Evidence for a $B_s^0\pi^\pm$ state

(The D0 Collaboration*)

1 LAFEX, Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, RJ 22290, Brazil
2 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, RJ 20550, Brazil
3 Universidade Federal do ABC, Santo André, SP 09210, Brazil
4 University of Science and Technology of China, Hefei 230026, People’s Republic of China
5 Universidad de los Andes, Bogotá, 111711, Colombia
6 Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, 116 36 Prague 1, Czech Republic
7 Czech Technical University in Prague, 116 36 Prague 6, Czech Republic
8 Institute of Physics, Academy of Sciences of the Czech Republic, 182 21 Prague, Czech Republic
9 Universidad San Francisco de Quito, Quito, Ecuador
10 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, F-63178 Aubière Cedex, France
11 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, F-38026 Grenoble Cedex, France
12 CPPM, Aix-Marseille Université, CNRS/IN2P3, F-13288 Marseille Cedex 09, France
13 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91405 Orsay Cedex, France
14 LPNHE, Universités Paris VI et VII, CNRS/IN2P3, F-75005 Paris, France
15 CEA Saclay, Irfu, SPP, F-91191 Gif-Sur-Yvette Cedex, France
16 IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France
17 IPNL, Université Lyon 1, CNRS/IN2P3, F-69622 Villeurbanne Cedex, France
18 III. Physikalisches Institut A, RWTH Aachen University, 52056 Aachen, Germany
19 Physikalisches Institut, Universität Freiburg, 79085 Freiburg, Germany
20 II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen, Germany
21 Institut für Physik, Universität Mainz, 55099 Mainz, Germany
22 Ludwig-Maximilians-Universität München, 80539 München, Germany
23 Panjab University, Chandigarh 160014, India
24 Delhi University, Delhi-110 007, India
25 Tata Institute of Fundamental Research, Mumbai-400 005, India
26 University College Dublin, Dublin 4, Ireland
27 Korea Detector Laboratory, Korea University, Seoul, 02841, Korea
28 CINVESTAV, Mexico City 07360, Mexico
29 Nikhef, Science Park, 1098 XG Amsterdam, the Netherlands
30 Radboud University Nijmegen, 6525 AJ Nijmegen, the Netherlands
31 Joint Institute for Nuclear Research, Dubna 141980, Russia
32 Institute for Theoretical and Experimental Physics, Moscow 117259, Russia
33 Moscow State University, Moscow 119991, Russia
34 Institute for High Energy Physics, Protvino, Moscow region 142281, Russia
35 Petersburg Nuclear Physics Institute, St. Petersburg 188300, Russia
36 Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), 08193 Bellaterra (Barcelona), Spain
37 Uppsala University, 751 05 Uppsala, Sweden
38 Taras Shevchenko National University of Kyiv, Kiev, 01601, Ukraine
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 Florida State University, Tallahassee, Florida 32306, USA
44 University of California Riverside, Riverside, California 92521, 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 Louisiana Tech University, Ruston, Louisiana 71272, USA
55 Northeastern University, Boston, Massachusetts 02115, USA
56 University of Michigan, Ann Arbor, Michigan 48109, USA
57 Michigan State University, East Lansing, Michigan 48824, USA
58 University of Mississippi, University, Mississippi 38677, USA
We report evidence for a narrow structure, $X(5568)$, in the decay sequence $X(5568) \to B^+_c\pi^-$, $B^+_c \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$. This is evidence for the first instance of a hadronic state with valence quarks of four different flavors. These states have one common feature: they consist of a tightly bound di-quark anti-diquark pair such as $[bu][ds]$, $[bd][su]$, $[su][bd]$, or $[sd][br]$, or a “molecule” of the loosely bound $B$ and $K$ mesons. This Letter presents a study of the $B^+_c\pi^-$ invariant mass spectrum using a data sample of 10.4 fb$^{-1}$ collected with the D0 experiment at the Fermilab Tevatron collider.


(Dated: June 15, 2016)

During the last few years several resonant states that cannot be conventional quark-antiquark mesons or three-quark baryons have been observed [1–8]. Taking into account the decay modes and charges of these states they may be interpreted as four-quark or five-quark states. These states have one common feature: they consist of a combination of heavy and light quarks. These discoveries open up a new era of multi-quark hadron spectroscopy. Various combinations of heavy and light mesons may be tested. One such system is the combination of the heavy $B^0_c$ or $\bar{B}^+_c$ meson and the light $\pi^\pm$ meson. Such systems are composed of two quarks and two antiquarks of four different flavors: $b,s,u,d$, which might be a
are required to penetrate the toroid.

