DØ Note 6488-CONF

Search for the $X(5568)$ with semileptonic decays of the B_s^0 meson

The D0 Collaboration
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The D0 collaboration presents a progress report on a search for the $X(5568)$ with semileptonic decays of the B_s^0 meson using the full Run II integrated luminosity of 10.4 fb^{-1} in proton-antiproton collisions collected with the D0 detector at the Fermilab Tevatron Collider. A preliminary comparison of the data with Monte Carlo simulations of the background is presented. There is an excess of events in the data which is in the mass region expected from events produced by the decay $X(5568) \to B_s^0\pi^\pm \to J/\psi\phi\pi^\pm$ as measured in Ref. [1].

Preliminary Results for Summer 2016 Conferences

I. INTRODUCTION

Recently the D0 collaboration found evidence for a possible four-quark state designated the $X(5568)$ with a significance of 5.1σ in the decay to $B_s^0\pi^\pm$ using $B_s^0 \to J/\psi\phi$ [1] with mass $m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})$ MeV/c^2 and natural width $\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})$ MeV/c^2. This system would be composed of two quarks and two anti-quarks of four different flavors: b, s, u, d, which might be a tightly bound di-quark anti-diquark pair such as $[bd][\bar{s}\bar{u}]$, $[bu][\bar{d}\bar{s}]$, $[su][\bar{b}\bar{d}]$, or $[sd][\bar{b}\bar{u}]$, or a "molecule" of loosely bound B and K mesons. This note presents a progress report on the search for $X(5568)$ in the decay to $B_s^0\pi^\pm$ using semileptonic B_s^0 decays, $B_s^0 \to \mu^+ D_s^- X$ from the full Run II integrated luminosity of 10.4 fb^{-1} in proton-antiproton collisions collected with the D0 detector at the Fermilab Tevatron Collider (charge conjugate states are assumed in this note).

II. THE D0 DETECTOR

The detector components most relevant to this analysis are the central tracking and the muon systems. 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 iron toroidal magnets, followed by two similar layers after the toroids [5].

III. DATA SELECTION

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 combinatoric background in the signal region.

The data were collected using a suite of single and dimuon triggers. The selection and reconstruction of $\mu^+ D_s^- X$ decays requires tracks with at least two hits in both the CFT and SMT. 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 which has transverse momentum $3 < p_T < 25$ GeV/c.

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 combinatoric 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 missed 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 have $p_T > 10$ GeV/c. The cosine of the angle between the combined $\mu^+ D_s^-$ direction and 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 angular criteria ensure that the D_s^- and μ^+ momenta are correlated with a B_s^0 parent and that the D_s^- is not mistakenly associated with a random muon.

The impact parameter (IP) in the transverse plane with respect to the primary vertex [7] of the four tracks that form the $\mu^+ D_s^-$ candidate are required to satisfy the following criteria: the 2 dimensional (2D) IPs of the tracks for the muon and the pion are required to be at least 50μm and the three dimensional (3D) IPs of all four of the tracks are required to be less than 2 cm.

The $M(K^+K^-\pi^-)$ mass distribution of the candidates that pass these cuts is 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, where the uncertainty is statistical.

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 $N_{\text{ev}} = 8932$ with a combinatoric background of 8285 events.

