# Evidence for a $B_s^0\pi^\pm$ State

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We report evidence for a narrow structure, $X(5568)$, in the decay sequence $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$. This is evidence for the first instance of a hadronic state with valence quarks of four different flavors. The mass and natural width of this state are measured to be $m = 5567.8 \pm 2.9(\mathrm{stat})^{+0.9}_{-1.9}(\mathrm{syst})$ MeV$/c^2$ and $\Gamma = 21.9 \pm 6.4(\mathrm{stat})^{+5.0}_{-2.5}(\mathrm{syst})$ MeV$/c^2$. If the decay is $X(5568) \to B_s^{*}\pi^\pm \to B_s^0\gamma\pi^\pm$ with an unseen $\gamma$, $m(X(5568))$ will be shifted up by $m(B_s^*) - m(B_s^0) \sim$ 49 MeV$/c^2$. This measurement is based on 10.4 fb$^{-1}$ of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected by the D0 experiment at the Fermilab Tevatron collider.

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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 combination of heavy and light quarks. These discoveries open up a new era of multiquark hadron spectroscopy. Various combinations of heavy and light mesons may be tested. One such system is the combination of the heavy $B_s^0$ or $\bar{B}_s^0$ 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 tightly bound diquark anti-diquark pair such as $[bu][\bar{d}\,\bar{s}]$, $[bd][\bar{s}\,\bar{u}]$, $[su][\bar{b}\,\bar{d}]$, or $[sd][\bar{b}\,\bar{u}]$, 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 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 [10] 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 $J/\psi\phi$ 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 3 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 $5.303 < m(J/\psi\phi) < 5.423\ \mathrm{GeV}/c^2$, 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 $m(B_s^0) = 5363.3 \pm 0.6\ \mathrm{MeV}/c^2$, $\sigma(B_s^0) = 31.6 \pm 0.6\ \mathrm{MeV}/c^2$ and the number of signal events $N_{\mathrm{ev}} = 5582 \pm 100$. 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 $m(B_s^0\pi^\pm) = m(J/\psi\phi\pi^\pm) - m(J/\psi\phi) + 5.3667\ \mathrm{GeV}/c^2$, where $m(J/\psi)$ is not constrained to the nominal value. We study events as a function of mass in the range $5.5 < m(J/\psi\phi) < 5.9\ \mathrm{GeV}/c^2$.

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 $p_T > 10\ \mathrm{GeV}/c$. 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.

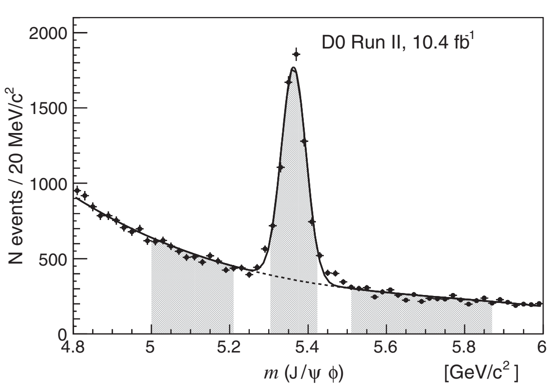


FIG. 1. Invariant mass distribution of $J/\psi\phi$ candidates. The signal region and two sideband regions are indicated. The solid curve presents the fit results to the function, modeled by a sum of a third-order polynomial to describe the combinatorial background and a Gaussian to describe the $B_s^0$ signal. The dotted curve shows the combinatorial background.

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 $5.0 < m(J/\psi\phi) < 5.21\ \mathrm{GeV}/c^2$ and $5.51 < m(J/\psi\phi) < 5.87\ \mathrm{GeV}/c^2$ 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 $5.5 < m(B_s^0\pi^\pm) < 5.6\ \mathrm{GeV}/c^2$ ($\sim 5\%$) is lower than for masses above $5.7\ \mathrm{GeV}/c^2$ ($\sim 8\%$).

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

$$F_{\mathrm{bgr}}(m_0) = P_{4(C1=0)} \exp(P_2). \quad (1)$$

Here, $P_{4(C1=0)}$ 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 $B_s^0\pi^\pm$ invariant mass spectrum is shown in Fig. 3(a) with the cone cut and (b) without the cone cut. An enhancement is seen near $5.57\ \mathrm{GeV}/c^2$. To extract the signal parameters, the distributions are fitted with a function $F$ [Eq. (2)] that includes two terms: the background term $F_{\mathrm{bgr}}(m_{B\pi})$ with fixed shape parameters as in Fig. 2 and the signal term $F_{\mathrm{sig}}(m_{B\pi}, M_X, \Gamma_X)$, 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 $\sigma_{\mathrm{res}} = 3.8\ \mathrm{MeV}/c^2$ is taken from simulations.

