PHYSICAL REVIEW LETTERS **120,** 202006 (2018)

Search for the Exotic Meson $X(5568)$ with the Collider Detector at Fermilab

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0031-9007/18/120(20)/202006(7)

Published by the American Physical Society

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(Received 29 December 2017; revised manuscript received 5 March 2018; published 18 May 2018)

A search for the exotic meson $X(5568)$ decaying into the $B_s^0\pi^\pm$ final state is performed using data corresponding to 9.6 fb^{-1} from $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV recorded by the Collider Detector at Fermilab. No evidence for this state is found and an upper limit of 6.7% at the 95% confidence level is set on the fraction of B_s^0 produced through the $X(5568) \to B_s^0\pi^\pm$ process.

DOI: 10.1103/PhysRevLett.120.202006

The new and unexpected structure in the $B_s^0\pi^\pm$ final state recently reported by the D0 Collaboration [1,2] in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV cannot be interpreted as a meson composed of a quark-antiquark pair. This reported signal, named $X(5568)$, is measured with a mass of $5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV}/c^2$ and a width of $21.9 \pm 6.4^{+5.0}_{-2.5}\ \text{MeV}/c^2$. Several collaborations in both electron-positron and hadronic collision experiments have found evidence for other exotic hadron candidates formed with four or more quarks [3]. The $B_s^0\pi^\pm$ final state contains four quark flavors, which cannot result from the decay of any standard meson. An observation of this state, if confirmed, would represent the first tetraquark (four-quark) candidate containing four different quark flavors. However, efforts by the LHCb, CMS, and ATLAS Collaborations to confirm the $X(5568)$ provide no supporting evidence for its existence [4–6].

In this Letter we report the results of a search for the exotic meson $X(5568)$. This search is made in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV using the Collider Detector at Fermilab (CDF II) by reconstructing the decay chain $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, and $\phi \to K^+K^-$. These studies use the full CDF II data sample corresponding to an integrated luminosity of 9.6 fb^{-1} and constitute the first search for $X(5568)$ production in the same initial conditions as the D0 observation.

The CDF II detector is described in detail elsewhere [7]. This analysis uses the tracking and muon identification systems. The tracking system measured the trajectories of charged particles (tracks) and consisted of five layers of double-sided silicon detectors [8] and a 96 layer open-cell drift chamber (COT) [9] that operated inside a solenoid with a 1.4 T field oriented along the beam direction. Charged particles with transverse momentum (p_T) greater than 250 MeV/c that originated from the collision point were measured in the tracking system with a transverse-momentum resolution of $\sigma(p_T)/p_T^2 \approx 0.0008\ (\text{GeV}/c)^{-1}$. Muon candidates from the decay $J/\psi \to \mu^+\mu^-$ were identified by two sets of drift chambers located radially outside electromagnetic and hadronic calorimeters [10]. The central muon chambers covered the pseudorapidity region $|\eta| < 0.6$ and were sensitive to muons with $p_T > 1.4\ \text{GeV}/c$. A second muon system covered the region $0.6 < |\eta| < 1.0$ and detected muons having $p_T > 2.0\ \text{GeV}/c$.

The mass resolution and acceptance for the $X(5568)$ and B_s^0 decays are studied with a Monte Carlo simulation that generates $X(5568) \to B_s^0\pi^\pm$ decays consistent with CDF measurements of p_T and rapidity distributions for inclusive

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B_s^0 production. The simulated $X(5568)$ and B_s^0 decay isotropically and other final-state decay processes are simulated with the EvtGen [11] program. The generated events are passed through the detector and trigger simulation based on a GEANT3 description [12] and processed through the same reconstruction and analysis algorithms used for the data.

This analysis is based on events recorded with a three-level trigger that was dedicated to the collection of a $J/\psi \to \mu^+\mu^-$ sample. The first level of the trigger system required two muon candidates with tracks in the COT and muon chamber systems that matched in the plane transverse to the beam direction. At this stage, the trigger system identified trigger tracks with $p_T > 1.4$ GeV/c and segmented into 1.25° in the azimuthal angle. The second level imposed the requirement that the muon candidates have opposite charge and limited the accepted range of opening angle between them [13]. The third level of the trigger reconstructed the muon pair with the full resolution of the COT, and required that the invariant mass of the pair fall within the range 2.7–4.0 GeV/c^2.

