Heavy Quark Spectroscopy
Results from LHCb

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on behalf of the LHCb collaboration
Lake Louise Winter Institute 2015
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Introduction and overview

- **New results** on $D^{**}$ states from $B^- \rightarrow D^+ K^- \pi^-$
  - First observation of decay mode
  - Resonant structure studied with a Dalitz plot analysis
  - Observed spin-1 resonance $D_1^*(2760)$

- **New results** on $B^{**}$ states in $B^+ \pi^-$ and $B^0 \pi^+$ spectra
  - Low mass states precisely measured
  - Structures observed at higher mass
  - $B_2^*(5747)$ and $B_1(5721)$ states observed

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*LHCb-PAPER-2015-007* to be submitted to PRD
Dalitz plot analysis is a powerful tool

- Previously used by B-factories to study charm spectroscopy
- Used at LHCb for $D_s$ spectroscopy ($B^0_s \rightarrow \bar{D}^0 K^- \pi^+$) [Phys. Rev. D90, 072003 (2014), Phys. Rev. Lett. 113, 162001 (2014)]
- Clean and constrained method compared to inclusive production studies
- Allows determination of quantum numbers for states

$B^- \rightarrow D^+ K^- \pi^-$ is an interesting mode to study $D^{**}$ states

- Decay previously unobserved, first measure branching fraction
- No resonances expected to decay to $D^+ K^-$ or $K^- \pi^-$

- Use Laura++ Dalitz plot fitting software
- Available on Hepforge
Dalitz plot of $B^- \to D^+ K^- \pi^-$

- See resonant structures in invariant mass of pairs of daughters
- Reflections visible in other invariant mass pairs
- 2D representation is “Dalitz plot”
- Interference effects visible
• Charm spectrum predicted [S. Godfrey, N. Isgur, Phys.Rev. D32, 189 (1985)]
• Experimental results come from Dalitz plot analyses and prompt production
• Some discrepancies between predicted and measured values
• Evidence for higher mass states, but not yet possible to assign quantum numbers

Parameters of orbitally excited (1P) states measured at B-factories and LHCb

JHEP 1309 (2013) 145
Evidence for several high mass states but no spin-parity information yet

- Spectrum can be studied with a Dalitz plot analysis of $B^- \rightarrow D^+ K^- \pi^-$
- Only states with natural spin-parity ($J^P$) can decay to $D^+ \pi^-$
- $D_0^*(2400)^0$, $D_2^*(2460)^0$ and higher mass states expected to contribute
- Amplitude analysis techniques give spin-parity information
Branching fraction measurement

- Events selected with loose cuts and neural network used to reduce backgrounds

- $\sim 2000 \ B^- \rightarrow D^+ K^- \pi^- \ \text{candidate events (> 60}\sigma\ \text{observation!)}$

- Branching fraction measured wrt to $B^- \rightarrow D^+ \pi^- \pi^-$

\[
\mathcal{B}(B^- \rightarrow D^+ K^- \pi^-) = (7.92 \pm 0.23 \pm 0.24 \pm 0.42) \times 10^{-5}
\]

Uncertainties are statistical, systematic and due to PDG uncertainty on $B^- \rightarrow D^+ \pi^- \pi^-$ BF
Dalitz plot model

- Efficiency and background distributions studied and used as input

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Spin</th>
<th>DP axis</th>
<th>Model</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0^*(2400)^0$</td>
<td>0</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>$m = 2318 \pm 29$ MeV/c$^2$, $\Gamma = 267 \pm 40$ MeV</td>
</tr>
<tr>
<td>$D_2^*(2460)^0$</td>
<td>2</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>Floated</td>
</tr>
<tr>
<td>$D_J^*(2760)^0$</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>Floated</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>0</td>
<td>$m^2(D\pi)$</td>
<td>EFF</td>
<td>Floated</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>EFF</td>
<td>Floated</td>
</tr>
<tr>
<td>$D_v^*(2007)^0$</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>$m = 2006.98 \pm 0.15$ MeV/c$^2$, $\Gamma = 2.1$ MeV</td>
</tr>
<tr>
<td>$B_v^{*0}$</td>
<td>1</td>
<td>$m^2(DK)$</td>
<td>RBW</td>
<td>$m = 5325.2 \pm 0.4$ MeV/c$^2$, $\Gamma = 0.0$ MeV</td>
</tr>
</tbody>
</table>

