Studies of excited charm and beauty mesons at LHCb

V.V. Gligorov, CERN
On behalf of the LHCb collaboration
23rd April 2013
Today I will discuss two topics

1) Studies of excited charm mesons, specifically $D_{sJ}^*$ decays to $D^0 K^+$ and $D^+ K_S$ final states

2) Studies of excited beauty mesons, specifically the properties of orbitally excited $B_s$ mesons

As we are late in the day, I won’t be reviewing the LHCb detector but all the information is in the backup slides so please ask if you have questions on this!
Studies of excited charm mesons
Motivation for studies

System of the heavy and the light quarks: \( Q\bar{q}. \ \vec{S} = \vec{s}_Q + \vec{s}_{\bar{q}}, \ \vec{J} = \vec{L} + \vec{S}. \)

- \( L = 0. \) Doublet with \( J^P = (0^-, 1^-): (D_s, D^*_s) \)
- Orbital excitations with \( L = 1. \) Two doublets:
  - \( \vec{j}_q = \vec{L} + \vec{s}_{\bar{q}} = 1/2. \ J^P = (0^+, 1^+): (D^*_s0, D^*_s1) \)
  - \( \vec{j}_q = \vec{L} + \vec{s}_{\bar{q}} = 3/2. \ J^P = (1^+, 2^+): (D_{s1}, D^*_s2) \)
Analysis strategy

Study $D_{sJ}$ mesons produced directly in the pp interaction at the LHC

=> Takes advantage of the LHC’s huge prompt charm production cross-section
(see talk by Alex Kozlinskiy earlier today)

Use both $D^0K^+$ and $D^+K_S$ final states to maximize signal yields and reduce the possibility of fake peaks due to background, cross-feed, etc.

$D^{0,+}$ mesons selected cleanly using their transverse momentum and displacement from the primary interaction: most background is from fake DK combinations.
Event selection

Remove a lot of combinatorial background by cutting on $\cos\theta > 0$, the angle between the kaon momentum (in the $D_{sJ}$ rest frame) and the $D_{sJ}$ momentum in the lab frame.

Then optimize further for the significance of the $D_{s2}^*(2573)^+$.
Event selection

Remove a lot of combinatorial background by cutting on $\cos\theta > 0$, the angle between the kaon momentum (in the $D_{sJ}$ rest frame) and the $D_{sJ}$ momentum in the lab frame.

Then optimize further for the significance of the $D_{s2}^*(2573)^+$

$\Rightarrow$ Add cuts on the $DK_pT$ and $K^+$ particle identification cuts.
The mass spectrum

Similar features in both spectra:

- $D_{s2}^*(2573)^+$
- $D_{s1}(2536)^+$ feed down via $D^*K$ decays
- $D_{s1}(2700)^+$ and $D_{sJ}^*(2860)^+$ states (will be clearer in a slide or two)
Fit model

=> Exclude the $D_{s1}(2536)^+$ feed down to avoid modelling the turn-on;

=> Relativistic Breit-Wigners with Blatt-Weisskopf form factors for the signal states (resolution neglected as these are so broad);

=> Chebyshev polynomials for the combinatorial background;

=> Signal parameters shared between the two modes.
Fit results

=> Exclude the $D_{s1}(2536)^+$ feed down to avoid modelling the turn-on;

=> Relativistic Breit-Wigners with Blatt-Weisskopf form factors for the signal states (resolution neglected as these are so broad);

=> Chebyshev polynomials for the combinatorial background;

=> Signal parameters shared between the two modes.
We clearly observe the $D^{*+}_{s1}(2700)$ and $D^{*+}_{sJ}(2860)$ states.

We do not see any significant excess of events above 3 GeV.
Fit results, systematics

The systematic uncertainties are dominated by the background and signal models.

In particular, the background model has to describe not only the combinatorial background from unrelated DK pairs, but also from DK pairs produced in a correlated way in the fragmentation (but not coming from a resonant state).

At present all measurements are therefore systematics limited.

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta m )</th>
<th>( \delta \Gamma )</th>
<th>( \delta m )</th>
<th>( \delta \Gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal model</td>
<td>2.2</td>
<td>3.0</td>
<td>5.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Background model</td>
<td>2.1</td>
<td>10.2</td>
<td>3.8</td>
<td>4.2</td>
</tr>
<tr>
<td>High mass state</td>
<td>0.0</td>
<td>0.3</td>
<td>0.0</td>
<td>0.2</td>
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<tr>
<td>Selection criteria</td>
<td>2.1</td>
<td>3.5</td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>2.1</td>
<td>3.6</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Feed-down reflections</td>
<td>1.2</td>
<td>2.9</td>
<td>0.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Bin size</td>
<td>0.2</td>
<td>0.9</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>4.5</td>
<td>12.1</td>
<td>6.3</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Mini conclusion

