

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Kenneth Bloom Publications

Research Papers in Physics and Astronomy

10-31-2008

Measurement of the Polarization of the $Y(1S)$ and $Y(2S)$ States in pp Collisions at $\sqrt{s} = 1.96$ TeV

V. M. Abazov

Joint Institute for Nuclear Research, Dubna, Russia

Kenneth A. Bloom

University of Nebraska-Lincoln, kbloom2@unl.edu

Gregory Snow

University of Nebraska-Lincoln, gsnow1@unl.edu

D0 Collaboration

Follow this and additional works at: <https://digitalcommons.unl.edu/physicsbloom>



Part of the [Physics Commons](#)

Abazov, V. M.; Bloom, Kenneth A.; Snow, Gregory; and Collaboration, D0, "Measurement of the Polarization of the $Y(1S)$ and $Y(2S)$ States in pp Collisions at $\sqrt{s} = 1.96$ TeV" (2008). *Kenneth Bloom Publications*. 266. <https://digitalcommons.unl.edu/physicsbloom/266>

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Kenneth Bloom Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

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. Alkhalaf,⁴⁰ A. Alton,^{64,*} G. Alverson,⁶³ G. A. Alves,² M. Anastasoae,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,+} 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. Crépe-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. Dufлот,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,§} K. Herner,⁷² G. Hesketh,⁶³ M. D. Hildreth,⁵⁵ R. Hirosky,⁸¹ J. D. Hobbs,⁷² B. Hoeneisen,¹² H. Hoeth,²⁶ M. Hohlfield,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,§} 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,§} 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,‡} 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,§} 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-Seguiet,⁴³ P. Vint,⁴³ P. Vokac,¹⁰ E. Von Toerne,⁵⁹
M. Voutilainen,^{68,||} 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,¶} 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. Yacoub,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. Zverev³⁸

(The DØ Collaboration)

¹Universidad de Buenos Aires, Buenos Aires, Argentina

²LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

³Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

⁴Universidade Federal do ABC, Santo André, Brazil

⁵Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil

⁶University of Alberta, Edmonton, Alberta, Canada,

Simon Fraser University, Burnaby, British Columbia, Canada,

York University, Toronto, Ontario, Canada,

and McGill University, Montreal, Quebec, Canada

⁷University of Science and Technology of China, Hefei, People's Republic of China

⁸Universidad de los Andes, Bogotá, Colombia

⁹Center for Particle Physics, Charles University, Prague, Czech Republic

¹⁰Czech Technical University, Prague, Czech Republic

¹¹Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

¹²Universidad San Francisco de Quito, Quito, Ecuador

¹³LPC, Univ Blaise Pascal, CNRS/IN2P3, Clermont, France

¹⁴LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, France

¹⁵CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

¹⁶LAL, Univ Paris-Sud, IN2P3/CNRS, Orsay, France

¹⁷LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France

¹⁸DAPNIA/Service de Physique des Particules, CEA, Saclay, France

¹⁹IPHC, Université Louis Pasteur et Université de Haute Alsace, CNRS/IN2P3, Strasbourg, France

