Exotic states at D0

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(On behalf of D0 Collaboration)

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Exotic states at D0

\[ X(5568) \rightarrow B_s\pi \]

\[ B_s\pi^\pm \text{ state with } B_s^0 \rightarrow J/\psi\phi \]

(PRL 117, 022003 (2016))

New: \[ B_s^0 \rightarrow D_s\mu\nu \text{ channel} \]
Exotic states at D0

D0 detector in Tevatron Run II

Scintillator counters and drift tubes
Thick calorimeter and iron toroids
**Excellent muon triggering and ID**

Silicon Microstrip Tracker
**Excellent vertex resolution**

Central Fiber Tracker
**Good mass resolution**

Excellent for $B$ physics with muons
Data

Looking for a state decaying strongly to $B_s \pi^\pm$ using the full Run II dataset of 10.4 fb$^{-1}$ collected at Tevatron between 2001 and 2011.

Require a single muon or dimuon trigger.
Reconstruct $B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$
Require a displaced decay vertex $L_{xy}/\sigma(L_{xy}) > 3$

Add a track assumed to be a pion, consistent with coming from $p\bar{p}$ interaction vertex

- $p_T(\pi) > 0.5$ GeV, $IP_{xy} < 200$ $\mu$m, $IP_{3D} < 1200$ $\mu$m (charm decay not ruled out)
- $p_T(B_s \pi) > 10$ GeV, $|y(B_s \pi)| < 2$
- We perform the analysis with and without a limit on the angular separation between the $B_s^0$ and the pion:
  $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$ (the “cone” cut)
Two background components

The $B_s^0$ signal:

$M = 5363.3 \pm 0.6$ MeV

$\sigma = 31.6 \pm 0.6$ MeV

$N = 5582 \pm 100$

$B_s^0$ signal region ($\pm 2\sigma$)

$5303 < m(J/\psi\phi) < 5423$ MeV

$B_s^0$/non-$B_s^0 = 71%/29%$

We pair a $B_s^0$ candidate in the signal region with a charged track assumed to be a pion to form a $B_s^0\pi^\pm$ candidate.

In the $B_s^0$ signal region, there is (1) $B_s^0$ signal and (2) Non-$B_s^0$ background. (1) is simulated with Pythia, (2) is taken from sidebands selected such that their “center-of-gravity” is at $M(B_s)$. (1) + (2) are combined in the right proportion.

We define the $B_s^0\pi$ mass as:

$m(B_s^0\pi^\pm) = m(J/\psi\phi\pi^\pm) - m(J/\psi\phi) + 5366.7$ MeV/c$^2$
Background model

The two background components have a very similar shape. It is parametrized as $(c_0 + c_2 \cdot x^2 + c_3 \cdot x^3 + c_4 \cdot x^4) \times \exp(c_5 + c_6 \cdot x + c_7 \cdot x^2)$, $x \equiv m(B_s^0 \pi^\pm) - 5.5$.

The same parametrization (with different values) works for background with and without the $\Delta R < 0.3$ cut. The cut efficiency is 100% up to $m = 5.57$ GeV, then it drops. It is taken into account in the signal model.
Results for the case with $\Delta R$ cut

$M_X = 5567.8 \pm 2.9$ MeV

$\Gamma_X = 21.9 \pm 6.4$ MeV

$N = 133 \pm 31$

Signif. (with syst and LEE) $S = 5.1\sigma$

(“Local” $S = 6.6\sigma$).

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Signal is modeled by a relativistic Breit-Wigner function convolved with a Gaussian resolution of $\sigma = 3.8$ MeV (MC) and multiplied by mass-dependent efficiency.

With background shape parameters obtained from a mixture of MC and side-bands, the only free parameters are the signal and background normalizations and the signal mass and natural width.

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Alternative signal extraction

Reverse the search: Look for the $B_s^0$ signal as a function of $m(J/\psi\phi\pi)$

For each of 20 bins in the $m(J/\psi\phi\pi)$ distribution, fit for the number of $B_s^0$. Plot the $B_s^0$ yield as a function of $m(J/\psi\phi\pi)$ as shown in the figure. Fit this distribution to obtain the yield of $X(5568)$. This method only has the background from real $B_s^0$ and a random pion.

$\Delta R < 0.3$

$M_X \equiv 5567.8$ MeV

$\Gamma_X \equiv 21.9$ MeV

$N = 118 \pm 22$
Exotic states at D0

No $\Delta R$ cut analysis

Data (red points) vs background model (blue lines) at $m(B_s^0\pi^\pm) > 5.6$ GeV

\[ \Delta R < 0.3 \text{ KS probability} = 0.999 \quad \text{No cone cut KS probability} = 0.003 \]

In the case of no $\Delta R$ cut, the model is above data at lower masses and below data at higher masses. This may be due to sources of $B_s^0$ not included in the simulations, e.g. $B_c \rightarrow B_s^0\pi^+\pi^0$.

Without the $\Delta R$ cut, $N = 106 \pm 33$.
Significance (with syst and LEE) = 3.9$\sigma$.

