

Evidence for Simultaneous Production of J/ψ and Υ Mesons

V. M. Abazov,³¹ B. Abbott,⁶⁷ B. S. Acharya,²⁵ M. Adams,⁴⁶ T. Adams,⁴⁴ J. P. Agnew,⁴¹ G. D. Alexeev,³¹ G. Alkhalaf,³⁵ A. Alton,^{56,a} A. Askew,⁴⁴ S. Atkins,⁵⁴ K. Augsten,⁷ V. Aushev,³⁸ C. Avila,⁵ F. Badaud,¹⁰ L. Bagby,⁴⁵ B. Baldin,⁴⁵ D. V. Bandurin,⁷⁴ S. Banerjee,²⁵ E. Barberis,⁵⁵ P. Baringer,⁵³ J. F. Bartlett,⁴⁵ U. Bassler,¹⁵ V. Bazterra,⁴⁶ A. Bean,⁵³ M. Begalli,² L. Bellantoni,⁴⁵ S. B. Beri,²³ G. Bernardi,¹⁴ R. Bernhard,¹⁹ I. Bertram,³⁹ M. Besançon,¹⁵ R. Beuselinck,⁴⁰ P. C. Bhat,⁴⁵ S. Bhatia,⁵⁸ V. Bhatnagar,²³ G. Blazey,⁴⁷ S. Blessing,⁴⁴ K. Bloom,⁵⁹ A. Boehnlein,⁴⁵ D. Boline,⁶⁴ E. E. Boos,³³ G. Borissov,³⁹ M. Borysova,^{38,l} A. Brandt,⁷¹ O. Brandt,²⁰ R. Brock,⁵⁷ A. Bross,⁴⁵ D. Brown,¹⁴ X. B. Bu,⁴⁵ M. Buehler,⁴⁵ V. Buescher,²¹ V. Bunichev,³³ S. Burdin,^{39,b} C. P. Buszello,³⁷ E. Camacho-Pérez,²⁸ B. C. K. Casey,⁴⁵ H. Castilla-Valdez,²⁸ S. Caughron,⁵⁷ S. Chakrabarti,⁶⁴ K. M. Chan,⁵¹ A. Chandra,⁷³ E. Chapon,¹⁵ G. Chen,⁵³ S. W. Cho,²⁷ S. Choi,²⁷ B. Choudhary,²⁴ S. Cihangir,⁴⁵ D. Claes,⁵⁹ J. Clutter,⁵³ M. Cooke,^{45,k} W. E. Cooper,⁴⁵ M. Corcoran,⁷³ F. Couderc,¹⁵ M.-C. Cousinou,¹² J. Cuth,²¹ D. Cutts,⁷⁰ A. Das,⁷² G. Davies,⁴⁰ S. J. de Jong,^{29,30} E. De La Cruz-Burelo,²⁸ F. Déliot,¹⁵ R. Demina,⁶³ D. Denisov,⁴⁵ S. P. Denisov,³⁴ S. Desai,⁴⁵ C. Deterre,^{41,c} K. DeVaughan,⁵⁹ H. T. Diehl,⁴⁵ M. Diesburg,⁴⁵ P. F. Ding,⁴¹ A. Dominguez,⁵⁹ A. Dubey,²⁴ L. V. Dudko,³³ A. Duperrin,¹² S. Dutt,²³ M. Eads,⁴⁷ D. Edmunds,⁵⁷ J. Ellison,⁴³ V. D. Elvira,⁴⁵ Y. Enari,¹⁴ H. Evans,⁴⁹ A. Evdokimov,⁴⁶ V. N. Evdokimov,³⁴ A. Fauré,¹⁵ L. Feng,⁴⁷ T. Ferbel,⁶³ F. Fiedler,²¹ F. Filthaut,^{29,30} W. Fisher,⁵⁷ H. E. Fisk,⁴⁵ M. Fortner,⁴⁷ H. Fox,³⁹ J. Franc,⁷ S. Fuess,⁴⁵ P. H. Garbincius,⁴⁵ A. Garcia-Bellido,⁶³ J. A. García-González,²⁸ V. Gavrilov,³² W. Geng,^{12,57} C. E. Gerber,⁴⁶ Y. Gershtein,⁶⁰ G. Ginther,⁴⁵ O. Gogota,³⁸ G. Golovanov,³¹ P. D. Grannis,⁶⁴ S. Greder,¹⁶ H. Greenlee,⁴⁵ G. Grenier,¹⁷ Ph. Gris,¹⁰ J.-F. Grivaz,¹³ A. Grohsjean,^{15,c} S. Grünendahl,⁴⁵ M. W. Grünewald,²⁶ T. Guillemain,¹³ G. Gutierrez,⁴⁵ P. Gutierrez,⁶⁷ J. Haley,⁶⁸ L. Han,⁴ K. Harder,⁴¹ A. Harel,⁶³ J. M. Hauptman,⁵² J. Hays,⁴⁰ T. Head,⁴¹ T. Hebbeker,¹⁸ D. Hedin,⁴⁷ H. Hegab,⁶⁸ A. P. Heinson,⁴³ U. Heintz,⁷⁰ C. Hensel,¹ I. Heredia-De La Cruz,^{28,d} K. Herner,⁴⁵ G. Hesketh,^{41,f} M. D. Hildreth,⁵¹ R. Hirosky,⁷⁴ T. Hoang,⁴⁴ J. D. Hobbs,⁶⁴ B. Hoeneisen,⁹ J. Hogan,⁷³ M. Hohlfeld,²¹ J. L. Holzbauer,⁵⁸ I. Howley,⁷¹ Z. Hubacek,^{71,5} V. Hynek,⁷ I. Iashvili,⁶² Y. Ilchenko,⁷² R. Illingworth,⁴⁵ A. S. Ito,⁴⁵ S. Jabeen,^{45,m} M. Jaffré,¹³ A. Jayasinghe,⁶⁷ M. S. Jeong,²⁷ R. Jesik,⁴⁰ P. Jiang,⁴ K. Johns,⁴² E. Johnson,⁵⁷ M. Johnson,⁴⁵ A. Jonckheere,⁴⁵ P. Jonsson,⁴⁰ J. Joshi,⁴³ A. W. Jung,^{45,o} A. Juste,³⁶ E. Kajfasz,¹² D. Karmanov,³³ I. Katsanos,⁵⁹ M. Kaur,²³ R. Kehoe,⁷² S. Kermiche,¹² N. Khalatyan,⁴⁵ A. Khanov,⁶⁸ A. Kharchilava,⁶² Y. N. Kharzhev,³¹ I. Kiselevich,³² J. M. Kohli,²³ A. V. Kozelov,³⁴ J. Kraus,⁵⁸ A. Kumar,⁶² A. Kupco,⁸ T. Kurča,¹⁷ V. A. Kuzmin,³³ S. Lammers,⁴⁹ P. Lebrun,¹⁷ H. S. Lee,²⁷ S. W. Lee,⁵² W. M. Lee,⁴⁵ X. Lei,⁴² J. Lellouch,¹⁴ D. Li,¹⁴ H. Li,⁷⁴ L. Li,⁴³ Q. Z. Li,⁴⁵ J. K. Lim,²⁷ D. Lincoln,⁴⁵ J. Linnemann,⁵⁷ V. V. Lipaev,³⁴ R. Lipton,⁴⁵ H. Liu,⁷² Y. Liu,⁴ A. Lobodenko,³⁵ M. Lokajicek,⁸ R. Lopes de Sa,⁴⁵ R. Luna-Garcia,^{28,g} A. L. Lyon,⁴⁵ A. K. A. Maciel,¹ R. Madar,¹⁹ R. Magaña-Villalba,²⁸ S. Malik,⁵⁹ V. L. Malyshev,³¹ J. Mansour,²⁰ J. Martínez-Ortega,²⁸ R. McCarthy,⁶⁴ C. L. McGivern,⁴¹ M. M. Meijer,^{29,30} A. Melnitchouk,⁴⁵ D. Menezes,⁴⁷ P. G. Mercadante,³ M. Merkin,³³ A. Meyer,¹⁸ J. Meyer,^{20,i} F. Miconi,¹⁶ N. K. Mondal,²⁵ M. Mulhearn,⁷⁴ E. Nagy,¹² M. Narain,⁷⁰ R. Nayyar,⁴² H. A. Neal,⁵⁶ J. P. Negret,⁵ P. Neustroev,³⁵ H. T. Nguyen,⁷⁴ T. Nunnemann,²² J. Orduna,⁷³ N. Osman,¹² J. Osta,⁵¹ A. Pal,⁷¹ N. Parashar,⁵⁰ V. Parihar,⁷⁰ S. K. Park,²⁷ R. Partridge,^{70,e} N. Parua,⁴⁹ A. Patwa,^{65,j} B. Penning,⁴⁰ M. Perfilov,³³ Y. Peters,⁴¹ K. Petridis,⁴¹ G. Petrillo,⁶³ P. Pétroff,¹³ M.-A. Pleier,⁶⁵ V. M. Podstavkov,⁴⁵ A. V. Popov,³⁴ M. Prewitt,⁷³ D. Price,⁴¹ N. Prokopenko,³⁴ J. Qian,⁵⁶ A. Quadt,²⁰ B. Quinn,⁵⁸ P. N. Ratoff,³⁹ I. Razumov,³⁴ I. Ripp-Baudot,¹⁶ F. Rizatdinova,⁶⁸ M. Rominsky,⁴⁵ A. Ross,³⁹ C. Royon,⁸ P. Rubinov,⁴⁵ R. Ruchti,⁵¹ G. Sajot,¹¹ A. Sánchez-Hernández,²⁸ M. P. Sanders,²² A. S. Santos,^{1,h} G. Savage,⁴⁵ M. Savitskiy,³⁸ L. Sawyer,⁵⁴ T. Scanlon,⁴⁰ R. D. Schamberger,⁶⁴ Y. Scheglov,³⁵ H. Schellman,^{69,48} M. Schott,²¹ C. Schwanenberger,⁴¹ R. Schwienhorst,⁵⁷ J. Sekaric,⁵³ H. Severini,⁶⁷ E. Shabalina,²⁰ V. Shary,¹⁵ S. Shaw,⁴¹ A. A. Shchukin,³⁴ V. Simak,⁷ P. Skubic,⁶⁷ P. Slattery,⁶³ D. Smirnov,⁵¹ G. R. Snow,⁵⁹ J. Snow,⁶⁶ S. Snyder,⁶⁵ S. Söldner-Rembold,⁴¹ L. Sonnenschein,¹⁸ K. Soustruznik,⁶ J. Stark,¹¹ D. A. Stoyanova,³⁴ M. Strauss,⁶⁷ L. Suter,⁴¹ P. Svoisky,⁶⁷ M. Titov,¹⁵ V. V. Tokmenin,³¹ Y.-T. Tsai,⁶³ D. Tsybychev,⁶⁴ B. Tuchming,¹⁵ C. Tully,⁶¹ L. Uvarov,³⁵ S. Uvarov,³⁵ S. Uzunyan,⁴⁷ R. Van Kooten,⁴⁹ W. M. van Leeuwen,²⁹ N. Varelas,⁴⁶ E. W. Varnes,⁴² I. A. Vasilyev,³⁴ A. Y. Verkheev,³¹ L. S. Vertogradov,³¹ M. Verzocchi,⁴⁵ M. Vesterinen,⁴¹ D. Vilanova,¹⁵ P. Vokac,⁷ H. D. Wahl,⁴⁴ M. H. L. S. Wang,⁴⁵ J. Warchol,⁵¹ G. Watts,⁷⁵ M. Wayne,⁵¹ J. Weichert,²¹ L. Welty-Rieger,⁴⁸ M. R. J. Williams,^{49,n} G. W. Wilson,⁵³ M. Wobisch,⁵⁴ D. R. Wood,⁵⁵ T. R. Wyatt,⁴¹ Y. Xie,⁴⁵ R. Yamada,⁴⁵ S. Yang,⁴ T. Yasuda,⁴⁵ Y. A. Yatsunenko,³¹ W. Ye,⁶⁴ Z. Ye,⁴⁵ H. Yin,⁴⁵ K. Yip,⁶⁵ S. W. Youn,⁴⁵ J. M. Yu,⁵⁶ J. Zennaro,⁶² T. G. Zhao,⁴¹ B. Zhou,⁵⁶ J. Zhu,⁵⁶ M. Zielinski,⁶³ D. Zieminska,⁴⁹ and L. Zivkovic¹⁴