²⁰IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

²¹III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany

²²Physikalisches Institut, Universität Bonn, Bonn, Germany

²³Physikalisches Institut, Universität Freiburg, Freiburg, Germany

²⁴Institut für Physik, Universität Mainz, Mainz, Germany

²⁵Ludwig-Maximilians-Universität München, München, Germany

²⁶Fachbereich Physik, University of Wuppertal, Wuppertal, Germany

²⁷Panjab University, Chandigarh, India

²⁸Delhi University, Delhi, India

²⁹Tata Institute of Fundamental Research, Mumbai, India

³⁰University College Dublin, Dublin, Ireland

³¹Korea Detector Laboratory, Korea University, Seoul, Korea

³²SungKyunKwan University, Suwon, Korea

³³CINVESTAV, Mexico City, Mexico

³⁴FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands

- ³⁵Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
³⁶Joint Institute for Nuclear Research, Dubna, Russia
³⁷Institute for Theoretical and Experimental Physics, Moscow, Russia
³⁸Moscow State University, Moscow, Russia
³⁹Institute for High Energy Physics, Protvino, Russia
⁴⁰Petersburg Nuclear Physics Institute, St. Petersburg, Russia
⁴¹Lund University, Lund, Sweden,
Royal Institute of Technology and Stockholm University, Stockholm, Sweden,
and Uppsala University, Uppsala, Sweden
⁴²Lancaster University, Lancaster, United Kingdom
⁴³Imperial College, London, United Kingdom
⁴⁴University of Manchester, Manchester, United Kingdom
⁴⁵University of Arizona, Tucson, Arizona 85721, USA
⁴⁶Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
⁴⁷California State University, Fresno, California 93740, USA
⁴⁸University of California, Riverside, California 92521, USA
⁴⁹Florida State University, Tallahassee, Florida 32306, USA
⁵⁰Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
⁵¹University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁵²Northern Illinois University, DeKalb, Illinois 60115, USA
⁵³Northwestern University, Evanston, Illinois 60208, USA
⁵⁴Indiana University, Bloomington, Indiana 47405, USA
⁵⁵University of Notre Dame, Notre Dame, Indiana 46556, USA
⁵⁶Purdue University Calumet, Hammond, Indiana 46323, USA
⁵⁷Iowa State University, Ames, Iowa 50011, USA
⁵⁸University of Kansas, Lawrence, Kansas 66045, USA
⁵⁹Kansas State University, Manhattan, Kansas 66506, USA
⁶⁰Louisiana Tech University, Ruston, Louisiana 71272, USA
⁶¹University of Maryland, College Park, Maryland 20742, USA
⁶²Boston University, Boston, Massachusetts 02215, USA
⁶³Northeastern University, Boston, Massachusetts 02115, USA
⁶⁴University of Michigan, Ann Arbor, Michigan 48109, USA
⁶⁵Michigan State University, East Lansing, Michigan 48824, USA
⁶⁶University of Mississippi, University, Mississippi 38677, USA
⁶⁷University of Nebraska, Lincoln, Nebraska 68588, USA
⁶⁸Princeton University, Princeton, New Jersey 08544, USA
⁶⁹State University of New York, Buffalo, New York 14260, USA
⁷⁰Columbia University, New York, New York 10027, USA
⁷¹University of Rochester, Rochester, New York 14627, USA
⁷²State University of New York, Stony Brook, New York 11794, USA
⁷³Brookhaven National Laboratory, Upton, New York 11973, USA
⁷⁴Langston University, Langston, Oklahoma 73050, USA
⁷⁵University of Oklahoma, Norman, Oklahoma 73019, USA
⁷⁶Oklahoma State University, Stillwater, Oklahoma 74078, USA
⁷⁷Brown University, Providence, Rhode Island 02912, USA
⁷⁸University of Texas, Arlington, Texas 76019, USA
⁷⁹Southern Methodist University, Dallas, Texas 75275, USA
⁸⁰Rice University, Houston, Texas 77005, USA
⁸¹University of Virginia, Charlottesville, Virginia 22901, USA
⁸²University of Washington, Seattle, Washington 98195, USA
(Received 18 April 2008; published 31 October 2008)

We present a study of the polarization of the $Y(1S)$ and $Y(2S)$ 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^Y) for the $Y(1S)$ and $Y(2S)$. Significant p_T^Y -dependent longitudinal polarization is observed for the $Y(1S)$. A comparison with theoretical models is presented.

The production of heavy quarks and quarkonium states at high energies is under intense experimental and theoretical study [1]. The nonrelativistic 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 $p\bar{p}$ 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 [6] 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

$$\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L), \quad (1)$$

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

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

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 $Y(nS)$ 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 $Y(1S)$ should dominate and increase steadily with p_T^Y for $p_T^Y \gtrsim 10$ GeV/ c and that the $Y(2S)$ and $Y(3S)$ should be even more strongly transversely polarized. The k_T -factorization model [10], using a semihard approach, predicts a longitudinal polarization of $Y(1S)$ at $p_T^Y > 5$ GeV/ c [11]. In this context, the experimental measurement of the Y 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 relevant to this analysis are a central-tracking system, consisting of a silicon microstrip tracker (SMT), 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 $Y(nS)$ 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 $p_T^\mu > 3.5$ 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 $Y(nS)$ with rapidity $|y^Y| < 1.8$ when fitting the dimuon invariant mass distribution as described below.

