Charm spectroscopy at LHCb

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on behalf of the LHCb collaboration

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Quark model has enjoyed significant success in predicting charm spectra.

Many charm states have been recently identified at various experiments.

But still many not found!

And still some interesting tensions between theory and experiment.

Today will present some LHCb results in the field.

Meson $c\bar{u}$ spectra - Phys. Rev. D32 (1985) 189

The LHCb Detector

- Forward arm spectrometer designed for precision flavour measurements

- VELO - powerful secondary vertex discrimination to trigger on heavy flavour decays
- Tracker momentum resolution: $\Delta p/p = 0.4\%$ at 5 GeV/c to 0.6\% at 100 GeV/c
- RICH - daughter particle discrimination:
  - Kaon ID efficiency $\sim 95\%$ for $\sim 5\% \pi \to K$ mis-id probability
Considerable progress in past 10 years on measuring charm baryon spectra.

Variety of $\Sigma_c$, $\Omega_c$ and $\Xi_c$ states identified by the B factories.

Quark model has been very successful in predicting masses of singly charmed states, and mass splittings.

One of the more interesting sagas in spectroscopy is the case of doubly-charmed production, and in searches for the $\Xi_{cc}^{++}$.

$\Omega_c(2770)^0$ at BaBar - Phys. Rev. Lett. 97, 232001

$\Xi_c(2980)$ and $\Xi_c(3077)$ at BELLE - Phys. Rev. Lett. 97, 162001

Baryons with u,d,s,c form SU(4) multiplets

Ground state baryons shown

Three weakly decaying $C = 2, J^P = 1/2^+$ states:
- $\Xi_{cc}$ isodoublet ($ccu, ccd$)
- $\Omega_{cc}$ singlet ($ccs$)

Numerous predictions for $\Xi_{cc}^{++}$ masses and lifetimes:
- Production relative to $\Lambda_c^+$ generally expected to be highly suppressed - e.g. Physics-Uspekhi 45 (2002), no. 5 455
SELEX reported signals in $\Lambda_c^+ K^- \pi^+$ and $p^+ D^+ K^-$ final states
- $m(\Xi_{cc}^{++})$: $(3519 \pm 2)$ MeV/$c^2$, $\tau(\Xi_{cc}^{++})$: < 30 fs @ 90 % CL
- SELEX calculate 20 % of their $\Lambda_c$ produced in $\Xi_{cc}^{++}$ decays

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Charm spectroscopy at LHCb  
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LHCb 2011 $\Xi_{cc}^+$ search

- Search for particle in decay $\Xi_{cc}^+ \rightarrow \Lambda_c^+(pK^-\pi^+)K^-\pi^+$
- Using 0.65 fb$^{-1}$ of 2011 data at $\sqrt{s} = 7$ TeV
- Measure production ratio relative to control channel $\Lambda_c^+ \rightarrow pK^-\pi^+$:
  \[ R \equiv \frac{\sigma(\Xi_{cc}^+)B(\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{signal}}{N_{control}} \frac{\epsilon_{control}}{\epsilon_{signal}} \]

- Measured LHCb $\Lambda_c$ cross-section at $\sqrt{s} = 7$ TeV $\approx 230$ µb
- NUCL.PHYS.B871,1-20
- Predicted LHC $\Xi_{cc}^{++/++}$ cross-section at $\sqrt{s} = 7$ TeV $\approx (30 - 900)$ nb.

