliveira Martins[3], J.D. Degenhardt[64], F. Déliot[18], M. Demarteau[50], R. Demina[71], D. Denisov[50], S.P. Denisov[39], S. Desai[50], H.T. Diehl[50], M. Diesburg[50], A. Dominguez[67], H. Dong[72], L.V. Dudko[38], L. Duflot[16], S.R. Dugad[29], D. Duggan[49], A. Duperrin[15], J. Dyer[65], A. Dyshkant[52], M. Eads[67], D. Edmunds[65], J. Ellison[48], V.D. Elvira[50], Y. Enari[77], S. Eno[61], P. Ermolov[38], H. Evans[54], A. Evdokimov[73], V.N. Evdokimov[39], A.V. Ferapontov[59], T. Ferbel[71], F. Fiedler[24], F. Filthaut[35], W. Fisher[50], H.E. Fisk[50], M. Fortner[52], H. Fox[42], S. Fu[50], S. Fuess[50], T. Gadfort[70], C.F. Galea[35], E. Gallas[50], C. Garcia[71], A. Garcia-Bellido[82], V. Gavrilov[37], P. Gay[13], W. Geist[19], D. Gelé[19], C.E. Gerber[51], Y. Gershtein[49], D. Gillberg[6], G. Ginther[71], N. Gollub[41], B. Gómez[8], A. Goussiou[82], P.D. Grannis[72], H. Greenlee[50], Z.D. Greenwood[60], E.M. Gregores[4], G. Grenier[20], Ph. Gris[13], J.-F. Grivaz[16], A. Grohsjean[25], S. Grünendahl[50], M.W. Grünewald[30], F. Guo[72], J. Guo[72], G. Gutierrez[50], P. Gutierrez[75], A. Haas[70], N.J. Hadley[61], P. Haefner[25], S. Hagopian[49], J. Haley[68], I. Hall[65], R.E. Hall[47], L. Han[7], K. Harder[44], A. Harel[71], J.M. Hauptman[57], R. Hauser[65], J. Hays[43], T. Hebbeker[21], D. Hedin[52], J.G. Hegeman[34], A.P. Heinson[48], U. Heintz[62], C. Hensel[22,d], K. Herner[72], G. Hesketh[63], M.D. Hildreth[55], R. Hirosky[81], J.D. Hobbs[72], B. Hoeneisen[12], H. Hoeth[26], M. Hohlfeld[22], S.J. Hong[31], S. Hossain[75], P. Houben[34], Y. Hu[72], Z. Hubacek[10], V. Hynek[9], I. Iashvili[69], R. Illingworth[50], A.S. Ito[50], S. Jabeen[62], M. Jaffré[16], S. Jain[75], K. Jakobs[23], C. Jarvis[61], R. Jesik[43], K. Johns[45], C. Johnson[70], M. Johnson[50], A. Jonckheere[50], P. Jonsson[43], A. Juste[50], E. Kajfasz[15], J.M. Kalk[60], D. Karmanov[38], P.A. Kasper[50], I. Katsanos[70], D. Kau[49], V. Kaushik[78], R. Kehoe[79], S. Kermiche[15], N. Khalatyan[50], A. Khanov[76], A. Kharchilava[69], Y.M. Kharzheev[36], D. Khatidze[70], T.J. Kim[31], M.H. Kirby[53], M. Kirsch[21], B. Klima[50], J.M. Kohli[27], J.-P. Konrath[23], A.V. Kozelov[39], J. Kraus[65], D. Krop[54], T. Kuhl[24], A. Kumar[69], A. Kupco[11], T. Kurča[20], V.A. Kuzmin[38], J. Kvita[9], F. Lacroix[13], D. Lam[55], S. Lammers[70], G. Landsberg[77], P. Lebrun[20], W.M. Lee[50], A. Leflat[38], J. Lellouch[17], J. Leveque[45], J. Li[78], L. Li[48], Q.Z. Li[50], S.M. Lietti[5], J.G.R. Lima[52], D. Lincoln[50], J. Linnemann[65], V.V. Lipaev[39], R. Lipton[50], Y. Liu[7], Z. Liu[6], A. Lobodenko[40], M. Lokajicek[11], P. Love[42], H.J. Lubatti[82], R. Luna[3], A.L. Lyon[50], A.K.A. Maciel[2], D. Mackin[80], R.J. Madaras[46], P. Mättig[26], C. Magass[21], A. Magerkurth[64], P.K. Mal[82], H.B. Malbouisson[3], S. Malik[67], V.L. Malyshev[36], H.S. Mao[50], Y. Maravin[59], B. Martin[14], R. McCarthy[72], A. Melnitchouk[66], L. Mendoza[8], P.G. Mercadante[5], M. Merkin[38], K.W. Merritt[50], A. Meyer[21], J. Meyer[22,d], T. Millet[20], J. Mitrevski[70], R.K. Mommsen[44], N.K. Mondal[29], R.W. Moore[6], T. Moulik[58], G.S. Muanza[20], M. Mulhearn[70], O. Mundal[22], L. Mundim[3], E. Nagy[15], M. Naimuddin[50], M. Narain[77], N.A. Naumann[35], H.A. Neal[64], J.P. Negret[8], P. Neustroev[40], H. Nilsen[23], H. Nogima[3], S.F. Novaes[5], T. Nunnemann[25], V. O'Dell[50], D.C. O'Neil[6], G. Obrant[40], C. Ochando[16], D. Onoprienko[59], N. Oshima[50], N. Osman[43], J. Osta[55], R. Otec[10], G.J. Otero y Garzón[50], M. Owen[44], P. Padley[80], M. Pangilinan[77], N. Parashar[56], S.-J. Park[22,d], S.K. Park[31], J. Parsons[70], R. Partridge[77], N. Parua[54], A. Patwa[73],