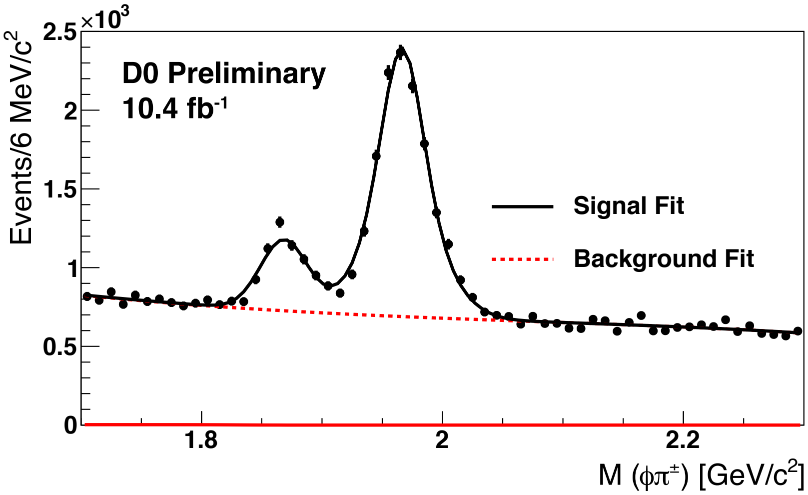


FIG. 1: The $K^+K^-\pi^{\mp}$ invariant mass distribution for the $\mu^{\pm}\phi\pi^{\mp}$ sample with the solid line representing the signal fit and the dashed line showing the background fit. The lower mass peak is due to the decay $D^{\mp} \rightarrow \phi\pi^{\mp}$ and the second peak is due to the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

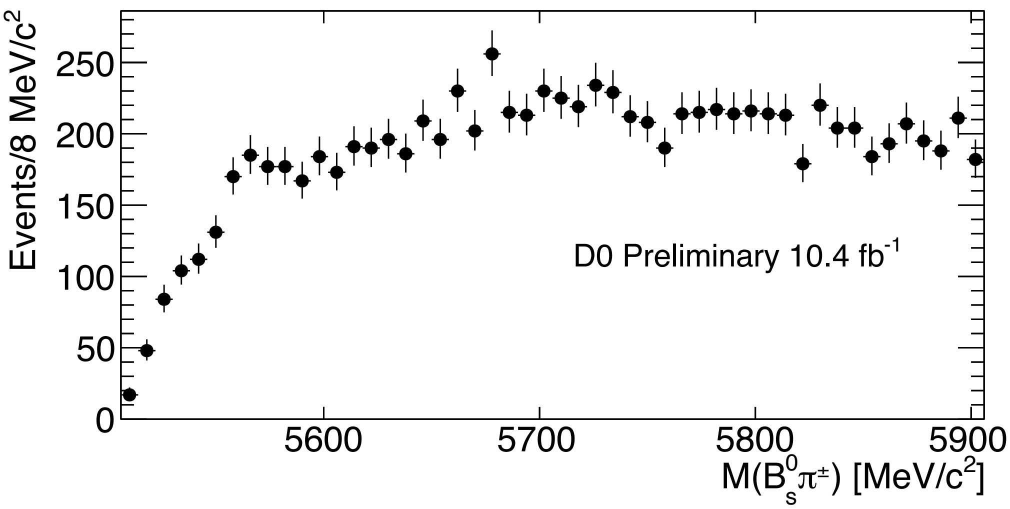


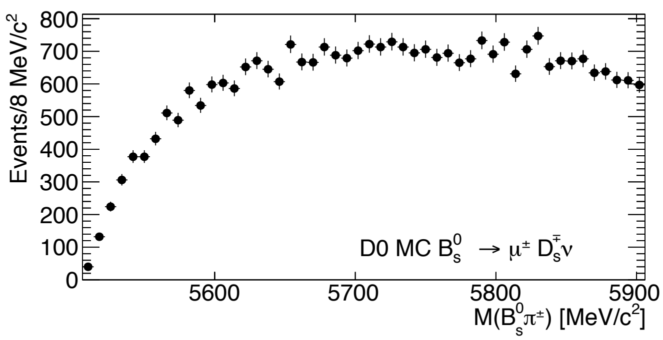
FIG. 2: The $M(B_s^0\pi^{\pm}) = m(\mu D_s^{\pm}\pi) - m(\mu D_s^{\pm}) + m(B_s^0)$ invariant mass distribution for the selected data sample.

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 that is consistent with the PV. If there are more than 20 tracks that can be associated with the B_s^0 then the event is rejected. 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 $m(B_s^0) = 5366.7$ MeV/c^2 [8]. We study events as a function of mass in the range $5506 < M(B_s^0\pi^{\pm}) < 5906$ MeV/c^2. The mass distribution is shown in Fig. 2.