(D0 Collaboration)

- ¹LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
²Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
³Universidade Federal do ABC, Santo André, Brazil
⁴University of Science and Technology of China, Hefei, People's Republic of China
⁵Universidad de los Andes, Bogotá, Colombia
⁶Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
⁷Czech Technical University in Prague, Prague, Czech Republic
⁸Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
⁹Universidad San Francisco de Quito, Quito, Ecuador
¹⁰LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
¹¹LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
¹²CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
¹³LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
¹⁴LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
¹⁵CEA, Irfu, SPP, Saclay, France
¹⁶IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
¹⁷IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
¹⁸III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
¹⁹Physikalisches Institut, Universität Freiburg, Freiburg, Germany
²⁰II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
²¹Institut für Physik, Universität Mainz, Mainz, Germany
²²Ludwig-Maximilians-Universität München, München, Germany
²³Panjab University, Chandigarh, India
²⁴Delhi University, Delhi, India
²⁵Tata Institute of Fundamental Research, Mumbai, India
²⁶University College Dublin, Dublin, Ireland
²⁷Korea Detector Laboratory, Korea University, Seoul, Korea
²⁸CINVESTAV, Mexico City, Mexico
²⁹Nikhef, Science Park, Amsterdam, The Netherlands
³⁰Radboud University Nijmegen, Nijmegen, The Netherlands
³¹Joint Institute for Nuclear Research, Dubna, Russia
³²Institute for Theoretical and Experimental Physics, Moscow, Russia
³³Moscow State University, Moscow, Russia
³⁴Institute for High Energy Physics, Protvino, Russia
³⁵Petersburg Nuclear Physics Institute, St. Petersburg, Russia
³⁶Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain
³⁷Uppsala University, Uppsala, Sweden
³⁸Taras Shevchenko National University of Kyiv, Kiev, Ukraine
³⁹Lancaster University, Lancaster LA1 4YB, United Kingdom
⁴⁰Imperial College London, London SW7 2AZ, United Kingdom
⁴¹The University of Manchester, Manchester M13 9PL, United Kingdom
⁴²University of Arizona, Tucson, Arizona 85721, USA
⁴³University of California Riverside, Riverside, California 92521, USA
⁴⁴Florida State University, Tallahassee, Florida 32306, USA
⁴⁵Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
⁴⁶University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁴⁷Northern Illinois University, DeKalb, Illinois 60115, USA
⁴⁸Northwestern University, Evanston, Illinois 60208, USA
⁴⁹Indiana University, Bloomington, Indiana 47405, USA
⁵⁰Purdue University Calumet, Hammond, Indiana 46323, USA
⁵¹University of Notre Dame, Notre Dame, Indiana 46556, USA
⁵²Iowa State University, Ames, Iowa 50011, USA
⁵³University of Kansas, Lawrence, Kansas 66045, USA
⁵⁴Louisiana Tech University, Ruston, Louisiana 71272, USA
⁵⁵Northeastern University, Boston, Massachusetts 02115, USA
⁵⁶University of Michigan, Ann Arbor, Michigan 48109, USA
⁵⁷Michigan State University, East Lansing, Michigan 48824, USA
⁵⁸University of Mississippi, University, Mississippi 38677, USA
⁵⁹University of Nebraska, Lincoln, Nebraska 68588, USA
⁶⁰Rutgers University, Piscataway, New Jersey 08855, USA

- ⁶¹Princeton University, Princeton, New Jersey 08544, USA
⁶²State University of New York, Buffalo, New York 14260, USA
⁶³University of Rochester, Rochester, New York 14627, USA
⁶⁴State University of New York, Stony Brook, New York 11794, USA
⁶⁵Brookhaven National Laboratory, Upton, New York 11973, USA
⁶⁶Langston University, Langston, Oklahoma 73050, USA
⁶⁷University of Oklahoma, Norman, Oklahoma 73019, USA
⁶⁸Oklahoma State University, Stillwater, Oklahoma 74078, USA
⁶⁹Oregon State University, Corvallis, Oregon 97331, USA
⁷⁰Brown University, Providence, Rhode Island 02912, USA
⁷¹University of Texas, Arlington, Texas 76019, USA
⁷²Southern Methodist University, Dallas, Texas 75275, USA
⁷³Rice University, Houston, Texas 77005, USA
⁷⁴University of Virginia, Charlottesville, Virginia 22904, USA
⁷⁵University of Washington, Seattle, Washington 98195, USA
(Received 9 November 2015; published 25 February 2016)

We report evidence for the simultaneous production of J/ψ and Υ mesons in 8.1 fb^{-1} of data collected at $\sqrt{s} = 1.96 \text{ TeV}$ by the D0 experiment at the Fermilab $p\bar{p}$ Tevatron Collider. Events with these characteristics are expected to be produced predominantly by gluon-gluon interactions. In this analysis, we extract the effective cross section characterizing the initial parton spatial distribution, $\sigma_{\text{eff}} = 2.2 \pm 0.7(\text{stat}) \pm 0.9(\text{syst}) \text{ mb}$.

DOI: [10.1103/PhysRevLett.116.082002](https://doi.org/10.1103/PhysRevLett.116.082002)

The importance of multiple parton interactions (MPI) in hadron-hadron collisions as a background to processes such as Higgs production or various new phenomena has been often underestimated in the past. For instance, in the associated production of Higgs and weak bosons, where the Higgs boson decays into $b\bar{b}$, the MPI background, in which one interaction produces the vector boson and another produces a pair of jets, may exceed the size of the Higgs signal even after the application of strict event selections [1]. Recent data [2–9] examining various double parton interactions have attracted considerable theoretical attention [1,10–14].

In this Letter, we measure for the first time the cross section for simultaneous production of J/ψ and Υ ($1S, 2S, 3S$) mesons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. The production of two quarkonium states can be used to probe the interplay of perturbative and nonperturbative phenomena in quantum chromodynamics (QCD) and to search for new bound states of hadronic matter such as tetraquarks [10,15]. Here we focus on double quarkonium production as a measure of the spatial distribution of partons in the nucleon.

Unlike other quarkonium processes such as double J/ψ production, or processes involving jets or vector bosons, the production of J/ψ and Υ mesons is expected to be dominated by double parton (DP) interactions involving the

collisions of two independent pairs of partons within the colliding beam particles. The simultaneous production through single parton (SP) interactions is suppressed by additional powers of α_s and by the small size of the allowed color octet matrix elements [11]. The DP process is estimated in Ref. [13] to give the dominant contribution to the total $J/\psi + \Upsilon$ production at the Tevatron. In this analysis, we assume that there is no SP contribution [16]. Because of the dominance of gg interactions in producing heavy quarkonium states, the spatial distribution of gluons in a proton [17–19] is directly probed by the DP scattering rate, which represents simultaneous, independent parton interactions. In contrast, the DP studies involving vector bosons and jets probe the spatial distributions of quark-quark or quark-gluon initial states [2–6].

