Observation of a narrow mass state decaying into $\Upsilon(1S) + \gamma$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV


1 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
2 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
3 Universidade Federal do ABC, Santo André, Brazil
4 University of Science and Technology of China, Hefei, People’s Republic of China
5 Universidad de los Andes, Bogotá, Colombia
6 Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
7 Czech Technical University in Prague, Prague, Czech Republic
8 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
9 Universidad San Francisco de Quito, Quito, Ecuador
10 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
11 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
12 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
13 LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
14 LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
15 CEA, Irfu, SPP, Saclay, France
16 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
17 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
18 III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
19 Physikalisches Institut, Universität Freiburg, Freiburg, Germany
20 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
21 Institut für Physik, Universität Mainz, Mainz, Germany
22 Ludwig-Maximilians-Universität München, München, Germany
23 Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany
24 Panjab University, Chandigarh, India
25 Delhi University, Delhi, India
26 Tata Institute of Fundamental Research, Mumbai, India
27 University College Dublin, Dublin, Ireland
28 Korea Detector Laboratory, Korea University, Seoul, Korea
29 CINVESTAV, Mexico City, Mexico
30 Nikhef, Science Park, Amsterdam, the Netherlands
31 Radboud University Nijmegen, Nijmegen, the Netherlands
32 Joint Institute for Nuclear Research, Dubna, Russia
33 Institute for Theoretical and Experimental Physics, Moscow, Russia
34 Moscow State University, Moscow, Russia
35 Institute for High Energy Physics, Protvino, Russia
36 Petersburg Nuclear Physics Institute, St. Petersburg, Russia
37 Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), Barcelona, Spain
38 Uppsala University, Uppsala, Sweden
39 Lancaster University, Lancaster LA1 4YB, United Kingdom
40 Imperial College London, London SW7 2AZ, United Kingdom
41 The University of Manchester, Manchester M13 9PL, United Kingdom
42 University of Arizona, Tucson, Arizona 85721, USA
43 University of California Riverside, Riverside, California 92521, USA
44 Florida State University, Tallahassee, Florida 32306, USA
45 Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
46 University of Illinois at Chicago, Chicago, Illinois 60607, USA
47 Northern Illinois University, DeKalb, Illinois 60115, USA
48 Northwestern University, Evanston, Illinois 60208, USA
49 Indiana University, Bloomington, Indiana 47405, USA
50 Purdue University Calumet, Hammond, Indiana 46323, USA
51 University of Notre Dame, Notre Dame, Indiana 46556, USA
52 Iowa State University, Ames, Iowa 50011, USA
53 University of Kansas, Lawrence, Kansas 66045, USA
54 Kansas State University, Manhattan, Kansas 66506, USA
The study of heavy quarkonium is of fundamental importance to our understanding of perturbative and non-perturbative quantum chromodynamics (QCD). The heavy quarkonium state is one of the simplest QCD systems and the observed masses and branching fractions are in quantitative agreement with theoretical expectations for almost all of the known states. The recent observations of unexpected quarkonium-like states have, however, raised new questions. The discovery of the $\Upsilon(3872)$ in 2003\footnote{University of Michigan, Ann Arbor, Michigan 48109, USA} provided the first surprise. One explanation for this state is a $b\bar{b}$ molecule\footnote{University of Minnesota, Minneapolis, Minnesota 55455, USA}, but the subsequent discoveries of several other unexpected particles containing a $c\bar{c}$ pair have suggested otherwise. The $\Upsilon(4S)$\footnote{University of Nebraska, Lincoln, Nebraska 68588, USA} is most naturally explained as a hybrid $c\bar{c}$-gluon state\footnote{University of Texas, Arlington, Texas 76019, USA}, but it could also be a four-quark state\footnote{Michigan State University, East Lansing, Michigan 48824, USA}. The $Z(4430)$\footnote{Brown University, Providence, Rhode Island 02912, USA} is likely a four-quark charmonium-like particle by virtue of its non-zero electric charge, and the recently observed charged structures decaying into $\pi\Upsilon$