G. Pawloski[80], B. Penning[23], M. Perfilov[38], K. Peters[44], Y. Peters[26], P. Pétroff[16], M. Petteni[43], R. Piegaia[1], J. Piper[65], M.-A. Pleier[22], P.L.M. Podesta-Lerma[33,c], V.M. Podstavkov[50], Y. Pogorelov[55], M.-E. Pol[2], P. Polozov[37], B.G. Pope[65], A.V. Popov[39], C. Potter[6], W.L. Prado da Silva[3], H.B. Prosper[49], S. Protopopescu[73], J. Qian[64], A. Quadt[22,d], B. Quinn[66], A. Rakitine[42], M.S. Rangel[2], K. Ranjan[28], P.N. Ratoff[42], P. Renkel[79], S. Reucroft[63], P. Rich[44], J. Rieger[54], M. Rijssenbeek[72], I. Ripp-Baudot[19], F. Rizatdinova[76], S. Robinson[43], R.F. Rodrigues[3], M. Rominsky[75], C. Royon[18], P. Rubinov[50], R. Ruchti[55], G. Safronov[37], G. Sajot[14], A. Sánchez-Hernández[33], M.P. Sanders[17], B. Sanghi[50], A. Santoro[3], G. Savage[50], L. Sawyer[60], T. Scanlon[43], D. Schaile[25], R.D. Schamberger[72], Y. Scheglov[40], H. Schellman[53], T. Schliephake[26], C. Schwanenberger[44], A. Schwartzman[68], R. Schwienhorst[65], J. Sekaric[49], H. Severini[75], E. Shabalina[51], M. Shamim[59], V. Shary[18], A.A. Shchukin[39], R.K. Shivpuri[28], V. Siccardi[19], V. Simak[10], V. Sirotenko[50], P. Skubic[75], P. Slattery[71], D. Smirnov[55], G.R. Snow[67], J. Snow[74], S. Snyder[73], S. Söldner-Rembold[44], L. Sonnenschein[17], A. Sopczak[42], M. Sosebee[78], K. Soustruznik[9], B. Spurlock[78], J. Stark[14], J. Steele[60], V. Stolin[37], D.A. Stoyanova[39], J. Strandberg[64], S. Strandberg[41], M.A. Strang[69], E. Strauss[72], M. Strauss[75], R. Ströhmer[25], D. Strom[53], L. Stutte[50], S. Sumowidagdo[49], P. Svoisky[55], A. Sznajder[3], P. Tamburello[45], A. Tanasijczuk[1], W. Taylor[6], J. Temple[45], B. Tiller[25], F. Tissandier[13], M. Titov[18], V.V. Tokmenin[36], T. Toole[61], I. Torchiani[23], T. Trefzger[24], D. Tsybychev[72], B. Tuchming[18], C. Tully[68], P.M. Tuts[70], R. Unalan[65], L. Uvarov[40], S. Uvarov[40], S. Uzunyan[52], B. Vachon[6], P.J. van den Berg[34], R. Van Kooten[54], W.M. van Leeuwen[34], N. Varelas[51], E.W. Varnes[45], I.A. Vasilyev[39], M. Vaupel[26], P. Verdier[20], L.S. Vertogradov[36], M. Verzocchi[50], F. Villeneuve-Seguier[43], P. Vint[43], P. Vokac[10], E. Von Toerne[59], M. Voutilainen[68,e], R. Wagner[68], H.D. Wahl[49], L. Wang[61], M.H.L.S. Wang[50], J. Warchol[55], G. Watts[82], M. Wayne[55], G. Weber[24], M. Weber[50], L. Welty-Rieger[54], A. Wenger[23,f], N. Wermes[22], M. Wetstein[61], A. White[78], D. Wicke[26], G.W. Wilson[58], S.J. Wimpenny[48], M. Wobisch[60], D.R. Wood[63], T.R. Wyatt[44], Y. Xie[77], S. Yacoob[53], R. Yamada[50], M. Yan[61], T. Yasuda[50], Y.A. Yatsunenko[36], K. Yip[73], H.D. Yoo[77], S.W. Youn[53], J. Yu[78], C. Zeitnitz[26], T. Zhao[82], B. Zhou[64], J. Zhu[72], M. Zielinski[71], D. Zieminska[54], A. Zieminski[54,‡], L. Zivkovic[70], V. Zutshi[52], and E.G. Zverev[38]