- $D_0^*(2400)^0$ and $D_2^*(2460)^0$ states expected
- High mass $D_J^*(2760)^0$ state included, previously unknown spin
- Two virtual states
- Relativistic Breit-Wigner shape used to model resonances
- Two non-resonant components (S-wave and P-wave), exponential model
  - Model independent tests support need for both
Dalitz plot fit

- Data
- $D^+_s(2460)^0$
- Full fit
- $D^+_s(2760)^0$
- Background
- $B^+_s$
- $D^0(2007)^0$
- Nonresonant S-wave
- $D^0(2400)^0$
- Nonresonant P-wave
Dalitz plot fit

- (Right) helicity angle distributions for (left) interesting $m(D^+\pi^-)$ regions
Dalitz plot analysis results

• $D_1^*(2760)^0$ determined to have spin-1
  • Other hypotheses rejected with high significance

• Masses and widths of $D_2^*(2460)^0$ and $D_1^*(2760)^0$ reported:

\[
\begin{align*}
  m(D_2^*(2460)^0) & = (2464.0 \pm 1.4 \pm 0.5 \pm 0.2) \text{ MeV}/c^2 \\
  \Gamma(D_2^*(2460)^0) & = (43.8 \pm 2.9 \pm 1.7 \pm 0.6) \text{ MeV} \\
  m(D_1^*(2760)^0) & = (2781 \pm 18 \pm 11 \pm 6) \text{ MeV}/c^2 \\
  \Gamma(D_1^*(2760)^0) & = (177 \pm 32 \pm 20 \pm 7) \text{ MeV}
\end{align*}
\]

Uncertainties are statistical, experimental systematic and model uncertainties

• Product branching fractions ($\times 10^{-4}$) measured:

\[
\begin{array}{|c|c|}
\hline
\text{Resonance} & \text{Branching fraction} \\
\hline
D_0^*(2400)^0 & 6.6 \pm 2.1 \pm 0.5 \pm 1.5 \pm 0.4 \\
D_2^*(2460)^0 & 25.2 \pm 1.2 \pm 0.7 \pm 1.1 \pm 1.7 \\
D_1^*(2760)^0 & 3.9 \pm 1.0 \pm 0.3 \pm 0.7 \pm 0.3 \\
\text{S-wave nonresonant} & 30.1 \pm 5.9 \pm 1.2 \pm 8.6 \pm 2.0 \\
\text{P-wave nonresonant} & 18.9 \pm 4.4 \pm 1.6 \pm 2.9 \pm 1.3 \\
D_0^*(2007)^0 & 6.0 \pm 1.8 \pm 1.0 \pm 1.2 \pm 0.4 \\
B_v^* & 2.9 \pm 1.5 \pm 0.7 \pm 1.3 \pm 0.2 \\
\hline
\end{array}
\]

Final errors due to uncertainty on $D K \pi$ BF result
$B^{**}$ Spectroscopy
**B****S**pectroscopy

- Heavy Quark Effective Theory predicts spectrum of excited $B$ states
  - Spectrum should be almost identical for charged and neutral $B^{**}$ states
  - Higher excitations decay to $B/B^*$ plus $\pi$

- Current knowledge is limited

- Broad $B_0^*$ and $B_1$ states predicted
- Evidence for higher mass states from CDF [Phys.Rev. D90 (2014) 1, 012013]
Fit to data

- Simultaneous fit to 3 bins for $p_T$ of companion pion
  - Fit results shown for (left) $B^+\pi^-$ and (right) $B^0\pi^+$ (integrated over $p_T$ bins)

