Searches for exotic hadronic states at D0

Search for exotic baryons decaying to $J/\psi\Lambda$ pairs

Confirmation of $X(5568)$ with semileptonic decays of the $B_s$

Iain Bertram, Lancaster University
for the D0 Collaboration
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The D0 Detector

- Multi-purpose, high acceptance, well understood detector.

Excellent muon id and acceptance. $\int \mathcal{L} \, dt \sim 10 \text{ fb}^{-1}$
Search for exotic baryons decaying to J/ψΛ

- LHCb observed two exotic baryon states (P^c) in \( \Lambda_b \rightarrow J/\psi p K^- \) at 4380 MeV/c^2 and 4450 MeV/c^2.
- Numerous states with the quark contents including a \( \bar{c}c \) pair and three light quarks are expected to exist within 500 MeV of the 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
- \( p_T(\mu) > 1 \text{ GeV/c} \); \( p_T(\mu\mu) > 4 \text{ GeV/c} \)
- \( 2.92 < M(\mu\mu) < 3.25 \text{ GeV}/c^2 \)
- \( p_T(\Lambda) > 0.7 \text{ GeV/c} \)
- \( 1.110 < M(\Lambda) < 1.122 \text{ GeV}/c^2 \)
- \( p_T(p) > 0.15 \text{ GeV/c} \)
- 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: concentrate on Non-prompt sample
  - no indication of signal in prompt sample.
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$^2$.

$$F_{\text{fit}}(M, M_X, \Gamma_X) = f_{\text{bg}} F_{\text{bg}} + f_{\text{sig}} F_{\text{sig}}$$

- $F_{\text{sig}}(M, M_X, \sigma_X)$ is a Gaussian with free mass and width.
- $f_{\text{bg}}$ and $f_{\text{sig}}$ are normalisation constants.
- The background is a threshold function where $M_{\text{th}}$ is the $J/\psi \Lambda$ invariant mass threshold.

$$F_{\text{bg}} \propto M \left( \frac{M^2}{M_{\text{th}}^2} \right)^{c_1} \exp(c_2 M) \left[ 1 - \exp \left( \frac{M - M_{\text{th}}}{c_3} \right) \right]$$
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 $\sqrt{-2 \ln (L_0/L_{\text{max}})}$.
- The highest local significance of 3.45σ occurs at $M = 4.32$ GeV/c².
- If LEE is taken into account it leads to the global significance of 2.8σ.

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

... but could point the way for other searches.
Previous Result: Evidence for $X(5568)$, $B_s \rightarrow J/\psi\phi$


\[ X(5568) \]

\[ M_X = 5567.8 \pm 2.9 \text{ (stat)} \pm 0.9 \text{ (syst)} \text{ MeV}/c^2 \]

\[ \Gamma_X = 21.9 \pm 6.4 \text{ (stat)} \pm 5.0 \text{ (syst)} \text{ MeV}/c^2 \]

\[ \rho = [8.6 \pm 1.9 \text{ (stat)} \pm 1.4 \text{ (syst)}] \% \]

Statistical significance of signal (including systematics and LEE)

\[ \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3 \]

With $\Delta R$ Cut: 5.1 $\sigma$, Without $\Delta R$ Cut: 3.9 $\sigma$

Not seen at LHCb and CMS
Confirmation of $X(5568)$ with semileptonic decays of the $B_s$

- Look to confirm $X(5568)$ using additional channel
  - Optimise cuts to minimise effect of missing neutrino and reduce size of background.

$B_s \to D_s \mu \nu$ reconstruction:
Reconstruct $D_s \to \phi \pi$, $\phi \to K^+K^-$. 
Require $1.92 < m(\phi\pi) < 2.02$ GeV.
Add a muon that forms a vertex with the $D_s$.
Require $4.5 < m(\mu D_s) < 5.4$ GeV
to minimise the effect of the missing neutrino.

$X(5568) \to B_s \pi$ candidates:
Add a charged pion with $p_T > 0.5$ GeV/c consistent with coming from the PV

Additional pion chosen with identical cuts as used in $B_s^0 \to J/\psi \phi$ analysis.

- To improve mass resolution we define the invariant mass as

$$M(B_s^0 \pi^\pm) = m(\mu D_s \pi) - m(\mu D_s) + m(B_s^0)$$
Data

- Look to confirm $X(5568)$ using additional channel
  - Optimise cuts to minimise effect of missing neutrino and reduce size of background.
• Model signal with modified spin-0 meson in Pythia.

• Background $\mu^- D_s^+$ events generated inclusively and selected based on kinematics.

