Charm spectroscopy at LHCb

BEACH 2014 Birmingham

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on behalf of the LHCb collaboration

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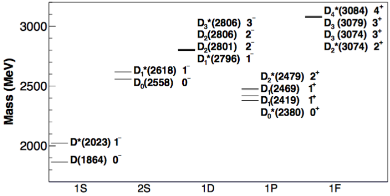
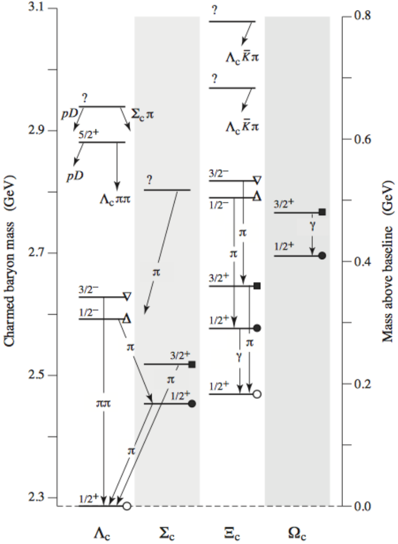
University of Glasgow | Experimental Particle Physics

Outline

- 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.



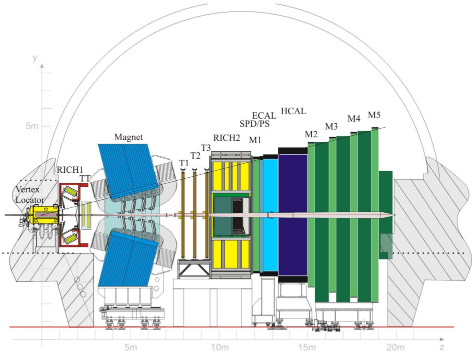
Meson $c\overline{u}$ spectra - Phys. Rev. D32 (1985) 189

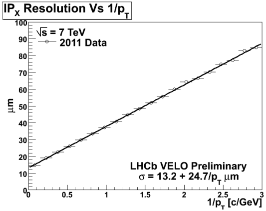


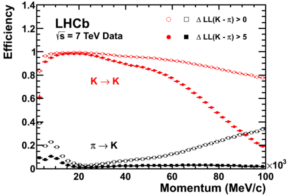
Baryon Spectra - Phys. Rev. D86, 010001 (2012)

The LHCb Detector

- Forward arm spectrometer designed for precision flavour measurements

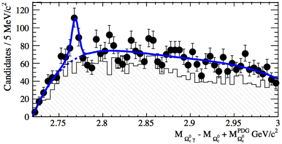




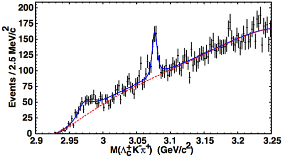


- VELO - powerful secondary vertex discrimination to trigger on heavy flavour decays
- Tracker momentum resolution: $\Delta p/p = 0.4$ % at 5 GeV/c to 0.6 % at 100 GeV/c
- RICH - daughter particle discrimination:
  Kaon ID efficiency $\sim$ 95 % for $\sim$ 5 % $\pi \to K$ mis-id probability

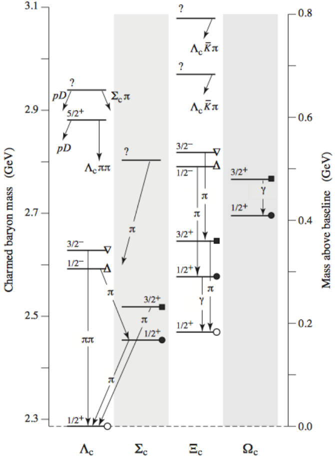
- Considerable progress in past 10 years on measuring charm baryon spectra.
- Variety of Σ_c, Ω_c and Ξ_c states identified by the B factories.
- Quark model has been very successful in predicting masses of singly charmed states, and mass splittings.
- One of the more interesting sagas in spectroscopy is the case of doubly-charmed production, and in searches for the $\Xi_{cc}^{+/++}$.



