Search for Multi-quark Exotic States with Heavy Flavor at D0 Experiment

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Abstract. We present the results for multi-quark exotic states search from D0 Collaboration at the FNAL Tevatron. This includes an evidence for a $B^0_s\pi^\pm$ state ($X(5568)$) with hadronic decays of $B_s$ meson, a confirmation of the $X(5568)$ state with semileptonic decays of $B_s$ meson, and a search for exotic baryons decaying to $J/\psi\Lambda$ pairs.

1. Introduction
Since the creation of the quark model it was understood that exotic mesons containing more than one quark-antiquark pairs and exotic baryons containing more than three quarks are possible. It was also understood that multi-quark states that contain heavy quarks can be more recognizable owing to the distinctive decay structure of heavy quark hadrons. The 2003 discovery by the Belle experiment [1] of the $X(3872)$ in the channel $B^\pm \rightarrow K^\mp X(\rightarrow \pi^+\pi^-\pi^-J/\psi)$ was the first accepted exotic meson in which heavy flavor quarks participate. From that time more than 20 multi-quark exotic states candidates have been discovered. We present the recent results for such search from D0 collaboration.

2. Evidence for a $B^0_s\pi^\pm$ state
In 2016 the D0 collaboration presented evidence for a possible four-quark state with the decay to $B^0_s\pi^\pm$ where $B^s_0 \rightarrow J/\psi\phi$ [2]. A study of the $B^0_s\pi^\pm$ invariant mass spectrum was performed using a data sample of 10.4 fb$^{-1}$ collected with the D0 detector at the Fermilab Tevatron collider.

Events used in this analysis are collected both with single muon and dimuon triggers. They 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 with two additional oppositely charged particles assumed to be kaons, each with $p_T > 0.7$ GeV/$c$, with an invariant mass $1.012 < m(K^+K^-) < 1.03$ GeV/$c^2$, consistent with $\phi$ decay, and a third charged particle with $p_T > 0.5$ GeV/$c$ assumed to be a pion. To form a $B^0_s\pi^\pm$ combination, we select the $B^0_s$ candidates in the mass range $5.303 < m(J/\psi\phi) < 5.423$ GeV/$c^2$. To improve the resolution of the invariant mass of the $B^0_s\pi^\pm$ system we define this mass as $m(B^0_s\pi^\pm) = m(J/\psi\phi\pi^\pm) - m(J/\psi\phi) + m(B^0_s)$, where $m(B^0_s) = 5.3667$ GeV/$c^2$. We study events as a function of mass in the range $5.5 < m(B^0_s\pi^\pm) < 5.9$ GeV/$c^2$. To suppress background the $B^0_s\pi^\pm$ 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 $B^0_s$ 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

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addition to increasing the signal-to-background ratio this “cone cut” limits backgrounds that are not included in available simulations.

The $B_0^0\pi^\pm$ background with a real $B_0^0$ meson is modeled using a Monte Carlo (MC) simulation. The background with a false $B_0^0$ meson is modeled using the sideband events obtained from data. The two background components are found to have similar shapes and are mixed in the right proportion to obtain the combined background. It was modeled by a function of the parameter $m_0 = m(B_0^0\pi^\pm) - \Delta, \Delta = 5.5$ GeV/c$^2$, of the form

$$F_{\text{bgr}}(m) = (c_1 + c_2 \cdot m_0^2 + c_3 \cdot m_0^3 + c_4 \cdot m_0^4) \cdot e^{c_5 + c_6 \cdot m_0 + c_7 \cdot m_0^2},$$

(1)

This empirical function gives a good description of the combined backgrounds.

The $B_0^0\pi^\pm$ invariant mass spectrum is shown in Fig. 1a) 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

$$F(m) = f_{\text{sig}} \cdot F_{\text{sig}}(m, M_X, \Gamma_X) + f_{\text{bgr}} \cdot F_{\text{bgr}}(m),$$

(2)

where $F_{\text{sig}}(m, M_X, \Gamma_X)$ is a signal function, $M_X$ and $\Gamma_X$ are the mass and natural width of the resonance and $f_{\text{sig}}, f_{\text{bgr}}$ are normalization factors. The shape parameters in the background term $F_{\text{bgr}}$ are fixed to the values obtained from fitting the combined background distribution. Signal function is modeled by a relativistic Breit-Wigner function convolved with a Gaussian term

$$F(m; M, \Gamma) = \frac{c}{2 \sqrt{\pi \sigma}} \cdot e^{-m^2/2\sigma^2},$$

where $c$ is a normalization factor.

