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The exotic state $X(5568)$

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The D0 collaboration has reported evidence for a possible four-quark state named $X(5568)$ in the decay sequence $X(5568) \to B_s^0 \pi^{\pm}$, $B_s^0 \to J/\psi\phi$. Here we present a progress report on our search for the $X(5568)$ with semileptonic decays of the B_s^0 meson. A comparison of the data with MC simulations of the background shows an excess of events in the data at the mass and yield as expected from events produced by the decay $X(5568)$.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

*A footnote may follow.

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Recently the D0 collaboration has reported evidence for a possible four-quark state designated the $X(5568)$ in the decay to $B_s^0\pi^\pm$ using $B_s^0 \to J/\psi\phi$ [1] . This system would be composed of two quarks and two antiquarks of four different flavors: b, s, u, d, which might be a tightly bound di-quark anti-diquark pair such as $[bd][\overline{su}]$, $[bu][\overline{ds}]$, $[su][\overline{bd}]$, or $[sd][\overline{bu}]$, or a "molecule" of loosely bound B and K mesons. We briefly recall that evidence and present a progress report on the search for $X(5568)$ in the decay to $B_s^0\pi^\pm$ using semileptonic B_s^0 decays, $B_s^0 \to \mu^+ D_s^- X$ (charge conjugate states are assumed in this note).

1. The D0 Detector and Data

The D0 detector has a central tracking system consisting of a silicon microstrip tracker (SMT) and the central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet [2, 3]. A muon system, covering $|\eta| < 2$ [4], consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two similar layers after the toroids [5].

The $B_s^0 \to J/\psi\phi$ and $B_s^0 \to \mu^+ D_s^- X$ data are collected with a suite of single and dimuon triggers. Muons are required to have hits in at least two layers of the muon system, with segments reconstructed both inside and outside the toroid. The muon track segment has to be matched to a particle found in the central tracking system.

The $B_s^0 \to \mu^+ D_s^- X$ data selection requirements have been chosen to optimise the mass resolution of the $B_s^0\pi^\pm$ system and to minimise the combinatorial background to the signal. The $D_s^- \to \phi\pi^-$; $\phi \to K^+K^-$ decay is reconstructed as follows. The two particles from the ϕ decay are assumed to be kaons and are required to have $p_T > 1.0$ GeV/c, opposite charge and a mass $1.012 < M(K^+K^-) < 1.03$ GeV/c^2. The charge of the third particle, assumed to be the charged pion, has to be opposite to that of the muon with $0.5 < p_T < 25$ GeV/c. The three tracks are combined to create a common D_s^- decay vertex using the algorithm described in Ref. [6]. To reduce combinatorial background, the D_s^- vertex is required to have a displacement from the $p\bar{p}$ interaction vertex (PV) in the transverse plane with a significance of at least three standard deviations. The cosine of the angle between the D_s^- momentum and the vector from the PV to the D_s^- decay vertex is required to be greater than 0.9. The trajectories of the muon and D_s^- candidates are required to be consistent with originating from a common vertex (assumed to be the B_s^0 decay vertex) consistent with coming from a B_s^0 semileptonic decay. To reduce combinatoric backgrounds and to minimise the effect of the neutrino in the final state the effective mass is limited to $4.5 < M(\mu^+ D_s^-) < 5.4$ GeV$/c^2$. To reduce background the transverse momentum of $\mu^+ D_s^-$ system is required to be greater than 10 GeV/c. The cosine of the angle between the combined $\mu^+ D_s^-$ direction, an approximation of the B_s^0 direction in the direction from the PV to the B_s^0 decay vertex has to be greater than 0.95. The B_s^0 decay vertex has to be displaced from the PV in the transverse plane with a significance of at least four standard deviations. These criteria ensure that the D_s^- and μ^+ momenta are correlated with that of their B_s^0 parent and that the D_s^- is not mistakenly associated with a random muon.

The impact parameters with respect to the primary vertex (IP) [7] of the tracks that form the $\mu^+ D_s^-$ candidate are required to satisfy the following criteria: the two-dimensional (2D) IPs of the tracks for the muon and the pion are required to be at least 50 μm and the three-dimensional

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(3D) IPs of all four tracks are required to be less than 2 cm. The $M(K^+K^-\pi^-)$ distribution of the candidates that pass these cuts are shown in Fig. 1, where the the invariant mass distributions in data is compared to the signal and background fit. The number of $D_s^\pm$ signal decays determined from a fit is 9511 ± 83.