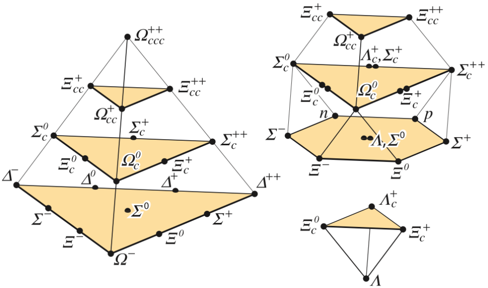
$\Omega_c(2770)^0$ at BaBar - Phys. Rev. Lett. 97 232001



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



Baryon Spectra - Phys. Rev. D86, 010001 (2012)

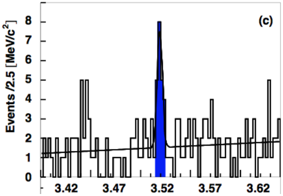


Phys. Rev. D86, 010001 (2012)

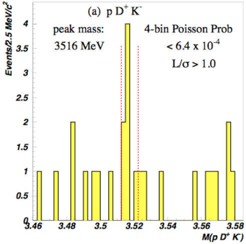
- Baryons with u,d,s,c form SU(4) multiplets
- Ground state baryons shown
- Three weakly decaying $C = 2, J^P = 1/2^+$ states:
  - Ξ_{cc} isodoublet (ccu, ccd)
  - Ω_{cc} singlet (ccs)

- Numerous predictions for $\Xi_{cc}^{+/++}$ masses and lifetimes:
  - $m(\Xi_{cc}^{+/++})$: 3500 – 3700 MeV/c^2 - Phys. Rev. D70 (2004) 094004
  - $\tau(\Xi_{cc}^{+/++})$: 100 – 250 fs - Eur. Phys. J. A45 (2010) 267
  - Production relative to Λ_c^+ generally expected to be highly suppressed - e.g. Physics-Uspekhi 45 (2002), no. 5 455

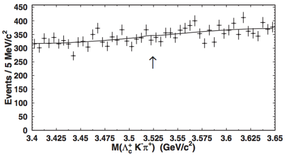
- SELEX reported signals in $\Lambda_c^+ K^- \pi^+$ and $p^+ D^+ K^-$ final states
  - $m(\Xi_{cc}^{+/++})$: (3519 ± 2) MeV/c^2, $\tau(\Xi_{cc}^{+/++})$: < 30 fs @ 90 % CL
  - SELEX calculate 20 % of their Λ_c produced in $\Xi_{cc}^{+/++}$ decays



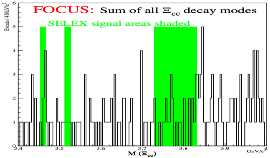
SELEX - Phys.Rev.Lett.89:112001



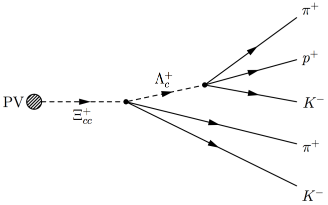
SELEX - Phys.Lett.B628:18-24



BELLE - PhysRevLett.97.162001



FOCUS - NuclPhysB 115:33-36



- Search for particle in decay $\Xi_{cc}^{+} \to \Lambda_c^{+}(pK^{-}\pi^{+})K^{-}\pi^{+}$
- Using 0.65 fb^{-1} of 2011 data at $\sqrt{s} = 7$ TeV
- Measure production ratio relative to control channel $\Lambda_c^{+} \to pK^{-}\pi^{+}$:

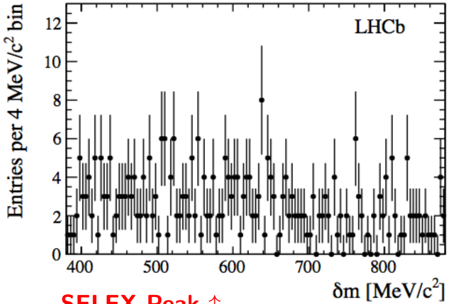
$$R \equiv \frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+})}{\sigma(\Lambda_c^{+})} = \frac{N_{signal}}{N_{control}} \frac{\epsilon_{control}}{\epsilon_{signal}}$$

  - Measured LHCb Λ_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 $\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}) \approx \mathcal{B}(\Lambda_c^{+} \to p^{+}K^{-}\pi^{+}) \approx 5$ %
  - expected value of R at LHCb is of order $10^{-5} - 10^{-4}$

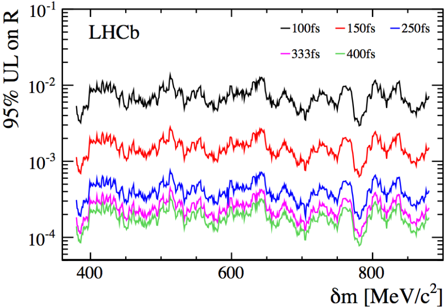
- Define:

$$\delta m \equiv m(\Lambda_c^+ K^- \pi^+) - m_{meas}(\Lambda_c^+) - m(K^-) - m(\pi^+)$$

- Perform 2D fit in $m(\Lambda_c)$ and δm to extract signal yields.
- No observed excess in δm spectrum in data.
- Calculate 95% CL_s ULs of R as function of δm for variety of lifetime hypotheses.