The strategy for this analysis is to reconstruct the $B_s^0\pi^\pm$ final state using similar methods to those used by previous CDF analyses [13,14]. The measured yields and acceptances are used to calculate the fraction of B_s^0 produced through the process $X(5568) \to B_s^0\pi^\pm$, given by

$$\begin{aligned} f_{B_s^0/X(5568)} &= \frac{\sigma(p\bar{p} \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0\pi^\pm)}{\sigma(p\bar{p} \to B_s^0 + \text{anything})} \\ &= \frac{N_X}{N_{B_s^0}} \frac{1}{\alpha_{X,B_s^0}}, \end{aligned} \tag{1}$$

where σ corresponds to the indicated inclusive cross section, $\mathcal{B}$ the indicated branching fractions, N_X and $N_{B_s^0}$ are the numbers of $X(5568)$ and B_s^0 reconstructed in the data, respectively, and α_{X,B_s^0} is the acceptance and reconstruction efficiency for the $X(5568)$ in events where the B_s^0 is reconstructed. In the absence of an $X(5568)$ signal, this expression is used to calculate a limit on $f_{B_s^0/X(5568)}$.

The analysis of the data begins with a selection of well-measured $J/\psi \to \mu^+\mu^-$ candidates. The trigger requirements are confirmed by selecting events that contain two oppositely charged muon candidates, each with matching COT and muon chamber tracks. Both muon tracks are required to have associated measurements in at least three layers of the silicon detector, and are fit with the constraint that they originate from a common decay point. Dimuon candidates are measured with an average mass resolution of 20 MeV/c^2 and candidates with a mass within 80 MeV/c^2 of the world-average J/ψ mass [15] are retained as J/ψ candidates. Approximately 1.5×10^7 J/ψ candidates are obtained.

The reconstruction of ϕ candidates uses all additional tracks found in each event containing a J/ψ candidate. Pairs of oppositely charged tracks with three or more silicon layer measurements and $p_T > 400$ MeV/c are assigned the $K^\pm$ mass and have their track parameters recalculated according to a fit that constrains them to intersect. Candidates whose fits converge have a mass measurement resolution that is insignificant compared to the ϕ natural width of 4.2 MeV/c^2 [15], and those with an invariant mass within 10 MeV/c^2 of the world-average ϕ mass [15] are retained as ϕ candidates.

The sample of B_s^0 candidates is obtained by selecting all candidates where the four tracks satisfy a fit that constrains the tracks to originate from a common decay point and the dimuon to have the world-average J/ψ mass [15]. Further requirements placed on the B_s^0 candidates include $p_T > 10$ GeV/c and $ct > 100$ μm, where t is the proper decay time of the candidate. These requirements remove candidates for which the acceptance of the detector is low and reduce background due to prompt combinations. The $J/\psi\phi$ mass distribution obtained is shown in Fig. 1. The number of B_s^0 candidates in the data is obtained by performing a binned likelihood fit on the distribution in Fig. 1 with a linear background model and two Gaussian functions with a common central value as a signal model. We measure a B_s^0 yield of $N_{B_s^0} = 3552 \pm 65$ candidates and a mass of 5366.5 ± 0.2 MeV/c^2, consistent with the world average [15]. The weighted average of the two width terms from the fit is 11 MeV/c^2 and candidates with mass within 20 MeV/c^2 of the nominal B_s^0 mass are used for the $X(5568)$ search. Mass sidebands are also indicated in Fig. 1 and are defined as two mass ranges of 20 MeV/c^2 full width centered ±100 MeV/c^2 from the nominal B_s^0 mass.