In $p\bar{p}$ collisions, there are three main production mechanisms for J/ψ mesons: prompt production; as a radiative decay product of promptly produced heavier charmonium states such as the 3P_1 state χ_{1c} and the 3P_2 state χ_{2c} ; and nonprompt B hadron decays. A particle is considered produced promptly if it originates in the initial $p\bar{p}$ interaction or if it originates in either an electromagnetic or strong force mediated decay and thus the tracks appear to be produced at the $p\bar{p}$ interaction vertex. Υ mesons are only produced promptly, either directly or as decay products of higher mass states, such as χ_{1b} or χ_{2b} . Prompt heavy quarkonium production is described by three types of models: the color-singlet (CS) model [20]; the color evaporation model [21,22] with a subsequent soft color interaction model [23]; and the color-octet (CO) model [24,25].

In this Letter, we present the first measurement of the cross section of the simultaneous production of prompt

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

J/ψ and Υ mesons, as well as a measurement of the single prompt J/ψ production cross section. The Υ cross section was measured previously by D0 [26]. The measurements are based on a data sample collected by the D0 experiment at the Tevatron corresponding to an integrated luminosity of $8.1 \pm 0.5 \text{ fb}^{-1}$ [27]. Assuming that the simultaneous production of J/ψ and Υ mesons is caused solely by DP scattering, we extract the effective cross section (σ_{eff}), a parameter related to an initial state parton spatial density distribution within a nucleon (see, e.g., Ref. [19]):

$$\sigma_{\text{eff}}^{-1} = \int d^2\beta [F(\beta)]^2 \quad (1)$$

with $F(\beta) = \int f(\mathbf{b})f(\mathbf{b}-\beta)d^2b$, where β is the vector impact parameter of the two colliding hadrons, and $f(\mathbf{b})$ is a function describing the transverse spatial distribution of the partonic matter inside a hadron. The $f(\mathbf{b})$ may depend on the parton flavor.

The cross section for double parton scattering, σ_{DP} , is related to σ_{eff} for the production of J/ψ and Υ mesons:

$$\sigma_{\text{eff}} = \frac{\sigma(J/\psi)\sigma(\Upsilon)}{\sigma_{\text{DP}}(J/\psi + \Upsilon)}. \quad (2)$$

Both the J/ψ and Υ mesons are fully reconstructed via their decay $J/\psi(\Upsilon) \rightarrow \mu^+\mu^-$, where the muons are required to have transverse momenta $p_T^\mu > 2 \text{ GeV}/c$ and pseudorapidity $|\eta^\mu| < 2.0$ [28]. The cross sections measured with these kinematic requirements are referred to below as “fiducial cross sections.”

The general purpose D0 detector is described in detail elsewhere [29,30]. The two subdetectors used to trigger and reconstruct muon final states are the muon and the central tracking systems. The central tracking system, used to reconstruct charged particle tracks, consists of the inner silicon microstrip tracker (SMT) [31] and outer central fiber tracker (CFT) detector both placed inside a 1.9 T solenoidal magnet. The solenoidal magnet is located inside the central calorimeter. The muon detectors [32] surrounding the calorimeters consist of three layers of drift tubes and three layers of scintillation counters, one inside the 1.8 T iron toroidal magnets and two outside. The luminosity is measured using plastic scintillation counters surrounding the beams at small polar angles [27].

We require events to pass at least one of a set of low- p_T dimuon triggers. The identification of muons starts with requiring hits at least in the muon detector layer in front of the toroids [33] and proceeds by matching the hits in the muon system to a charged particle track reconstructed by the central tracking system. The track is required to have at least one hit in the SMT and at least two hits in the CFT detectors. To suppress cosmic rays, the muon candidates must satisfy strict timing requirements. Their distance of the closest approach to the beam line has to be less than

0.5 cm and their matching tracks have to pass within 2 cm of the primary $p\bar{p}$ interaction vertex along the beam axis. We require two oppositely charged muons, isolated in the calorimeter and tracking detectors [33], with good matching of the tracks in the inner tracking and those in the muon detector, and masses within the ranges $2.4 < M_{\mu\mu} < 4.2 \text{ GeV}$ or $8 < M_{\mu\mu} < 12 \text{ GeV}$ for the J/ψ and Υ candidates, respectively. The mass windows are chosen to be large enough to provide an estimate of backgrounds on either side of the J/ψ or Υ mass peaks. Events that have a pair of such muons in each of the two invariant mass windows are identified as J/ψ and Υ simultaneous production candidates. Background events are mainly due to random combinations of muons from π^\pm , K^\pm decays (decay background), continuous nonresonant $\mu^+\mu^-$ Drell-Yan (DY) production, and B hadron decays into $J/\psi + X$. In the case of $J/\psi + \Upsilon$ production, there is also a background where one muon pair results from a genuine J/ψ or Υ decay and the other pair is a nonresonant combination of muons [$J/\psi(\Upsilon) + \mu\mu$].

In our single quarkonium sample, the backgrounds from π^\pm , K^\pm decays and DY events are estimated simultaneously with the number of signal events by performing a fit to the $M_{\mu\mu}$ invariant mass distribution using a superposition of Gaussian functions for signal and a quadratic function for the background. The $\psi(2S)$ events are included in the fitted region but omitted for the single J/ψ cross section calculation, while all three Υ mass states (1S, 2S, 3S) are included in the Υ cross section calculation. The number of single J/ψ events found in the fit is 6.9×10^6 , while the number of single Υ events is 2.1×10^6 .

The single J/ψ trigger efficiency is estimated using events with a reconstructed J/ψ which pass zero-bias (ZB) triggers requiring only a beam crossing, or minimum bias (MB) triggers which only require hits in the luminosity detectors, and that do or do not satisfy the dimuon trigger requirement. To estimate the trigger efficiency for the Υ selection, we use the $\Upsilon(1S)$ cross section previously measured by the D0 experiment [26], extrapolated to our fiducial region using events generated with the PYTHIA [34] Monte Carlo (MC) event generator and increased to include the $\Upsilon(2S, 3S)$ contributions. Using PYTHIA for the extrapolation introduces a negligible bias because the fiducial regions are similar and the D0 muon system acceptance outside both fiducial regions is low. The trigger efficiencies for single J/ψ mesons and for single Υ mesons in the fiducial region are $0.13 \pm 0.03(\text{syst})$ and $0.29 \pm 0.05(\text{syst})$, respectively, where the systematic uncertainties are dominated by the small size of the ZB and MB samples. The trigger efficiency for the $J/\psi + \Upsilon$ selection is estimated using the single J/ψ and Υ trigger efficiencies and MC samples of $J/\psi + \Upsilon$ events generated with the PYTHIA MC generator. The events are passed through a GEANT based [35] simulation of the D0 detector and overlaid with data ZB events to mimic event pileup,

and processed with the same reconstruction software as data. We calculate the trigger efficiency for every possible pairing of muons in DP $J/\psi + \Upsilon$ MC events using the parametrizations of the dimuon trigger efficiencies as a function of $p_T^{J/\psi}$ and p_T^Υ and obtain an efficiency of $0.77 \pm 0.04(\text{syst})$. The substantial increase in the trigger efficiency is due to the presence of four muons in the $J/\psi + \Upsilon$ events.

