Search for Multi-quark Exotic states with Heavy Flavor at DØ Experiment

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on behalf of the DØ Collaboration
Outline

- Evidence for a $X(5568) \rightarrow B_s \pi$
- Confirmation of the $X(5568)$ with semileptonic decays of $B_s$ meson
- Search for exotic baryons decaying to $J/\psi \Lambda$ pairs
- Conclusion
Evidence for $B_s\pi$ state, $B_s \rightarrow J/\psi \phi(1020)$

$X(5568) \rightarrow B_s^0 \pi^\pm,$

$B_s^0 \rightarrow J/\psi \phi, J/\psi \rightarrow \mu^+\mu^-, \phi \rightarrow K^+K^-.$

**Event reconstruction and selection**

D0 Run II integrated luminosity 10.4 fb$^{-1}$

- $p_T(\mu) < 1.5$ GeV/c;
- $2.92 < M(\mu\mu) < 3.25$ GeV/c$^2$;
- $p_T(K) > 0.7$ GeV/c;
- $1.012 < M(K^+K^-) < 1.03$ GeV/c$^2$;
- $5.303 < M(J/\psi K^+K^-) < 5.423$ GeV/c$^2$;

- $p_T(\pi) > 0.5$ GeV/c;
- $p_T(B_s^0\pi) > 10$ GeV/c;

$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} < 0.3$, the “cone” cut between $B_s$ and $\pi$.

$M(B_s\pi) = M(J/\psi\phi\pi) - M(J/\psi\phi) + M(B_s),$

where $M(B_s) = 5.3667$ GeV/c$^2$

$5.5 < M(B_s\pi) < 5.9$ GeV/c$^2$
Evidence for $B_s \pi$ state, $B_s \to J/\psi \phi(1020)$

**Background:**
- a.) Real $B_s$ – modeled by MC; b.) non-$B_s$ (combinatorial) – taken from $B_s$ sidebands (data). Both have a similar shape and were combined in right proportion.

**Background parametrization:**
$$(c_1 + c_2 \cdot m^2 + c_3 \cdot m^3 + c_4 \cdot m^4) \times \exp(c_5 + c_6 \cdot m + c_7 \cdot m^2),$$
where $m = M - 5.5 \text{ GeV}/c^2$.

**Signal:** Relativistic $S$-wave Breit-Wigner convoluted with Gaussian resolution $\sigma = 3.8 \text{ MeV}/c^2$.

**Fitting function:**
$$N_X \cdot F_{\text{sig}}(m, M_X, \Gamma_X) + f_{\text{bkg}} \cdot F_{\text{bkg}}(m),$$
with free $N_X, M_X, \Gamma_X, f_{\text{bkg}}$.
Evidence for $B_s \pi$ state, $B_s \to J/\psi \phi(1020)$

$X(5568)$

$M = 5567.8 \pm 2.9\,\text{(stat)}^{+0.9}_{-1.9}\,\text{(syst)}\,\text{MeV}/c^2$

$\Gamma = 21.9 \pm 6.4\,\text{(stat)}^{+5.0}_{-2.5}\,\text{(syst)}\,\text{MeV}/c^2$

$\rho(X(5568)/B_s) = 8.6 \pm 1.9\,\text{(stat)} \pm 1.4\,\text{(syst)}\%$

Statistical significance (with systematics and LEE)

With $\Delta R = \sqrt{\Delta \eta + \Delta \phi} < 0.3$ cut: $5.1\sigma$

Without $\Delta R$ cut: $3.9\sigma$

Not seen by LHCb and CMS in pp collisions at 7 and 8 TeV/c$^2$.

**X(5568) → B_sπ** with semileptonic decays of the B_s mesons

\[ X(5568) \rightarrow B_s \pi, \ B_s \rightarrow D_s \mu X_{\text{any}}, \ D_s \rightarrow \phi(1020) \pi \]

**Event reconstruction and selection**

D0 Run II integrated luminosity 10.4 fb\(^{-1}\)

- \(3 < p_T(\mu) < 25 \text{ GeV/c};\) \(p_T(K) > 1 \text{ GeV/c};\)
- \(1.012 < M(KK) < 1.03 \text{ GeV/c}^2\)
- \(4.5 < M(D_s\mu) < M(B_s);\) \(p_T(D_s\mu) > 10 \text{ GeV/c}\)

\[ M(B_s\pi) = M(D_s\mu\pi) - M(D_s\mu) + M(B_s), \]

where \(M(B_s) = 5.3667 \text{ GeV/c}^2\)

- \(5.506 < M(B_s\pi) < 5.906 \text{ GeV/c}^2\)

**Graphs:**

- Good mass resolution even in presence of missing neutrino

**Equation:**

\[ M(B_s\pi) = M(D_s\mu\pi) - M(D_s\mu) + M(B_s), \]
\( \mathcal{X}(5568) \to B_s \pi \) with semileptonic decays of the \( B_s \) mesons

**Background parametrization**

Background distribution is obtained from MC and reweighted to data.

\[
F_{\text{bgr}}(m) = (C_1 \cdot m + C_2 \cdot m^2 + C_3 \cdot m^3 + C_4 \cdot m^4) \times \exp(C_5 \cdot m + C_6 \cdot m^2), \quad \text{where} \quad m = M - M_{\text{thr}}
\]

Several alternative parametrizations of the background were used to model the background for background shape systematics estimation.