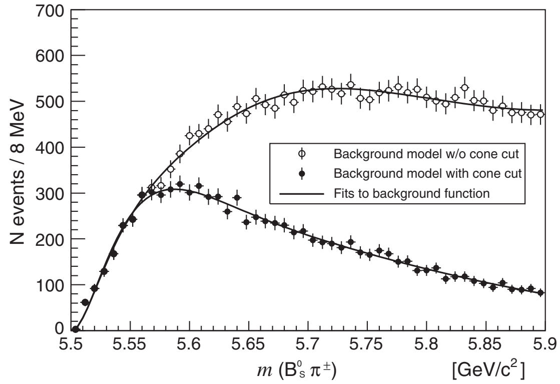


FIG. 2. The combined background for the $m(B_s^0\pi^\pm)$ distribution described in the text and the fit to that distribution with the $\Delta R < 0.3$ cone cut and without the cone cut.

The fit function has the form

$$F = f_{\rm sig} F_{\rm sig}(m_{B\pi}, M_X, \Gamma_X) + f_{\rm bgr} F_{\rm bgr}(m_{B\pi}), \qquad (2)$$

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

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

$$BW(m_{B\pi}) \propto \frac{M_X^2 \Gamma(m_{B\pi})}{(M_X^2 - m_{B\pi}^2)^2 + M_X^2 \Gamma^2(m_{B\pi})}. \qquad (3)$$

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 $B_s^0$ meson in the rest frame of the $B_s^0\pi^\pm$ system at the invariant mass equal to $m_{B\pi}$ and $M_X$, respectively.

In the fit shown in Fig. 3(a), the normalization parameters $f_{\rm sig}$ and $f_{\rm bgr}$ and the Breit-Wigner parameters $M_X$ and $\Gamma_X$ are allowed to vary. The fit yields the mass and width of $M_X = 5567.8 \pm 2.9\ \mathrm{MeV}/c^2$, $\Gamma_X = 21.9 \pm 6.4\ \mathrm{MeV}/c^2$, 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 $X(5568) \to B_s^0\pi^\pm$ is a strong decay. The statistical significance of the signal is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ and $\mathcal{L}_0$ 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 $B_s^0\pi^\pm$ threshold (5506 MeV/$c^2$) and the $B_d^0 K^\pm$ mass threshold (5774 MeV/$c^2$).

We also extract the signal from the $m(B_s^0\pi^\pm)$ 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 exceed background for $m(B_s^0\pi^\pm) > M_X$ [13]. We perform a fit in the restricted range $m(B_s^0\pi^\pm) < 5.7\ \mathrm{GeV}/c^2$ [Fig. 3(b)] and find the

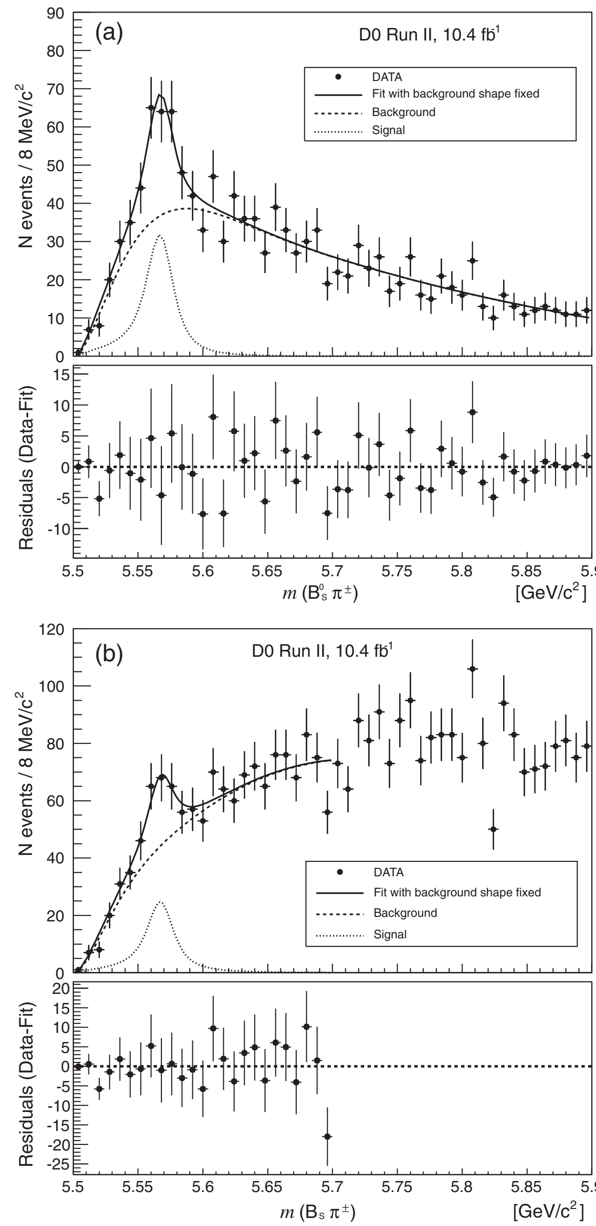


FIG. 3. The $m(B_s^0\pi^\pm)$ distribution together with the background distribution and the fit results (a) after applying the $\Delta R < 0.3$ cone cut and (b) without the cone cut.