• MC is weighted as a function of $p_T(\mu)$ and $p_T(\mu D_s)$ to account for trigger and reconstruction efficiencies.
Signal Extraction

- Fix shape of background by fitting MC background simulation.
- Fit data to background model plus signal
  - signal represented by relativistic Breit-Wigner
    \[ BW(m) \propto \frac{M_X^2 \Gamma(m)}{(M_X^2 - m^2)^2 + M_X^2 \Gamma^2(m)} \]
  - convoluted with detector resolution and smearing due to the missing neutrino.

Background
\[ F_{\text{bgr}}(m) = (C_1 m_0 + C_2 m_0^2 + C_3 m_0^3 + C_4 m_0^4) \exp(C_5 m_0 + C_7 m_0^2), \]

function:
where \( m = m(B_s^0 \pi^\pm), m_0 = m - m_{\text{th}} \) and \( m_{\text{th}} = 5.5063 \text{ GeV/c}^2 \) is the threshold value.

Results of signal injection closure test

D0 Background MC
\[ \chi^2/\text{ndf} = 1.1 \]

D0 Simulation
Fit results

\[
\chi^2/\text{ndf} = 0.7
\]

\[
N_X = 139^{+51}_{-63}
\]

\[
M_X = 5566.7^{3.6}_{-3.4} \text{ MeV}/c^2
\]

\[
\Gamma_X = 6.0^{+9.5}_{-6.0} \text{ MeV}/c^2
\]

Local Significance

\[
\sqrt{-2 \ln \frac{\mathcal{L}_0}{\mathcal{L}_{\text{max}}}}
\]

Statistical Significance 4.5 \sigma. Including Systematics 3.2 \sigma.
Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>mass, MeV/c²</th>
<th>width, MeV/c²</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>Total</td>
<td>+1.0 ; -1.0</td>
<td>+1.9 ; -4.6</td>
<td>+10.9 ; -31.5</td>
</tr>
</tbody>
</table>

Alternate Background Shape

- **Argus Type background**
  - $\chi^2$/ndf = 0.95
- **Smoothed MC**
  - $\chi^2$/ndf = 0.88
### Combination with Hadronic Channel

<table>
<thead>
<tr>
<th></th>
<th>Semileptonic</th>
<th>Hadronic, cone cut</th>
<th>Hadronic, no cone 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 natural 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>$139^{+51}<em>{-63}^{+10.9}</em>{-31.5}$</td>
<td>$133 \pm 31 \pm 15$</td>
<td>$106 \pm 23$</td>
</tr>
<tr>
<td>Local significance</td>
<td>$4.5\sigma$</td>
<td>$6.6\sigma$</td>
<td>$4.8\sigma$</td>
</tr>
<tr>
<td>Significance with systematics</td>
<td>$3.2\sigma$</td>
<td>$5.6\sigma$</td>
<td>-</td>
</tr>
<tr>
<td>Significance with LEE+systematics</td>
<td>-</td>
<td>$5.1\sigma$</td>
<td>$3.9\sigma$</td>
</tr>
</tbody>
</table>

- Assume measurements are independent
  - presence of neutrino in semileptonic supports this assumption

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

- Combine with J/ψφ with ΔR Cut
  \[ p\text{-value} = 5.6 \times 10^{-9} \text{ corresponding to } 5.7 \sigma. \]

  If combined with J/ψφ without ΔR Cut significance is 4.7 σ.
Cross Checks

- Alternative Fits
  - Fix $M_\chi = 5567.8$ MeV/$c^2$ and $\Gamma_\chi = 21.9$ MeV/$c^2$ from Hadronic analysis
  - Free all background parameters.

<table>
<thead>
<tr>
<th></th>
<th>Hadronic Values</th>
<th>Free Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/ndf</td>
<td>0.68</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Cross Checks

- Alternative Fits
  - Fix $M_\chi = 5567.8$ MeV/$c^2$ and $\Gamma_\chi = 21.9$ MeV/$c^2$ from Hadronic analysis
  - Free all background parameters.

<table>
<thead>
<tr>
<th></th>
<th>Nominal Fit</th>
<th>All Parameters free</th>
<th>Mass and Width Fixed to $J/\psi\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted mass, MeV/$c^2$</td>
<td>5566.7$^{+3.6}_{-3.4}$</td>
<td>5566.6 ± 3.5</td>
<td>5567.8</td>
</tr>
<tr>
<td>Fitted width, MeV/$c^2$</td>
<td>6.0$^{+9.5}_{-6.0}$</td>
<td>8.4 ± 14.5</td>
<td>21.9</td>
</tr>
<tr>
<td>Fitted number of signal events</td>
<td>138.6$^{+50.8}_{-63.3}$</td>
<td>143.7 ± 101.1</td>
<td>168 ± 42</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>30.4/(50 − 4)</td>
<td>27.4/(50 − 10)</td>
<td>32.8/(50 − 2)</td>
</tr>
<tr>
<td>Local significance</td>
<td>4.5 $\sigma$</td>
<td>4.4 $\sigma$</td>
<td>4.2 $\sigma$</td>
</tr>
</tbody>
</table>
Fraction of $B_s$ from $X(5568)$ decays