(The DØ Collaboration)

[1] *Universidad de Buenos Aires, Buenos Aires, Argentina*
[2] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[3] *Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[4] *Universidade Federal do ABC, Santo André, Brazil*
[5] *Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[6] *University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada*
[7] *University of Science and Technology of China, Hefei, People's Republic of China*
[8] *Universidad de los Andes, Bogotá, Colombia*
[9] *Center for Particle Physics, Charles University, Prague, Czech Republic*
[10] *Czech Technical University, Prague, Czech Republic*
[11] *Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[12] *Universidad San Francisco de Quito, Quito, Ecuador*
[13] *LPC, Univ Blaise Pascal, CNRS/IN2P3, Clermont, France*
[14] *LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, France*
[15] *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[16] *LAL, Univ Paris-Sud, IN2P3/CNRS, Orsay, France*
[17] *LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France*
[18] *DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[19] *IPHC, Université Louis Pasteur et Université de Haute Alsace, CNRS/IN2P3, Strasbourg, France*
[20] *IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France*
[21] *III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany*
[22] *Physikalisches Institut, Universität Bonn, Bonn, Germany*
[23] *Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[24] *Institut für Physik, Universität Mainz, Mainz, Germany*
[25] *Ludwig-Maximilians-Universität München, München, Germany*
[26] *Fachbereich Physik, University of Wuppertal, Wuppertal, Germany*
[27] *Panjab University, Chandigarh, India*
[28] *Delhi University, Delhi, India*