Monte Carlo (MC) samples for unpolarized $Y(1S)$ and $Y(2S)$ 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^Y for a set of $|\cos\theta^*|$ bins. A previous measurement of the $Y(1S)$ cross section by the D0 experiment [15] showed that a double Gaussian function is required to model the mass distribution of the $Y(1S)$ candidates. Studies performed on the $Y(1S)$ 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-driven function 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 calculations 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 $Y(nS)$ mass. The width and relative fraction are taken from Monte Carlo calculations. Figure 1 shows an example of a fit to the mass distribution for a single p_T^Y and $|\cos\theta^*|$ bin ignoring or including non-Gaussian tails. The signal consists of three mass peaks, the $Y(1S)$, $Y(2S)$, and $Y(3S)$ 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 do not allow us to differentiate between the two approximations, and hence we average them.

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

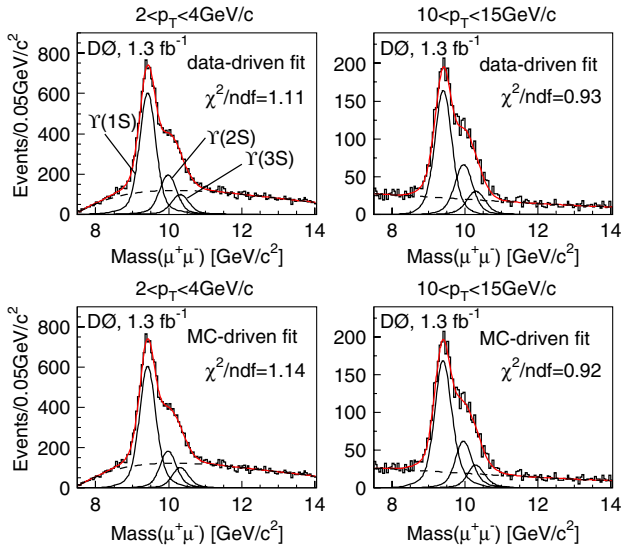


FIG. 1 (color online). Signal extraction from the dimuon invariant mass distribution for events in the $0.4 < |\cos\theta^*| < 0.5$ region. (a), (c) $2 < p_T^Y < 4$ GeV/c; (b), (d) $10 < p_T^Y < 15$ GeV/c. Dashed curves are the combinatoric background.

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 sensitivity of the D0 detector to the $Y(1S)$ polarization for the lowest and highest $p_T^{Y(nS)}$ intervals. The PYTHIA simulation does not accurately model the kinematic distributions of $Y(nS)$ production at the Tevatron (e.g., the $p_T^{Y(nS)}$ distribution). To correct the Monte Carlo distributions, we introduced additional weights to improve the agreement with data of the $Y(nS)$ momentum distribution. Instead of the weight w_α in our algorithm, we used the weight $w = w_\alpha w_{p_T^Y} w_{p^Y}$, where $w_{p_T^Y}$ and w_{p^Y} are weights to achieve agreement between data and Monte Carlo distributions of p_T^Y and p^Y . After this reweighting procedure, we obtained good agreement between data and MC calculations for the $Y(nS)$ and muon kinematic distributions. An example for

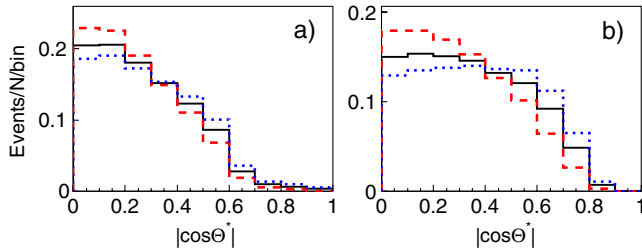


FIG. 2 (color online). Monte Carlo $|\cos\theta^*|$ distributions after all selection requirements for different α values: -1 (dashed histogram), 0 (solid histogram), and $+1$ (dotted histogram). (a) $0 < p_T^Y < 1$ GeV/c, (b) $p_T^Y > 15$ GeV/c.

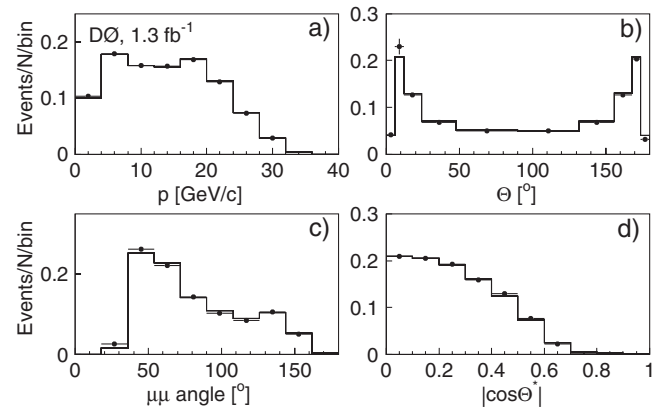


FIG. 3. Comparison of data (points) and Monte Carlo (solid histogram) for $Y(1S)$ with $2 < p_T^Y < 4$ GeV/c: (a) momentum of $Y(1S)$, (b) polar angle of $Y(1S)$, (c) angle between muons, (d) $|\cos\theta^*|$.