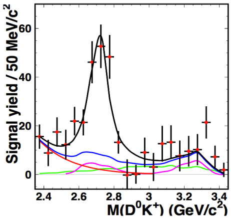


SELEX Peak ↑

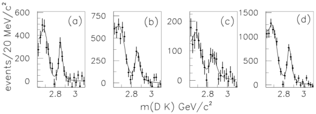


$\Xi_{cc}^{+/++}$ search update

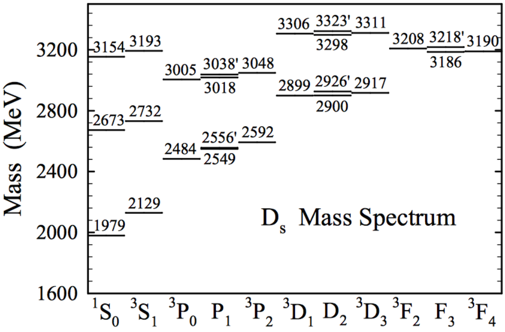
- 2011 analysis a strong proof of concept
- Prospects for 2011+2012 dataset look bright
- Full 2.08 fb^{-1} at $\sqrt{s} = 8$ TeV available for analysis
- $\Lambda_c^+ \to pK^-\pi^+$ trigger and selection performance improved for 2012
- Now searching for $\Xi_{cc}^{+/++}$ in multiple final states
  - Notable inclusion: $\Xi_{cc}^+ \to (D^+ \to K^-\pi^+\pi^+)p^+K^-$.
  - High D^+ lifetime (1 ps) vs. Λ_c^+ (0.2 ps) - more efficient selections
- Updated analysis will have far greater sensitivity.



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



$D_{sJ}(2860)^+$ at BaBar - Phys Rev Lett. 1;97(22):222001

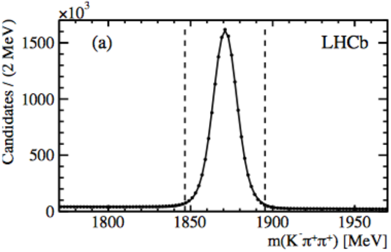


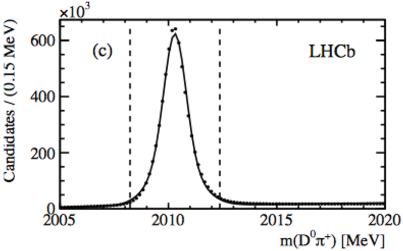
Predicted $c\bar{s}$ spectra - Phys. Rev. D 89, 074023

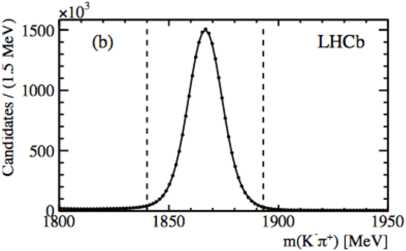
- Along with baryons, much recent progress in identifying charmed mesons.
- However, still many states missing which were predicted in 1980s.
- And some interesting tensions between theory and experiment - e.g. masses of $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ significantly lower than theory predictions.

Charm meson spectroscopy at LHCb

- 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:
    - 15.1×10^6 D^+
    - 20.4×10^6 D^0
    - 6.4×10^6 D^{*+}



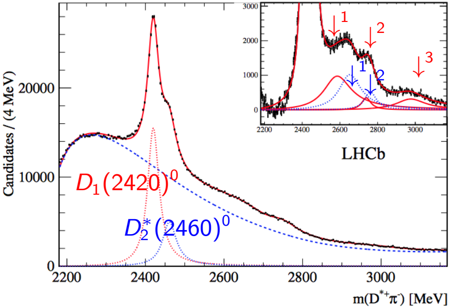




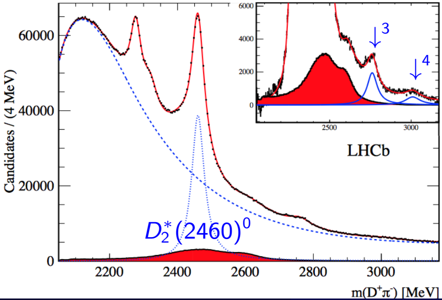
- Following on observations of a variety of excited charm mesons by BaBar (Phys. Rev. D82 111101), search in the final states:
    - $p\overline{p} \rightarrow D^+\pi^-X$, $p\overline{p} \rightarrow D^0\pi^+X$, $p\overline{p} \rightarrow D^{*+}\pi^-X$.
- Search uses full 2011 dataset: 1.0 fb^{-1} at $\sqrt{s} = 7\ \text{TeV}$.
- 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.