We use PYTHIA-generated single J/ψ and Υ events to estimate the combined geometric and kinematic acceptance and reconstruction efficiency. The generated and reconstructed events are selected using the same muon selection criteria. We correct the number of simulated reconstructed events for the different reconstruction efficiencies in data and MC events, calculated in (p_T^μ, η^μ) bins. The product of the acceptance and efficiency for single J/ψ events produced in the color singlet model is $0.19 \pm 0.01(\text{syst})$. The product of the acceptance and efficiency for single Υ events is $0.43 \pm 0.05(\text{syst})$. The systematic uncertainties are due to muon identification efficiency mismodeling and to the differences in the kinematic distributions between the data and simulated J/ψ or Υ events. The $\cos\theta^*$ distribution, where θ^* is the polar angle of the decay muon in the Collins-Soper frame [36], is sensitive to the J/ψ and Υ polarizations [37–41]. Data-to-MC reweighting factors based on the observed $\cos\theta^*$ distribution are used to recalculate the acceptance, and lead to $\lesssim 1\%$ difference with the default acceptance value for single J/ψ events and $\approx 11\%$ for single Υ events, which we take as systematic uncertainties.

The vertex of a B hadron decay into the $J/\psi + X$ final state is on average several hundred microns away from the $p\bar{p}$ interaction vertex, while prompt J/ψ production occurs directly at the interaction point. To identify promptly produced J/ψ mesons, we examine the decay length from the primary $p\bar{p}$ interaction vertex (in the plane transverse to the beam) to the J/ψ production vertex, defined as $c\tau = L_{xy} m_{J/\psi} / p_T^{J/\psi}$, where L_{xy} is calculated as the distance between the intersection of the muon tracks and the $p\bar{p}$ interaction vertex, $m_{J/\psi}$ is the world average J/ψ mass [42], and $p_T^{J/\psi}$ is the J/ψ transverse momentum.

The fraction of prompt J/ψ mesons in the data sample is estimated by performing a maximum likelihood fit of the $c\tau$ distribution. The fit uses templates for the prompt J/ψ signal events, taken from the single J/ψ MC sample, and for nonprompt J/ψ events, taken from the $b\bar{b}$ MC sample. Both are generated with PYTHIA. The prompt J/ψ fraction obtained from the fit is $0.83 \pm 0.03(\text{syst})$. The systematic uncertainty is dominated by the uncertainty in the MC modeling of the $c\tau$. The fit result is shown in Fig. 1. By applying the selection $c\tau < 0.02 (> 0.03)$ cm, we verify that the $p_T^{J/\psi}$ spectra of the prompt (nonprompt) J/ψ events in data are well described by MC simulations in the prompt (B -decay) dominated regions.

The fiducial cross section of the prompt single J/ψ production is calculated using the number of J/ψ

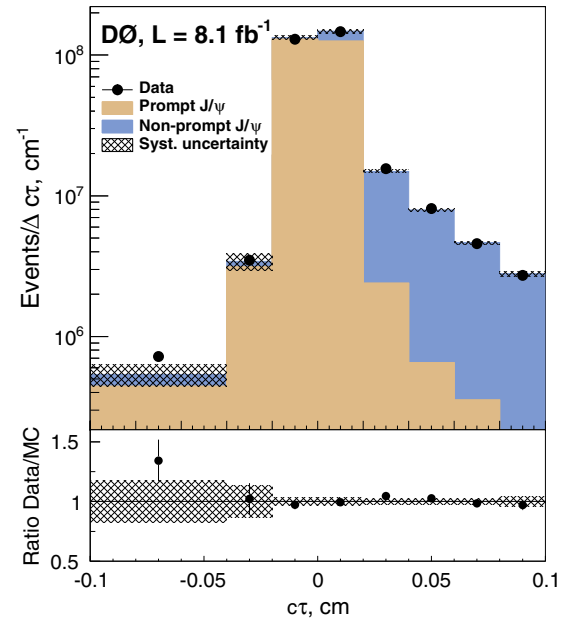


FIG. 1. The $c\tau$ distribution of background subtracted single J/ψ events after all selection criteria. The distributions for the signal and background templates are shown normalized to their respective fitted fractions with $\chi^2/\text{Ndof} = 1.6$, $\text{Ndof} = 6$. The shaded uncertainty band corresponds to the total systematic uncertainty on the sum of signal and background events.

candidates in data, the fraction of prompt J/ψ events, the trigger efficiency, the acceptance and selection efficiencies, as well as the integrated luminosity. The fiducial cross section is

$$\sigma(J/\psi) = 28 \pm 7(\text{syst}) \text{ nb.} \quad (3)$$

The systematic uncertainty in the single J/ψ cross section mainly arises from the trigger efficiency. The statistical uncertainty is negligible. The measured single J/ψ cross section is in agreement with the measurement by D0 [7] [$23.9 \pm 4.6(\text{stat}) \pm 3.7(\text{syst}) \text{ nb}$] in a similar fiducial region and with the measurement by CDF [43] if an interpolation to the CDF fiducial region is performed.

The cross section for single Υ production is extrapolated to our fiducial region from the previous D0 measurement [26]. Using the ratio of $\Upsilon(1S)$ to Υ (sum of $1S, 2S, 3S$ states) of $0.73 \pm 0.03(\text{syst})$, estimated in Υ selection data, we obtain the Υ cross section (the statistical uncertainty is negligible):

$$\sigma(\Upsilon) = 2.1 \pm 0.3(\text{syst}) \text{ nb.} \quad (4)$$

The systematic uncertainty in $\sigma(\Upsilon)$ includes that from Ref. [26] as well as those from the $\Upsilon(1S)$ fraction and the extrapolation to the fiducial region.

