The New Results from Multi-quark Exotic States Searches at D0 Experiment

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Abstract. Recent results from a search for multi-quark exotic states at D0 experiment (FNAL, USA) are presented. This includes the new data for possible tetraquark state \( X(5568) \) decaying to \( B^0_s \pi^\pm \), in the channels with semileptonic decays of \( B^0_s \) mesons. Also, result from the \( J/\psi \pi \) system analysis and an evidence for exotic charged charmoniumlike state \( Z_c(3900) \) in semi-inclusive weak decays of \( B^- \)-flavored hadrons are presented as well.

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. The 2003 discovery by the Belle experiment [1] of the \( X(3872) \) in the channel \( B^\pm \rightarrow K^\pm X(\rightarrow \pi^+\pi^- J/\psi) \) 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 which include \( Z_c(4430) \rightarrow \psi(2S)\pi, X(4140) \rightarrow J/\psi\phi, P_c(4380), P_c(4450) \rightarrow J/\psi p \) to name a few. We present the recent results for such search from D0 Collaboration. More detailed review of the known multi-quark exotic states can be found in [2].

2. Confirmation of the \( X(5568) \) with semileptonic decays of \( B^0_s \) meson

In 2016 the D0 Collaboration presented evidence for a possible four-quark state with the decay to \( B^0_s \pi^\pm \) where \( B^0_s \rightarrow J/\psi\phi \) [3]. 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 addition to increasing the signal-to-background ratio this “cone cut” limits backgrounds that are not included in available simulations. The obtained mass and natural width of the \( X(5568) \) state were \( M_X = 5567.8 \pm 2.9 \text{(stat.)}^{+0.9}_{-1.9} \text{(syst. MeV/c}^2 \) and \( \Gamma_X = 21.9 \pm 6.4 \text{(stat.)}^{+5.0}_{-2.5} \text{(syst.) MeV/c}^2 \).

When the systematic uncertainties are included, the significance of the observed signal, including the look-elsewhere effect [4], is 5.1σ with the “cone cut” and 3.9σ without it.

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

Subsequent analysis by LHCb [5], CMS [6], ATLAS [7] and CDF [8] have not confirmed the existence of \( X(5568) \rightarrow J/\psi\phi \), which can be attributed to the different center of mass energy (in case of LHC experiments) or to the different kinematic coverage (in case of CDF). It should be noted, that the upper limit to the ratio of the yield of the new state \( X(5568) \) to the yield of
the $B^0_s$ meson, reported by CDF, is in $\sim 2\sigma$ tension with the result, obtained by D0. Thus, the additional studies of $B^0_s\pi^\pm$ final state are very important.

To confirm the result of this analysis, we present here a search for $X(5568)$ in the decay to $B^0_s\pi^\pm$ using semileptonic $B^0_s$ decays, $B^0_s \rightarrow \mu^+D^-_s + X$ (charge conjugate states are assumed) from the full Run II integrated luminosity of 10.4 fb$^{-1}$ in $pp$ collisions [9]. Here $X$ includes the unseen neutrino and possibly other hadrons from the $B^0_s$ decay. The background in semileptonic channel is 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 $3 < p_T < 25$ 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 $p_T > 1.0$ GeV/c, opposite charge and mass $1.012 < m(K^+K^-) < 1.03$ 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 $p_T > 10$ GeV/c. To minimize the effect of the missing neutrino in the final state the effective mass is limited to $4.5$ 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 $0.5 < p_T(\pi) < 25$ GeV/c. To improve the resolution of the invariant mass of the $B^0_s\pi^\pm$ system we define the invariant mass as $m(B^0_s\pi) = m(\mu^+D^-_s) - m(\mu^+D^-_s) + m(B^0_s)$, where $m(B^0_s) = 5.3667$ GeV/c$^2$. We study events as a function of mass in the range $5.506 < m(B^0_s\pi^\pm) < 5.906$ GeV/c$^2$.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The $m(B^0_s\pi^\pm)$ distribution with the fitting function superimposed for (a) with and (b) without the cone cut, see text for details.

The background parametrization was taken from the Monte-Carlo (MC) background sample generated using the PYTHIA [10] inclusive jet production model and also from the “wrong sign” data sample in which the muon has the same sign as a $D_s$ candidate. 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 agrees with those in the data. The $m(B^0_s\pi^\pm)$ invariant mass distribution of the background is modeled by:

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

where $m = m(B^0_s\pi^\pm)$, $m_0 = m - m_{thr}$, and $m_{thr} = 5.5063$ GeV/c$^2$ is the $B^0_s\pi^\pm$ mass threshold. Several alternative parameterizations 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 shown in Eq. 2.