We clearly observe the \( D^{*}_{s1}(2700)^{+} \) and \( D^{*}_{sJ}(2860)^{+} \) states

We do not see any significant excess of events above 3 GeV

We have made mass and width measurements which are competitive with the B\(-\)factory precisions

Need studies of the \( D^{*}K \) spectra in order to shed any further light on the spin-parity assignments of these modes

\[
\begin{align*}
m(D^{*}_{s1}(2700)^{+}) &= 2709.2 \pm 1.9\,(\text{stat}) \pm 4.5\,(\text{syst}) \, \text{MeV}/c^2, \\
\Gamma(D^{*}_{s1}(2700)^{+}) &= 115.8 \pm 7.3\,(\text{stat}) \pm 12.1\,(\text{syst}) \, \text{MeV}/c^2, \\
m(D^{*}_{sJ}(2860)^{+}) &= 2866.1 \pm 1.0\,(\text{stat}) \pm 6.3\,(\text{syst}) \, \text{MeV}/c^2, \\
\Gamma(D^{*}_{sJ}(2860)^{+}) &= 69.9 \pm 3.2\,(\text{stat}) \pm 6.6\,(\text{syst}) \, \text{MeV}/c^2.
\end{align*}
\]
Studies of excited beauty mesons
Motivation for studies

Precise measurements of excited B meson properties are an important test of Heavy Quark Effective Theory (HQET).

HQET is a crucial tool in predicting Standard Model values for CP violation, lifetimes, mixing... and hence setting a benchmark for measurements sensitive to physics beyond the Standard Model.
Motivation for studies

Precise measurements of excited B meson properties are an important test of Heavy Quark Effective Theory (HQET).

HQET is a crucial tool in predicting Standard Model values for CP violation, lifetimes, mixing... and hence setting a benchmark for measurements sensitive to physics beyond the Standard Model.

Here we will focus on measurements of the narrow $B_s^*$ states.
Analysis strategy and event selection

Use several B meson final states to maximize signal yields and reduce the possibility of fake peaks due to background, cross-feed, etc.

Almost all background is due to fake BK combinations.

We reduce remaining backgrounds with a multivariate selection using the following variables:

=> B and K transverse momenta
=> Kaon particle identification
=> BK vertex fit
=> Distance of closest approach of the BK system to the primary interaction

The B candidate mass spectra are fitted using a double Gaussian function for the 3

\[ m(J/\psi(\mu^+\mu^-)K) \text{[MeV}/c^2] \]

\[ m(D^0(K^+\pi^-)\pi^+) \text{[MeV}/c^2] \]

\[ m(D^0(K^+\pi^-\pi^+)\pi^-) \text{[MeV}/c^2] \]

\[ m(D^+(K^+\pi^-\pi^+)\pi^-) \text{[MeV}/c^2] \]
Mass spectrum and fit model

Figure 2: Mass diﬀerence distribution $m(B^+K^-) - m(B^-) - m(K^+)$. The three peaks are identified as (left) $B_s^1 \rightarrow B^*+K^-$, (middle) $B_s^* \rightarrow B^+K^-$, and (right) $B_s^* \rightarrow B^+K^-$. The total fit function is shown as a solid blue line, while the shaded red region is the spectrum of like-charge $B_s+B^-K^+$ combinations. The inset shows an expanded view of the $B_s^1/B_s^* \rightarrow B^*+K^-$ signals. The bottom plot shows the fit pulls.

The total fit function is shown as a solid blue line, while the shaded red region is the spectrum of like-charge $B_s+B^-K^+$ combinations. The inset shows an expanded view of the $B_s^1/B_s^* \rightarrow B^*+K^-$ signals. The bottom plot shows the fit pulls.

These ratios are corrected by the relative selection eﬃciencies, $\epsilon_{rel}^{1,2}$. The fit results are given in Table 2. A binne $\chi^2$ test gives a confidence level of 43% for the fit.

To determine the significance of the $B_s^* \rightarrow B^+K^-$ signal, a similar maximum likelihood fit is performed, where all parameters of the signal are fixed according to expectation, except its yield. The likelihood of this fit is compared to the result of a fit where the yield.
Mass spectrum and fit model

- Relativistic Breit-Wigner convolved with simulated Gaussian resolution for the BK signal.
- Gaussians as “effective parametrizations” for the $B^*K$ feeddown signals, since these are affected by the missing photon and cannot be fully simulated due to a lack of knowledge of the $B^*_s$ properties.
- A threshold function for the combinatorial background validated on the wrong-sign sample:
  \[ f(Q) = Q^\alpha e^{\beta Q} + \delta \]
What do we actually measure?