[29]Tata Institute of Fundamental Research, Mumbai, India
[30]University College Dublin, Dublin, Ireland
[31]Korea Detector Laboratory, Korea University, Seoul, Korea
[32]SungKyunKwan University, Suwon, Korea
[33]CINVESTAV, Mexico City, Mexico
[34]FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
[35]Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
[36]Joint Institute for Nuclear Research, Dubna, Russia
[37]Institute for Theoretical and Experimental Physics, Moscow, Russia
[38]Moscow State University, Moscow, Russia
[39]Institute for High Energy Physics, Protvino, Russia
[40]Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[41]Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
[42]Lancaster University, Lancaster, United Kingdom
[43]Imperial College, London, United Kingdom
[44]University of Manchester, Manchester, United Kingdom
[45]University of Arizona, Tucson, Arizona 85721, USA
[46]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
[47]California State University, Fresno, California 93740, USA
[48]University of California, Riverside, California 92521, USA
[49]Florida State University, Tallahassee, Florida 32306, USA
[50]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[51]University of Illinois at Chicago, Chicago, Illinois 60607, USA
[52]Northern Illinois University, DeKalb, Illinois 60115, USA
[53]Northwestern University, Evanston, Illinois 60208, USA
[54]Indiana University, Bloomington, Indiana 47405, USA
[55]University of Notre Dame, Notre Dame, Indiana 46556, USA
[56]Purdue University Calumet, Hammond, Indiana 46323, USA
[57]Iowa State University, Ames, Iowa 50011, USA
[58]University of Kansas, Lawrence, Kansas 66045, USA
[59]Kansas State University, Manhattan, Kansas 66506, USA
[60]Louisiana Tech University, Ruston, Louisiana 71272, USA
[61]University of Maryland, College Park, Maryland 20742, USA
[62]Boston University, Boston, Massachusetts 02215, USA
[63]Northeastern University, Boston, Massachusetts 02115, USA
[64]University of Michigan, Ann Arbor, Michigan 48109, USA
[65]Michigan State University, East Lansing, Michigan 48824, USA
[66]University of Mississippi, University, Mississippi 38677, USA
[67]University of Nebraska, Lincoln, Nebraska 68588, USA
[68]Princeton University, Princeton, New Jersey 08544, USA
[69]State University of New York, Buffalo, New York 14260, USA
[70]Columbia University, New York, New York 10027, USA
[71]University of Rochester, Rochester, New York 14627, USA
[72]State University of New York, Stony Brook, New York 11794, USA
[73]Brookhaven National Laboratory, Upton, New York 11973, USA
[74]Langston University, Langston, Oklahoma 73050, USA
[75]University of Oklahoma, Norman, Oklahoma 73019, USA
[76]Oklahoma State University, Stillwater, Oklahoma 74078, USA
[77]Brown University, Providence, Rhode Island 02912, USA
[78]University of Texas, Arlington, Texas 76019, USA
[79]Southern Methodist University, Dallas, Texas 75275, USA
[80]Rice University, Houston, Texas 77005, USA
[81]University of Virginia, Charlottesville, Virginia 22901, USA and
[82]University of Washington, Seattle, Washington 98195, USA

(Dated: October 31, 2008)

We present a study of the polarization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ states using a 1.3 fb^{-1} data sample collected by the D0 experiment in 2002–2006 during Run II of the Fermilab Tevatron Collider. We measure the polarization parameter $\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$, where σ_T and σ_L are the transversely and longitudinally polarized components of the production cross section, as a function of the transverse momentum (p_T^{Υ}) for the $\Upsilon(1S)$ and $\Upsilon(2S)$. Significant p_T^{Υ}-dependent longitudinal polarization is observed for the $\Upsilon(1S)$. A comparison with theoretical models is presented.

PACS numbers: 14.40.Nd, 13.88.+e, 13.20.Gd

The production of heavy quarks and quarkonium states at high energies is under intense experimental and theoretical study [1]. The non-relativistic QCD (NRQCD) factorization approach has been developed to describe the inclusive production and decay of quarkonia [2] including high transverse momentum (p_T) S-wave charmonium production at the Fermilab Tevatron Collider [3]. The theory introduces several nonperturbative color-octet matrix elements (MEs). These MEs are universal and are fitted to data of the Fermilab Tevatron Collider [4]. The universality of the MEs has been tested in various experimental situations [5]. A remarkable prediction of the NRQCD approach is that the S-wave quarkonium produced in the $p\overline{p}$ collision should be transversely polarized at sufficiently large p_T [6]. This prediction is based on the dominance of gluon fragmentation in quarkonium production at large p_T [3] and on the approximate heavy-quark spin symmetry of NRQCD [2]. Measurements of the polarization of prompt J/ψ by the CDF Collaboration do not confirm this prediction [7].

A convenient measure of the polarization is the variable

$$\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L), \tag{1}$$

where σ_T and σ_L are the transversely and longitudinally polarized components of the production cross section. If we consider the decays of quarkonium to a charged lepton-antilepton pair, then the angular distribution is given by

$$\frac{dN}{d(\cos\theta^*)} \propto 1 + \alpha\cos^2\theta^*, \tag{2}$$

where θ^* is the angle of the positive lepton in the quarkonium center-of-mass frame with respect to the momentum of the decaying particle in the laboratory frame.