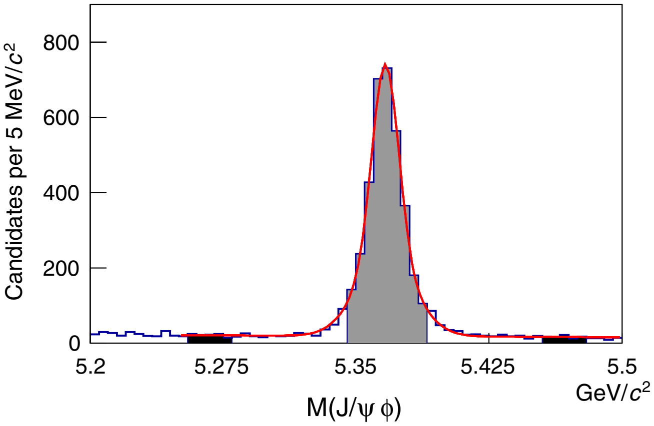

FIG. 1. Distribution of $J/\psi\phi$ mass for $p_T > 10$ GeV/c with the fit overlaid on the histogram. The B_s^0 signal region is highlighted in gray. Areas used to define backgrounds based on the mass sidebands are indicated in black.

The final $B_s^0\pi^\pm$ sample is obtained by combining the B_s^0 candidate tracks with the remaining tracks, assumed to be pions, that have three or more silicon detector hits and $p_T > 400$ MeV/c. A constrained fit is performed and requires the B_s^0 and $\pi^\pm$ candidates to originate from the same point. This final selection also requires the transverse displacement of the full final state with respect to the beam line to be less than 100 μm. A mass resolution of 1.8 MeV/c^2 is obtained for the $B_s^0\pi^\pm$ final state by defining $M(B_s^0\pi^\pm) = M(J/\psi\phi\pi^\pm) - M(J/\psi\phi) + M_{B_s^0}$, where $M_{B_s^0}$ is the world-average value of the mass of the B_s^0 [15]. No requirement is made on the opening between the B_s^0 and $\pi^\pm$ as is done in the first report of the $X(5568)$ [1] due to the distortion in the $M(B_s^0\pi^\pm)$ distribution created by such a selection.

Simulated events are used to estimate the acceptance of the B_s^0 and the relative acceptance α_{X,B_s^0} for the $X(5568)$ for events containing a reconstructed B_s^0. A correction is made to the generated $X(5568)$ sample so that the simulated $p_T(B_s^0)$ distribution is identical to the acceptance-corrected $p_T(B_s^0)$ distribution observed in the data. Three simulated samples are generated using widths of the $X(5568)$, with values of 21.6, 15.5, and 28.7 MeV/c^2. These correspond to the central value and the range of the uncertainty for the width measured in the reported $X(5568)$ [1].

The shape of the $B_s^0\pi^\pm$ mass distributions obtained from simulated events is dependent on p_T, due to the acceptance and efficiency of the tracking system. The reconstructed signal shape expected for the $X(5568)$ is obtained by integrating the p_T-dependent mass distribution shapes found in simulation with a weighting determined by the observed $p_T(B_s^0)$ distribution. The expected mass-distribution shape is parametrized with an empirical function using two Gaussians and a tail term on the high-mass side from the peak. The yield of $X(5568)$ observed in the simulated events provides a value of $\alpha_{X,B_s^0} = 0.445 \pm 0.027$ for $p_T(B_s^0) > 10$ GeV/c, where the uncertainty is statistical. A systematic variation on α_{X,B_s^0} of ± 0.018 is found due to the uncertainty on the reported width of the $X(5568)$.