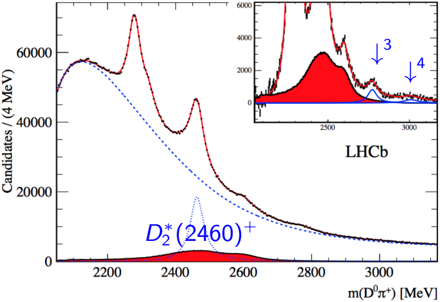
D_J mass fits.

JHEP09(2013)145

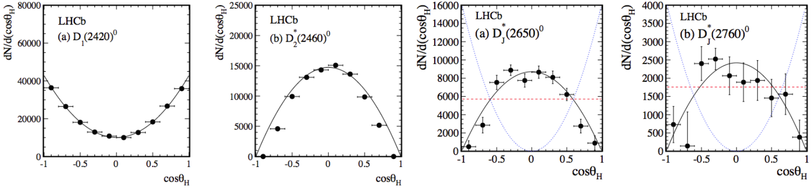


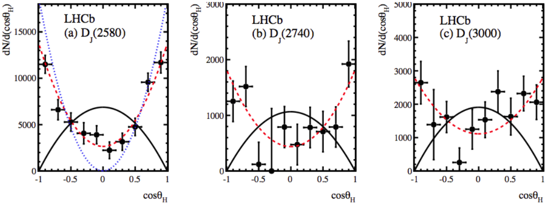
- $\downarrow^1$ - $D_J(2580)^0$, $\downarrow^2$ - $D_J(2740)^0$, $\downarrow^3$ - $D_J(3000)^0$
- $\downarrow^1$ - $D_J^*(2650)^0$, $\downarrow^2$ - $D_J^*(2760)^0$
- $\downarrow^3$ - $D_J^*(2760)^+$, $\downarrow^4$ - $D_J^*(3000)^+$





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

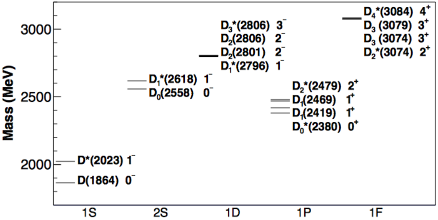




D_J spectroscopy summary

- Number of charm states identified in the final states $p\overline{p} \rightarrow D^+\pi^-X$, $p\overline{p} \rightarrow D^0\pi^+X$, $p\overline{p} \rightarrow D^{*+}\pi^-X$.
  - 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 $1\mathrm{F}$ states.
- Identifications suggested by us and by the theory community - e.g. Phys.Rev.D88 (2013) 114003.

- $D_J^*(2650)^0$: $J^P = 1^-$, $2\mathrm{S}$ $D_1^*(2618)$
- $D_J^*(2760)^+$: $J^P = 1^-$, $1\mathrm{D}$ $D_1^*(2796)$
- $D_J(2740)^0$: $J^P = 2^-$, $1\mathrm{D}$ $D_2(2801)$



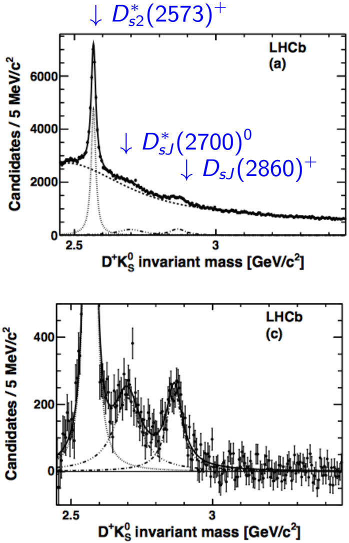
D_{sJ} spectroscopy - outline

JHEP10(2012)151

- 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 existance of these states and to measure their parameters.
- Look for resonances in the final states:
  - D^+ $(K^- \ \pi^+ \ \pi^+)$ $K^0_{\rm S}$ $(\pi^+ \ \pi^-)$
  - D^0 $(K^- \ \pi^+)$ K^+
- Again, full 2011 dataset used: 1.0 fb^{-1} at $\sqrt{s} = 7\,$ TeV.