Candidate events are required to include a pair of oppositely charged muons both with \( p_T > 1.5 \text{ GeV}/c \) in the invariant mass range \( 2.92 < m(\mu^+\mu^-) < 3.25 \text{ GeV}/c^2 \), consistent with \( J/\psi \) decay, accompanied by two additional particles of opposite charge assumed to be kaons, each with \( p_T > 0.7 \text{ GeV}/c \), with an invariant mass of \( 1.012 < m(K^+K^-) < 1.030 \text{ GeV}/c^2 \), consistent with \( \phi \) decay, and a third charged particle with \( p_T > 0.5 \text{ GeV}/c \) assumed to be a pion.

In the event selection, both muons are required to be detected in the muon chambers inside the toroidal magnet, and at least one of the muons is required to be also detected outside the iron toroid. Each muon candidate is required to match a track found in the central tracking system, and each of the five final-state tracks is required to have at least one SMT hit and at least one CFT hit. The dimuon invariant mass is constrained to the world-average \( J/\psi \) mass \([11]\), and the four tracks forming a \( J/\psi \) candidate are required to satisfy a fit to a common vertex that is displaced from the primary vertex in the plane perpendicular to the beam direction by at least three times the standard deviation of the measurement uncertainty. The pion candidate is required to be consistent with originating from the primary \( pp \) collision vertex.

To form a \( B_s^{0}\pi^{\pm} \) combination, we select the \( B_s^{0} \) candidates in the mass range \( 5.303 < m(J/\psi \phi) < 5.423 \text{ GeV}/c^2 \), corresponding to an interval of \( \pm 2 \) standard deviations around the mean value of the reconstructed \( B_s^{0} \) mass. The \( m(J/\psi \phi) \) distribution is shown in Fig. [1]. The fit, including a third-order polynomial describing the combinatorial background and a Gaussian function describing the signal, yields the Gaussian signal parameters \( m(B_s^{0}) = 5363.3 \pm 0.6 \text{ MeV}/c^2 \), \( \sigma(B_s^{0}) = 31.6 \pm 0.6 \text{ MeV}/c^2 \) and the number of signal events \( N_{\text{ev}} = 5582 \pm 100 \). To improve the resolution of the invariant mass of the \( B_s^{0}\pi^{\pm} \) system and to remove the measured \( B_s^{0} \) mass bias, we define it as 

\[
m(B_s^{0}\pi^{\pm}) = m(J/\psi \phi \pi^{\pm}) - m(J/\psi \phi) + 5.3667 \text{ GeV}/c^2,
\]

where \( m(J/\psi) \) is not constrained to the nominal value.

We study events as a function of mass in the range \( 5.5 < m(J/\psi \phi) < 5.9 \text{ GeV}/c^2 \).

Background in the \( B_s^{0}\pi^{\pm} \) invariant mass spectrum results from random combinations of selected \( B_s^{0} \) candidates with low momentum charged particles coming mostly from the primary vertex. To suppress background the \( B_s^{0}\pi^{\pm} \) system is required to have \( p_T > 10 \text{ GeV}/c \). To further reduce background, we impose a limit on the difference between the directions of the \( B_s^{0} \) candidate and the pion to be \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3 \), where \( \eta \) is the pseudorapidity and \( \phi \) is the azimuthal angle. In addition to increasing the signal-to-background ratio this “cone cut” limits backgrounds that are not included in available simulations.

The \( B_s^{0} \) candidates include genuine \( B_s^{0} \) mesons and the combinatorial background under the \( B_s^{0} \) signal, as seen in Fig. [1]. The \( B_s^{0}\pi^{\pm} \) background with a real \( B_s^{0} \) meson is modeled using a Monte Carlo (MC) simulation \([12]\) of events containing a \( B_s^{0} \) meson and additional pions tuned to reproduce the \( B_s^{0} \) transverse momentum distribution in data.

The background with a false \( B_s^{0} \) meson is modeled using the sideband events obtained from data. The chosen sideband regions \( 5.0 < m(J/\psi \phi) < 5.21 \text{ GeV}/c^2 \) and \( 5.51 < m(J/\psi \phi) < 5.87 \text{ GeV}/c^2 \) are indicated in Fig. [1]. The sidebands are separated by \( \sim 5 \sigma \) from the \( B_s^{0} \) nominal mass. The left and right sideband ranges are chosen to provide a large event sample and to have an average mass of \( m(B_s^{0}) \).