We fit for

- The yields of all three peaks

- The means of the $B_{s1}$ and $B^*_{s2}$ peaks, and the width of the $B^*_{s2}\rightarrow BK$ peak

- The difference in the means of the $B^*_{s2}\rightarrow BK$ and $B^*_{s2}\rightarrow B^*K$ peaks

The branching fraction measurements are corrected for reconstruction efficiencies measured offline

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(B_{s1}) - m(B^+) - m(K^-)$</td>
<td>$10.46 \pm 0.04 \pm 0.04$ MeV/$c^2$</td>
</tr>
<tr>
<td>$m(B^*_{s2}) - m(B^+) - m(K^-)$</td>
<td>$67.06 \pm 0.05 \pm 0.11$ MeV/$c^2$</td>
</tr>
<tr>
<td>$m(B^{*+}) - m(B^+)$</td>
<td>$45.01 \pm 0.30 \pm 0.23$ MeV/$c^2$</td>
</tr>
<tr>
<td>$\Gamma(B^*_{s2})$</td>
<td>$1.56 \pm 0.13 \pm 0.47$ MeV/$c^2$</td>
</tr>
<tr>
<td>$\frac{B(B^<em>_{s2}\rightarrow B^{</em>+}K^-)}{B(B^*_{s2}\rightarrow B^+K^-)}$</td>
<td>$(9.3 \pm 1.3 \pm 1.2)%$</td>
</tr>
<tr>
<td>$\frac{\sigma(pp\rightarrow B_{s1}X)B(B_{s1}\rightarrow B^{<em>+}K^-)}{\sigma(pp\rightarrow B^</em><em>{s2}X)B(B^*</em>{s2}\rightarrow B^+K^-)}$</td>
<td>$(23.2 \pm 1.4 \pm 1.3)%$</td>
</tr>
<tr>
<td>$N_{B_{s1}\rightarrow B^{*+}K^-}$</td>
<td>$750 \pm 36$</td>
</tr>
<tr>
<td>$N_{B^<em>_{s2}\rightarrow B^{</em>+}K^-}$</td>
<td>$307 \pm 46$</td>
</tr>
<tr>
<td>$N_{B^*_{s2}\rightarrow B^+K^-}$</td>
<td>$3140 \pm 100$</td>
</tr>
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What do we actually measure?

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=> The yields of all three peaks

=> The means of the $B_{s1}$ and $B_{s2}^*$ peaks, and the width of the $B_{s2}^* \to BK$ peak

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</tr>
<tr>
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<td></td>
</tr>
<tr>
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</tr>
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The world-best $B^*-B$ mass difference measurement is a particular highlight

No photon reconstruction so much smaller (and uncorrelated) systematics compared to other measurements
Systematic uncertainties in detail

For the $Q$ values, the momentum scale and selection dominate

$\Rightarrow$ Selection evaluated by varying the cut on the multivariate discriminant

For the width of the $B^{*s2}$, the experimental resolution dominates, because we take it from simulation and can only trust this to $\sim 20\%$

For the branching fractions there are many significant contributions

<table>
<thead>
<tr>
<th>Source</th>
<th>$Q(B_{s1})$ (MeV/c²)</th>
<th>$Q(B_{s2}^{*})$ (MeV/c²)</th>
<th>$m(B^{*+}) - m(B^{+})$ (MeV/c²)</th>
<th>$\Gamma(B_{s2}^{*})$ (MeV/c²)</th>
<th>$R_{B_{s2}}^{B_{s1}}$ (%)</th>
<th>$\sigma_{B_{s1}/B_{s2}}^{B_{s1}/B_{s2}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit model</td>
<td>0.00</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>$B^{+}$ decay mode</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Selection</td>
<td>0.03</td>
<td>0.02</td>
<td>0.19</td>
<td>0.05</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>$B^{+}$ signal region</td>
<td>0.01</td>
<td>0.03</td>
<td>0.11</td>
<td>0.07</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.46</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Momentum scale</td>
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<td>0.10</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Efficiency ratios</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Missing photon</td>
<td>0.01</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>0.04</td>
<td>0.11</td>
<td>0.23</td>
<td>0.47</td>
<td>1.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Conversion into absolute masses

For this we use the PDG values of the $B^+$ mass at the time of the paper:

The measurements are already systematics dominated

\[
\begin{align*}
  m(B^{*+}) &= 5324.26 \pm 0.30 \pm 0.23 \pm 0.17 \text{ MeV}/c^2, \\
  m(B_{s1}) &= 5828.40 \pm 0.04 \pm 0.04 \pm 0.41 \text{ MeV}/c^2, \\
  m(B_{s2}^*) &= 5839.99 \pm 0.05 \pm 0.11 \pm 0.17 \text{ MeV}/c^2,
\end{align*}
\]
Conclusion
Summary and prospects