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Does the $\Delta R$ cut sculpt the $X(5568)$ signal?

We repeated the fits varying the $\Delta R$ cut below and above 0.3. (The non-$\Delta R$ point is marked in red.) The signal mass is stable.
Cross-checks performed

- Use left (right) sideband for the non-$B_s^0$ background
- Use two versions of Pythia for the $B_s^0$ background
- Compare sidebands with “undersignal”
- Allow background shape parameters to be free
- Use different $B_s^0$ mass ranges; modify the $B_s^0$ vertex cuts
- Compare $\pi^+$ and $\pi^-$ subsamples
- Examine different detector regions ($\phi$, $\eta$)
- Examine different data taking periods (over 10 years)
- Test $B_s^0K$ and $B_s^0p$ hypotheses
- Study $m(B_d^0\pi^{\pm})$ on the full Run II data sample *
- Look for decay $B_s^{**} \rightarrow B_s^0\pi^+\pi^-$
Cross-check with $B^0_d \pi^\pm$

The decay chain $B^0_d \rightarrow J/\psi K^*, \ K^* \rightarrow K^\pm \pi^\mp$ has a topology similar to $B^0_s \rightarrow J/\psi \phi, \ \phi \rightarrow K^+ K^-$. We reconstructed the quantity $m(J/\psi K^* \pi^\pm) - m(J/\psi K^*) + 5.3667 \text{ GeV}/c^2$ using the same selection criteria, including the $\Delta R$ cut.

The distribution is in agreement with the background model derived for the published analysis. The observed enhancements correspond to three known excited $B$ meson states reported by D0 in PRL 99, 172001 (2007).
## Systematic uncertainties

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

Systematic errors smaller than statistical error.

The yield of the $X(5568)$ signal reconstructed through $B_s^0\pi^\pm$, $B_s^0 \rightarrow J/\psi\phi$ is $N = 133 \pm 31 \pm 15$. 

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New channel: $B^0_s \rightarrow D_s \mu\nu$ reconstruction

Reconstruct $D_s \rightarrow \phi\pi$, $\phi \rightarrow K^+K^-$ require $1.92 < m(\phi\pi) < 2.02$ GeV

Add a $\mu$ coming from the same vertex require $4.5 < m(\mu D_s) > 5.4$ GeV

The lower peak is due to $D^\pm$ decays.

MC: $\sigma = 10$ MeV at $M = 5.57$ GeV.

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New channel: $B_s^0 \pi^\pm$, $B_s^0 \rightarrow D_s \mu \nu$

Estimate the number of expected events

$B_s^0 \rightarrow D_s \mu \nu$

The number of reconstructed $D_s$ decays in $D_s$ window is $\approx 8900$
MC: more than 90% of them come from from $B_s$.
So, we have $\approx 8000$ $B_s$ events compared to $\approx 5500$ in the $J/\psi \phi$ channel.

$X(5568) \rightarrow B_s^0 \pi^\pm$ candidates:
Add a charged pion as in the published analysis.
Focus on the case of no $\Delta R$ cut where the significance was lower.
Based on the $\approx 100$ event yield in the $J/\psi \phi$ channel, we expect $\approx 150$ $X(5568)$ events in the $B_s^0 \rightarrow D_s \mu \nu$ channel.
Comparison of data and simulated background

We simulate the component of the background due to random combinations of $B_s^0 \to D_s \mu \nu$ with a track assumed to be a pion and compare it to data.

We see an enhancement whose mass, width and yield are consistent with those in the $X(5568) \to B_s^0 \pi^\pm$, $B_s^0 \to J/\psi \phi$ publication.
Summary

D0 reported seeing a state decaying to $B_s^0\pi^\pm$ with $B_s^0 \rightarrow J/\psi\phi$

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It is produced in $p\bar{p}$ collisions promptly or via charm decay

It undergoes a strong decay to $B_s\pi$ or to $B_s^*\pi$ followed by $B_s^* \rightarrow B_s\gamma$ with unseen $\gamma$

$X \rightarrow B_s^0\pi^\pm$ ($J^P = 0^+$) $m = 5567.8 \pm 2.9$ (stat)$^{+0.9}_{-1.9}$ (syst) MeV

$X \rightarrow B_s^*\pi^\pm$ ($J^P = 1^+$) $m = 5616$ MeV

The mass is 60 MeV (if $0^+$) and 110 MeV (if $1^+$) above the $B_s\pi$ threshold and $\approx$200 MeV below the $BK$ threshold.

$\Gamma = 21.9 \pm 6.4$ (stat)$^{+5.0}_{-2.5}$ (syst) MeV

$\rho = \sigma(X(5568)^\pm)BF(X \rightarrow B_s^0\pi^\pm)/\sigma(B_s^0) = (8.6 \pm 1.9 \pm 1.4)\%$

New: We see an enhancement in $m(B_s^0\pi^\pm)$ with $B_s^0 \rightarrow D_s\mu\nu$

at the same mass and at the expected width and rate.