Baryonic and mesonic resonances at LHCb

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Outline

- Introduction
- Study of D_s family
- Search for $B_c^*(2S)$
- Muonic decays of χ_{c1} and χ_{c2}
- Doubly charmed baryons Ξ_{cc}^{++}
- Study of Ω_c^{**} family
- Summary and future perspective

Resonances

- The simplest definition for resonances is that they are extremely short lived particles, with lifetime around 10^{-23} seconds or less. In more technical a way, resonances are poles in the unphysical sheets of the S-matrix, which manifest themselves as structures in experimental observables.
- Well isolated, relatively narrow and far from the threshold resonances can be described by standard **Breit-Wigner** parametrization.
- If there are overlapping resonances, it is generally incorrect to use a sum of Breit-Wigner functions. **K-matrix formalism** can be more appropriate.
- Resonances at threshold can be better treated using the **Flatté** parametrization.

Angular analysis

As with everything else resonances carry quantum numbers and are, of course, also subject to conservation laws. The study of the angular distributions and correlations is mandatory to determine the quantum numbers of the resonances. There are different spin formalisms:

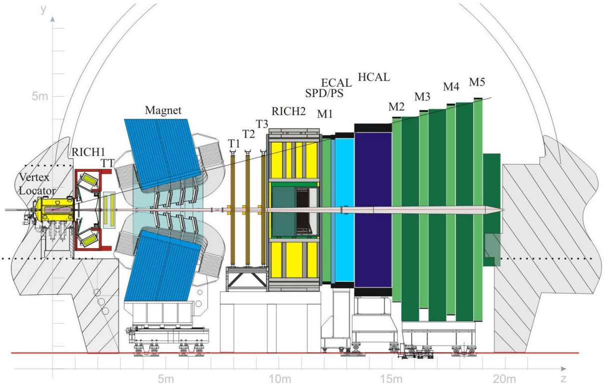
- Non-relativistic tensor formalism (Zemach)
- Spin-projection formalisms:
  - **Helicity Formalism.** Quantization axis parallel to the direction of motion.
  - **Canonical Formalism.** The quantization axis is diagonal to the direction of motion.
  - **Tranversality Formalism.** Similar to helicity formalism, but the quantization axis is chosen to be normal to the direction of motion.
- Relativistic tensor Formalisms (Rarita-Schwinger)

How to measure quantum number of resonance?

- Be sure the bump you are observing is signal.
- Identify the possible quantum number assignments (respect the conservation laws).
- Write down an amplitude and a fit model corresponding to each possible resonance quantum number.
- Fit the models and perform hypothesis tests to identify which is the model prefered by data.
- Each model corresponds to a set of quantum numbers for the resonance.

The LHCb experiment [Int. J. Mod. Phys. A 30 (2015) 1530022]

- High precision tracking system: $\sigma(IP) = 20\,\mu m$, $\delta p/p = 0.4 - 0.6\%$
- Excellent particle ID with two RICH detectors ($\epsilon_{PID}(K) \approx 95\%$, $MisID(K \to \pi) \approx 5\%$)



Despite the high background level inherent to hadronic collisions the detector allows to search for resonances produced in heavy flavour decays.

Hadron spectroscopy

LHCb focuses on Heavy Flavour hadrons (hadrons with charm (c) or beauty (b) quarks).

Beyond ground-state hadrons:

- spin excitations
- angular momentum excitations
- radial excitations

C=1

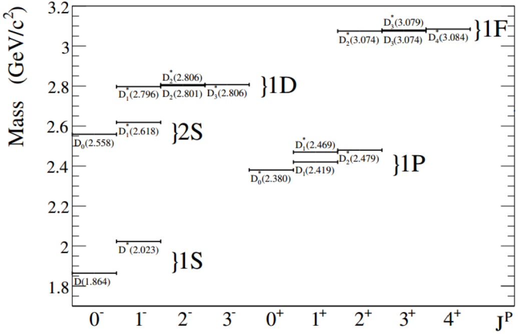
mesons: $D^+(c\bar{d})$, $D^0(c\bar{u})$, $D_s^+(c\bar{s})$
baryons: $\Lambda_c^+(cdu)$, $\Xi_c^+(cus)$, $\Xi_c^0(cds)$, $\Omega_c^0(css)$