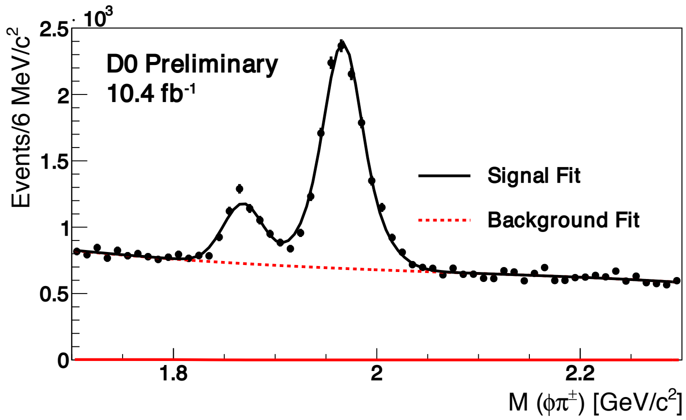

Figure 1: The $K^+K^-\pi^\mp$ invariant mass distribution for the $\mu^\pm\phi\pi^\mp$ sample with the solid line representing the signal fit and the dashed line showing the background fit. The lower mass peak is due to the decay $D^\mp \to \phi\pi^\mp$ and the second peak is due to the $D_s^\mp$ meson decay.

To form a $B_s^0\pi^\pm$ combination, we select $D_s^\pm$ candidates in the mass range $1.92 < M(K^+K^-\pi^-) < 2.02$ GeV$/c^2$ corresponding to an interval of approximately ± 2 standard deviations around the mean value of the reconstructed $D_s^\pm$ mass. The number of signal events in this region is $N_{\rm ev} = 8932$ with a combinatorial background of 8285 events.

A track representing the additional pion is required to have transverse momentum $0.5 < p_T < 25$ GeV$/c$. The additional track and the B_s^0 candidate are combined to form a decay vertex. The event is rejected if there are more than 20 tracks that can be associated with the B_s^0. The additional pion is required to be associated with the PV and have a 2D IP of at most 290 μm and a 3D IP that is less than 0.12 cm. To improve the resolution of the invariant mass of the $B_s^0\pi^\pm$ system we define the invariant mass as $M(B_s^0\pi^\pm) = m(\mu D_s^\pm\pi) - m(\mu D_s^\pm) + m(B_s^0)$ where $m(B_s^0) = 5.3667$ GeV$/c^2$. We study events as a function of mass in the range $5.506 < M(B_s^0\pi^\pm) < 5.906$ GeV$/c^2$.

2. Monte Carlo Simulation

We generate the background MC sample using the PYTHIA event generator [8] modified to use EVTGEN [9] for the decay of hadrons containing b or c quarks. The PYTHIA inclusive QCD production model is used. Events recorded in random beam crossings are overlaid over the simulated events to quantify the effect of additional collisions in the same or nearby bunch crossings. Events are selected that contain at least one muon and a $D_s^\pm \to \phi\pi^\pm$ decay. The generated events are processed by the full simulation chain, and then by the same reconstruction and selection algorithms as used to select events from real data. The resulting invariant mass distribution is shown in Fig. 2a.

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The signal MC sample for $X(5568)$ decays where $B_s^0 \to \mu^+ D_s^- X$ is generated by modifying the mass of the B^+ meson and forcing it to decay to $B_s^0\pi$. Four samples were generated with masses of 5550, 5568, 5600, and 5625 MeV/c^2. The $X(5568)$ was simulated with no natural width (0 MeV). The resulting invariant mass distribution is shown in Fig. 2b. . The detector resolution depends on M_X and is determined using the MC signal simulations to be 8.1 MeV at $M_X = 5550$ MeV$/c^2$ and 16.8 MeV$/c^2$ at $M_X = 5625$ MeV$/c^2$.

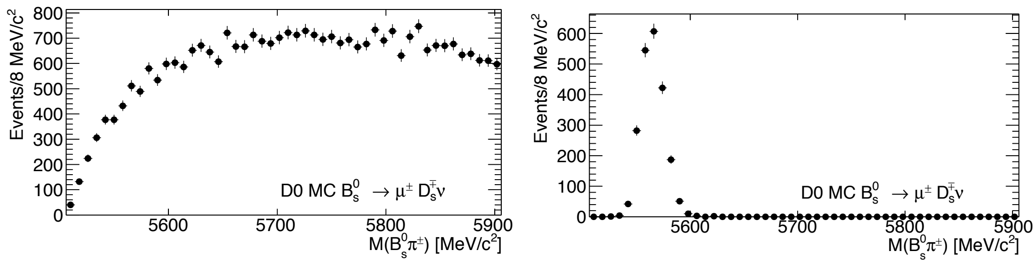

Figure 2: MC simulation of $X \to B_s^0\pi^\pm$ where $B_s^0 \to \mu^+ D_s^- X$. The background sample is plotted on the left and a signal sample with $M_X = 5568$ MeV$/c^2$ and $\Gamma_X = 0$ is on the right.