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

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 normalization parameters \( f_{\text{sig}}, f_{\text{bgr}} \) and the Breit-Wigner parameters \( M_X, \Gamma_X \) are allowed to vary. The graphical representation of the fit results is shown on Fig. 1. The fit yields the mass and natural width of \( M_X = 5566.7^{+3.6}_{-3.4}(\text{stat.})^{+1.0}_{-0.6}(\text{syst.}) \) MeV/\( c^2 \), \( \Gamma_X = 6.0^{+9.5}_{-6.0}(\text{stat.})^{+1.9}_{-4.6}(\text{syst.}) \) MeV/\( c^2 \), and the number of signal events, \( N = 139^{+51}_{-63}(\text{stat.})^{+11}_{-32}(\text{syst.}) \). These numbers include the systematic uncertainties due to background shape description, background reweighting, \( B^0_s \) 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 3.4\( \sigma \). In a case, when the “cone cut” \( \Delta R < 0.3 \) is used, the corresponding parameters are \( M_X = 5566.4^{+3.4}_{-2.8}(\text{stat.})^{+1.5}_{-0.6}(\text{syst.}) \) MeV/\( c^2 \), \( \Gamma_X = 2.0^{+9.5}_{-2.0}(\text{stat.})^{+2.8}_{-2.0}(\text{syst.}) \) MeV/\( c^2 \), and the number of signal events, \( N = 121^{+51}_{-34}(\text{stat.})^{+1.9}_{-28}(\text{syst.}) \). The local statistical significance of the signal is 4.3\( \sigma \) in this case. If the systematic uncertainties are taken into account, the statistical significance of the signal is 3.2\( \sigma \).

The ratio of the number of \( B^0_s \) which come from the decay of \( X(5568) \) to all \( B^0_s \) (\( X(5568) \) production ratio) was measured to be \( [7.3^{+2.8}_{-2.3}(\text{stat.})^{+0.6}_{-1.7}(\text{syst.})] \)% in the semileptonic channel.

![Figure 2. The \( m(B^0_s \pi^\pm) \) distributions for the hadronic (red squares) and semileptonic (black circles) data with the combined fitting function superimposed (a) with and (b) without the cone cut (see text for details and Tab. 1 for numerical results).](image-url)

The mass, natural width and \( X(5568) \) production ratio are in the agreement between the semileptonic and hadronic channels within uncertainties \[3\]. If we assume that we observe the same object in both channels and the semileptonic and hadronic measurements are independent, we can perform a combined simultaneous fit of the hadronic and semileptonic data sets. The shape parameters of the background terms are fixed to the values obtained from fitting the respective background models for the hadronic and semileptonic samples to the Eq. 1. The same Breit-Wigner parameters \( M_X, \Gamma_X \) are used for the hadronic and semileptonic samples. In the fits the normalization parameters and Breit-Wigner parameters \( M_X, \Gamma_X \) are allowed to vary. For the data without the cone cut the combined data are fitted in the range...
J/ψ be greater than 2. For accepted J/ψ and the transverse impact parameter significance vertex is required to be displaced from the primary vertex in the transverse plane by at least 5 J/ψ particle with p kaon or a proton.

b reconstructed direct decays of J/ψ be pions and select events in the mass range 4 coming from a displaced decay vertex. Unless indicated otherwise, we assume the hadrons to reconstructed invariant mass of the two muons must be 2 H where. One can see the substantial increase in significance combining two independent data samples.

Data Group as ψ(3900) in decays of b hadrons is unclear by now. It is possible, that there could be such hadrons is not well modeled for m(B_s π±) > 5.706 GeV/c² [3]. The obtained results are shown on Fig. 2 and in the Table 1. One can see the substantial increase in significance combining two independent data samples.

In conclusion we can say, that the X(5568) state reported in the case of the hadronic decay of B_s meson [3] is confirmed for the case of semileptonic decay of B_s meson [9]. The analysis of the hadronic and semileptonic data give similar measurements of the mass, width and production ratio of X(5568) to a B_s meson. The p-value for the null signal hypothesis to represent the data, obtained from the combined fit to hadronic and semileptonic data sets, is 1.5 × 10⁻¹¹ (6.7σ).