- Assume $B(\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+) \approx B(\Lambda_c^+ \rightarrow p^+K^-\pi^+) \approx 5 \%$
- expected value of $R$ at LHCb is of order $10^{-5} - 10^{-4}$
Define:
\[ \delta m \equiv m(\Lambda_c^+ K^- \pi^+) - m_{\text{meas}}(\Lambda_c^+) - m(K^-) - m(\pi^+) \]

- Perform 2D fit in \( m(\Lambda_c) \) and \( \delta m \) to extract signal yields.
- No observed excess in \( \delta m \) spectrum in data.
- Calculate 95% \( CL_s \) ULs of \( R \) as function of \( \delta m \) for variety of lifetime hypotheses.
2011 analysis a strong proof of concept
Prospects for 2011+2012 dataset look bright
Full 2.08 fb$^{-1}$ at $\sqrt{s} = 8$ TeV available for analysis
$\Lambda_c^+ \rightarrow pK^−\pi^+$ trigger and selection performance improved for 2012
Now searching for $\Xi_{cc}^{+/++}$ in multiple final states
  - Notable inclusion: $\Xi_{cc}^{++} \rightarrow (D^+ \rightarrow K^-\pi^+\pi^+)p^+K^-$. 
  - High $D^+$ lifetime (1 ps) vs. $\Lambda_c^+$ (0.2 ps) - more efficient selections
Updated analysis will have far greater sensitivity.
Charm meson overview

$D_{sJ}(2700)^+$ at Belle - Phys. Rev. Lett. 100, 092001

$D_{sJ}(2860)^+$ at BaBar - Phys Rev Lett. 197(22):222001

- Along with baryons, much recent progress in identifying charmed mesons.
- However, still many states missing which were predicted in 1980s.
- And some interesting tensions between theory and experiment - e.g. masses of $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ significantly lower than theory predictions.
Today present LHCb searches in the $c\bar{u}$ and $c\bar{s}$ meson spectra:

- Clean $D$ reconstruction at LHCb.
- Candidates in $D_J$ analysis:
  - $15.1 \times 10^6 \ D^+$
  - $20.4 \times 10^6 \ D^0$
  - $6.4 \times 10^6 \ D^{*+}$
Following on observations of a variety of excited charm mesons by BaBar (Phys. Rev. D82 111101), search in the final states:

- $p\bar{p} \rightarrow D^+\pi^- X$, $p\bar{p} \rightarrow D^0\pi^+ X$, $p\bar{p} \rightarrow D^{*+}\pi^- X$.

Search uses full 2011 dataset: 1.0 fb$^{-1}$ at $\sqrt{s} = 7$ TeV.

$D$ selections uses a variety of fiducial and kinematic cuts to increase purity.

PID discrimination used to mitigate cross-feed.

Aim to confirm previously observed states, and use high charms statistics at LHCb to search for new ones.
$D_J$ mass fits.

\[ \begin{align*}
\downarrow^1 & - D_J(2580)^0, \downarrow^2 - D_J(2740)^0, \\
\downarrow^3 & - D_J(3000)^0 \\
\downarrow^1 & - D_J^*(2650)^0, \downarrow^2 - D_J^*(2760)^0 \\
\downarrow^3 & - D_J^*(2760)^+, \downarrow^4 - D_J^*(3000)^+ 
\end{align*} \]
$D_J$ spin-parity analysis

- Measure yields of each state as a function of helicity angle $\cos \theta_H$.
  - angle between the bachelor $\pi^-$ and $\pi^+$ from $D^{*+}$ decay in the rest frame of the $D^{*+}$ $\pi^-$ rest frame.
- Tests for natural ($J^p = 1^-, 2^+, 3^- ...$) and unnatural ($J^p = 1^+, 2^-, 3^+ ...$) parity.
- Natural parity states: $\frac{dN}{d \cos \theta_H} \propto \sin^2 \theta_H$, unnatural parity $\frac{dN}{d \cos \theta_H} \propto 1 + h \cos^2 \theta_H$
Number of charm states identified in the final states $p\bar{p} \rightarrow D^+\pi^- X$, $p\bar{p} \rightarrow D^0\pi^+ X$, $p\bar{p} \rightarrow D^{*+}\pi^- X$.