The fit shown in Fig. 1a 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 $N = 133 \pm 31$. The local statistical significance of the signal, defined as $\sqrt{-2 \ln(L_0/L_{\text{max}})}$, where $L_0, L_{\text{max}}$ are likelihood values at the signal yield fixed to zero and at the best-fit signal yield obtained from a binned maximum likelihood fit, is 6.6$\sigma$. With the look-elsewhere effect [3] taken into account, the global statistical significance is 6.1$\sigma$.

We obtain the systematic uncertainties for the measured values of the $X(5568)$ state mass, width, and the number of signal events. The dominant uncertainties are due to the background and signal shapes. When the systematic uncertainties are included, the

Figure 1. The $m(B_0^0\pi^\pm)$ distribution with the background distribution and the fitting function superimposed a) after applying $\Delta R < 0.3$ cone cut and b) without the cone cut.
significance of the observed signal, including the look-elsewhere effect, is reduced to 5.1σ. For the analysis without the ΔR cut (Fig. 1b) we obtain a significance including the systematic uncertainty and look-elsewhere effect of 3.9σ. Note, that the fit range in this case is reduced to \( m(B^0_s \pi^\pm) = 5.7 \text{ GeV}/c^2 \) due to the possible background processes not present in our MC calculations, which lead to a tendency for data to exceed background at higher masses. The mass and natural width of the \( X(5568) \) state with obtained systematic uncertainties are \( M_X = 5567.8 \pm 2.9 \text{(stat.)}^{+0.9}_{-1.5} \text{(syst.)} \text{ MeV}/c^2 \) and \( \Gamma_X = 21.9 \pm 6.4 \text{(stat.)}^{+5.0}_{-2.5} \text{(syst.)} \text{ MeV}/c^2 \).

The ratio of the yield of the new state \( X(5568) \) to the yield of the \( B^0_s \) meson is measured to be \( [8.6 \pm 1.9 \text{(stat.)} \pm 1.4 \text{(syst.)}] \% \).

A possible interpretation of the observed structure is a four-quark state made up of a diquark-antidiquark pair. With the \( B^0_s \pi^\pm \) produced in an S wave, its quantum numbers would be \( J^P = 0^+ \). On the other hand, the state can decay through the chain \( B^0_s \pi^\pm, B^0_s \rightarrow B^0_s \gamma, \) where the low-energy photon is not detected. In this case, the quantum number of this state would be \( J^P = 1^- \). The mass of the new state would be shifted by addition of the nominal mass difference \( m(B^0_s) - m(B^0_s) \), while its width would remain unchanged. If this structure is interpreted as a tetraquark state, it would be the first state with four different valence quark flavors \( b, s, u, d \).

### 3. Confirmation of the \( X(5568) \) with semileptonic decays of \( B_s \) meson

Subsequent analysis by LHCb [4] and CMS [5] have not confirmed the existence of \( X(5568) \) in \( pp \) interactions at \( \sqrt{s} = 7 \) and 8 TeV/c\(^2\). Thus, the additional studies of \( B^0_s \pi^\pm \) final state are very important.

We present here a search for \( X(5568) \) in the decay to \( B^0_s \pi^\pm \) using semileptonic \( B^0_s \) decays, \( B^0_s \rightarrow \mu^\pm D^\pm_s + X \) (charge conjugate states are assumed) from the full Run II integrated luminosity of 10.4 fb\(^{-1}\) in \( pp \) collisions. Here \( X \) includes the unseen neutrino and possibly other hadrons from the \( B^0_s \) decay. The background in semileptonic channel are mostly independent of those in the hadronic channel. The presence of the neutrino in the final state leads to the wider mass resolution for the signal. The character of possible reflections of other resonant structures is quite different in the semileptonic and hadronic channels. Thus, a study of \( X(5568) \) in the semileptonic decay channel may provide an independent confirmation of its existence.