55Louisiana Tech University, Ruston, Louisiana 71272, USA
56Boston University, Boston, Massachusetts 02215, USA
57Northeastern University, Boston, Massachusetts 02115, USA
58University of Michigan, Ann Arbor, Michigan 48109, USA
59Michigan State University, East Lansing, Michigan 48824, USA
60University of Mississippi, University, Mississippi 38677, USA
61University of Nebraska, Lincoln, Nebraska 68588, USA
62Rutgers University, Piscataway, New Jersey 08855, USA
63Princeton University, Princeton, New Jersey 08544, USA
64State University of New York, Buffalo, New York 14260, USA
65Columbia University, New York, New York 10027, USA
66University of Rochester, Rochester, New York 14627, USA
67State University of New York, Stony Brook, New York 11794, USA
68Brookhaven National Laboratory, Upton, New York 11973, USA
69Langston University, Langston, Oklahoma 73050, USA
70University of Oklahoma, Norman, Oklahoma 73019, USA
71Oklahoma State University, Stillwater, Oklahoma 74078, USA
72Brown University, Providence, Rhode Island 02912, USA
73University of Texas, Arlington, Texas 76019, USA
74Southern Methodist University, Dallas, Texas 75275, USA
75Rice University, Houston, Texas 77005, USA
76University of Virginia, Charlottesville, Virginia 22901, USA
77University of Washington, Seattle, Washington 98195, USA

(Dated: March 26, 2012)

Using data corresponding to an integrated luminosity of 1.3 fb$^{-1}$, we observe a narrow mass state decaying into $\Upsilon(1S) + \gamma$, where the $\Upsilon(1S)$ meson is detected by its decay into a pair of oppositely charged muons, and the photon is identified through its conversion into an electron-positron pair. The significance of this observation is 5.6 standard deviations. The mass of the state is centered at 10.551 ± 0.014(stat.) ± 0.017(syst.) GeV/c$^2$, which is consistent with that of the state recently observed by the ATLAS Collaboration.

PACS numbers: 12.38-t, 14.40.Pq, 14.65.Fy
tracks are required to be loosely associated to the same event selection for this analysis is chosen to maximize the signal significances of the known \( \chi_b(1P) \) and \( \chi_b(2P) \) states, as well as those of the charmonium \( \chi_c \) states which are observed in the analogous \( J/\psi + \gamma \) decay mode. The search region above the \( \chi_b(2P) \) mass and below the \( BB \) mass threshold (10.38 - 10.63 GeV/c\(^2\)) is not examined in this optimization procedure. Muon candidates are required to be reconstructed in both the inner and outer layers of the muon detector and must be matched to tracks in the central tracking system with \( p_T > 1.5 \) GeV/c. The tracks are required to originate from a common \( p\bar{p} \) interaction vertex. The resulting mass distribution for muon pairs of opposite charge is shown in Fig. 1. We select events in the mass range 9.1 GeV/c\(^2\) < \( M_{\mu\mu} \) < 9.7 GeV/c\(^2\), which contains approximately 275,000 \( \Upsilon(1S) \) candidates after background subtraction.

Photons are detected via their conversions into electron-positron pairs. We use this technique instead of direct detection in the calorimeter because the energies of photons from quarkonia decay are typically too low to be precisely measured in the calorimeter, while the tracking system provides excellent resolution in this kinematic region. This allows for a separation of closely-spaced mass states. Well-measured track pairs of opposite charge that form a good vertex are selected. These tracks are required to be loosely associated to the same \( p\bar{p} \) interaction vertex as the muon tracks, but since photons travel some distance before they are converted in the material of the detector, the electron-positron tracks are required to originate away from that vertex. The two tracks are combined to form a photon candidate. The resulting photon trajectory is required to intersect the beam axis within 0.8 cm of where each of the tracks intersect it. The momentum vector of the photon must also point back from its reconstructed conversion point to the \( p\bar{p} \) collision vertex, and the invariant mass of the conversion pair must be \( M_{\mu\mu} \approx 80 \) MeV/c\(^2\). These selection criteria are confirmed by a study of double conversion pairs from \( \pi^0 \rightarrow \gamma\gamma \) decays. The origin, in the plane transverse to the beam direction, of the track pairs passing these criteria is shown in Fig. 2, where the structure of the silicon tracker is clearly visible.

Converted photons passing these requirements are combined with muons passing the \( \Upsilon(1S) \) selection. The photon and both muons must be consistent with coming from a common vertex, and both muon trajectories must intersect the beam axis within a distance of 1.2 cm from that of the photon. The \( \Upsilon(1S) \gamma \) system is also required to have \( p_T > 5 \) GeV/c.