**Fit to data**

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

where \( F_{\text{sig}}(m, M_x, \Gamma_X) \) - S-wave BW function convoluted with resolution (including missing neutrino effect), \( f_{\text{bgr}}, f_{\text{sig}} \) - normalization coefficients.

\[
M_x = 5566.7^{+3.6}_{-3.4} \text{ MeV/c}^2, \quad \Gamma_X = 6.0^{+9.5}_{-6.0} \text{ MeV/c}^2, \quad N_{\text{ev}} = 139^{+51}_{-63}
\]
$X(5568) \rightarrow B_s \pi$ with semileptonic decays of the $B_s$ mesons

**Local statistical significance**

$$\sqrt{-2 \cdot \ln \frac{\mathcal{L}_0}{\mathcal{L}_{\text{max}}}}$$

4.5σ from the fit, 3.2σ with the systematic uncertainties.

**Systematic uncertainties**

Background shape description, background reweighting, $B_s$ mass scale (MC and data), detector resolution and missing neutrino effect, P-wave Breit-Wigner.

**Comparison with hadronic channel**

<table>
<thead>
<tr>
<th></th>
<th>Semileptonic</th>
<th>Hadronic, $\Delta R$ cut</th>
<th>Hadronic, no $\Delta R$ cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted mass, MeV/c²</td>
<td>$5566.7^{+3.6}<em>{-3.4}^{+1.0}</em>{-1.0}$</td>
<td>$5567.8 \pm 2.9^{+0.9}_{-1.9}$</td>
<td>$5567.8$</td>
</tr>
<tr>
<td>Fitted width, MeV/c²</td>
<td>$6.0^{+9.5}<em>{-6.0}^{+1.9}</em>{-4.6}$</td>
<td>$21.9 \pm 6.4^{+5.0}_{-2.5}$</td>
<td>$21.9$</td>
</tr>
<tr>
<td>Fitted number of signal events</td>
<td>$139^{+51}<em>{-63}^{+11}</em>{-32}$</td>
<td>$133 \pm 31 \pm 15$</td>
<td>$106 \pm 23$</td>
</tr>
</tbody>
</table>

Results in semileptonic channel are compatible with those in hadronic channel within uncertainties.
### X(5568)→B_sπ with semileptonic decays of the B_s mesons

<table>
<thead>
<tr>
<th></th>
<th>Semileptonic</th>
<th>Hadronic, ΔR cut</th>
<th>Hadronic, no ΔR cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local significance</td>
<td>4.5σ</td>
<td>6.6σ</td>
<td>4.8σ</td>
</tr>
<tr>
<td>Significance with systematics</td>
<td>3.2σ</td>
<td>5.6σ</td>
<td>-</td>
</tr>
<tr>
<td>Significance LEE+systematics</td>
<td>-</td>
<td>5.1σ</td>
<td>3.9σ</td>
</tr>
</tbody>
</table>

#### Combined significance

\[
p_{\text{comb}} = p_{\text{sl}} \cdot p_{\text{had}} \cdot [1 - \ln(p_{\text{sl}} \cdot p_{\text{had}})],
\]

\[p_{\text{comb}} = 5.6 \cdot 10^{-9} (1.1 \cdot 10^{-6} \text{ without } \Delta R \text{ cut})\]

which corresponds to combined significance \(5.7\sigma \) (\(4.7\sigma \) without \(\Delta R \) cut)

#### Production ratio of X(5568) to B_s

Calculated by fitting \(M(\phi \pi)\) distributions in the opposite sign and same sign \(D_s \mu\) samples.

\[
\rho(\text{X(5568)}/B_s) = 7.3^{+2.8}_{-2.4} \text{(stat)}^{+0.6}_{-1.7} \text{(syst)}\%
\]

which is in agreement with the ratio measured in the hadronic channel.
Search for exotic baryons decaying to $J/\psi \Lambda$

- Observation of two $J/\psi p$ states named $P_c$ around 4380 MeV/c$^2$ and 4450 MeV/c$^2$ in $\Lambda_b \rightarrow J/\psi p K^-$ decays reported by LHCb.