3. Evidence for Z_c±(3900) in semi-inclusive decays of b–flavored hadrons

The charged charmoniumlike state Z_c±(3900) was discovered in 2013 simultaneously by the Belle [11] and BESIII [12] collaborations in the sequential process e⁺e⁻ → Y(4260) → Z_c±(3900)π±, Z_c±(3900) → J/ψπ±. The BESIII Collaboration has measured the e⁺e⁻ → J/ψπ±π⁻ cross section at a range of energies from 3.77 to 4.6 GeV and reported that Y(4260) may consists of two states: the narrow state at about 4.22 GeV (denoted by the Particle Data Group [13] as ψ(4260)) and wider one at about 4.32 GeV (denoted as ψ(4360)) above a continuum, that may also be consistent with a broad resonance near 4.0 GeV [14]. The presence of Z_c±(3900) in decays of b hadrons is unclear by now. It is possible, that there could be such a production through the two-step process H_b → Y(4260) + anything, Y(4260) → Z_c±(3900)π±, where H_b represents any hadron containing a b quark. In this analysis [15], we look at the presence of such two-step processes, using 10.4 fb⁻¹ of data, collected by D0 experiment.

For this analysis we reuse a sample of events prepared for an earlier study of b hadron decays, containing a non-prompt J/ψ and a pair of oppositely charged particles, consistent with coming from a displaced decay vertex. Unless indicated otherwise, we assume the hadrons to be pions and select events in the mass range 4.1 < m(J/ψπ⁺π⁻) < 5.0 GeV that includes the Y(4260) states, and is high enough for production of Z_c±(3900) but low enough to exclude fully reconstructed direct decays of b hadrons to final states J/ψh+h⁻, where h stands for a pion, a kaon or a proton.

Candidate events are selected by requiring a pair of oppositely charged muons and a charged particle with p_T > 1 GeV at a common vertex with χ² < 10 for 3 degrees of freedom. The reconstructed invariant mass of the two muons must be 2.92 < m(μ⁺μ⁻) < 3.25 GeV, consistent with the J/ψ mass. To select final states originating from b hadron decays, the J/ψ + 1 track vertex is required to be displaced from the primary vertex in the transverse plane by at least 5σ, and the transverse impact parameter significance IP/σ(IP) of the hadronic track is required to be greater than 2. For accepted J/ψ + 1 track combinations, another track with p_T > 0.8 GeV and a charge opposed to the first track is added to form a common J/ψ + 2 tracks system. The

| Cone cut | No cone cut |
|----------|-------------|
| Fitted mass, MeV/c² | 5566.9±3.2(stat.)±0.3(syst.) | 5565.8±2.4(stat.)±1.2(syst.) |
| Fitted width, MeV/c² | 18.6±7.9(stat.)±3.5(syst.) | 16.3±9.8(stat.)±1.2(syst.) |
| Fitted number of hadronic signal events | 131±33(stat.)±13(syst.) | 99±40(stat.)±15(syst.) |
| Fitted number of semileptonic signal events | 147±32(stat.)±14(syst.) | 112±30(stat.)±9(syst.) |
| χ²/ndf | 94.7/(100 − 6) | 54.2/(50 − 6) |
| p-value | 2.2 × 10⁻¹⁴ | 1.9 × 10⁻⁸ |
| Local significance | 7.6σ | 5.6σ |
| Significance with LEE | 6.9σ | 5.0σ |
| Significance with LEE + systematics | 6.7σ | 4.7σ |
second track must have an $IP$ significance greater than 1, and its contribution to the $\chi^2$ of the $J/\psi + 2$ tracks vertex should be less than 6. We remove the events from decays $K^* \rightarrow K\pi$ or $\phi \rightarrow KK$ by applying the corresponding vetoes to the $K\pi$ or $KK$ invariant masses. Photon conversion is also vetoed with a cut on $m(\pi^+\pi^-)$.

![Graph](image)

**Figure 3.** Left: the invariant mass distribution of $J/\psi\pi^\pm$ candidates in the range $4.2 < m(J/\psi\pi^+\pi^-) < 4.7$ GeV. The solid line shows the result of the fit. The dashed line shows the combinatorial background parametrized with the fifth–order Chebyshev polynomial, and the dotted line shows the signal contribution. Right: the $Z^\pm_2(3900)$ signal yield per 50 MeV for the six intervals of $m(J/\psi\pi^+\pi^-)$: 4.1–4.2, 4.2–4.25, 4.25–4.3, 4.3–4.4, 4.4–4.7 and 4.7–5.0 GeV. The points are placed at the bin centers (see text for details).