- Resonances - Relativistic Breit-Wigner shape
  - Most natural spin-parity states can decay to both $B\pi$ and $B^*\pi$
  - Since $B^*\pi \rightarrow B\pi\gamma$, include two peaks for natural spin-parity states

- Combinatorial background - Shape from wrong sign decays in data (i.e. $B^+\pi^+$)
- Associated production - Fitted with empirical model from simulation
  - From very broad resonances or non-resonant production of $B$ and $\pi$
$B^+\pi^-$ candidate fit in $p_T$ bins

Data binned in $p_T$ of $\pi^-$
- (top left) $0.5 < p_T < 1$ GeV
- (top left) $1 < p_T < 2$ GeV
- (bottom) $p_T > 2$ GeV

Similar plots for $B^0\pi^+$ in backup

Two RBWs used to fit high mass structure – alternative models with 3 RBWs
Results

• Mass and width measurements presented for narrow states
  • Measurements agree with (but are more precise than) CDF results
    
    \[
    \begin{array}{lcccc}
    m_{B_1(5721)^0} & = 5727.7 \pm 0.7 \pm 1.4 \pm 0.17 \pm 0.4 \text{ MeV} \\
    m_{B_2(5747)^0} & = 5739.44 \pm 0.37 \pm 0.33 \pm 0.17 \text{ MeV} \\
    m_{B_1(5721)^+} & = 5725.1 \pm 1.8 \pm 3.1 \pm 0.17 \pm 0.4 \text{ MeV} \\
    m_{B_2(5747)^+} & = 5737.20 \pm 0.72 \pm 0.40 \pm 0.17 \text{ MeV} \\
    \Gamma_{B_1(5721)^0} & = 30.1 \pm 1.5 \pm 3.5 \text{ MeV} \\
    \Gamma_{B_2(5747)^0} & = 24.5 \pm 1.0 \pm 1.5 \text{ MeV} \\
    \Gamma_{B_1(5721)^+} & = 29.1 \pm 3.6 \pm 4.3 \text{ MeV} \\
    \Gamma_{B_2(5747)^+} & = 23.6 \pm 2.0 \pm 2.1 \text{ MeV} \\
    \end{array}
    \]

(Uncertainties are stat., syst., uncertainty on $B$ meson mass, uncertainty on $B^* - B$ mass difference)

• Branching fraction ratios measured for $B_2^*$ states – in agreement with theory predictions
  • First evidence of $B_2^*(5747)^0 \rightarrow B^{*+}\pi^-$ decay
    
    \[
    \begin{array}{l}
    \frac{B(B_2^*(5747)^0 \rightarrow B^{*+}\pi^-)}{B(B_2^*(5747)^0 \rightarrow B^{+}\pi^-)} = 0.71 \pm 0.14 \pm 0.30 \\
    \frac{B(B_2^*(5747)^+ \rightarrow B^{*0}\pi^+)}{B(B_2^*(5747)^+ \rightarrow B^{0}\pi^+)} = 1.0 \pm 0.5 \pm 0.8
    \end{array}
    \]

(Uncertainties are statistical and systematic)

• Structure at high mass clearly observed; measured parameters and interpretation depend on model assumptions

Charlotte Wallace, LLWI 2015
Conclusions

• Several spectroscopy results produced from LHCb in the last few months
  • Observation of $\Xi_b^-$ resonances [Phys. Rev. Lett. 114, 062004 (2015)]
  • Dalitz plot analysis $B_s^0 \to D^0 K^- \pi^+$ [Phys. Rev. D90, 072003 (2014), Phys. Rev. Lett. 113, 162001 (2014)]

• New $D^{**}$ results from Dalitz plot analysis of $B^- \to D^+ K^- \pi^-$ decays
  • First observation of $B^- \to D^+ K^- \pi^-$ decay
  • $D_1^+(2760)^0$ determined to have spin-1
  • Masses and widths of $D_2^*(2460)^0$ and $D_1^*(2760)^0$ measured
  • Product branching fractions of resonances measured