- Numerous states with the quark contents including $c\bar{c}$ pair and three light quarks are expected to exist within 500 MeV of the $J/\psi p$ threshold.

Search in the $M(J/\psi \Lambda)$, where $J/\psi \rightarrow \mu \mu$, $\Lambda \rightarrow p\pi^{-}$.

**Event reconstruction**

D0 Run II integrated luminosity 10.4 fb$^{-1}$

- $p_T(\mu) > 1$ GeV/c; $p_T(\mu\mu) > 4$ GeV/c
- $2.92 < M(\mu\mu) < 3.25$ GeV/c$^2$
- $p_T(\Lambda) > 0.7$ GeV/c
- $1.110 < M(\Lambda) < 1.122$ GeV/c$^2$
- $p_T(\pi) > 0.15$ GeV/c

Non-prompt: $J/\psi$ decay length significance in the transverse plane is greater than 3 and $\Lambda$ decay vertex is closer to $J/\psi$ decay vertex than to the primary vertex.
Search for exotic baryons decaying to $J/\psi\Lambda$

Search procedure

Binned maximum likelihood fits to the distribution of the $J/\psi\Lambda$ invariant mass in the range from the $J/\psi\Lambda$ threshold to 4.7 GeV/$c^2$.

$$F_{\text{fit}}(M, M_x, \Gamma_x) = f_{\text{bgr}} \cdot F_{\text{bgr}}(M) + f_{\text{sig}} \cdot F_{\text{sig}}(M, M_x, \sigma_x),$$

where $F_{\text{sig}}(M, M_x, \sigma_x)$ - Gaussian function with $M_x, \sigma_x$; $f_{\text{bgr}}, f_{\text{sig}}$ - normalization coefficients.

$$F_{\text{bgr}}(M) \propto M \cdot (M^2/M_{\text{thr}}^2 - 1)^{c_1} \cdot e^{-c_2 M} \cdot (1 - e^{-(M-M_{\text{thr}})/b}),$$

where $M_{\text{thr}}$ is the $J/\psi\Lambda$ threshold.
Search for exotic baryons decaying to $J/\psi \Lambda$

Mass fits of the sum of signal + background or background only to the data were performed with the signal mass set at fixed values in 10 MeV steps. Local statistical significance is defined as $\sqrt{-2 \cdot \ln (\mathcal{L}_0/\mathcal{L}_\text{max})}$. The highest local significance of $3.45\sigma$ occurs at $M = 4.32 \text{ GeV}/c^2$. If LEE (computed in the same 500 MeV interval) is taken into account it leads to the global significance of $2.8\sigma$.

No evidence for new baryons decaying to $J/\psi \Lambda$
Conclusion

- **X(5568) → B_s π, B_s → J/ψφ(1020)**. We report evidence for a narrow structure, X(5568). This is evidence for the first instance of a hadronic state with valence quarks of four different flavors (u,d,b,s). The statistical significance of this evidence is 5.1σ with ΔR<0.3 cut and 3.9σ without it.
  

- **X(5568) → B_s π, B_s → D_s μ X**. There is an excess of events in the data consistent with the decay X(5568) → B_s π, B_s → J/ψ φ. The mass, natural width and production rates in the semileptonic and hadronic channels are consistent. Combined significance for semileptonic and hadronic channels is 5.7σ.
  
  *https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B68/

- Search for exotic baryons → J/ψ Λ. In the mass range between threshold and 4.7 GeV/c^2 no evidence for new baryons decaying to J/ψ Λ have been found, the most significant deviation from background-only hypothesis is seen at M(J/ψ Λ) = 4.32 GeV/c^2 with a global significance (including LEE) 2.8σ.
  
  *https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B69/
Backup slides
**Evidence for $B_s \pi$ state, $B_s \to J/\psi \phi(1020)$**