In the data, 21 events pass the selection criteria for $J/\psi + \Upsilon$ pair production in the J/ψ mass window $2.88 < M_{\mu\mu} < 3.36 \text{ GeV}/c^2$ and Υ mass window $9.1 < M_{\mu\mu} < 10.2 \text{ GeV}/c^2$. Figure 2 shows the distribution of the two

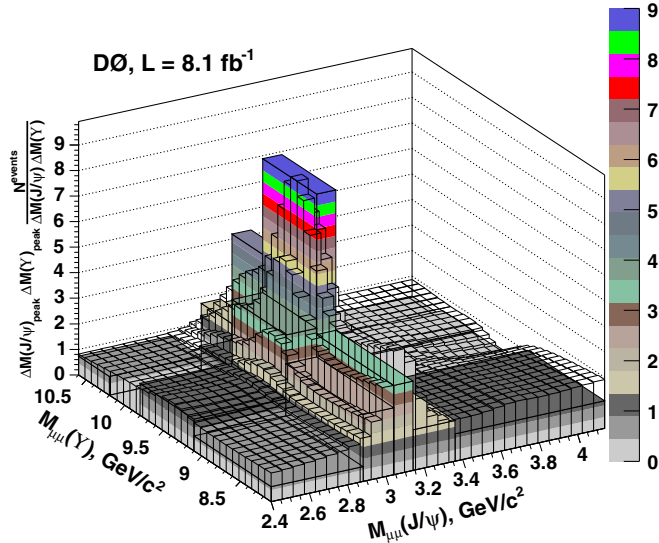


FIG. 2. Dimuon invariant mass distribution in data for two muon pairs, $M_{\mu\mu}(J/\psi)$, $M_{\mu\mu}(\Upsilon)$, divided by the bin area, after the selection criteria. Also shown is the two-dimensional fit surface. The factor $\Delta M(J/\psi)_{\text{peak}} \Delta M(\Upsilon)_{\text{peak}}$ is applied so that the height of the peak bin is the number of observed events in that bin.

dimuon masses [$M_{\mu\mu}(J/\psi, \Upsilon)$] in these and surrounding mass regions. We estimate the accidental and $J/\psi(\Upsilon) + \mu\mu$ backgrounds using the same technique of combining the one-dimensional functional forms utilized in single J/ψ and Υ signal and background parametrizations as in Ref. [7]. We fit a two-dimensional distribution of the $M_{\mu\mu}(J/\psi, \Upsilon)$ with the resulting two-dimensional functional form and estimate the number of $J/\psi + \Upsilon$ events is $14.5 \pm 4.6(\text{stat}) \pm 3.4(\text{syst})$. This corresponds to a prompt $J/\psi + \Upsilon$ signal of $12.0 \pm 3.8(\text{stat}) \pm 2.8(\text{syst})$ events. The probability of the observed number of events to have arisen from the background is 6.3×10^{-4} , corresponding to 3.2 standard deviation evidence for the production of prompt $J/\psi + \Upsilon$. The probability calculation includes the systematic uncertainties in the background estimates. The distribution of the azimuthal angle between the J/ψ and Υ candidates $\Delta\phi(J/\psi, \Upsilon)$ after the subtraction of backgrounds is shown in Fig. 3. The data distribution is consistent with the DP MC model, which is uniform [11], substantiating our assumption that the DP process is the dominant contribution to the selected $J/\psi + \Upsilon$ data sample.

We estimate the acceptance, reconstruction, and selection efficiencies for $J/\psi + \Upsilon$ events using MC DP samples. The product of the acceptance and the selection efficiency for the DP events is found to be $(A\epsilon_s) = 0.071 \pm 0.007(\text{syst})$, where the systematic uncertainty is dominated by the uncertainty in the modeling of the J/ψ and Υ kinematics and muon identification efficiency for our sample with low p_T muons.

Using the numbers presented above, we obtain the cross section of the simultaneous production of J/ψ and Υ mesons:

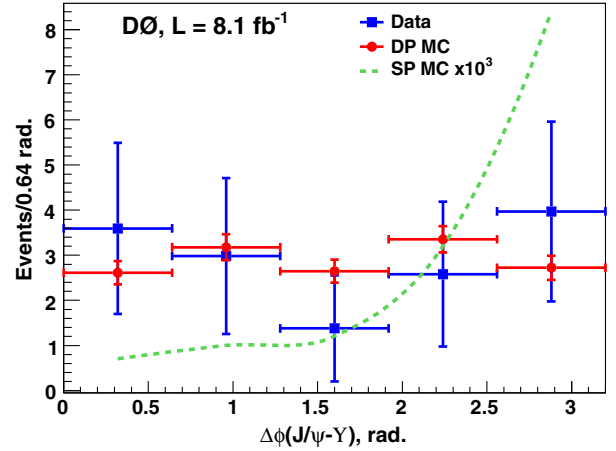


FIG. 3. The distribution of the azimuthal angle between the J/ψ and Υ candidates, $\Delta\phi(J/\psi, \Upsilon)$, in data after background subtraction, in DP MC [34], and SP MC [44] results. MC events are in arbitrary units.

$$\sigma_{\text{DP}}(J/\psi + \Upsilon) = 27 \pm 9(\text{stat}) \pm 7(\text{syst}) \text{ fb.} \quad (5)$$

From the measured cross sections of prompt single J/ψ , DP $J/\psi + \Upsilon$, and the estimate of the single Υ cross section, we calculate the effective cross section, σ_{eff} . The main sources of systematic uncertainty in the σ_{eff} measurement are the estimates of the trigger efficiency and combinatorial background. Based on Eq. (2) and upon the assumption [16] that $J/\psi + \Upsilon$ production has a negligible SP contribution, we obtain

$$\sigma_{\text{eff}} = 2.2 \pm 0.7(\text{stat}) \pm 0.9(\text{syst}) \text{ mb.} \quad (6)$$

The measured σ_{eff} agrees with the result reported by the AFS Collaboration in the 4-jet final state [45] (≈ 5 mb) and D0 in the double J/ψ final state [7] [$4.8 \pm 0.5(\text{stat}) \pm 2.5(\text{syst})$ mb]. However, it is lower than the CDF results in the 4-jet final state [46] [$12.1^{+10.7}_{-5.4}$ mb] and $\gamma/\pi^0 + 3$ -jet final state [2] [$14.5 \pm 1.7(\text{stat})^{+1.7}_{-2.3}$ (syst) mb]; the D0 [4] result in $\gamma + 3$ -jet events [4] [$12.7 \pm 0.2(\text{stat}) \pm 1.3(\text{syst})$ mb]; both ATLAS [3] [$15 \pm 3(\text{stat})^{+5}_{-3}$ (syst) mb] and CMS [5] [$20.7 \pm 0.8(\text{stat}) \pm 6.6(\text{syst})$ mb] results in the $W + 2$ -jet final state; and the LHCb [47] [$18.0 \pm 1.3(\text{stat}) \pm 1.2(\text{syst})$ mb] result in $\Upsilon +$ open charm events. The DP $J/\psi + \Upsilon$, double J/ψ , and 4-jet production are dominated by gg initial states, whereas the $\gamma(W) +$ jets events are produced predominantly by $q\bar{q}'$, and qg processes. The values of σ_{eff} measured in different final state channels indicate that gluons occupy a smaller region of space within the proton than quarks. The pion cloud model [48] predicts a smaller average transverse size of the gluon distribution in a nucleon than that for quarks.