3. Estimation of Size of the Expected Signal

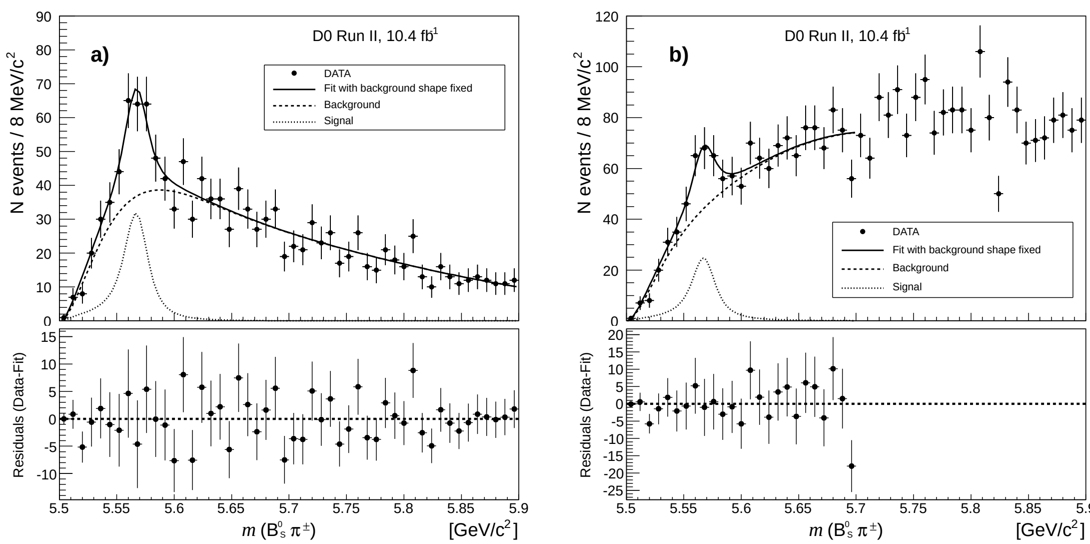

Figure 3: The $m(B_s^0\pi^\pm)$ distribution together with the background distribution and the fit results (a) after applying the $\Delta R < 0.3$ cone cut and (b) without the cone cut for the decay channel $B_s^0 \to J/\psi\phi$.

In Ref [1] a signal of approximately 100 $X(5568)$ events was found from a sample of 5582 $B_s^0 \to J/\psi\phi$ events, see Fig. 3. This corresponds to approximately 0.018 $X(5568)$ events for each B_s^0 event in the data sample. The percentage of B_s^0 events in the $\mu^+ D_s^- X$ peak has been measured in Ref. [10] and is approximately 90%. This means we expect ~ 150 signal events in our sample.

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4. Comparison of MC Background Sample with the Data

To test the agreement between the simulation of the MC background sample and the data the Kolmogorov-Smirnov (KS) test is used. The data in the mass window $5.530 < M_{B_s^0\pi} < 5.586$ GeV$/c^2$ is excluded from the KS test since this is the location of the expected signal. A KS test probability of 0.796 is determined indicating excellent agreement between the two distributions. The KS test probability drops to 0.136 if the comparison is carried out over the full mass range.

The data and MC are then shown on Fig. 4. The MC has been normalised to the data excluding the bins in the mass range $5.530 < M_{B_s^0\pi} < 5.586$ GeV$/c^2$. An excess of events can be seen at the same mass as the $X(5568)$ as reported in Ref. [1]. The difference in the number of events between the data and the MC simulation in the mass window $5.530 < M_{B_s^0\pi} < 5.586$ GeV$/c^2$ is consistent with yield expected from events produced by the decay $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$.

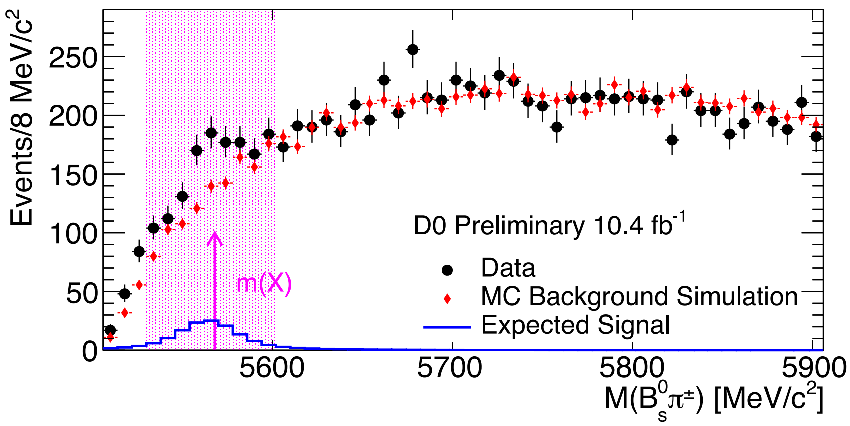

Figure 4: The invariant mass distribution $M(B_s^0\pi^\pm)$ for data and the MC. The MC has been normalised to the data excluding the bins in the mass range $5.530 < M_{B_s^0\pi} < 5.586$ GeV$/c^2$. The arrow indicates the mass of the mass of the $X(5568)$ as measured in Ref. [1]

5. Conclusion

In summary, we have presented a progress report on our search for the $X(5568)$ with semileptonic decays of the B_s^0 meson. We have shown a comparison of the data with MC simulations of the background. There is an excess of events in the data consistent in mass and yield with the decay $X(5568) \to B_s^0\pi^\pm$ reported in Ref. [1].

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[4] $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity and θ is the polar angle between the track momentum and the proton beam direction. ϕ is the azimuthal angle of the track.

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