- Determine number of $B_s$ mesons by fitting the $m(\phi\pi^\pm)$ distribution.
- Remove prompt/non $B_s$ mesons using same sign $\mu D_s$ samples.
- Semileptonic sample satisfies $p_T(\mu D_s) > 10$ GeV/c

For $p_T(\mu^+ D_s^-) > 10$ GeV/c and $4.5$ GeV/$c^2 < m(\mu^+ D_s^-) < m(B_s^0)$

$$\rho(\text{sl}) = \left[7.3^{+2.8}_{-2.4} \text{ (stat)}^{+0.6}_{-1.7} \text{ (syst)}\right] \%$$

For $p_T(J/\psi\phi) > 10$ GeV/c

$$\rho(\text{had}) = [8.6 \pm 1.9 \text{ (stat)} \pm 1.4 \text{ (syst)}] \%$$
Conclusion

\textbf{X(5568)}

- We have presented the results of a search for the X(5568) → B_s^0\pi^\pm with semileptonic decays of the B_s^0 meson. There is an excess of events in the data consistent with the decay X(5568) → B_s^0\pi^\pm with B_s^0 → J/\psi\phi.

- The mass, natural width and production rates in the semileptonic and hadronic channels are consistent.

- The signal p-value for the semileptonic channel is $6.4 \times 10^{-4}$ and the significance is $3.2\sigma$ when including systematic uncertainties.

- The combined p-value for the hadronic and semileptonic channels is $5.6 \times 10^{-9}$ with a corresponding significance is $5.7\sigma$.

\textbf{Search for exotic baryons → J/\psi}\Lambda

- In the mass range between threshold and 4.7 GeV/c^2 no evidence for new baryons decaying to J/\psi\Lambda have been found.

- The most significant deviation from background-only hypothesis is seen at $M(J/\psi\Lambda)= 4.32$ GeV/c^2 with a global significance (including LEE) $2.8\sigma$. 
Bibliography

\textbf{X(5568)}

- D0 Conference Note 6496: https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B68/

  \textbf{Search for exotic baryons} → \textbf{J/ψΛ}

- D0 Conference Note 6494: https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B69/
“Four” quark states

- Four quark states can be distinguished from regular mesons by comparing the mass, width, charge, other quantum numbers, production and decay modes with predictions.

- Exotic four-quark states can be described as tightly bound (tetraquark) or loosely bound (molecule, hadroquarkonium):

- Observed four-quark states (high statistical significance): $Z(4430)^+ \rightarrow \psi'\pi^+$, $X(4140) \rightarrow J/\psi\phi$, $Z_b(10610)^+ \rightarrow \gamma\pi^+$, $Z_b(10650)^+ \rightarrow \gamma\pi^+$.

- Not well established: $Z(4050)^+ \rightarrow \chi_{c1}\pi^+$, $Z(4250)^+ \rightarrow \chi_{c1}\pi^+$.

- $X(3872)$ is probably a mixture of two- and four-quark states.

- All of these states can be interpreted as molecules (their masses are close to the sum of two regular mesons).

- Also, pentaquarks $P_c(4450)^+ \rightarrow J/\psi p$, $P_c(4380)^+ \rightarrow J/\psi p$.
MC Cross Checks

- Comparison between same sign ($\mu^+D_s^+$) data and MC background

\[ \chi^2/\text{ndf} = 1.0 \]
Tests of Procedure

- Use weighted MC background to generate 45k invariant mass distributions with same sample size of the data.
  - Apply the fit procedure to each trial with initial mass of 5600 MeV.
  - Blue arrows represent $M_X = 5568$ MeV and $\Gamma_X = 8$ MeV
  - Confirm that there is no bias in the method that would produce the peak and the significance calculation.

![Graphs showing distribution of fitted $M_X$ and $\Gamma_X$](image)
Alternate Background Shapes

**Argus Type background**

- **Fitted mass, MeV/c^2**: 5566.7^{+3.6}_{-3.4}
- **Fitted width, MeV/c^2**: 6.0^{+9.5}_{-6.0}
- **Fitted number of signal events**: 138.6^{+50.8}_{-63.3}
- **χ^2/ndf**: 30.4/(50 - 4)
- **Local significance**: 4.5 σ

**Smoothed MC**

- **Fitted mass, MeV/c^2**: 5566.0^{+3.6}_{-3.4}
- **Fitted width, MeV/c^2**: 6.5^{+8.9}_{-6.5}
- **Fitted number of signal events**: 145.7^{+50.7}_{-54.3}
- **χ^2/ndf**: 43.8/(50 - 4)
- **Local significance**: 4.7 σ