• New $B^{**}$ results from studies of $B^0 \pi^+$ and $B^+ \pi^-$ mass distributions
  • First evidence of $B_2^*(5747)^0 \to B^{**+} \pi^-$ decay
  • Masses and widths of $B_1(5721)$ and $B_2^+(5747)$ states measured
  • Results for higher mass states depend on fit model used

• Look out for studies of additional modes coming soon!
Backup
• Long lived heavy hadrons are predominantly produced in the forward direction
• LHCb geometry exploits this fact

• Vertex Locator (VELO) – precise tracking very close to the interaction point
• Two Ring Imaging Cherenkov (RICH) detectors – separation of kaons and pions
Trigger categories at LHCb

- **Trigger On Signal** – particle from signal decay fires trigger
  - HCAL deposits

- **Trigger Independent of Signal** – particle from rest of the event fires trigger
  - HCAL deposits and muon hits
Square Dalitz plot

• Coordinate transform of Dalitz plot to give a square phase space

• In this choice of SDP representation, $m'$ is related to $m(D\pi)$ in reverse and $\theta'$ is the $D\pi$ helicity angle
  • Resonances decaying to $D^+\pi^-$ appear vertically at high $m'$
$B^- \rightarrow D^+ K^- \pi^-$ branching fraction

- Systematics evaluated:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+$ veto</td>
<td>0.2</td>
</tr>
<tr>
<td>Fit model</td>
<td>2.0</td>
</tr>
<tr>
<td>Particle identification</td>
<td>2.1</td>
</tr>
<tr>
<td>Efficiency modelling</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- BF measured w.r.t. topologically similar $B^- \rightarrow D^+ \pi^- \pi^-$

$$\frac{\mathcal{B}(B^- \rightarrow D^+ K^- \pi^-)}{\mathcal{B}(B^- \rightarrow D^+ \pi^- \pi^-)} = 0.0702 \pm 0.0020 \pm 0.0021$$

$$\mathcal{B}(B^- \rightarrow D^+ K^- \pi^-) = (7.92 \pm 0.23 \pm 0.24 \pm 0.42) \times 10^{-5}$$

Uncertainties are statistical, systematic and due to PDG uncertainty on $B^- \rightarrow D^+ \pi^- \pi^-$ BF
$B^- \rightarrow D^+K^-\pi^-$ selection

• Identical selection applied to $D\pi\pi$ and $DK\pi$ candidates apart from Particle Identification (PID) requirement on the one different track.

• $D$ candidates reconstructed as $D^+ \rightarrow K^-\pi^+\pi^+$

• Loose initial requirements applied to suppress background contributions

• $D\pi\pi$ data used to train two neural networks – first to clean up $D$ candidates, second to suppress combinatorial background
  • sPlot technique used to statistically separate signal and background events
  • Combinatorial background reduced by an order of magnitude, 90% signal kept

• PID requirements applied to all 5 final state tracks
Backgrounds

- Signal region is taken as $\pm 2.5\sigma$

- Signal region is 93.2% pure – three backgrounds contribute: $B^- \rightarrow D_s^+K^-\pi^-$ (1.4%), $B^- \rightarrow D^+\pi^-\pi^-$ (1.7%), combinatorial (3.5%)
Efficiency and background distributions

- Signal efficiency distribution for events triggered by (left) particles in the candidate decay, (right) other particles in the event

- Signal region is 93% pure – three backgrounds contribute: (left) $B^- \rightarrow D_s^+ K^- \pi^-$, (middle) $B^- \rightarrow D^+ \pi^- \pi^-$, (right) combinatorial
Previous $D^{**}$ spectroscopy measurements