In conclusion, we have presented the first evidence of simultaneous production of prompt J/ψ and Υ ($1S, 2S, 3S$) mesons with a significance of 3.2 standard deviations. The process is expected to be dominated by double parton

scattering. The distribution of the azimuthal angle between the J/ψ and Y candidates is consistent with the double parton scattering predictions. Under the assumption of it being entirely composed of double parton scattering, in the fiducial region of $p_T^H > 2$ GeV and $|\eta^H| < 2$ we measure the cross section $\sigma_{\text{DP}}(J/\psi + Y) = 27 \pm 9(\text{stat}) \pm 7(\text{syst})$ fb. We also measure the single J/ψ and estimate the single Y ($1S, 2S, 3S$) production cross sections in the same fiducial region as the $J/\psi + Y$ cross section and find the effective cross section for this gg dominated process to be $\sigma_{\text{eff}} = 2.2 \pm 0.7(\text{stat}) \pm 0.9(\text{syst})$ mb, lower than the values found in the $q\bar{q}$ and qg dominated double parton processes. This suggests that the spatial region occupied by gluons within the proton is smaller than that occupied by quarks.

We thank S.P. Baranov for useful discussions and providing us with the SP MC results. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (United States of America); Alternative Energies and Atomic Energy Commission and National Center for Scientific Research/National Institute of Nuclear and Particle Physics (France); Ministry of Education and Science of the Russian Federation, National Research Center “Kurchatov Institute” of the Russian Federation, and Russian Foundation for Basic Research (Russia); National Council for the Development of Science and Technology and Carlos Chagas Filho Foundation for the Support of Research in the State of Rio de Janeiro (Brazil); Department of Atomic Energy and Department of Science and Technology (India); Administrative Department of Science, Technology and Innovation (Colombia); National Council of Science and Technology (Mexico); National Research Foundation of Korea (Korea); Foundation for Fundamental Research on Matter (Netherlands); Science and Technology Facilities Council and The Royal Society (United Kingdom); Ministry of Education, Youth and Sports (Czech Republic); Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research) and Deutsche Forschungsgemeinschaft (German Research Foundation) (Germany); Science Foundation Ireland (Ireland); Swedish Research Council (Sweden); China Academy of Sciences and National Natural Science Foundation of China (China); and Ministry of Education and Science of Ukraine (Ukraine).

^aVisitor from Augustana College, Sioux Falls, SD, USA.

^bVisitor from The University of Liverpool, Liverpool, UK.

^cVisitor from DESY, Hamburg, Germany.

^dVisitor from CONACyT, Mexico City, Mexico.

^eVisitor from SLAC, Menlo Park, CA, USA.

^fVisitor from University College London, London, UK.

^gVisitor from Centro de Investigacion en Computacion—IPN, Mexico City, Mexico.

^hVisitor from Universidade Estadual Paulista, São Paulo, Brazil.

ⁱVisitor from Karlsruhe Institut für Technologie (KIT)—Steinbuch Centre for Computing (SCC), D-76128 Karlsruhe, Germany.

^jVisitor from Office of Science, U.S. Department of Energy, Washington, D.C. 20585, USA.

^kVisitor from American Association for the Advancement of Science, Washington, D.C. 20005, USA.

^lVisitor from Kiev Institute for Nuclear Research, Kiev, Ukraine.

^mVisitor from University of Maryland, College Park, MD 20742, USA.

ⁿVisitor from European Organization for Nuclear Research (CERN), Geneva, Switzerland.

^oVisitor from Purdue University, West Lafayette, IN 47907, USA.

- [1] D. Bandurin, G. Golovanov, and N. Skachkov, Double parton interactions as a background to associated HW production at the Tevatron, *J. High Energy Phys.* **04** (2011) 054.
- [2] F. Abe *et al.* (CDF Collaboration), Double parton scattering in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. D* **56**, 3811 (1997).
- [3] G. Aad *et al.* (ATLAS Collaboration), Measurement of hard double-parton interactions in $W(\rightarrow l\nu) + 2$ -jet events at $\sqrt{s} = 7$ TeV with the ATLAS detector, *New J. Phys.* **15**, 033038 (2013).
- [4] V.M. Abazov *et al.* (D0 Collaboration), Double parton interactions in $\gamma + 3$ jet and $\gamma + b/c$ jet + 2jet events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. D* **89**, 072006 (2014).
- [5] S. Chatrchyan *et al.* (CMS Collaboration), Study of double parton scattering using $W + 2$ -jet events in proton-proton collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **03** (2014) 032.
- [6] G. Aad *et al.* (ATLAS Collaboration), Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Eur. Phys. J. C* **75**, 229 (2015).
- [7] V.M. Abazov *et al.* (D0 Collaboration), Observation and studies of double J/ψ production at the Tevatron, *Phys. Rev. D* **90**, 111101(R) (2014).
- [8] R. Aaij *et al.* (LHCb Collaboration), Observation of J/ψ -pair production in pp collisions at $\sqrt{s} = 7$ TeV, *Phys. Lett. B* **707**, 52 (2012).
- [9] V. Khachatryan *et al.* (CMS Collaboration), Measurement of prompt J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **09** (2014) 094.
- [10] A. V. Berezhnoy, A. K. Likhoded, A. V. Luchinsky, and A. A. Novoselov, Production of J/ψ -meson pairs and $4c$ tetraquark at the LHC, *Phys. Rev. D* **84**, 094023 (2011).
- [11] S.P. Baranov, A.M. Snigirev, and N.P. Zotov, Double heavy meson production through double parton scattering in hadronic collisions, *Phys. Lett. B* **705**, 116 (2011).
- [12] C. Brenner Mariotto and V.P. Goncalves, Double J/ψ production in central diffractive processes at the LHC, *Phys. Rev. D* **91**, 114002 (2015).
- [13] J.-P. Lansberg and H.-S. Shao, Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC), *Nucl. Phys.* **B900**, 273 (2015).