B=1

mesons: $B^+(\bar{b}u)$, $B^0(\bar{b}d)$, $B_s^0(\bar{b}s)$, $B_c^+(\bar{b}c)$
baryons: $\Lambda_b^0(bdu)$, $\Xi_b^0(bus)$, $\Xi_b^-(bds)$, $\Omega_b^-(bss)$

Excited charmed D_s mesons

Spectrum of charmed mesons ($c\bar{s}$) is predicted theoretically [S. Godfrey, N. Isgur, Phys. Rev. D32 (1985) 189]



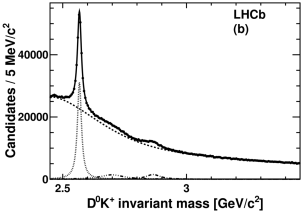
- Besides two S-wave states (D_s, D_s^*) four P-wave states have been observed ($D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$, $D_{s1}(2536)^+$, $D_{s2}^*(2573)^+$)
- Later at B-factories in DK and D^*K modes the $D_{s1}(2700)^+$, $D_{sJ}(2860)^+$ and $D_{sJ}(3040)^+$ have been observed with quantum number assignements not known.

Excited charmed D_s mesons

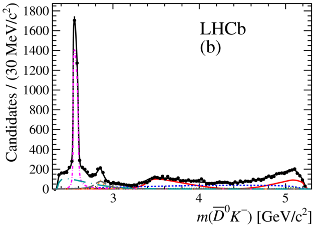
LHCb performed two studies of D_s spectra:

- in production analysing D^+K_s and D^0K^+ final state [JHEP 1210(2012)151]
- in Dalitz plot analysis of $B_s^0 \to \bar{D}^0 K^- \pi^+$ [PRL113 162001(2014)].

[JHEP 1210(2012)151]



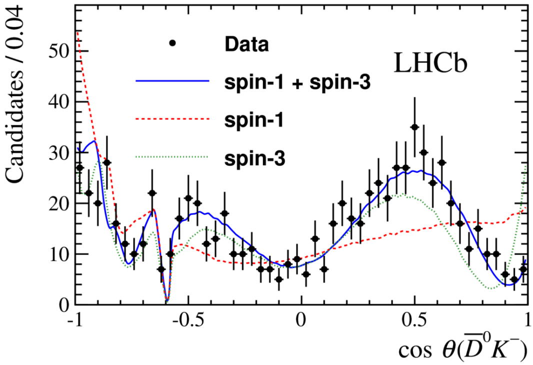
[PRL113 162001(2014)]



In the first measurement $D_{s1}(2700)^+$ and $D_{sJ}(2860)^+$ have been observed for the first time in hadronic interactions and their mass and width have been measured.

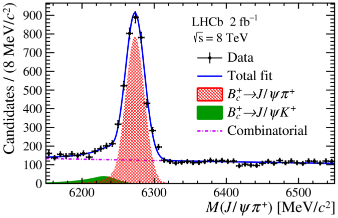
Excited charmed D_s mesons

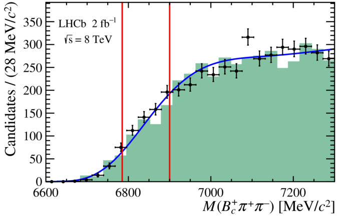
Second work performed full amplitude analysis (angular distributions are given in the Zemach tensor formalism). It shows with more than 10 σ significance that structure at $m(\bar{D}^0 K^-) \approx 2.86\,MeV/c^2$ contains both spin-1 and spin-3 components. Mass and width for both spin-1 and spin-3 components have been measured.



Search for excited $B_c(2S)^+$ state [JHEP 138 (2018) 1801]

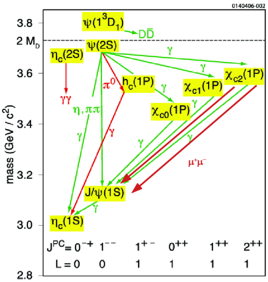
- First excited $B_c(2S)^+$ state is observed by ATLAS [Phys. Rev. Lett. 113 (2014) 212004]: $m = 6842 \pm 4(stat) \pm 5(syst)\ MeV/c^2$
- LHCb searched for this decay in the same final state: $B_c(2S)^+ \to B_c^+\pi^+\pi^-$ $B_c(2S)^{*+} \to B_c^{*+}(\to B_c^+\gamma)\pi^+\pi^-$
- LHCb has a large sample of Bc mesons ($\sim 3k$); no signal is observed
- The results from ATLAS and LHCb are compatible only if the (unpublished) relative efficiency of reconstructing $B_c(2S)^+$ w.r.t. the B_c^+ is much larger for ATLAS.