The resulting distribution of \( \Delta M = M_{\mu\mu\gamma} - M_{\mu\mu} \) is shown in Fig. 3. Peaks corresponding to the \( \chi_b(1P) \) and \( \chi_b(2P) \) states are clearly seen at \( \Delta M \approx 0.4 \) GeV/c\(^2\) and \( \Delta M \approx 0.8 \) GeV/c\(^2\), respectively. A third peak is also observed centered around \( \Delta M \approx 1 \) GeV/c\(^2\), which is consistent with the recent observation of a new state by the ATLAS Collaboration. The mass resolution is not good enough to separate the hyperfine splitting of the known \( \chi_b \) states, and we find no indication of substructure in the mass region of the new state. The mean-
measured values $\Delta M_{\chi_b(1P)} = 0.418 \pm 0.005$ GeV/$c^2$ and $\Delta M_{\chi_b(2P)} = 0.760 \pm 0.014$ GeV/$c^2$ are shifted from their true values due to energy loss of the electron/positrons. A scale factor of $0.96 \pm 0.01$ is determined by comparing these measurements to their world average values assuming an equal mixture of $J = 1$ and $J = 2$ components for each $\chi_b$ state (the $J = 0$ components are suppressed in this decay mode) [10]. The measured masses of the $\chi_c$ states and the $\pi^0$ detected using photon conversions have a shift consistent with this scale factor.

The shape of the background distribution is determined from the data by combining $\Upsilon(1S)$ and photon candidates from different events. As seen in Fig. 3 this mixed event background model describes the data for a wide range of $\Delta M$ outside the region of interest. We also study the $\Delta M$ distributions for events with dimuons in the $\Upsilon(1S)$ mass sideband regions and for events with dimuons with the same charge in the $\Upsilon(1S)$ mass region. The resulting $\Delta M$ distributions for these selections show no peaking structure and have shapes similar to that of the mixed-event background model.

The mass distribution $M = M_{\mu\mu\gamma} - M_{\mu\mu} + m_{\Upsilon(1S)}$, where $m_{\Upsilon(1S)}$ is the world average value 9.4603 GeV/$c^2$ [10], is shown in Fig. 4 along with the results of an unbinned maximum likelihood fit with three signal peaks and a background shape determined from the mixed event model. Crystal Ball functions [11] are used to describe the signal mass shapes to take into account the radiative tails due to bremsstrahlung. We use single Crystal Ball functions to describe the mass of the $\chi_b(1P)$ and $\chi_b(2P)$ systems and that of the new state. The center for each $\chi_b$ mass function is fixed to its world average value corrected by the electron/positron energy loss scale factor. The widths of the signal functions are described by a single parameter scaled by the mass of each state, and the lengths of the radiative tails are the same for all three states. These constraints, determined from the data without consideration of the new structure, have also been verified using Monte Carlo simulations. The widths of all three peaks obtained in the fit are compatible with the D0 detector’s resolution. The fit yields 65 $\pm$ 11 events above background corresponding to the new state. A similarly good fit is also obtained by using an exponential function multiplied by a low-mass turn on curve to describe the background. The shape of the resulting background agrees well with that of the mixed-event model.

A significance of more than six standard deviations is determined from the difference in the log likelihood of the fits with and without the new state’s contribu-
tion. Considering the probability of an upward fluctuation of the background producing a signal of this width anywhere in the search region, reduces the significance to 5.6 standard deviations. The mass of the new state is corrected by the same scale factor used to fit the $\chi_b(1P, 2P)$ states and is measured to be $10.551 \pm 0.014{\text{(stat.)}} \pm 0.017{\text{(syst.)}}$ GeV/$c^2$. The main sources of systematic uncertainty are due to the unknown mixture of $\chi_b$ spin states (13 MeV/$c^2$), the mass scale correction (10 MeV/$c^2$), and variations in the background model (5 MeV/$c^2$).

In summary, we present a search for new particles with masses below the $B\bar{B}$ threshold which decay into $\Upsilon(1S)+\gamma$. In addition to the known states $\chi_b(1P)$ and $\chi_b(2P)$, a third peak is observed at a mass consistent with the new state observed by the ATLAS collaboration. No other mass peaks are observed. The background distribution is well described over a wide mass range by a background model which mixes $\Upsilon(1S)$ and $\gamma$ candidates from different events. A likelihood fit to the mass distribution results in a measured mass of $10.551 \pm 0.014{\text{(stat.)}} \pm 0.017{\text{(syst.)}}$ GeV/$c^2$ for the new state with a width consistent with the D0 detector’s mass resolution. Further analysis is underway to determine whether this structure is due to the $\chi_b(3P)$ system or some exotic bottom-quark state.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); MON, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); NRF (Korea); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).