The two background components are found to have similar shapes \([13]\). The fraction of the real \( B_s^{0} \) events in the signal region is obtained from the fit to the \( B_s^{0} \) meson in the \( m(J/\psi \phi) \) distribution and is found to be \((70.9 \pm 0.6)\%\). MC events and the sideband events are mixed in this proportion to obtain the combined background that includes pions from both sources. The event selection results in pions that mainly come from the primary vertex, although pions originating from heavy flavor decays are also present in the sample.

Multiple entries for a single event may occur when more than one pion candidate passes the event selection and they are retained in the sample. The rate of duplicate entries in the mass range \( 5.5 < m(B_s^{0}\pi^{\pm}) < 5.6 \text{ GeV}/c^2 \) (\( \sim 5\% \)) is lower than for masses above \( 5.7 \text{ GeV}/c^2 \) (\( \sim 8\% \)).

The combined background is modeled by a function of the parameter \( m_0 = m_{B_s} - \Delta \), where \( m_{B_s} \equiv m(B_s^{0}\pi^{\pm}) \) and \( \Delta = 5.5 \text{ GeV}/c^2 \), of the form:

\[
F_{bg}(m_0) = P_4(C_{1=0}) \times \exp(P_2).
\]

Here \( P_4(C_{1=0}) \) and \( P_2 \) are fourth- and second-order polynomials, and the linear term of the first polynomial is set.
to zero. This empirical function gives a good description of the combined backgrounds, as seen in Fig. 2.

The $B^0 \pi^\pm$ invariant mass spectrum is shown in Fig. 3(a) with the cone cut and (b) without the cone cut. An enhancement is seen near 5.57 GeV/$c^2$. To extract the signal parameters, the distributions are fitted with a function $F$ (Eq. 2) that includes two terms: the background term $F_{bgr}(m_{B\pi})$ with fixed shape parameters as in Fig. 2 and the signal term $F_{sig}(m_{B\pi}, M_X, \Gamma_X)$, modeled by a relativistic Breit-Wigner function convolved with a Gaussian detector resolution function and with the mass-dependent efficiency of the cone cut [13]. Here $M_X$ and $\Gamma_X$ are the mass and the natural width of the resonance. The Gaussian width parameter $\sigma_{res} = 3.8$ MeV/$c^2$ is taken from simulations.

The fit function has the form:

$$F = f_{sig} \times F_{sig}(m_{B\pi}, M_X, \Gamma_X) + f_{bgr} \times F_{bgr}(m_{B\pi}),$$

(2)

where $f_{sig}$ and $f_{bgr}$ are normalization factors.

We use the Breit-Wigner parametrization appropriate for an $S$-wave two-body decay near threshold:

$$BW(m_{B\pi}) \propto \frac{M_X^2 \Gamma(m_{B\pi})}{(M_X - m_{B\pi})^2 + M_X^2 \Gamma^2(m_{B\pi})}.$$  

(3)

The mass-dependent width $\Gamma(m_{B\pi}) = \Gamma_X \cdot (q_1/q_0)$ is proportional to the natural width $\Gamma_X$, where $q_1$ and $q_0$ are three-vector momenta of the $B^0\pi^\pm$ system at the invariant mass equal to $m_{B\pi}$ and $M_X$, respectively.

In the fit shown in Fig. 3a, the normalization parameters $f_{sig}$ and $f_{bgr}$ and the Breit-Wigner parameters $M_X$ and $\Gamma_X$ are allowed to vary. The fit yields the mass and width of $M_X = 5567.8 \pm 2.9$ MeV/$c^2$, $\Gamma_X = 21.9 \pm 6.4$ MeV/$c^2$, and the number of signal events of $N = 133 \pm 31$. As the measured width is significantly larger than the experimental mass resolution, we infer that $X(5568) \rightarrow B^0_s\pi^\pm$ is a strong decay. The statistical significance of the signal is defined as $\sqrt{-2 \ln(L_0/L_{max})}$, where $L_{max}$ and $L_0$ are likelihood values at the best-fit signal yield and the signal yield fixed to zero. The obtained local statistical significance is 6.6$\sigma$ for the given mass and width values. With the look-elsewhere effect [14] taken into account, the global statistical significance is 6.1$\sigma$. The search window is taken as the interval between the $B^0\pi^\pm$ threshold (5506 MeV/$c^2$) and the $B^0_dK^\pm$ mass threshold (5774 MeV/$c^2$).