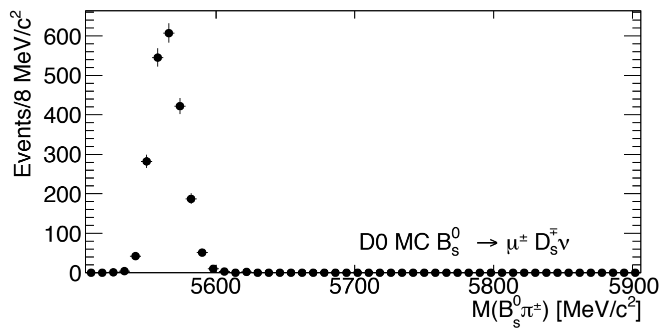
IV. MONTE CARLO SIMULATION

We generate a background Monte Carlo (MC) sample using the PYTHIA event generator [9] modified to use EVTGEN [10] 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 on 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 $D_s^{\pm} \rightarrow \phi\pi^{\pm}$ decay. The generated events are processed by the full simulation chain, and then by the same reconstruction and selection algorithms and requirements as used to select events in data. The resulting invariant mass distribution is shown in Fig. 3a. There is no simulation of the $D_s^{\pm}$ combinatoric background where a random track is associated with a ϕ that represents the background fit in Fig. 1.

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 $B_s^0\pi^{\pm}$. 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/c^2). The resulting invariant mass distribution is shown in Fig. 3b. This distribution was fitted with a Gaussian function to give a mean of 5565 ± 0.3 MeV/c^2 and a width of 10.7 MeV/c^2. The detector resolution is smaller than the measured natural width of the $X(5568)$, $\Gamma_X = 21.9$ MeV/c^2, so the total width will be approximately 25 MeV/c^2. The detector resolution depends on M_X and is determined from the MC signal simulations to be 8.1 MeV/c^2 at $M_X = 5550$ MeV/c^2 and 16.8 MeV/c^2 at $M_X = 5625$ MeV/c^2.



(a) MC simulation of the background.



(b) MC simulation of the signal.

FIG. 3: MC simulation of $X \to B_s^0\pi$ 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 $\Gamma_x = 0$ MeV/c^2 is on the right.

V. ESTIMATION OF SIZE OF THE EXPECTED SIGNAL

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, corresponding 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. [11] and is at least 90%. This means we expect approximately 150 signal events in the sample.

VI. COMPARISON OF MC BACKGROUND SAMPLE WITH THE DATA

To test the agreement between the simulation of the MC background sample of real $\mu D_s^{\pm}$ events only (i.e. excluding the combinatoric background in Fig. 1) and the data, the Kolmogorov-Smirnov (KS) test is used. The data in the mass window $5530 < M_{B_s^0\pi} < 5602$ MeV/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 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 in Fig. 4. The MC has been normalised to the data excluding the bins in the mass range $5530 < M_{B_s^0\pi} < 5602$ MeV/c^2. An excess of events can be seen at the same mass as the $X(5568)$ as observed in Ref. [1]. The difference in the number of events between the data and the MC simulation in the mass window $5530 < M_{B_s^0\pi} < 5602$ MeV/c^2 is consistent with yield expected from events produced by the decay $X(5568) \to B_s^0\pi^{\pm}$ with $B_s^0 \to J/\psi\phi$.

VII. CONCLUSION

In summary, we have presented a progress report on a search for the $X(5568) \to B_s^0\pi^{\pm}$ with semileptonic decays of the B_s^0 meson. We have shown a preliminary comparison of the data with MC simulations of the background. There is an excess of events in the data in the mass region expected from events produced by the decay $X(5568) \to B_s^0\pi^{\pm}$ with $B_s^0 \to J/\psi\phi$ as measured in Ref. [1] with similar width and consistent yield.