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 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 GeV/$c^2$ can increase the fitted signal

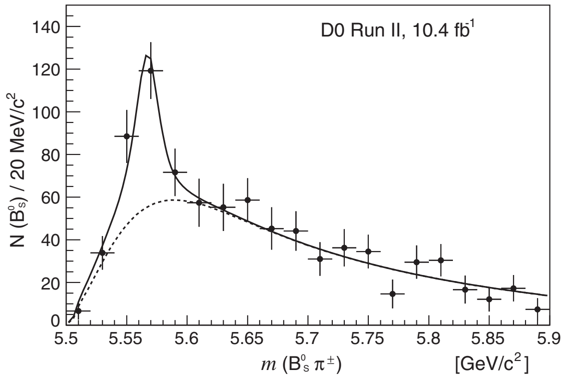


FIG. 4. The $m(B_s^0\pi^\pm)$ distribution resulting from fits of the $B_s^0$ signal to $m(J/\psi\phi)$ in twenty mass intervals of $(B_s^0\pi^\pm)$ candidates described in the text. The solid line shows the result of the fit. The dashed line shows the contribution of events due to the $B_s^0$ background from simulations. There is no non-$B_s^0$ background.

yield above that obtained using the default background model. Additional background processes not present in our MC calculations such as $B_c \to B_s n\pi$ 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$/c^2$ intervals in the range $5.5 < m(B_s^0\pi^\pm) < 5.9$ MeV$/c^2$. Results of those fits are shown in Fig. 4. A fit to the dependence of resulting $B_s^0$ 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 (i) using different models of bottom pair production in generating the $B_s^0$ MC samples, (ii) varying the sideband mass intervals, (iii) 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, (iv) changing the ratio of the MC to the sideband events within $1\sigma$, (v) 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 (vi) varying the nominal $B_s^0$ mass within $\pm 1$ 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 (i) varying the detector resolution within $\pm 1$ MeV$/c^2$ around the mean value, (ii) using a non-relativistic Breit-Wigner function, and (iii) 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 I. 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 [11,16] 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. 3(b)] we obtain a significance including the systematic uncertainty and the look-elsewhere effect of $3.9\sigma$.

TABLE I. Systematic uncertainties for the observed $X(5568)$ state mass, natural width, and number of events.

| Source | Mass, MeV$/c^2$ | Width, MeV$/c^2$ | Rate, % |
|---|---|---|---|
| Background shape | | | |
| MC samples with soft or hard $B_s^0$ | +0.2; −0.6 | +2.6; −0.0 | +8.2; −0.0 |
| Sideband mass ranges | +0.2; −0.1 | +0.7; −1.7 | +1.6; −9.3 |
| Sideband mass calculation method | +0.1; −0.0 | +0.0; −0.4 | +0.0; −1.3 |
| MC to sideband events ratio | +0.1; −0.1 | +0.5; −0.6 | +2.8; −3.1 |
| Background function used | +0.5; −0.5 | +0.1; −0.0 | +0.2; −1.1 |
| $B_s^0$ mass scale, MC and data | +0.1; −0.1 | +0.7; −0.6 | +3.4; −3.6 |
| Signal shape | | | |
| Detector resolution | +0.1; −0.1 | +1.5; −1.5 | +2.1; −1.7 |
| Non-relativistic BW | +0.0; −1.1 | +0.3; −0.0 | +3.1; −0.9 |
| $P$-wave BW | +0.0; −0.6 | +3.1; −0.0 | +3.8; −0.0 |
| Other | | | |
| Binning | +0.6; −1.1 | +2.3; −0.0 | +3.5; −3.3 |
| Total | +0.9; −1.9 | +5.0; −2.5 | +11.4; −11.2 |

The stability of the result is checked by examining subsamples with (i) different signs of the $\pi^\pm$ meson, (ii) different ranges of the azimuth and rapidity, (iii) the distance between the $B_s^0$ vertex and the primary vertex changed to five standard deviations, (iv) different $B_s^0$ mass windows ($1.7\sigma$, $1.5\sigma$, $1.2\sigma$), (v) different $B_s^0\pi^\pm$ momentum intervals ($p_T > 9$ GeV/$c$, $p_T > 12$ GeV/$c$), and (vi) 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 resonantlike 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, $10 < p_T(B_s^0) < 15$ GeV/$c$ and $15 < p_T(B_s^0) < 30$ GeV/$c$, by repeating the $m(B_s^0\pi)$ fits with free mass and width parameters for the $X(5568)$ signal [13]. 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 samples of events with a spinless particle of mass equal to 5568 MeV/$c^2$ 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 calculations 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 analog 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 $B_s^*\pi^\pm$, $B_s^* \to B_s^0\gamma$, where the low-energy photon is not detected. In this case, the quantum numbers of this state would be $J^P = 1^+$, which 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 $m = 5567.8 \pm 2.9(\mathrm{stat})^{+0.9}_{-1.9}(\mathrm{syst})$ MeV/$c^2$ and $\Gamma = 21.9 \pm 6.4(\mathrm{stat})^{+5.0}_{-2.5}(\mathrm{syst})$ MeV/$c^2$.

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