We also extract the signal from the $m(B_s\pi^\pm)$ distribution without the $\Delta R$ cone cut, fixing the mass and natural width of the signal and the background mass shape to their default values. We see a tendency for data to
form a fit in the restricted range \( m \) non-

exceed background for \( m(B_s \pi^\pm) > M_X \) [13]. We

perform a fit in the restricted range \( m(B_s \pi^\pm) < 5.7 \text{ GeV}/c^2 \)

(Fig. 3b) and find the fitted number of signal events to be \( 106 \pm 23 \), with a corresponding local statistical significance of \( 4.8 \sigma \). The difference in yields with and

without the cone cut is not fully explained by statistical fluctuations. In a subsidiary study we used empirical functions [15] for the background fitted to the sidebands in data below the \( X(5568) \) region and above the signal region up to \( 5.9 \text{ GeV}/c^2 \) and found signal yields that are greater than those with the default background function and comparable to or greater than that found in the cone cut analysis. These results confirm that using a background function that agrees with data for masses above \( 5.7 \text{ GeV} \) can increase the fitted signal yield above that obtained using the default background model. Additional background processes are not present in our MC such as \( B_c \rightarrow B_n \pi \) with \( n > 1 \), or other new states at higher mass, would thus have the effect of reducing the \( X(5568) \) yield for the no-cone cut case.

As a cross-check, we extract a pure \( B_s^0 \pi^\pm \) signal by performing fits of the number of \( B_s^0 \) events in the \( J/\psi \phi \) mass distribution in 20 MeV intervals in the range \( 5.5 < m(B_s^0 \pi^\pm) < 5.9 \text{ MeV}/c^2 \). Results of those fits are shown in Fig. 4. A fit to the dependence of \( B_s^0 \) yields on \( m(B_s^0 \pi^\pm) \), with the mass and natural width fixed to the previously obtained values, gives \( 118 \pm 22 \) signal events. This result confirms that the observed signal is due to \( B_s^0 \pi^\pm \) candidates with genuine \( B_s^0 \) mesons and thus eliminates the possibility of non-\( B_s^0 \) processes mimicking the signal.

We obtain the systematic uncertainties for the measured values of the \( X(5568) \) state mass, natural width, and the number of events. The dominant uncertainties are due to the background and signal shapes. We evaluate the systematic uncertainties due to the background shape by a) using different models of bottom pair production in generating the \( B_s^0 \) MC samples, b) varying the sideband mass intervals, c) changing the way the \( B_s^0 \) mass constraint is applied in the calculation of \( m(B_s^0 \pi^\pm) \) for the sideband events by replacing the mass difference defined in the text by the kinetic energy obtained by forcing \( m(J/\psi \phi) \) to the world-average \( B_s^0 \) mass, d) changing the ratio of the MC to the sideband events within \( 1 \sigma \), e) using different background functions by replacing the fourth-order polynomial in Eq.1 with a third- or fifth-order polynomial or replacing the second-order polynomial in the exponential with the first- or third-order polynomial, and f) varying the nominal \( B_s^0 \) mass within \( \pm 1 \text{ MeV}/c^2 \) in the background samples, both for the sideband data and simulated events. The systematic uncertainties due to the signal shape are evaluated by a) varying the detector resolution within \( \pm 1 \text{ MeV}/c^2 \) around the mean value, b) using a non-relativistic Breit-Wigner function, and c) using a \( P \)-wave relativistic Breit-Wigner function.

Additionally, we estimate the systematic uncertainties due to the binning by changing the bin size to \( 5 \text{ MeV}/c^2 \) and to \( 10 \text{ MeV}/c^2 \) instead of \( 8 \text{ MeV}/c^2 \), and shifting the lower edge of the mass scale by \( 1/3 \), \( 1/2 \) and \( 2/3 \) of the bin size. All systematic uncertainty sources are summarized in Table 1. The uncertainties are added in quadrature separately for positive and negative values to obtain the total systematic uncertainties for each measured parameter and are treated as nuisance parameters to construct a prior predictive model [11, 17] of our test statistic. When the systematic uncertainties are included, the significance of the observed signal including the look-elsewhere effect is reduced to 5.1\( \sigma \). For the analysis without the \( \Delta R \) cut (Fig. 3b) we obtain a significance including the systematic uncertainty and the look-elsewhere effect of 3.9\( \sigma \).

The stability of the result is checked by examining subsamples with a) different signs of the \( \pi^\pm \) meson, b) different ranges of the azimuth and rapidity, c) the distance between the \( B_s^0 \) vertex and the primary vertex changed to five standard deviations, d) different \( B_s^0 \) mass windows (\( 1.7 \sigma \), \( 1.5 \sigma \), \( 1.2 \sigma \)), e) different \( B_s^0 \pi^\pm \) momentum intervals (\( p_T > 9 \text{ GeV}/c \), \( p_T > 12 \text{ GeV}/c \)), and f) different cone cuts (\( \Delta R < 0.2 \), \( \Delta R < 0.15 \)). Taking into account the efficiencies of these cuts, no unexpected behaviors are observed in these tests.