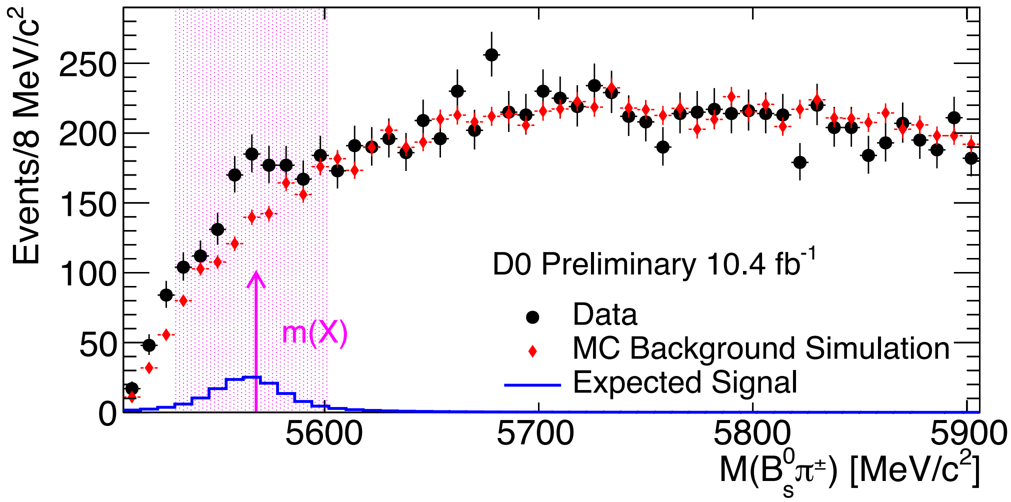


FIG. 4: The invariant mass distribution $M(B_s^0\pi^\pm)$ for data and the MC. The MC has been normalised to the data excluding the bins in the mass range $5530 < M_{B_s^0\pi} < 5602$ MeV/c^2 (pink rectangle). The arrow indicate the mass of the mass of the $X(5568)$ as measured in Ref. [1]. The blue histogram illustrates a relativistic Breit-Wigner with mass $M_X = 5602$ MeV/c^2 and a natural width $\Gamma = 21.9$ MeV/c^2 convoluted with a Gaussian function representing the detector resolution of 10.7 MeV/c^2 with the expected yield of 150 events.

VIII. ACKNOWLEDGEMENTS

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[1] V.M. Abazov *et al.*, (DØ Collaboration), *Evidence for a $B_s^0\pi^\pm$ State*, Phys. Rev. Lett. **117**, 022003 (2016).
[2] V. M. Abazov *et al.* (D0 Collaboration), *The upgraded D0 detector*, Nucl. Instrum. Methods Phys. Res. A **565**, 463 (2006).
[3] R. Angstadt *et al.*, *The layer 0 inner silicon detector of the D0 experiment*, Nucl. Instrum. Methods Phys. Res. A **622**, 278 (2010).
[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.
[5] V. M. Abazov *et al.* (D0 Collaboration), *The muon system of the Run II D0 detector*, Nucl. Instrum. Methods Phys. Res. A **552**, 372 (2005).
[6] J. Abdallah *et al.* (DELPHI Collaboration), *b-tagging in DELPHI at LEP*, Eur. Phys. J. C **32**, 185 (2004).
[7] The impact parameter IP is defined as the distance of closest approach of the track to the $p\bar{p}$ collision point projected onto the plane transverse to the $p\bar{p}$ beams.
[8] K.A. Olive *et al.* (Particle Data Group), *Review of Particle Physics*, Chin. Phys. C, **38**, 090001 (2014) and 2015 update.
[9] T. Sjöstrand, S. Mrenna and P. Z. Skands, *PYTHIA 6.4 physics and manual*, J. High Energy Phys. **05**, (2006) 026.
[10] D.G. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Methods Phys. Res. A **462**, 152 (2001); for details see http://www.slac.stanford.edu/~lange/EvtGen.
[11] V. M. Abazov *et al.* (D0 Collaboration), *Measurement of the Semileptonic Charge Asymmetry using $B_s^0 \to \mu^+ D_s^- X$ Decays* Phys. Rev. Lett. **110**, 011801 (2013).