- Observe $D_1(2420)^0$ in $D^{*+}\pi^-$ final state, $D_2^*(2460)$ resonance in $D^+\pi^-$, $D^0\pi^+$ and $D^{*+}\pi^-$ final states - spin-parity assignments confirmed.
- Observe two natural parity resonances - $D_j^*(2650)^0$ and $D_j^*(2760)^0$.
- Observe two unnatural parity resonances - $D_J(2580)^0$ and $D_J(2740)^0$.
- Observe further structure in $D^{*+}\pi^-$ final state - $D_J(3000)^0$ compatible with natural parity.
- Also observe several structures in $D^+\pi^-$ and $D^0\pi^+$ final states - $D_j^*(3000)^0$ and $D_j^*(3000)^+$ - possible result of superposition of several 1F states.

- Identifications suggested by us and by the theory community - e.g. Phys.Rev.D88 (2013) 114003.

$D_j^*(2650)^0$: $J^P = 1^-$, 2S $D_1^*(2618)$
$D_j^*(2760)^+$: $J^P = 1^-$, 1D $D_1^*(2796)$
$D_J(2740)^0$: $J^P = 2^-$, 1D $D_2(2801)$
Current state of $c\bar{s}$ spectroscopy - two S-wave and four P-wave states.

Some tension with $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ states - found at higher masses than theory predicts.

Among the observed high mass $D_{sJ}$ structures, none currently reported in PDG tables.

LHCb conducted analysis to help confirm existence of these states and to measure their parameters.

Look for resonances in the final states:
- $D^+ (K^- \pi^+ \pi^+) K_S^0 (\pi^+ \pi^-)$
- $D^0 (K^- \pi^+) K^+$

Again, full 2011 dataset used: $1.0 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$. 
$D_{sJ}$ mass fits

$\downarrow D_{s2}^*(2573)^+$

$\downarrow D_{sJ}^*(2700)^0 \downarrow D_{sJ}(2860)^+$
**$D_{sJ}$ yields and results**

- Extracted yields:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$D_{s1}^*(2700)^+$</th>
<th>$D_{sJ}^*(2860)^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+K_S^0$</td>
<td>$6724 \pm 596$</td>
<td>$4825 \pm 347$</td>
</tr>
<tr>
<td>$D^0K^+$</td>
<td>$45315 \pm 2186$</td>
<td>$31603 \pm 1257$</td>
</tr>
</tbody>
</table>

- Final extracted mass and width parameters:

\[
\begin{align*}
    m(D_{s1}^*(2700)^+) &= 2709.2 \pm 1.9\text{(stat)} \pm 4.5\text{(syst)} \text{ MeV}/c^2, \\
    \Gamma(D_{s1}^*(2700)^+) &= 115.8 \pm 7.3\text{(stat)} \pm 12.1\text{(syst)} \text{ MeV}/c^2, \\
    m(D_{sJ}^*(2860)^+) &= 2866.1 \pm 1.0\text{(stat)} \pm 6.3\text{(syst)} \text{ MeV}/c^2, \\
    \Gamma(D_{sJ}^*(2860)^+) &= 69.9 \pm 3.2\text{(stat)} \pm 6.6\text{(syst)} \text{ MeV}/c^2.
\end{align*}
\]

- All parameters agree with previous BaBar measurement, with factor 2 improvement in statistical sensitivity.
- Systematics remain dominant.
- Need decays from $B_s$ to definitively assign spin-parity.
- Now have just this!
Analysis overview

- Analysis of the resonance structure of $B_s \rightarrow \bar{D}^0 K^- \pi^+$
  - **New results!**
  - Perform fit using Laura++ package – http://laura.hepforge.org/
  - Use candidates with $\bar{D}^0 \rightarrow K^+ \pi^-$ from 3fb$^{-1}$ of LHCb data

LHCb-PAPER-2014-035, LHCb-PAPER-2014-036 (to be submitted to PRL and PRD)