In the charm studies:

=> We clearly observe the $D^{*}_{s1}(2700)^+$ and $D^{*}_{sJ}(2860)^+$ states

=> We do not see any significant excess of events above 3 GeV

=> Need studies of the $D^*K$ spectra in order to shed any further light on the spin-parity assignments of these modes

In the beauty studies:

=> We have made a first observation of the $B^{*}_{s2}\rightarrow B^*K$ decay and used it to make a world best measurement of the $B^*-B$ mass difference

=> Most precise measurements of the $B_{s1}$ and $B^{*}_{s2}$ masses, and a first measurement of the $B^{*}_{s2}$ width

<table>
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<td>$\Gamma(D^{*}_{s1}(2700)^+)$</td>
<td>$115.8 \pm 7.3$ (stat) $\pm 12.1$ (syst) MeV/$c^2$</td>
</tr>
<tr>
<td>$m(D^{*}_{sJ}(2860)^+)$</td>
<td>$2866.1 \pm 1.0$ (stat) $\pm 6.3$ (syst) MeV/$c^2$</td>
</tr>
<tr>
<td>$\Gamma(D^{*}_{sJ}(2860)^+)$</td>
<td>$69.9 \pm 3.2$ (stat) $\pm 6.6$ (syst) MeV/$c^2$</td>
</tr>
</tbody>
</table>
Stay tuned for more results, in particular an update of our preliminary $B^*_u,d$ measurements, and $D\pi$ spectroscopy studies should be coming soon!
Backups
$K_S$ signals

\[ \text{Candidates / 1.3 MeV/c}^2 \]

\[ \pi^+\pi^- \text{ invariant mass [GeV/c}^2 \]\n
(c) LHCb

(d) LHCb

Long-Long

Down-Down
Question: How is LHCb achieving clean signals in a much dirtier environment than either the B-factories or CDF?

Answer 1: A state of the art detector with ~0.5% momentum resolution and powerful particle identification.

Answer 2: An aggressive use of multivariate selections from the very first stage of the datataking process, the trigger.
A topological decision tree trigger

Figure 7: Lifetime acceptance function for an event of a two-body hadronic decay. The shaded, light blue regions show the bands for accepting a track $IP$. After $IP_2$ is too low in (a) it reaches the accepted range in (b). The actual measured lifetime lies in the accepted region (c), which continues to larger lifetimes (d).

Figure 1: $B$-candidate masses from $B \rightarrow K \pi \pi$ decays: (left) HLT2 2-body topological trigger candidates; (right) HLT2 3-body topological trigger candidates. In each plot, both the measured mass of the particle used in the trigger candidate (shaded) and the corrected mass obtained using Eq. 1 (unshaded) are shown. See Section 2 for discussion.

B mesons are long-lived particles; their mean flight distance in the LHC $b$ detector is $O(1 \text{ cm})$. The HLT2 topological lines exploit this fact by requiring that the trigger candidate's flight-distance $\chi^2$ value be greater than 64. The direction of flight is also required to be downstream, i.e., the secondary vertex must be downstream of the primary vertex. A large flight distance combined with a high parent mass results (on average) in daughters with large impact parameters. The HLT2 topological lines require that the sum of the daughter IP $\chi^2$ values be greater than 100, 150 and 200 for the 2-body, 3-body and 4-body lines, respectively.

One of the larger background contributions to the HLT2 topological lines comes from prompt $D$ mesons. To reduce this background, the HLT2 topological lines require that all $(n-1)$-body objects used by an $n$-body line either have a mass greater than 2.5 GeV (the object is too heavy to be a $D$) or that they have an IP $\chi^2 > 16$ (the object does not point at the primary vertex). An exhaustive list of the cuts used in all three of the HLT2 topological lines is given in Table 1.

Table 2 gives the efficiency of the HLT2 topological lines on events that pass the L0 and HLT1 one-track triggers for various offline-selected $B$-decay Monte Carlo samples.
A topological decision tree trigger

\[ m_{\text{corrected}} = \sqrt{m^2 + |p'_T\text{missing}|^2 + |p''_T\text{missing}|} \]
A topological decision tree trigger

The corrected mass is a good variable, but not good enough to deal with pileup on its own: deploy a boosted decision tree to discriminate between signal and background displaced vertices.

Left: $J/\psi K$ candidates with a dimuon trigger and no detachment required

Right: the subset of these candidates which pass the topological trigger

See LHCb public notes
LHCb-PUB-2011-002
LHCb-PUB-2011-003
LHCb-PUB-2011-016

Gligorov&Williams http://arxiv.org/abs/1210.6861
The LHCb spectrometer
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