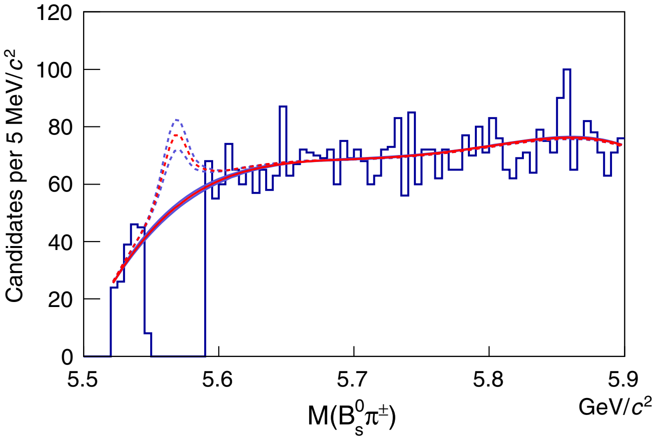

FIG. 2. Distribution of $B_s^0\pi^\pm$ mass where the candidates within 21.6 MeV/c^2 of the $X(5568)$ are omitted. The background model is overlaid in a solid line, where the line width indicates $\pm\sigma$ variations on the background model due to variations in the assumption for the $X(5568)$ signal amplitude. Dashed curves indicate the signal components used to obtain the background model and its variations.

The $B_s^0\pi^\pm$ mass distribution is analyzed with an unbinned likelihood fit with the likelihood calculated as

$$\mathcal{L} = \prod_i^N [f\mathcal{S}(m_i) + (1-f)\mathcal{B}(m_i)], \qquad (2)$$

where N is the number of entries in the distribution, m_i is the mass of entry i, f is the signal fraction obtained from the fit, $\mathcal{S}(m_i)$ is the signal model obtained from simulation and $\mathcal{B}(m_i)$ is the background model. The functional form of $\mathcal{B}(m_i)$ is obtained by fitting the mass distribution with all candidates within the central value of the reported width (21.6 MeV/c^2) [1] of the $X(5568)$ mass value omitted, with f fixed at the value that results from the D0 observation, and $\mathcal{B}(m_i)$ modeled with a polynomial. Variations in this fit are also made, corresponding to the uncertainty on the signal yield in the D0 measurement. The background model is shown overlaid on the data in Fig. 2.

The background model obtained in this process is fixed in the fit of the full set of candidates where f is allowed to float. This fit is overlaid on the data in Fig. 3 and estimates an $X(5568)$ yield of $N_X = 36 \pm 30$ candidates. The signal and background models were varied by the uncertainties in the D0 measurements on the mass, width, and production rate of the $X(5568)$ to provide a systematic uncertainty estimate of 14 candidates. This signal yield is used in Eq. (1) with the acceptance and B_s^0 yield to calculate $f_{B_s^0/X(5568)} = [2.3 \pm 1.9(\mathrm{stat}) \pm 0.9(\mathrm{syst})]\%$. This is compared to the value obtained by D0 of $[8.6 \pm 1.9(\mathrm{stat}) \pm 1.4(\mathrm{syst})]\%$ by

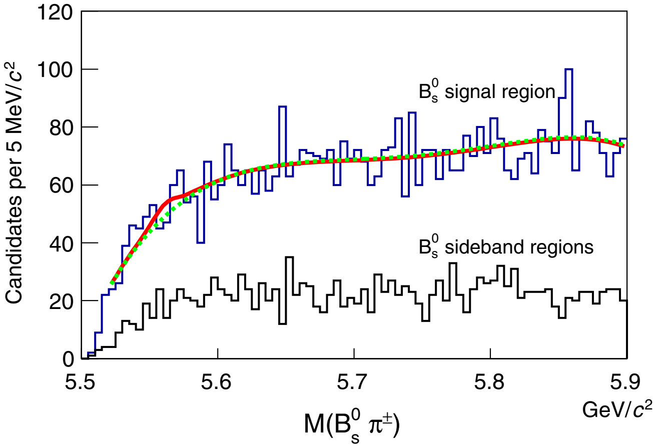

FIG. 3. Distribution of $B_s^0\pi^\pm$ mass for $p_T(B_s^0) > 10$ GeV/c, for candidates in the B_s^0 mass range and for the mass sidebands, as indicated. The fit to the data with a freely floating (null) signal is overlaid in a solid (dashed) line.

calculating $\chi^2 = (f_{D0} - f_{CDF})^2/\Sigma_i \sigma_i^2 = 4.0$ where the f_x are the central values obtained for each experiment and the σ_i are the associated uncertainties. This result would be expected to occur with a 4.6% frequency. Figure 3 also shows the $M(B_s^0\pi^\pm)$ distribution obtained from the $J/\psi\phi$ candidates in the B_s^0 mass sidebands indicated in Fig. 1 for comparison.