Quantitative calculations of the polarization for inclusive $\Upsilon(nS)$ mesons are carried out [8] by using the ME for direct bottomonium production determined from an analysis of Tevatron data [9]. They predict that the transverse polarization of $\Upsilon(1S)$ should dominate and increase steadily with p_T^Υ for $p_T^\Upsilon \gtrsim 10$ GeV/c and that the $\Upsilon(2S)$ and $\Upsilon(3S)$ should be even more strongly transversely polarized. The k_t-factorization model [10], using a semi-hard approach, predicts a longitudinal polarization of $\Upsilon(1S)$ at $p_T^\Upsilon > 5\,\text{GeV}/c$ [11]. In this context, the experimental measurement of the Υ polarization is a crucial test of two theoretical approaches to parton dynamics in QCD.

The D0 detector is described in detail elsewhere [12]. The main elements relevent to this analysis are a central-tracking system, consisting of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), and muon detector systems.

The data set used for this analysis includes approximately 1.3 fb^{-1} of integrated luminosity collected by the D0 detector between April 2002 and the end of 2006. We selected events where the $\Upsilon(nS)$ decayed into two muons. Muons were required to have hits in three muon layers, to have an associated track in the central tracking system with hits in both the SMT and CFT, and to have transverse momentum $p_T^\mu > 3.5\,\text{GeV}/c$. In this analysis only events that passed a dimuon trigger, which requires two opposite charge muon candidates, were included in the final sample. We observed about 260,000 $\Upsilon(nS)$ with rapidity $|y^\Upsilon| < 1.8$ when fitting the dimuon invariant mass distribution as described below.

Monte Carlo (MC) samples for unpolarized $\Upsilon(1S)$ and $\Upsilon(2S)$ inclusive production were generated using the PYTHIA [13] event generator and then passed through a GEANT-based [14] simulation of the D0 detector. The simulated events were then required to satisfy the same selection criteria as the data sample including a detailed simulation of all aspects of the trigger requirements.

We fitted the dimuon invariant mass distribution in several intervals of p_T^Υ for a set of $|\cos\theta^*|$ bins. A previous measurement of the $\Upsilon(1S)$ cross-section by the D0 experiment [15] showed that a double Gaussian function is required to model the mass distribution of the $\Upsilon(1S)$ candidates. Studies performed on the $\Upsilon(1S)$ Monte Carlo sample suggest that a more sophisticated parameterization of the invariant mass distribution for some $|\cos\theta^*|$ bins, where we observe non-Gaussian tails, is required. Two different parameterizations of the mass distribution were used, referred to as "data-driven" and "MC-driven" functions. The data-driven function has the advantage that no assumptions are made about how well the MC reproduces the true resolution. It consists of a double Gaussian function with equal means. The mean, widths, and relative fraction are free parameters. In contrast, the MC-driven function allows for a test of the effect of non-Gaussian components to the resolution that are observable in MC but are hidden in data by the detector resolution and the combinatoric background. Non-Gaussian tails are implemented via a third Gaussian component with a floating mean to account for an asymmetric tail in the reconstructed $\Upsilon(nS)$ mass. The width and relative fraction are taken from Monte Carlo. Figure 1 shows an example of a fit to the mass distribution for a single p_T^Υ and $|\cos\theta^*|$ bin ignoring or including non-Gaussian tails. The signal consists of three mass peaks, the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ where the mass differences were fixed to the measured values [16]. The background was modeled with a convolution of an exponential and a polynomial function. The degree of the polynomial was chosen to be between one and six depending on the complexity of the shape of the background. The χ^2 values in