The invariant mass spectra of \( B_s^0 \) candidates and charged tracks with kaon or proton mass hypotheses, are checked and no resonant-like enhancements in these distributions are found.

We measure the ratio \( \rho \) of the yield of the new state \( X(5568) \) to the yield of the \( B_s^0 \) meson in two kinematic ranges, \( 10 < p_T(B_s^0) < 15 \text{ GeV}/c \) and \( 15 < p_T(B_s^0) < 30 \text{ GeV}/c \), by repeating the \( m(B_s^0 \pi^\pm) \) fits with free mass and width parameters for the \( X(5568) \) signal [12]. The results for \( \rho \) are (9.1 \( \pm 2.6 \) \( \pm 1.6 \)% and (8.2 \( \pm 2.7 \) \( \pm 1.6 \)%), respectively, with an average of (8.6 \( \pm 1.9 \) \( \pm 1.4 \)%). The systematic uncertainties due to \( B_s^0 \) reconstruction efficiency cancel out in the ratio. The combined factor of the soft pion kinematic acceptance, reconstruction efficiency,
and selection efficiency is obtained from a simulated sample of events with a spinless particle of mass equal to 5568 MeV/c² decaying to $B_s^0$ and a charged pion. The pion efficiency increases with $p_T(B_s^0)$ from $(26.1 \pm 3.2)\%$ to $(42.1 \pm 6.5)\%$ for the two $p_T(B_s^0)$ ranges. The systematic uncertainty due to a potential difference of the soft pion reconstruction efficiency in MC and data of $\pm 5\%$ is accounted for in systematics. Within uncertainties, the production ratio $\rho$ does not depend on $p_T(B_s^0)$.

A possible interpretation of the observed structure is a four-quark state made up of a diquark-antidiquark pair. With the $B_s^0\pi^+$ produced in an $S$ wave, its quantum numbers would be $J^P = 0^\mp$. Thus, the state may be a heavy analogue of the isotriplet scalar state $a(980)$, with an $s$ quark replaced by a $b$ quark. Such open charm and open bottom scalar mesons are predicted in Ref. [17]. On the other hand, the state can decay through the chain $B_s^0\pi^\pm, B_s^\pm \to B_s^0\gamma$, where the low-energy photon is not detected. In this case, the quantum numbers of this state would be $J^P = 1^\mp$ that would make it a counterpart to other heavy tetraquark candidates. The mass of the new state would be shifted by addition of the nominal mass difference $m(B_s^+) - m(B_s^0)$, while its width would remain unchanged. The large difference between the mass of this state and the sum of the $B_d$ and $K^\pm$ masses implies [18] that $X(5568)$ is unlikely to be a molecular state composed of loosely bound $B_d$ and $K^\pm$ mesons.

In summary, a structure is seen in the $B_s^0\pi^\pm$ invariant mass spectrum near threshold with a statistical significance, including the look-elsewhere effect, of $6.1\sigma$. When the systematic uncertainties are included, the significance of the signal is $5.1\sigma$. For the alternate analysis without the $\Delta R$ cut, we find the corresponding significance of $3.9\sigma$. This structure may be interpreted as a tetraquark state with four different valence quark flavors, $b, s, u, d$. The mass and natural width of the $X(5568)$ state are $m = 5567.8 \pm 2.9 \text{(stat)} +2.0 \text{(syst)}$ MeV/c² and $\Gamma = 21.9 \pm 6.4 \text{(stat)} +4.9 \text{(syst)}$ MeV/c².

We thank E. Gross and O. Vittel for useful discussions. 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 (The Netherlands); Science and Technology Facilities Council and The Royal Society (United Kingdom); Ministry of Education, Youth and Sports (Czech Republic); Bundesministerium fü̈r 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).

[1] S.-K. Choi et al. (Belle Collaboration), “Observation of a Resonancelike Structure in the $\pi^\pm\psi'$ Mass Distribution in Exclusive $B \to K\pi^\pm\psi'$ Decays”, Phys. Rev. Lett. 100,


[13] See the supplemental material at [http://xxx/to be supplied by PRL/].


[15] One alternate background function is a third order Chebychev polynomial. The second is that employed in a previous study of exotic heavy flavor mesons, V. M. Abazov et al. (D0 Collaboration), “Inclusive production of the $X(4140)$ state in $p\bar{p}$ collisions at D0”, Phys. Rev. Lett. 115, 232001 (2015).