D_{sJ} mass fits

JHEP10(2012)151



- Extracted yields:

Decay mode	$D^*_{s1}(2700)^+$	$D^*_{sJ}(2860)^+$
$D^+K^0_S$	$6\,724 \pm 596$	$4\,825 \pm 347$
D^0K^+	$45\,315 \pm 2\,186$	$31\,603 \pm 1\,257$

- Final extracted mass and width parameters:

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

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

Analysis overview

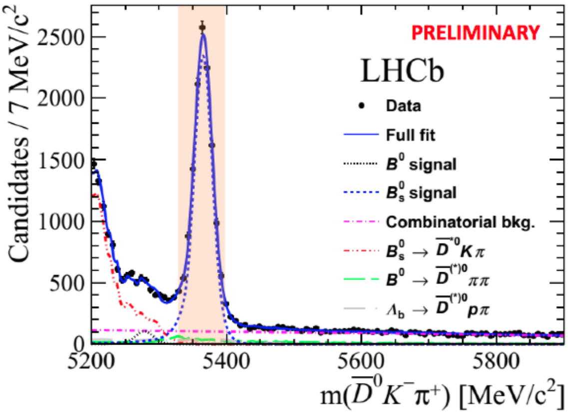
- Analysis of the resonance structure of $B_s \to \overline{D}^0 K^- \pi^+$
  - **New results!**
  - Perform fit using Laura++ package – http://laura.hepforge.org/
  - Use candidates with $\overline{D}^0 \to K^+ \pi^-$ from 3fb^{-1} of LHCb data

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

- Branching fractions of $B_s^0 \to \overline{D}^0 K^- \pi^+$ and $\mathrm{B}^0 \to \overline{D}^0 K^+ \pi^-$ 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

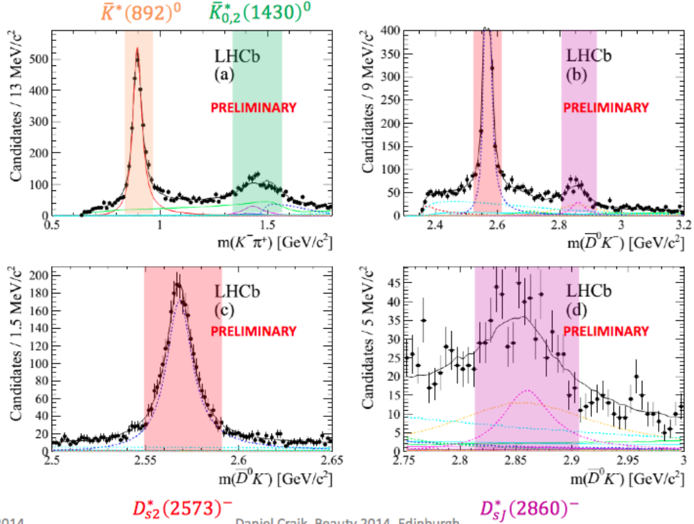
Phys. Rev. D 87, 112009 (2013)

Fit to B mass



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

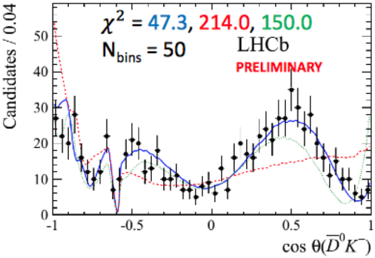
Dalitz plot fit



15/07/2014 Daniel Craik, Beauty 2014, Edinburgh 15

$D^*_{sJ}(2860)^-$ 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



PRELIMINARY

Spin hypothesis	ΔNLL	$\sqrt{2\Delta NLL}$	Masses and widths			
1+3	0	—				
0	141.0	16.8	2862	57		
0+1	113.2	15.0	2446	250*	2855	96
0+2	155.1	17.6	2870	61	2569	17*
0+3	105.1	14.5	2415	188*	2860	52
1	156.8	17.7	2866	92		
1+2	138.6	16.6	2851	99	3134	174*
2	287.9	24.0	3243	81*		
2	365.5	27.0	2569	17*		
2+3	131.2	16.2	2878	12	2860	56
3	136.5	16.5	2860	57		

* Indicates states that floated out of the 2.86 GeV/c^2 region

D_{sJ} 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 $B_s^0 \to \overline{D}K^-\pi^+$ 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 σ significance!
  - First observation of heavy-flavoured spin-3 state!