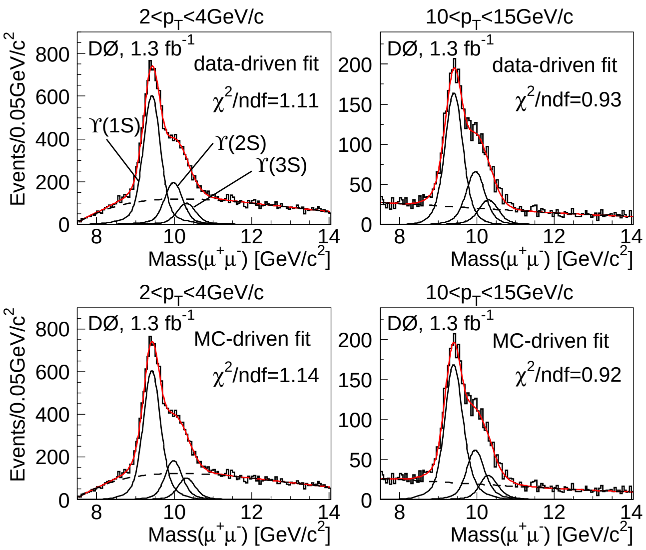

FIG. 1: [Color online] Signal extraction from the dimuon invariant mass distribution for events in the $0.4 < |\cos\theta^*| < 0.5$ region. a,c) $2 < p_T^{\Upsilon} < 4\,\mathrm{GeV}/c$; b,d) $10 < p_T^{\Upsilon} < 15\,\mathrm{GeV}/c$. Dashed curves are the combinatoric background.

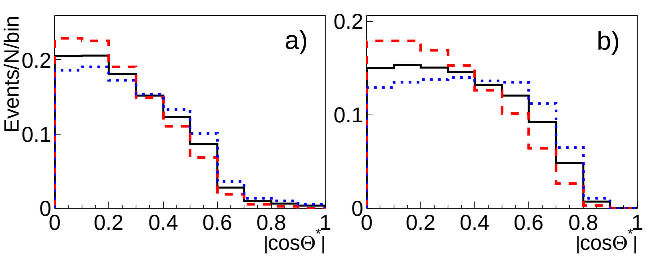

FIG. 2: [Color online] Monte Carlo $|\cos\theta^*|$ distributions after all selection requirements for different α values: -1 (dashed histogram), 0 (solid histogram) and $+1$ (dotted histogram). a) $0 < p_T^{\Upsilon} < 1\,\mathrm{GeV}/c$, b) $p_T^{\Upsilon} > 15\,\mathrm{GeV}/c$.

Fig. 1 do not allow us to differentiate between the two approximations and hence we average them.

The data were divided into bins in p_T^{Υ} and $|\cos\theta^*|$. For each of these bins the numbers of $\Upsilon(1S)$ and $\Upsilon(2S)$ candidates were extracted from the mass distribution. The number of $\Upsilon(3S)$ candidates was insufficient to extract angular distributions.

Polarization was not taken into account in the Monte Carlo generation. To compare them with data we calculated for each event the weight w_α, which converts the initial Monte Carlo $|\cos\theta^*|$ distribution with $\alpha = 0$ to a distribution with the chosen α. Figure 2 shows the sensivity of the D0 detector to the $\Upsilon(1S)$ polarization for the lowest and highest $p_T^{\Upsilon(nS)}$ intervals. The PYTHIA simulation does not accurately model the kinematic distributions of $\Upsilon(nS)$ production at the Tevatron (e.g., the $p_T^{\Upsilon(nS)}$ distribution). To correct the Monte Carlo distributions, we introduced additional weights to improve the agreement with data of the $\Upsilon(nS)$ momentum distribution. Instead of the weight w_α in our algorithm, we used the weight $w = w_\alpha w_{p_T^{\Upsilon}} w_{p^{\Upsilon}}$, where $w_{p_T^{\Upsilon}}$ and $w_{p^{\Upsilon}}$ are weights to achieve agreement between data and Monte Carlo distributions of p_T^{Υ} and p^{Υ}. After this reweighting procedure, we obtained good agreement between data and MC for the $\Upsilon(nS)$ and muon kinematic distributions. An example for Y(1S) with $2 < p_T^{\Upsilon} < 4\,\mathrm{GeV}/c$, using the MC-driven fit, is presented in Fig 3. All data distributions were derived by estimating the number of $\Upsilon(1S)$ events from a fit to the dimuon mass distribution for the corresponding bin of the histogram.