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass  (MeV/$c^2$)</th>
<th>Width (MeV)</th>
<th>$J^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0^{*}(2400)^0$</td>
<td>2318 ± 29</td>
<td>267 ± 40</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$D_1(2420)^0$</td>
<td>2421.4 ± 0.6</td>
<td>27.4 ± 2.5</td>
<td>1$^+$</td>
</tr>
<tr>
<td>$D'_1(2430)^0$</td>
<td>2427 ± 26 ± 20 ± 15</td>
<td>384$^{+107}_{-75}$ ± 24 ± 70</td>
<td>1$^+$</td>
</tr>
<tr>
<td>$D_2^{*}(2460)^0$</td>
<td>2462.6 ± 0.6</td>
<td>49.0 ± 1.3</td>
<td>2$^+$</td>
</tr>
<tr>
<td>$D^{*}(2600)$</td>
<td>2608.7 ± 2.4 ± 2.5</td>
<td>93 ± 6 ± 13</td>
<td>natural</td>
</tr>
<tr>
<td>$D^{*}(2650)$</td>
<td>2649.2 ± 3.5 ± 3.5</td>
<td>140 ± 17 ± 19</td>
<td>natural</td>
</tr>
<tr>
<td>$D^{*}(2760)$</td>
<td>2763.3 ± 2.3 ± 2.3</td>
<td>60.9 ± 5.1 ± 3.6</td>
<td>natural</td>
</tr>
<tr>
<td>$D^{*}(2760)$</td>
<td>2760.1 ± 1.1 ± 3.7</td>
<td>74.4 ± 3.4 ± 19.1</td>
<td>natural</td>
</tr>
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</table>

### Fit results

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Real part</th>
<th>Imaginary part</th>
<th>Magnitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^*_0(2400)^0$</td>
<td>$-0.04 \pm 0.07$</td>
<td>$-0.51 \pm 0.07$</td>
<td>$0.51 \pm 0.09$</td>
<td>$-1.65 \pm 0.16$</td>
</tr>
<tr>
<td>$D^*_2(2460)^0$</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$D^*_1(2760)^0$</td>
<td>$-0.32 \pm 0.06$</td>
<td>$-0.23 \pm 0.07$</td>
<td>$0.39 \pm 0.05$</td>
<td>$-2.53 \pm 0.24$</td>
</tr>
<tr>
<td>Nonresonant (S-wave)</td>
<td>$0.93 \pm 0.09$</td>
<td>$-0.58 \pm 0.08$</td>
<td>$1.09 \pm 0.09$</td>
<td>$-0.56 \pm 0.09$</td>
</tr>
<tr>
<td>Nonresonant (P-wave)</td>
<td>$-0.43 \pm 0.09$</td>
<td>0.75 \pm 0.09</td>
<td>$0.87 \pm 0.09$</td>
<td>$2.09 \pm 0.15$</td>
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<tr>
<td>$D^*_v(2007)^0$</td>
<td>$0.16 \pm 0.08$</td>
<td>$0.46 \pm 0.09$</td>
<td>$0.49 \pm 0.07$</td>
<td>$1.24 \pm 0.17$</td>
</tr>
<tr>
<td>$B^*_v$</td>
<td>$-0.07 \pm 0.08$</td>
<td>$0.33 \pm 0.07$</td>
<td>$0.34 \pm 0.06$</td>
<td>$1.78 \pm 0.23$</td>
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<table>
<thead>
<tr>
<th>Resonance</th>
<th>Fit fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^*_0(2400)^0$</td>
<td>8.3 $\pm$ 2.6 $\pm$ 1.9</td>
</tr>
<tr>
<td>$D^*_2(2460)^0$</td>
<td>31.8 $\pm$ 1.5 $\pm$ 1.4</td>
</tr>
<tr>
<td>$D^*_1(2760)^0$</td>
<td>4.9 $\pm$ 1.2 $\pm$ 0.9</td>
</tr>
<tr>
<td>Nonresonant (S-wave)</td>
<td>38.0 $\pm$ 7.4 $\pm$ 1.5</td>
</tr>
<tr>
<td>Nonresonant (P-wave)</td>
<td>23.8 $\pm$ 5.6 $\pm$ 3.7</td>
</tr>
<tr>
<td>$D^*_v(2007)^0$</td>
<td>7.6 $\pm$ 2.3 $\pm$ 1.5</td>
</tr>
<tr>
<td>$B^*_v$</td>
<td>3.6 $\pm$ 1.9 $\pm$ 1.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$\alpha_s$</td>
<td>0.36 $\pm$ 0.03</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>0.36 $\pm$ 0.04</td>
</tr>
</tbody>
</table>
Legendre moments for $B^- \to D^+ K^- \pi^-$

