Evidence for a $B^0_s\pi^\pm$ state

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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 tightly bound di-quark anti-di-quark pair such as $[bu]$, $[bd]$, $[su]$, $[sd]$, or a “molecule” of the loosely bound $B$ and $K$ mesons. This Letter presents a study of the $B_s^0\pi^\pm$ invariant mass spectrum using a data sample of 10.4 fb$^{-1}$ collected with the D0 detector at the Fermilab Tevatron collider.

The D0 detector consists of a central tracking system, calorimeters, and muon detectors [9]. The central tracking system comprises a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located inside a 1.9 T superconducting solenoidal magnet. The tracking system is designed to optimize tracking and vertexing for pseudorapidities $|\eta| < 3$, where $\eta = -\ln(\tan(\theta/2))$, and $\theta$ is the polar angle with respect to the proton beam direction. The SMT can reconstruct the $p\bar{p}$ interaction vertex (primary vertex) for interactions with at least three tracks with a precision of 40 $\mu$m in the plane transverse to the beam direction. The muon detector, positioned outside the calorimeter, consists of a central muon system covering the pseudorapidity region $|\eta| < 1$ and a forward muon system covering the pseudorapidity region $1 < |\eta| < 2$. Both central and forward systems consist of a layer of drift tubes and scintillators inside 1.8 T iron toroidal magnets with two similar layers outside the toroids.

Events used in this analysis are collected with both single muon and dimuon triggers. Single muon triggers require a coincidence of signals in trigger elements inside and outside the toroidal magnets. Dimuon triggers in the central rapidity region require at least one muon to penetrate the toroid. In the forward region, both muons


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are required to penetrate the toroid.

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

To form a $B_s^0\pi^\pm$ combination, we select the $B_s^0$ candidates in the mass range $5.303 < m(J/\psi\phi) < 5.423$ 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 $m(B_s^0) = 5363.3 \pm 0.6$ MeV/$c^2$, $\sigma(B_s^0) = 31.6 \pm 0.6$ MeV/$c^2$ and the number of signal events $N_{ev} = 5582 \pm 100$. 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 $m(B_s^0\pi^\pm) = m(J/\psi\phi\pi^\pm) - m(J/\psi\phi) + 5.3667$ 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 $5.5 < m(J/\psi\phi) < 5.9$ 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 $p_T > 10$ 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 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 $5.0 < m(J/\psi\phi) < 5.21$ GeV/$c^2$ and $5.51 < m(J/\psi\phi) < 5.87$ 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 $5.5 < m(B_s^0\pi^\pm) < 5.6$ GeV/$c^2$ ($\sim 5\%$) is lower than for masses above $5.7$ 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 $\Delta = 5.5$ 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.
The mass-dependent width $\Gamma(m_{B_s})$ is 6.1 $\sigma$ for the given mass and width values. With the look elsewhere effect taken into account, the global statistical significance is 6.6 $\sigma$. The statistical significance of the signal is defined as $\sqrt{-2 \ln(L_0/L_{\text{max}})}$, where $L_{\text{max}}$ 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 taken into account, the global statistical significance is 6.6 $\sigma$. The search window is taken as the interval between the $B_s\pi^\pm$ threshold (5506 MeV/$c^2$) and the $B_d K^\pm$ 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-

result of the fit. The dashed line shows the contribution of

functions [15] for the background fitted to the sidebands

$\sigma$ to be $10^6$ (Fig. 3b) and find the fitted number of signal events

as

additional background processes not present in our MC such

that obtained using the default background model. Addi-

tional background functions that agree with data for masses

the cone cut analysis. These results confirm that using

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 MeV/$c^2$
and to 10 MeV/$c^2$ instead of 8 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 sub-
samples with a) different signs of the $\pi^\pm$ meson, b) dif-
ferent 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 inter-
vals ($p_T > 9$ GeV/$c$, $p_T > 12$ 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 dis-
butions 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, $10 < p_T(B_s^0) < 15$ GeV/$c$ and $15 < p_T(B_s^0) < 30$
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 effi-
ciency cancel out in the ratio. The combined factor of the
soft pion kinematic acceptance, reconstruction efficiency,
and selection efficiency is obtained from a simulated samples 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 $J^{P} = 0^{+}$. 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 $B_{s}^{*+}\pi^{+}$, $B_{s}^{*+} \rightarrow B_{s}^{0}\gamma$, where the low-energy photon is not detected. In this case, the quantum numbers of this state would be $J^{P} = 1^{+}$ 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 $m = 5567.8 \pm 2.9^{+1.9}_{-1.9}$(stat) MeV/c² and $\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}$(syst) MeV/c².

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[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 $p\overline{p}$ collisions at D0”, Phys. Rev. Lett. 115, 232001 (2015).