The muons are required to have \( 3 < \pT < 25 \text{ GeV}/c \). The \( D^-_s \rightarrow \phi \pi^-, \phi \rightarrow K^+K^- \) is reconstructed as follows. The two particles from \( \phi \) decay are assumed to be kaons and are required to have \( \pT > 1.0 \text{ GeV}/c \), opposite charge and mass \( 1.012 < m(K^+K^-) < 1.03 \text{ GeV}/c^2 \). The charge of the third particle, assumed to be a pion, has to be opposite to that of the muon. The three tracks are combined to form a common \( D^-_s \) vertex. The \( D^-_s \) and \( B^0_s \) decay vertices should be well separated from the primary vertex. The transverse momentum of the \( \mu^+D^-_s \) system is required to satisfy the condition \( \pT > 10 \text{ GeV}/c \). To minimize the effect of the missing neutrino in the final state the effective mass is limited to \( 4.5 \text{ GeV}/c^2 < m(\mu^+D^-_s) < m(B^0_s) \). A track representing the pion in the \( B^0_s \pi^\pm \) combination is required to have transverse momentum \( 0.5 < \pT(\pi) < 25 \text{ GeV}/c \). To improve the resolution of the invariant mass of the \( B^0_s \pi^\pm \) system we define the invariant mass as \( m(B^0_s\pi) = m(\mu^+D^-_s\pi) - m(\mu^+D^-_s) + m(B^0_s) \), where \( m(B^0_s) = 5.3667 \text{ GeV}/c^2 \). We study events as a function of mass in the range 5.506 < \( m(B^0_s\pi^\pm) < 5.906 \text{ GeV}/c^2 \). The \( \Delta R \) cone cut was not used in this analysis.

The background parametrization was taken from the Monte-Carlo (MC) background sample generated using the PYTHIA [6] inclusive jet production model. To correct for the effects of the trigger selection and the reconstruction on the data, we weight each MC event so that the transverse momentum of the reconstructed muon and the \( \mu D_s \) system agree with those in the data. The \( m(B^0_s\pi^\pm) \) invariant mass distribution of the MC background is modeled by:

\[
F_{\text{bgr}}(m) = (c_1 \cdot m_0 + c_2 \cdot m_0^2 + c_3 \cdot m_0^3 + c_4 \cdot m_0^4) \cdot e^{c_5 \cdot m_0 + c_6 \cdot m_0^2},
\]
where \( m = m(B_0^0 \pi^\pm) \), \( m_0 = m - m_{\text{thr}} \), and \( m_{\text{thr}} = 5.5063 \text{ GeV}/c^2 \) is the \( B_0^0 \pi^\pm \) mass threshold. Several alternative parametrizations were also used to check the fit stability and for background shape systematics estimation.

The signal is modeled by a relativistic Breit-Wigner function convolved with a Gaussian detector resolution function which also takes into account the impact of the unseen neutrino. The fit function has the form similar to shown in Eq. 2. In the fit shown in Fig. 2 (left plot) the normalization parameters \( f_{\text{sig}}, f_{BG} \) and the Breit-Wigner parameters \( M_X, \Gamma_X \) are allowed to vary. The fit yields the mass and natural width of \( M_X = 5566.7^{+3.6}_{-3.4}(\text{stat.})^{+1.0}_{-1.9}(\text{syst.}) \text{ MeV}/c^2 \), \( \Gamma_X = 6.0^{+9.5}_{-6.0}(\text{stat.})^{+1.9}_{-4.6}(\text{syst.}) \text{ MeV}/c^2 \), and the number of signal events of \( N = 139^{+51}_{-63}(\text{stat.})^{+11}_{-32}(\text{syst.}) \). These numbers include the systematic uncertainties due to background shape description, background reweighting, \( B_0^0 \) mass scale in MC and data, detector resolution and the missing neutrino effect, signal modeling. The dominant systematic uncertainty is due to the background shape description. The local statistical significance of the signal is 4.5\( \sigma \). If the systematic uncertainties are taken into account, the statistical significance of the signal is 3.2\( \sigma \).

The ratio of the number of \( B_0^0 \) which come from the decay of \( X(5568) \) to all \( B_0^0 \) (\( X(5568) \) production ratio) was measured to be \( [7.3^{+2.5}_{-2.4}(\text{stat.})^{+0.6}_{-1.7}(\text{syst.})]\)% in the semileptonic channel.

The mass, natural width and \( X(5568) \) production ratio are in the agreement between the semileptonic and hadronic channels within uncertainties [2]. If we assume that we observe the same object in both channels and the semileptonic and hadronic measurements are independent, we can calculate the combined significance for the two channels using the formula to calculate the combined \( p \)-value: \( p_{\text{comb}} = p_{\text{had}} \cdot p_{\text{sl}} \cdot [1 - \ln(p_{\text{had}} \cdot p_{\text{sl}})] \), where \( p_{\text{had}} \) is the \( p \)-value for the hadronic channel, and \( p_{\text{sl}} \) is the \( p \)-value for the semileptonic channel. The obtained combined \( p \)-value corresponds to a significance of 5.7\( \sigma \) for the combination of the hadronic channel with the \( \Delta R \) cut and the semileptonic channel (4.7\( \sigma \) without \( \Delta R \) cut in the hadron channel). More details about this analysis can be found at [7].