- Moments for $m(D\pi)$
- Data and fit model
- No structure in $P_5$ and $P_6$ suggest no spin-3 contribution in data
Goodness of fit for $B^- \rightarrow D^+ K^- \pi^-$ Dalitz plot fit

- Adaptive binning – equal number of events per bin
- $1.38 < \chi^2/\text{ndf} < 1.68$
  - ndf between nbins-1 and nbins-npars-1
- Fits to toy data support result of $\chi^2/\text{ndf} = 1.68$ for binning choice
- Pulls across SDP shown:
$B^- \rightarrow D^+ K^- \pi^-$ DP systematics

- Extensive systematic studies performed
  - Systematic uncertainties calculated for all reported fit parameters
  - All systematics have varying effects on measured quantities but systematics that tend to dominate are shown in red

- Experimental systematics
  - Signal and background yields
  - Efficiency distribution
  - Background distributions
  - Fit bias

- Model uncertainties
  - Fixed parameters in DP model
  - Test model (add/remove marginal components)
  - Alternative models for non-resonant and virtual components
\( B^0\pi^+ \) candidate fit in \( p_T \) bins

Fit \( Q = m(B\pi) - m_B - m_\pi \) for \( B^0\pi^+ \)

Data binned in \( p_T \) of \( \pi^+ \)
- (top left) \( 0.5 < p_T < 1 \) GeV
- (top left) \( 1 < p_T < 2 \) GeV
- (bottom) \( p_T > 2 \) GeV
### Fit results (stat. uncertainties only)

<table>
<thead>
<tr>
<th>Fit parameter</th>
<th>$B^+\pi^-$</th>
<th>$B^0\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1(5721)^{0,+}$ $\mu$</td>
<td>263.9 ± 0.7</td>
<td>260.9 ± 1.8</td>
</tr>
<tr>
<td>$B_1(5721)^{0,+}$ $\Gamma$</td>
<td>30.1 ± 1.5</td>
<td>29.1 ± 3.6</td>
</tr>
<tr>
<td>$B_2^*(5747)^{0,+}$ $\mu$</td>
<td>320.6 ± 0.4</td>
<td>318.1 ± 0.7</td>
</tr>
<tr>
<td>$B_2^*(5747)^{0,+}$ $\Gamma$</td>
<td>24.5 ± 1.0</td>
<td>23.6 ± 2.0</td>
</tr>
<tr>
<td>$N_{B_1(5721)^{0,+}}$ low $p_T$</td>
<td>14200 ± 1400</td>
<td>3140 ± 750</td>
</tr>
<tr>
<td>$N_{B_1(5721)^{0,+}}$ mid $p_T$</td>
<td>16200 ± 1500</td>
<td>4020 ± 890</td>
</tr>
<tr>
<td>$N_{B_1(5721)^{0,+}}$ high $p_T$</td>
<td>4830 ± 470</td>
<td>940 ± 260</td>
</tr>
<tr>
<td>$N_{B_2^*(5747)^{0,+}}$ low $p_T$</td>
<td>7450 ± 420</td>
<td>1310 ± 180</td>
</tr>
<tr>
<td>$N_{B_2^*(5747)^{0,+}}$ mid $p_T$</td>
<td>7600 ± 340</td>
<td>2070 ± 180</td>
</tr>
<tr>
<td>$N_{B_2^*(5747)^{0,+}}$ high $p_T$</td>
<td>1690 ± 130</td>
<td>640 ± 80</td>
</tr>
<tr>
<td>$B(B_2^<em>(5747)^{0,+} \to B^</em>\pi)/B(B_2^*(5747)^{0,+} \to B\pi)$</td>
<td>0.71 ± 0.14</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td>$B_J(5840)^{0,+}$ $\mu$</td>
<td>444 ± 5</td>
<td>431 ± 13</td>
</tr>
<tr>
<td>$B_J(5840)^{0,+}$ $\Gamma$</td>
<td>127 ± 17</td>
<td>224 ± 24</td>
</tr>
<tr>
<td>$B_J(5960)^{0,+}$ $\mu$</td>
<td>550.4 ± 2.9</td>
<td>545.8 ± 4.1</td>
</tr>
<tr>
<td>$B_J(5960)^{0,+}$ $\Gamma$</td>
<td>82 ± 8</td>
<td>63 ± 15</td>
</tr>
<tr>
<td>$N_{B_J(5840)^{0,+}}$ low $p_T$</td>
<td>3200 ± 1300</td>
<td>1630 ± 970</td>
</tr>
<tr>
<td>$N_{B_J(5840)^{0,+}}$ mid $p_T$</td>
<td>5600 ± 1000</td>
<td>3230 ± 720</td>
</tr>
<tr>
<td>$N_{B_J(5840)^{0,+}}$ high $p_T$</td>
<td>3090 ± 550</td>
<td>2280 ± 450</td>
</tr>
<tr>
<td>$N_{B_J(5960)^{0,+}}$ low $p_T$</td>
<td>3270 ± 660</td>
<td>610 ± 240</td>
</tr>
<tr>
<td>$N_{B_J(5960)^{0,+}}$ mid $p_T$</td>
<td>4590 ± 610</td>
<td>910 ± 250</td>
</tr>
<tr>
<td>$N_{B_J(5960)^{0,+}}$ high $p_T$</td>
<td>2400 ± 320</td>
<td>500 ± 140</td>
</tr>
</tbody>
</table>
Parameters for high mass states