- Branching fractions of $B_s^0 \rightarrow \bar{D}^0 K^- \pi^+$ and $B^0 \rightarrow \bar{D}^0 K^+ \pi^-$ have been measured as $(1.00 \pm 0.14) \times 10^{-3}$ and $(9.0 \pm 1.3) \times 10^{-5}$ respectively
  - Uncertainties dominated by the uncertainty on the normalisation channel

Fit to $B$ mass

Fit to $D K \pi$ mass distribution from 3 fb$^{-1}$ of data showing the signal region ($\pm 2.5\sigma$). 
$\sim$11,000 signal decays, 87% pure in the nominal signal window. Backgrounds due to combinatorial background (7.3%), $B^0 \rightarrow D^{(*)0}\pi\pi$ (2.8%) and $\Lambda_b \rightarrow D^{(*)0}p\pi$ (2.3%)
Dalitz plot fit

\( \bar{K}^*(892)^0 \) \( \bar{K}_{0,2}(1430)^0 \)

LHCb (a)

Candidates / 13 MeV/c^2

LHCb (b)

Candidates / 9 MeV/c^2

LHCb (c)

Candidates / 15 MeV/c^2

LHCb (d)

Candidates / 5 MeV/c^2

\( D_{s2}^*(2573)^- \)

\( D_{sf}^*(2860)^- \)

15/07/2014

Daniel Craik, Beauty 2014, Edinburgh

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$D_{sJ}^*(2860)^-$ states

- Various spin hypotheses tested for the $m_{DK} \approx 2.86 \text{ GeV}/c^2$ region
- Spin-1 + spin-3 hypothesis offers best description of the data
- Spin-3 and spin-1 only hypotheses give poor descriptions of the DK helicity angle in the 2.86 GeV/$c^2$ region

\[ \chi^2 = 47.3, 214.0, 150.0 \]
\[ N_{\text{bins}} = 50 \]

<table>
<thead>
<tr>
<th>Spin hypothesis</th>
<th>$\Delta NLL$</th>
<th>$\sqrt{2\Delta NLL}$</th>
<th>Masses and widths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+3</td>
<td>0</td>
<td>---</td>
<td>2862               57</td>
</tr>
<tr>
<td>0+1</td>
<td>113.2</td>
<td>15.0</td>
<td>2446 250*          2855 96</td>
</tr>
<tr>
<td>0+2</td>
<td>155.1</td>
<td>17.6</td>
<td>2870 61            2569 17*</td>
</tr>
<tr>
<td>0+3</td>
<td>105.1</td>
<td>14.5</td>
<td>2415 188*          2860 52</td>
</tr>
<tr>
<td>1</td>
<td>156.8</td>
<td>17.7</td>
<td>2866 92</td>
</tr>
<tr>
<td>1+2</td>
<td>138.6</td>
<td>16.6</td>
<td>2851 99            3134 174*</td>
</tr>
<tr>
<td>2</td>
<td>287.9</td>
<td>24.0</td>
<td>3243 81*</td>
</tr>
<tr>
<td>2</td>
<td>365.5</td>
<td>27.0</td>
<td>2569 17*</td>
</tr>
<tr>
<td>2+3</td>
<td>131.2</td>
<td>16.2</td>
<td>2878 12            2860 56</td>
</tr>
<tr>
<td>3</td>
<td>136.5</td>
<td>16.5</td>
<td>2860 57</td>
</tr>
</tbody>
</table>

* Indicates states that floated out of the 2.86 GeV/$c^2$ region
DsJ spectroscopy summary

- $D_{sJ}^*(2700)^0$ and $D_{sJ}(2860)^+$ resonances first observed by BaBar confirmed by LHCb.
- Precision on masses and decay widths are markedly improved.
- First time states observed in a hadronic environment.
- Angular analysis of $B_s^0 \rightarrow \bar{D}K^-\pi^+$ decays have shown definitively that the $D_{sJ}(2860)^+$ is composed of two resonances:
  - $D_{s1}^*(2860)^-$ and $D_{s3}^*(2860)^-$, required at greater than 10 $\sigma$ significance!
  - First observation of heavy-flavoured spin-3 state!
Charm spectroscopy remains an active area, with lots to still find and a few interesting tensions along the way.