The $X(5568)$ yield obtained in the data is consistent with no signal. Therefore, the fit where the signal is allowed to float is compared to the null hypothesis by repeating the fit where the signal component is omitted. The value of twice the difference in the logarithm of the likelihood, $2\delta \log \mathcal{L}$, between the fits is then used as a measure of the compatibility of the data with the background-only hypothesis. An upper limit on the presence of an $X(5568)$ signal is calculated by following a frequentist Neyman construction. The technique uses simulated mass distributions with a shape given by the probability distribution in Eq. (2). Various signal-strength hypotheses are generated by fixing $f_{B_s^0/X(5568)}$ for each simulation, producing a signal fraction given by $f = N_X/N$. Ten thousand trials are run for each signal-strength hypothesis and the mass distributions obtained in each trial are fit twice as in the data, once with a floating signal fraction and once with the null signal hypothesis. The $2\delta \log \mathcal{L}$ is then evaluated for all simulated distributions.

The results of these simulations are used to set an upper limit on $f_{B_s^0/X(5568)}$. The cumulative probability distribution of $2\delta \log \mathcal{L}$ for a given $f_{B_s^0/X(5568)}$ provides the test statistic. The 95% confidence level, C.L., upper limit is obtained by determining the value of $f_{B_s^0/X(5568)}$ where the value of the cumulative probability distribution, evaluated at the value of $2\delta \log \mathcal{L}$ seen in the data, approximates 0.05. A value of $f_{B_s^0/X(5568)} = 0.055$ is obtained by this method. A cross-check of this calculation was performed by using the profile likelihood technique on the fit function, and a comparable result is obtained.

Alternative background models that use a $B^0 \to J/\psi K^*(892)^0$ sample have also been used to obtain upper limits on $f_{B_s^0/X(5568)}$ through this technique. The alternative models are found by fitting the $B^0\pi^-$ and $B^0\pi^+$ mass distributions and omitting mass regions corresponding to the $B_1(5721)^+$ or $B_2^*(5747)^+$ (for $B^0\pi^+$). These background models are then used to repeat the simulations used in the calculations for the upper limit. These alternatives give upper limits on $f_{B_s^0/X(5568)}$ that are comparable to the result based on the $B_s^0\pi^\pm$ fit.

Two systematic effects are considered that modify the upper limit obtained for $f_{B_s^0/X(5568)}$. The first takes into account uncertainties on the quantities in Eq. (1). The uncertainties on the quantities are combined in quadrature to obtain an overall relative uncertainty of 6.6%, where the uncertainty on the acceptance (α_{X,B_s^0}) provides the largest contribution (6.0%). The second systematic uncertainty is due to the background model. An alternative model, where the input value of $f_{B_s^0/X(5568)}$ is increased by one standard deviation with respect to the D0 central value tests this sensitivity. An upper limit of $f_{B_s^0/X(5568)} = 0.060$ is found for this background model, so a relative uncertainty of 9% is assigned to this effect. Combining these in quadrature gives a total systematic uncertainty of 11% on this measurement of $f_{B_s^0/X(5568)}$. We treat the systematic uncertainty as a normal distribution width, and consider twice its value to correspond to a 95% fluctuation. Consequently, inclusion of the systematic uncertainty provides a 95% C.L. upper limit on $f_{B_s^0/X(5568)}$ of 0.067.

In conclusion, a search for the exotic meson $X(5568)$ is performed with the full CDF II data set, which was obtained with the same collision conditions and similar kinematic range as in the original observation of this state by D0 [1]. No statistically significant evidence for the process $X(5568) \to B_s^0\pi^\pm$ is found. A comparison between this result and the report by D0 finds that the probability of consistency between the two experiments is 4.6%. A 95% C.L. upper limit of 6.7% is found for fraction of B_s^0 produced through this process. Consequently, this analysis does not confirm the existence of the $X(5568)$.

This document was prepared by the CDF Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A. P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, United Kingdom; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; the Australian Research Council (ARC); and the EU community Marie Curie Fellowship Contract No. 302103.

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