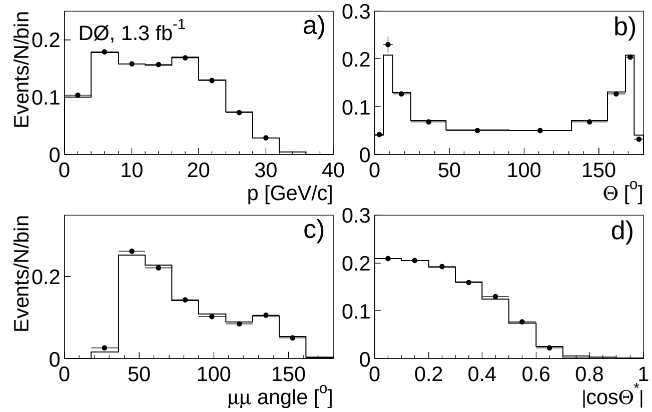

FIG. 3: Comparison of data (points) and Monte Carlo (solid histogram) for $\Upsilon(1S)$ with $2 < p_T^{\Upsilon} < 4\,\mathrm{GeV}/c$: a) momentum of $\Upsilon(1S)$, b) polar angle of $\Upsilon(1S)$, c) angle between muons, d) $|\cos\theta^*|$.

The systematic uncertainties on α for $\Upsilon(1S)$ are summarized in Table I. Values of α were found for several p_T^{Υ} intervals, using both parameterizations (data-driven and MC-driven) of the dimuon invariant mass distribution for the signal. Both α measurements are averaged and one half of the difference between them is assigned as systematic uncertainty due to the signal model. The uncertainty in the background was estimated by varying the mass range of the fit and the degree of the polynomial used to parameterize the background. The MC simulation does not reproduce exactly the mass of the $\Upsilon(1S)$ peak, which differs by about $40\,\mathrm{MeV}/c^2$ from the PDG value. The effect on the α determination was estimated and shown in Table I under "muon momentum." Finally, the systematic uncertainty due to the trigger simulation has also been considered and shown in Table I. The $\Upsilon(1S)$ polarization was calculated assuming that it is constant within a given p_T^{Υ} bin. This assumption leads to a small bias in the measured α that is estimated by reweighting the simulation using the observed p_T^{Υ} dependence of α. The final measured α is corrected by a factor ranging between -0.03 and $+0.06$, depending on p_T^{Υ}.

Figure 4 shows the measured α as a function of p_T^{Υ} for $\Upsilon(1S)$. Note that the bin for 14-20 GeV is not statistically independent from the adjacent bins. The arrow indicates that the highest p_T^{Υ} interval considered,

TABLE I: Systematic uncertainties on α for $\Upsilon(1S)$.

Source	Uncertainty on α^a	p_T^{Υ} ^{b} [GeV/c]
Signal model	$0.01 - 0.15$	$1 - 2$
Background model	$0.04 - 0.21$	$0 - 1$
Muon momentum	$0.00 - 0.06$	$0 - 1$
Trigger simulation	$0.00 - 0.06$	>15

[a]For all p_T^{Υ} intervals
[b]Interval with maximal uncertainty

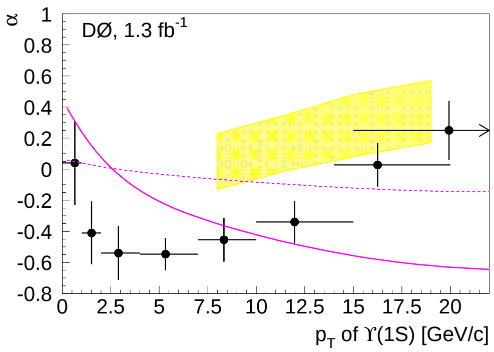

FIG. 4: [Color online] Dependence of α on p_T^{Υ} for inclusive $\Upsilon(1S)$ candidates. Black circles are data. The band is the NRQCD prediction [8]. Curves are two limiting cases (see text) of the k_t-factorization model [11].

$p_T^{\Upsilon} > 15\,\mathrm{GeV}/c$, does not have an upper limit. The uncertainties are the systematic and statistical uncertainties added in quadrature. Also shown are the NRQCD prediction [8] (yellow band), and the two limits of the k_t-factorization model [11] (curves). The lower line corresponds to the quark-spin conservation hypothesis, and the upper one to the full quark-spin depolarization hypothesis. The previous measurement by CDF of the polarization of $\Upsilon(1S)$ with rapidity $|y^{\Upsilon}| < 0.4$ is consistent with α equal to zero [17]. We expect the CDF and D0 results to be similar and we have no explanation for the observed difference. We also extracted the polarization of the $\Upsilon(2S)$, which is shown in Fig. 5 along with the NRQCD predictions [8]. Values of α for statistically independent p_T^{Υ} intervals, shown in Fig. 4 and Fig. 5, are given in Table II.