LHCb making contributions to knowledge of both charm mesons and baryons.

Presented results of:

- JHEP1312(2013)090 - $\Xi_{cc}^{+} / ++$ search, placing upper limits on hadronic production relative to $\Lambda_{c}^{+}$.
- JHEP09(2013)145 - $D_{J}$ spectroscopy, identifying several new states and confirming parity assignments.
- JHEP10(2012)151 - $D_{sJ}$ spectroscopy, confirming the existence of the $D_{J}^{*}(2760)^{0}$ and $D_{sJ}(2860)^{+}$ states.
- LHCb-PAPER-2014-035 - discovery of two $D_{sJ}$ resonances in $D_{sJ}(2860)^{-}$ structure: the $D_{s1}^{*}(2860)^{-}$ and $D_{s3}^{*}(2860)^{-}$.

Very active charm working group at LHCb carrying out a very wide variety of measurements.

Expect more spectroscopy from us soon!
**$\Xi^+_cc$ candidate Selection**

- Use same trigger requirements for control and signal based on $\Lambda^+_c \rightarrow pK^-\pi^+$ decay
  - One $\Lambda_c$ daughter track must fire calorimeter hardware trigger
  - One $\Lambda_c$ daughter track selected by inclusive software trigger
  - $\Lambda_c$ candidate reconstructed and accepted by dedicated $\Lambda^+_c \rightarrow pK^-\pi^+$ selection algorithm in software trigger - geometric and kinematic requirements, and using RICH PID info for proton.
- Offline reconstruction and selection based on PV displacement and particle identification requirements
- **To make $\Xi^{+}/++$ candidates:**
  - Pair $\Lambda_c$ with $K$ and $\pi$ at common vertex displaced from PV
  - Displacement cut reduces sensitivity to SELEX-like $\Xi^{+}/++$
  - Can be relaxed in future analyses
  - Artificial Neural Network final selection. Input variables chosen for minimal $\Xi^{+}/++$ lifetime dependence
$D_J$ meson decays - $D^+ \pi^-$ mass spectra

- Observed $D^+ \pi^-$ mass spectra and wrong-mass spectra (red) shown.
  - Double peak structure at 2300 MeV/$c^2$ from $D_1(2420)^0$ and $D_2^*(2460)^0$ cross feed when neutrals/photons not reconstructed.
  - Strong $D_2^*(2460)^0$ signal, weak structures at 2600 MeV/$c^2$ and 2750 MeV/$c^2$.
  - No structure in WM distribution.
Observed $D^0 \pi^+$ mass spectra and wrong-mass spectra (red) shown.

- Double peak structure at 2300 MeV/$c^2$ from $D_1(2420)^0$ and $D_2^*(2460)^0$ cross feed when neutrals/photons not reconstructed.
- Strong $D_2^*(2460)^+$ signal, weak structures at 2600 MeV/$c^2$ and 2750 MeV/$c^2$.
- Structure in WM distribution at 2300 MeV/$c^2$ due to cross feed from $D_1(2420)^+ / D_2^*(2460)^+ \rightarrow \pi^- D^{*+}(D^0 \pi^+)$.