$Y(1S)$ with $2 < p_T^Y < 4$ GeV/c, using the MC-driven fit, is presented in Fig. 3. All data distributions were derived by estimating the number of $Y(1S)$ events from a fit to the dimuon mass distribution for the corresponding bin of the histogram.

The systematic uncertainties on α for $Y(1S)$ are summarized in Table I. Values of α were found for several p_T^Y 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 $Y(1S)$ peak, which differs by about 40 MeV/c² 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 $Y(1S)$ polarization was calculated assuming that it is constant within a given p_T^Y bin. This assumption leads to a small bias in the measured α that is estimated by reweighting the simulation using the observed p_T^Y dependence of α . The final measured α is

TABLE I. Systematic uncertainties on α for $Y(1S)$.

Source	Uncertainty on α ^a	p_T^Y ^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

^aFor all p_T^Y intervals.

^bInterval with maximal uncertainty.

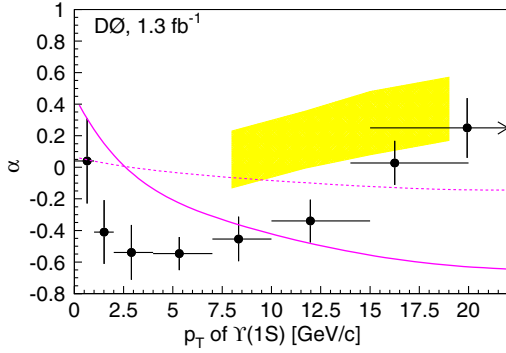


FIG. 4 (color online). Dependence of α on p_T^Y for inclusive $Y(1S)$ candidates. Black circles are data. The band is the NRQCD prediction [15]. Curves are two limiting cases (see text) of the k_t -factorization model [11].

corrected by a factor ranging between -0.03 and $+0.06$, depending on p_T^Y .

Figure 4 shows the measured α as a function of p_T^Y for $Y(1S)$. Note that the bin for 14–20 GeV is not statistically independent from the adjacent bins. The arrow indicates that the highest p_T^Y interval considered, $p_T^Y > 15$ 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 $Y(1S)$ with rapidity $|y^Y| < 0.4$ 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 $Y(2S)$, which is shown in Fig. 5 along with the NRQCD predictions [8]. Values of α for statistically independent p_T^Y intervals, shown in Figs. 4 and 5, are given in Table II.

In conclusion, we have presented measurements of the polarization of the $Y(1S)$ and $Y(2S)$ as functions of p_T^Y

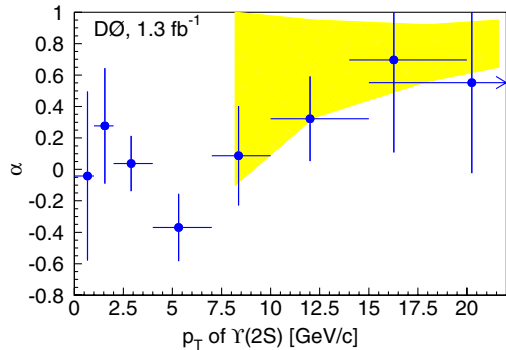


FIG. 5 (color online). Dependence of α on p_T^Y for inclusive $Y(2S)$ production. Circles are our data. The band is the NRQCD prediction [8].

TABLE II. Measurements of α for $Y(1S)$ and $Y(2S)$.

p_T^Y [GeV/c]	$\alpha[Y(1S)]$	$\alpha[Y(2S)]$
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

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

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

*Visitor from The University of Liverpool, Liverpool, UK.

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

§Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.

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

¶Visitor from Universität Zürich, Zürich, Switzerland.

**Deceased.

- [1] N. Brambilla, M. Kramer, R. Mussa, and A. Vairo, arXiv: hep-ph/0412158.
- [2] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D **51**, 1125 (1995); **55**, 5853(E) (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.
- [6] P. Cho and 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(R) (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 Zh. Eksp. Teor. Fiz. **86**, 499 (2007).
- [12] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. 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); **100**, 049902(E) (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).