In conclusion, we have presented measurements of the

TABLE II: Measurements of α for $\Upsilon(1S)$ and $\Upsilon(1S)$.

p_T^{Υ} [GeV/c]	$\alpha[\Upsilon(1S)]$	$\alpha[\Upsilon(2S)]$
$0 - 1$	0.04 ± 0.27	-0.04 ± 0.54
$1 - 2$	-0.41 ± 0.20	0.28 ± 0.37
$2 - 4$	-0.54 ± 0.17	0.04 ± 0.18
$4 - 7$	-0.55 ± 0.10	-0.37 ± 0.21
$7 - 10$	-0.45 ± 0.14	0.09 ± 0.32
$10 - 15$	-0.34 ± 0.14	0.32 ± 0.27
>15	0.25 ± 0.19	0.55 ± 0.58

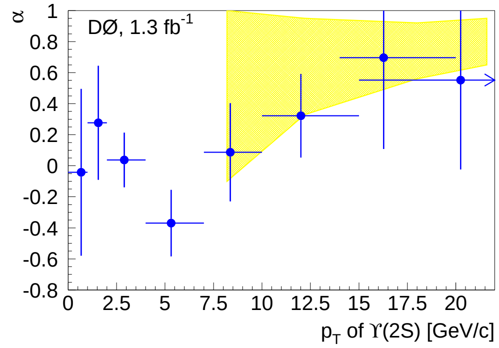

FIG. 5: [Color online] Dependence of α on p_T^{Υ} for inclusive $\Upsilon(2S)$ production. Circles are our data. The band is the NRQCD prediction [8].

polarization of the $\Upsilon(1S)$ and $\Upsilon(2S)$ as functions of p_T^{Υ} from $0\,\mathrm{GeV}/c$ to $20\,\mathrm{GeV}/c$. Significant p_T-dependent longitudinal polarization is observed for the $\Upsilon(1S)$ inconsistent with NRQCD predictions. At $p_T^{\Upsilon} > 7\,\mathrm{GeV}/c$ the fraction of transversely polarized $\Upsilon(2S)$ particles is higher than in $\Upsilon(1S)$ at the same value of p_T^{Υ}, in agreement with NRQCD predictions.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); and the Alexander von Humboldt Foundation.

[a] Visitor from Augustana College, Sioux Falls, SD, USA.
[b] Visitor from The University of Liverpool, Liverpool, UK.
[c] Visitor from ICN-UNAM, Mexico City, Mexico.
[d] Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
[e] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
[f] Visitor from Universität Zürich, Zürich, Switzerland.
[‡] Deceased.

[1] N. Brambila, M. Kramer, R. Mussa and A. Vairo, arXiv:hep-ph/0412158 (2004).
[2] G.T. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. D **51**, 1125 (1995) [Erratum-ibid. D **55**, 5853 (1997)].
[3] E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995).
[4] P. Cho and A.K. Leibovich, Phys. Rev. D **53**, 150 (1996); Phys. Rev. D **53**, 6203 (1996).
[5] K. Anikeev *et al.*, arXiv:hep-ph/0201071 (2002).

[6] P. Cho, M.B. Wise, Phys. Lett. B **346**, 129 (1995).
[7] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, 132001 (2007).
[8] E. Braaten and J. Lee, Phys. Rev. D **63**, 071501 (2001).
[9] E. Braaten, S. Fleming and A.K. Leibovich, Phys. Rev. D **63**, 094006 (2001).
[10] J.R. Andersen *et al.*, Eur. Phys. J. C **35**, 67 (2004)
[11] S.P. Baranov and N.P. Zotov, Pis'ma v ZhETF **86**, 499 (2007).
[12] V.M. Abazov *et al.* (D0 Collaboration), Nucl Instrum. Methods Phys. Res. A **565**, 463 (2006).
[13] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
[14] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).
[15] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **94**, 232001 (2005) [Erratum-ibid. **100**, 049902 (2008)].
[16] W.-M. Yao *et al.*, J. Phys. G **33**, 1 (2006).
[17] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **88**, 161802 (2002).