- [14] J.-P. Lansberg and H.-S. Shao, J/ψ -pair production at large momenta: Indications for double parton scatterings and large α_s^2 contributions, *Phys. Lett. B* **751**, 479 (2015).
- [15] B. Humpert and P. Mery, $\psi\psi$ production at collider energies, *Z. Phys. C* **20**, 83 (1983).
- [16] The earlier version of this Letter (arXiv:1511.02428 v1) assumed that the SP contribution was negligible based on an earlier version of Ref. [13], arXiv 1504.06531 v1. The new result in Ref. [13] only gives lower limits on the DP to SP fraction. A fit to the distribution of the difference in azimuthal angle between the J/ψ and Υ shown in Fig. 3 gives the fraction of 0.85 ± 0.28 . The results obtained in this Letter for the inclusive $J/\psi + \Upsilon$ cross section do not change as the fraction changes. A revised value of σ_{eff} obtained from this Letter can be easily recalculated if new theoretical or experimental information becomes available.
- [17] B. Blok, Yu. Dokshitzer, L. Frankfurt, and M. Strikman, The four jet production at LHC and Tevatron in QCD, *Phys. Rev. D* **83**, 071501 (2011).
- [18] M. Vanttinen, P. Hoyer, S. J. Brodsky, and W.-K. Tang, Hadroproduction and polarization of charmonium, *Phys. Rev. D* **51**, 3332 (1995).
- [19] S. P. Baranov, A. M. Snigirev, N. P. Zotov, A. Szczurek, and W. Schäfer, Interparticle correlations in the production of J/ψ pairs in proton-proton collisions, *Phys. Rev. D* **87**, 034035 (2013).
- [20] R. Baier and R. Rückl, Hadronic collisions: A quarkonium factory, *Z. Phys. C* **19**, 251 (1983).
- [21] H. Fritzsch, Producing heavy quark flavors in hadronic collisions a test of quantum chromodynamics, *Phys. Lett. B* **67**, 217 (1977).
- [22] C. B. Mariotto, M. B. Gay Ducati, and G. Ingelman, Soft and hard QCD dynamics in hadroproduction of charmonium, *Eur. Phys. J. C* **23**, 527 (2002), and references therein.
- [23] A. Edin, G. Ingelman, and J. Rathsmann, Quarkonium production at the Fermilab Tevatron through soft color interactions, *Phys. Rev. D* **56**, 7317 (1997).
- [24] P. Cho and A. Leibovich, Color-octet quarkonia production, *Phys. Rev. D* **53**, 150 (1996); **53**, 6203 (1996).
- [25] E. Braaten, S. Fleming, and A. Leibovich, Nonrelativistic QCD analysis of bottomonium production at the Fermilab Tevatron, *Phys. Rev. D* **63**, 094006 (2001), and references therein.
- [26] V. M. Abazov *et al.* (D0 Collaboration), Measurement of Inclusive Differential Cross Sections for $\Upsilon(1S)$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. Lett.* **94**, 232001 (2005).
- [27] T. Andeen *et al.*, Report No. FERMILAB-TM-2365, 2007.
- [28] Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the positive z axis along the proton beam direction, while the azimuthal angle ϕ is defined with respect to the x axis pointing away from the center of the Tevatron ring. The y axis points upward.
- [29] V. M. Abazov *et al.* (D0 Collaboration), The Upgraded D0 Detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **565**, 463 (2006).
- [30] R. Angstadt *et al.*, The Layer 0 Inner Silicon Detector of the D0 Experiment, *Nucl. Instrum. Methods Phys. Res., Sect. A* **622**, 298 (2010).
- [31] S. N. Ahmed *et al.*, The D0 Silicon Microstrip Tracker, *Nucl. Instrum. Methods Phys. Res., Sect. A* **634**, 8 (2011).
- [32] V. M. Abazov *et al.* (D0 Collaboration), The muon system of the Run II DØ detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **552**, 372 (2005).
- [33] V. M. Abazov *et al.* (D0 Collaboration), Muon reconstruction and identification with the Run II D0 detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **737**, 281 (2014).
- [34] T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 Physics and Manual, *J. High Energy Phys.* **05** (2006) 026.
- [35] R. Brun and F. Carminati, CERN Program Library Long Writeup, W5013 (1993), we use GEANT version v3.21.
- [36] J. C. Collins and D. E. Soper, Angular distribution of dileptons in high-energy hadron collisions, *Phys. Rev. D* **16**, 2219 (1977).
- [37] S. P. Baranov, A. V. Lipatov, and N. P. Zotov, Prompt J/ψ production at the LHC: New evidence for the k_T factorization, *Phys. Rev. D* **85**, 014034 (2012).
- [38] A. Abulencia *et al.* (CDF Collaboration), Polarizations of J/ψ and $\psi(2S)$ Mesons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. Lett.* **99**, 132001 (2007).
- [39] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of the prompt J/ψ and $\psi(2S)$ polarizations in pp collisions at $\sqrt{s} = 7$ TeV, *Phys. Lett. B* **727**, 381 (2013).
- [40] T. Aaltonen *et al.* (CDF Collaboration), Measurements of the Angular Distributions of Muons from Υ Decays in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. Lett.* **108**, 151802 (2012).
- [41] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ Polarizations in pp Collisions at $\sqrt{s} = 7$ TeV, *Phys. Rev. Lett.* **110**, 081802 (2013).
- [42] K. A. Olive *et al.*, The Review of Particle Physics, *Chin. Phys. C* **38**, 090001 (2014).
- [43] D. Acosta *et al.* (CDF Collaboration), Measurement of the J/ψ meson and b -hadron production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV, *Phys. Rev. D* **71**, 032001 (2005).
- [44] S. P. Baranov (private communication).
- [45] T. Åkeson *et al.* (AFS Collaboration), Double parton scattering in pp collisions at $\sqrt{s} = 63$ GeV, *Z. Phys. C* **34**, 163 (1987). The AFS collaboration does not report an uncertainty on σ_{eff} but it is expected to be at least 30% given the uncertainty quoted on the measured DP fraction.
- [46] F. Abe *et al.* (CDF Collaboration), Study of four-jet events and evidence for double parton interactions in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. D* **47**, 4857 (1993).
- [47] R. Aaij *et al.* (LHCb Collaboration), arXiv:1510.05949.
- [48] M. Strikman and C. Weiss, Chiral dynamics and partonic structure at large transverse distances, *Phys. Rev. D* **80**, 114029 (2009).