4. Search for exotic baryons decaying to \( J/\psi \Lambda \)

Recently the LHCb collaboration has reported an observation of two \( J/\psi p \) resonances named \( P_c \) at masses 4380 \text{ MeV}/c^2 and 4450 \text{ MeV}/c^2, consistent with pentaquark states, in \( \Lambda_b^0 \rightarrow J/\psi K^- p \) decays (charge conjugate states are assumed) [8]. Both states are within 400 \text{ MeV}/c^2 of the \( J/\psi p \) threshold. Numerous states with the quark contents including a \( \bar{c}c \) pair and three light quarks are expected to exist within 500 \text{ MeV}/c^2 of the appropriate threshold. This section presents a search for inclusive production of pentaquarks with hidden charm in the final state \( J/\psi \Lambda \), with \( J/\psi \rightarrow \mu^+\mu^- \) and \( \Lambda \rightarrow p\pi^- \). Such states could be produced promptly, directly in

![Figure 2](image-url)  
**Figure 2.** The \( m(B_0^0 \pi^\pm) \) distribution with the fitting function superimposed, see text for details (left). Results of the signal significance scan for the \( J/\psi \Lambda \) invariant mass (right).
$pp$ collisions by QCD processes or non-promptly, in weak decays of $b$-baryons. In the following we focus on the non-prompt production.

Events used in this analysis are selected from a Run II data sample of $10.4$ fb$^{-1}$. To reconstruct a $J/\psi$ candidate, two muons with the opposite charge, transverse momentum $p_T(\mu) > 1.0$ GeV/c, total transverse momentum $p_T(\mu \mu) > 4.0$ GeV/c, originated from a common vertex, and have an invariant mass in the range $2.92 < m(\mu \mu) < 3.25$ GeV/$c^2$, are selected. The reconstruction and selection of $\Lambda \rightarrow p\pi^-\pi^+$ candidates is similar to that in the D0 measurement of the $\Lambda^0_b$ lifetime [9]. To select $J/\psi\Lambda$ candidates, we define the signal window as $1.110 - 1.122$ GeV/$c^2$, the lower limit on the $\Lambda$ transverse momentum is set to $0.7$ GeV/c.

We define the search mass region as the range from the $J/\psi$ threshold to $4.72$ GeV/$c^2$ and perform binned maximum likelihood fits to the distributions of the $J/\psi$ invariant mass with the function, defined in Eq. 2. The signal is modeled by a Gaussian function with mass $M_X$ and width (standard deviation) $\Gamma_X$. The background is modeled with the following function:

$$F_{\text{bg}}(m) \propto m \cdot (m^2/m_{\text{thr}}^2 - 1)^{c_1} \cdot e^{-c_2 m} \cdot (1 - e^{-(m-m_{\text{thr}})}/c_3),$$

where $m$ stands for $m(J/\psi\Lambda)$ and $m_{\text{thr}}$ is its threshold value.

Using the signal and background models described above, we perform mass fits of the sum of signal and background or background only to the data, with the signal mass set at fixed values in $10$ MeV/$c^2$ steps. The signal width and the background shape parameters $c_1, c_2, c_3$ are varied. In each mass point the local statistical significance is determined. The result of this scan is showed on Fig. 2 (right plot). The highest local significance of $3.45\sigma$ occurs at $m(J/\psi\Lambda) = 4.32$ GeV/$c^2$. If looks-elsewhere effect is taken into account, the corresponding global significance is estimated to be $2.8\sigma$. We thus have no evidence for new baryons decaying to $J/\psi\Lambda$. More details about this analysis can be found at [10].

References

[1] Choi S K et al. 2003 Phys. Rev. Lett. 91 262001
[2] Abazov V M et al. 2016 Phys. Rev. Lett. 117 022003
[3] Gross E and Vitells O 2010 Eur. Phys. J. C 70 525
[4] Aaij R et al. 2016 Phys. Rev. Lett. 117 152003
[5] CMS Collaboration 2016 CMS-PAS-BPH-16-002 (Geneva: CERN)
[6] Sjöstrand T, Mrenna S and Skands P 2006 JHEP 05 026
[7] https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B68/
[8] Aaij R et al. 2015 Phys. Rev. Lett. 115 072001
[9] Abazov V M et al. 2012 Phys. Rev. D 85 112003
[10] https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B69/