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$D_J$ meson decays - $D^{*+} \pi^-$ mass spectra

- Observed $D^{*+} \pi^-$ mass spectra and wrong-mass spectra (red) shown.
  - Dominated by $D_1(2420)^0$ and $D_2^*(2460)^0$ signals.
  - Structures evident in high mass region.
  - No WM structure.
## $D_J$ meson properties

### Table

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Final state</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Yields ×10³</th>
<th>Significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_J(2420)^0$</td>
<td>$D^{*+}\pi^- $</td>
<td>2419.6 ± 0.1</td>
<td>35.2 ± 0.4</td>
<td>210.2 ± 1.9</td>
<td>24.5</td>
</tr>
<tr>
<td>$D_J(2460)^0$</td>
<td>$D^{*+}\pi^- $</td>
<td>2460.4 ± 0.4</td>
<td>140.2 ± 17.1</td>
<td>50.7 ± 2.2</td>
<td>10.2</td>
</tr>
<tr>
<td>$D_J(2650)^0$</td>
<td>$D^{*+}\pi^- $</td>
<td>2649.2 ± 3.5</td>
<td>74.4 ± 3.4</td>
<td>14.4 ± 1.7</td>
<td>18.8</td>
</tr>
<tr>
<td>$D_J(2760)^0$</td>
<td>$D^{*+}\pi^- $</td>
<td>2761.1 ± 5.1</td>
<td>177.5 ± 17.8</td>
<td>60.3 ± 3.1</td>
<td>9.5 ± 1.1</td>
</tr>
<tr>
<td>$D_J(2740)^0$</td>
<td>$D^{*+}\pi^- $</td>
<td>2737.0 ± 3.5</td>
<td>73.2 ± 13.4</td>
<td>7.7 ± 1.1</td>
<td>7.2</td>
</tr>
<tr>
<td>$D_J(3000)^0$</td>
<td>$D^{*+}\pi^- $</td>
<td>2971.8 ± 8.7</td>
<td>188.1 ± 44.8</td>
<td>9.5 ± 1.1</td>
<td>9.0</td>
</tr>
<tr>
<td>$D_J(2460)^0$</td>
<td>$D^{+}\pi^- $</td>
<td>2460.4 ± 0.1</td>
<td>45.6 ± 0.4</td>
<td>675.0 ± 9.0</td>
<td>55.8 ± 1.3</td>
</tr>
<tr>
<td>$D_J(2760)^0$</td>
<td>$D^{+}\pi^- $</td>
<td>2760.1 ± 1.1</td>
<td>74.4 ± 3.4</td>
<td>17.6 ± 1.1</td>
<td>17.3</td>
</tr>
<tr>
<td>$D_J(3000)^0$</td>
<td>$D^{+}\pi^- $</td>
<td>3008.1 ± 4.0</td>
<td>110.5 ± 11.5</td>
<td>17.6 ± 1.1</td>
<td>21.2</td>
</tr>
<tr>
<td>$D_J(2460)^+$</td>
<td>$D^0\pi^+$</td>
<td>2463.1 ± 0.2</td>
<td>48.6 ± 1.3</td>
<td>341.6 ± 22.0</td>
<td>18.8</td>
</tr>
<tr>
<td>$D_J(2760)^+$</td>
<td>$D^0\pi^+$</td>
<td>2771.7 ± 1.7</td>
<td>66.7 ± 6.6</td>
<td>20.1 ± 2.2</td>
<td>18.8</td>
</tr>
<tr>
<td>$D_J(3000)^+$</td>
<td>$D^0\pi^+$</td>
<td>3008.1 (fixed)</td>
<td>110.5 (fixed)</td>
<td>7.6 ± 1.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>
$D_{sJ}$ spectroscopy - selection

- Look for resonances in the final states:
  - $D^+ (K^- \pi^+ \pi^+) K_S^0 (\pi^+ \pi^-)$
  - $D^0 (K^- \pi^+) K^+$

- Selection of candidates places variety of fiducial and kinematic constraints.
- PID discrimination used to mitigate cross-feed.
- Defining $\theta$ as the angle between momentum of strange meson in $DK$ system and momentum direction of $DK$ system in lab frame - imposing $\cos \theta > 0$ vetoes 90% of combinatoric background.
- Further optimisation of the $D_{s2}^*(2573)^+$ peak significance using decay kinematics.