(Uncertainties are statistical, experimental systematic, uncertainty on $B$ meson mass, uncertainty on $B^* - B$ mass difference)

Any state not labelled “natural” is assumed to have unnatural spin-parity

<table>
<thead>
<tr>
<th></th>
<th>Empirical model</th>
<th>Quark model, $B_J(5840)^{0,+}$ natural</th>
<th>Quark model, $B_J(5960)^{0,+}$ natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{B_J(5840)^0}$</td>
<td>5862.9 ± 5.0</td>
<td>5889.7 ± 22.2 ± 6.7 ± 0.2</td>
<td>5907.8 ± 4.7 ± 6.7 ± 0.2</td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)^0}$</td>
<td>127.4 ± 16.7 ± 34.2</td>
<td>107.0 ± 19.6 ± 34.2</td>
<td>119.4 ± 17.2 ± 34.2</td>
</tr>
<tr>
<td>$m_{B_J(5960)^0}$</td>
<td>5969.2 ± 2.9</td>
<td>6015.9 ± 3.7 ± 5.1 ± 0.2 ± 0.4</td>
<td>5993.6 ± 6.4 ± 5.1 ± 0.2</td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)^0}$</td>
<td>82.3 ± 7.7 ± 9.4</td>
<td>81.6 ± 9.9 ± 9.4</td>
<td>55.9 ± 6.6 ± 9.4</td>
</tr>
<tr>
<td>$m_{B_J(5840)^+}$</td>
<td>5850.3 ± 12.7</td>
<td>5874.5 ± 25.7 ± 13.7 ± 0.2</td>
<td>5889.3 ± 15.0 ± 13.7 ± 0.2</td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)^+}$</td>
<td>224.4 ± 23.9 ± 79.8</td>
<td>214.6 ± 26.7 ± 79.8</td>
<td>229.3 ± 26.9 ± 79.8</td>
</tr>
<tr>
<td>$m_{B_J(5960)^+}$</td>
<td>5964.9 ± 4.1</td>
<td>6010.6 ± 4.0 ± 2.5 ± 0.2 ± 0.4</td>
<td>5966.4 ± 4.5 ± 2.5 ± 0.2</td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)^+}$</td>
<td>63.0 ± 14.5 ± 17.2</td>
<td>61.4 ± 14.5 ± 17.2</td>
<td>60.8 ± 14.0 ± 17.2</td>
</tr>
</tbody>
</table>