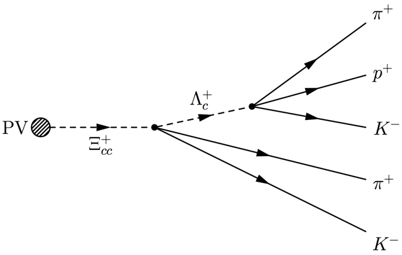
Charm spectroscopy summary

- 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 Λ_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!

BACKUP

Ξ_{cc}^{+} candidate Selection

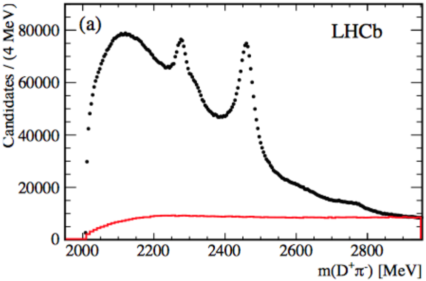
- Use same trigger requirements for control and signal based on $\Lambda_c^+ \to pK^-\pi^+$ decay
  - One Λ_c daughter track must fire calorimeter hardware trigger
  - One Λ_c daughter track selected by inclusive software trigger
  - Λ_c candidate reconstructed and accepted by dedicated $\Lambda_c^+ \to pK^-\pi^+$ 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 $\Xi_{cc}^{+/++}$ candidates:
  - Pair Λ_c with K and π at common vertex displaced from PV
  - Displacement cut reduces sensitivity to SELEX-like $\Xi_{cc}^{+/++}$
    Can be relaxed in future analyses
  - Artificial Neural Network final selection. Input variables chosen for minimal $\Xi_{cc}^{+/++}$ lifetime dependence

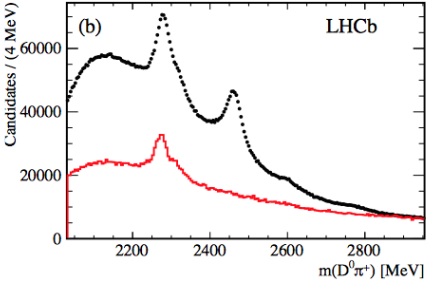
D_J meson decays - $D^+ \pi^-$ mass spectra

- 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.



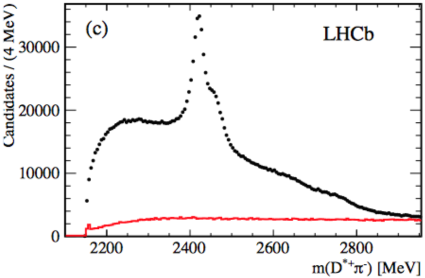
D_J meson decays - $D^0\ \pi^+$ mass spectra

- 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 /mevcc due to cross feed from $D_1(2420)^+/D_2^*(2460)^+ \to \pi^- D^{*+}(D^0\pi^+)$



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.



Resonance	Final state	Mass (MeV)	Width (MeV)	Yields $\times 10^3$	Significance (σ)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210.2 \pm 1.9 \pm 0.7$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81.9 \pm 1.2 \pm 0.9$	
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	$50.7 \pm 2.2 \pm 2.3$	24.5
$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14.4 \pm 1.7 \pm 1.7$	10.2
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	$60.3 \pm 3.1 \pm 3.4$	18.8
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	$7.7 \pm 1.1 \pm 1.2$	7.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.5 ± 1.1	9.0
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	$675.0 \pm 9.0 \pm 1.3$	
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	$55.8 \pm 1.3 \pm 10.0$	17.3
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	17.6 ± 1.1	21.2
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	$341.6 \pm 22.0 \pm 2.0$	
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	$20.1 \pm 2.2 \pm 1.0$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	7.6 ± 1.2	6.6

D_{sJ} spectroscopy - selection

- Look for resonances in the final states:
  - D^{+} (K^{-} π^{+} π^{+}) K^{0}_{S} (π^{+} π^{-})
  - D^{0} (K^{-} π^{+}) K^{+}
- Selection of candidates places variety of fiducial and kinematic constraints.
- PID discrimination used to mitigate cross-feed.
- Defining θ 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.