### TABLE I: Systematic uncertainties for the observed $X^+_{5568}$ state mass, natural width, and event number.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>mass, MeV/$c^2$</th>
<th>width, MeV/$c^2$</th>
<th>Events, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Background shape</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) MC sample soft or hard</td>
<td>+0.2 ; -0.6</td>
<td>+2.6 ; -0.</td>
<td>+8.2 ; -0.</td>
</tr>
<tr>
<td>b) Sideband mass ranges</td>
<td>+0.2 ; -0.1</td>
<td>+0.7 ; -1.7</td>
<td>+1.6 ; -9.3</td>
</tr>
<tr>
<td>c) Sideband mass calculation method</td>
<td>+0.1 ; -0.</td>
<td>+0. ; -0.4</td>
<td>+0 ; -1.3</td>
</tr>
<tr>
<td>d) MC to sideband events ratio</td>
<td>+0.1 ; -0.1</td>
<td>+0.5 ; -0.6</td>
<td>+2.8 ; -3.1</td>
</tr>
<tr>
<td>e) Background function used</td>
<td>+0.5 ; -0.5</td>
<td>+0.1 ; -0.</td>
<td>+0.2 ; -1.1</td>
</tr>
<tr>
<td>f) $B_s^0$ mass scale, MC and data</td>
<td>+0.1 ; -0.1</td>
<td>+0.7 ; -0.6</td>
<td>+3.4 ; -3.6</td>
</tr>
<tr>
<td><strong>Signal shape</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Detector resolution</td>
<td>+0.1 ; -0.1</td>
<td>+1.5 ; -1.5</td>
<td>+2.1 ; -1.7</td>
</tr>
<tr>
<td>c) Non-relativistic BW</td>
<td>+0. ; -1.1</td>
<td>+0.3 ; -0.</td>
<td>+3.1 ; -0.</td>
</tr>
<tr>
<td>d) P-wave BW</td>
<td>+0. ; -0.6</td>
<td>+3.1 ; -0.</td>
<td>+3.8 ; 0.</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Binning</td>
<td>+0.6 ; -1.1</td>
<td>+2.3 ; -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>
Evidence for $B_s \pi$ state, $B_s \rightarrow J/\psi \phi(1020)$

- ΔR < 0.2
  - D0 Run II, 10.4 fb⁻¹

- ΔR < 0.3
  - D0 Run II, 10.4 fb⁻¹

- ΔR < 0.5
  - D0 Run II, 10.4 fb⁻¹
**X(5568)→B_sπ with semileptonic decays of the B_s mesons**

**Alternative background parametrizations**

1. \( F_{\text{bgr}}(M) = (C_1 + C_2 \cdot m^2 + C_3 \cdot m^3 + C_4 \cdot m^4) \times \exp(C_5 \cdot m + C_6 \cdot m^2) \), where \( m = M - \Delta \), \( \Delta = 5.5 \text{ GeV/c}^2 \).

2. \( F_{\text{bgr}}(M) = M \cdot \left( \frac{M^2}{M^2_{\text{thr}}} - 1 \right)^{C_1} \times \exp(C_2 \cdot M) \), where \( M_{\text{thr}} \) is a \( B_s\pi \) threshold.

3. Histogram smoothing (one iteration of 353QH algorythm).

---

**Parametrization (1)**
- Fitted mass, MeV/c²: \( 5566.2^{+4.2}_{-4.1} \)
- Fitted width, MeV/c²: \( 6.0^{+12.9}_{-6.0} \)
- Fitted number of signal events: \( 115.9^{+51.8}_{-47.7} \)
- Local significance: \( 3.7\sigma \)

**Parametrization (2)**
- Fitted mass, MeV/c²: \( 5566.0^{+3.6}_{-3.4} \)
- Fitted width, MeV/c²: \( 6.5^{+8.9}_{-6.5} \)
- Fitted number of signal events: \( 145.7^{+50.7}_{-54.3} \)
- Local significance: \( 4.7\sigma \)

**Parametrization (3)**
- Fitted mass, MeV/c²: \( 5564^{+5}_{-5} \)
- Fitted width, MeV/c²: \( 10^{+17}_{-10} \)
- Fitted number of signal events: \( 136^{+59}_{-48} \)
- Local significance: \( 3.9\sigma \)
X(5568)→B_sπ with semileptonic decays of the B_s mesons

**Systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>mass, MeV/c^2</th>
<th>width, MeV/c^2</th>
<th>event yield, events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background shape description</td>
<td>+0.0 ; −0.7</td>
<td>+0.7 ; −2.5</td>
<td>+4.8 ; −28.0</td>
</tr>
<tr>
<td>Background reweighting</td>
<td>+0.1 ; −0.1</td>
<td>+0.7 ; −0.7</td>
<td>+5.0 ; −5.0</td>
</tr>
<tr>
<td>B_s^0 mass scale, MC and data</td>
<td>+0.3 ; −0.5</td>
<td>+1.0 ; −1.4</td>
<td>+7.5 ; −9.6</td>
</tr>
<tr>
<td>Detector resolution</td>
<td>+0.0 ; −0.5</td>
<td>+1.3 ; −2.6</td>
<td>+3.7 ; −6.4</td>
</tr>
<tr>
<td>P-wave Breit-Wigner</td>
<td>+0.0 ; −0.2</td>
<td>+0.0 ; −2.4</td>
<td>+0.0 ; −7.0</td>
</tr>
<tr>
<td>Missing neutrino effect</td>
<td>+1.0 ; −0.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+1.0 ; −1.0</td>
<td>+1.9 ; −4.6</td>
<td>+10.9 ; −31.5</td>
</tr>
</tbody>
</table>