The corresponding $m(J/\psi\pi^\pm)$ distribution is shown on Fig. 3 (left). We fit this distribution to the sum of a resonant signal represented by a relativistic $S$-wave Breit-Wigner function with a width fixed to $\Gamma = 28.2$ MeV smeared with the D0 mass resolution of $17 \pm 2$ MeV and a mass that is allowed to vary freely and an incoherent background parametrized with the Chebyshev polynomials of the first kind. The fit yields $N = 502 \pm 92$(stat.) $\pm 64$(syst.) signal events and $m = 3895.0 \pm 5.2$(stat.)$^{+14}_{-2.1}$(syst.) MeV. The local statistical significance of the signal is $5.6\sigma$.

The systematic uncertainties taken into account in this analysis include the mass calibration and mass resolution uncertainties, background shape uncertainty, bin size and signal model uncertainties, and uncertainty related to the natural width variation. When these uncertainties are taken into account in signal significance calculation, it changes from $5.6\sigma$ to $4.6\sigma$.

We perform binned maximum-likelihood fits to the $m(J/\psi\pi^\pm)$ distribution in six $J/\psi\pi^+\pi^-$ mass intervals of varying size, chosen to align with the $Y(4260)$ states (4.1–4.2, 4.2–4.25, 4.25–4.3, 4.3–4.4, 4.4–4.7, 4.7–5.0 GeV). These intervals contain roughly equal numbers of signal plus background events. The differential distribution of the signal yield, obtained from these fits, is shown in Fig. 3 (right). It can be seen, that there is a visible increase in the signal yield in the range $4.2 < m(J/\psi\pi^+\pi^-) < 4.25$ GeV, consistent with coming from $\psi(4260)$.

We also normalize the $Z^\pm_2(3900) \rightarrow J/\psi\pi^\pm$ signal in the parent mass range $4.2 < m(J/\psi\pi^+\pi^-) < 4.7$ GeV to the number of events in the decay $B_d^0 \rightarrow J/\psi K^*$. The latter are required to satisfy the same stringent kinematic and quality cuts as applied to the $J/\psi\pi^+\pi^-$ sample, except that the $K^*$ veto is “reversed” (it is required that at least one $K^\pm\pi^\mp$ pair in the event has an invariant mass which is consistent with the $K^*$ mass. If several such pairs are present, the pair with the invariant mass closer to the $K^*$ mass is selected). We fit the corresponding $J/\psi K^*$ distribution to obtain the number of $B_d^0 \rightarrow J/\psi K^*$ events and then calculate the ratio $N(Z^\pm_2(3900) \rightarrow J/\psi\pi^\pm)/N(B_d^0 \rightarrow J/\psi K^*)$. Since the two processes have the same topology and kinematic restrictions assure the uniform track finding efficiency, we assume that the efficiency factors cancel out in the ratio. The obtained value for the ratio is $0.085 \pm 0.019$. 


Belle collaboration did not see a significant signal from $Z_{c}^{\pm}(3900) \rightarrow J/\psi \pi^{\pm}$ in the decay $\bar{B}^{0} \rightarrow J/\psi \pi^{\pm} K^{\mp}$ [16]. We have studied the $J/\psi \pi^{\pm}$ mass in events consistent with this decay, excluding the events consistent with the decay $\bar{B}^{0} \rightarrow J/\psi K^{*}$. We observe no indications of the $Z_{c}^{\pm}(3900)$ and obtain the upper limit on the ratio to the $B_{d}^{0} \rightarrow J/\psi K^{*}$ decay of 0.015 at the 90% C.L.

In summary, our studies of the semi-inclusive decays of $b$ hadrons $H_{b} \rightarrow J/\psi \pi^{+} \pi^{-} +$ anything reveals a $Z_{c}^{\pm}(3900)$ signal that is correlated with the $J/\psi \pi^{+} \pi^{-}$ system in the invariant mass range 4.2–4.7 GeV that would include the neutral charmoniumlike states $\psi(4260)$ and $\psi(4360)$ [15]. The significance, including systematic uncertainties, is 4.6 standard deviations. Obtained ratio $N(Z_{c}^{\pm}(3900) \rightarrow J/\psi \pi^{\pm})/N(B_{d}^{0} \rightarrow J/\psi K^{*}) = 0.085 \pm 0.019$. We confirm the conclusion from [16], that there is no significant production of the $Z_{c}^{\pm}(3900)$ in the decay $\bar{B}^{0} \rightarrow J/\psi \pi^{\pm} K^{\mp}$ and set an upper limit on the rate of the process $B_{d}^{0} \rightarrow Z_{c}^{\pm}(3900) K^{\mp}$ relative to $B_{d}^{0} \rightarrow J/\psi K^{*}$ at 0.015 at the 90% C.L. With the present data sample we have no sensitivity to prompt production of the $Z_{c}^{\pm}(3900)$.

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