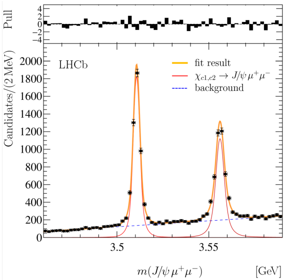




- First observation of $\chi_{cJ} \to J/\Psi\mu^+\mu^-$ [PRL 119 (2017) 221801] .
- The very low Q-value of the decay and the absence of Bremssrahlung of the soft muons allow extraordinary resolution.

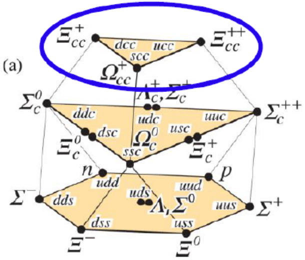
Fit parameter		Fitted value
$N(\chi_{c1})$		$4\,755 \pm 81$
$N(\chi_{c2})$		$3\,969 \pm 96$
$m(\chi_{c1})$	[MeV]	$3\,510.66 \pm 0.04$
$m(\chi_{c2})$	[MeV]	$3\,556.07 \pm 0.06$
$\Gamma(\chi_{c2})$	[MeV]	2.10 ± 0.20





Doubly charmed baryons

- Baryons containing 2 or 3 charmed constituent quarks are predicted by the quark model: $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$, $\Omega_{cc}^{+}(ccs)$, $\Omega_{ccc}^{++}(ccc)$
- Many theoretical calculations of their properties:
  - $M(\Xi_{cc}^{++}) \approx M(\Xi_{cc}^{+}) \approx 3600 \pm 100\, MeV/c^2$
  - Large ambiguity of lifetimes, but: $\tau(\Xi_{cc}^{++}) \sim 400 - 700\, fs \gg \tau(\Xi_{cc}^{+}) \sim 100 - 250\, fs$

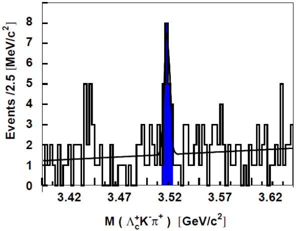


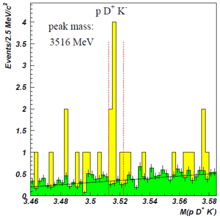
Observation of Ξ_{cc}^{+} by SELEX

Claims by SELEX:

- Observation of $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ in 2002 [PRL89(2002)112001]
- Confirmation with $\Xi_{cc}^{+} \rightarrow D^{+} p K^{-}$ in 2004 [PLB628(2005)18]
- Combined $m(\Xi_{cc}^{+}) = 3518.7 \pm 1.7 MeV/c^2$
- τ<33 fs is much shorter than expected
- Evidence of Ξ_{cc}^{+} in more decays

No evidence observed at Babar, FOCUS, Belle and LHCb

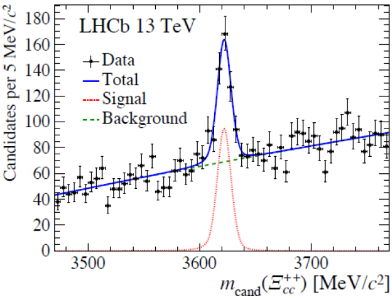




Observation of Ξ_{cc}^{++} by LHCb [PRL119(2017)112001]

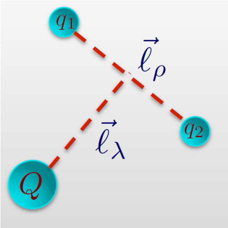
- LHCb searched for Ξ_{cc}^{++} signal in $\Lambda_c^+(\to pK^-\pi^+)K^-\pi^+\pi^-$ mass spectrum and found with 12σ significance in 13 TeV and 7σ in 8 TeV data set
- $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.17(\Lambda_c^+)\ MeV/c^2$
- Mass difference with the SELEX measurement ($\Delta m = 103 MeV/c^2$) is too large to be an isospin partner

- Signal persists when requiring a significant lifetime $\to$ weakly decaying
- Studies are ongoing on lifetime, production rate, other decay modes and the isospin partner



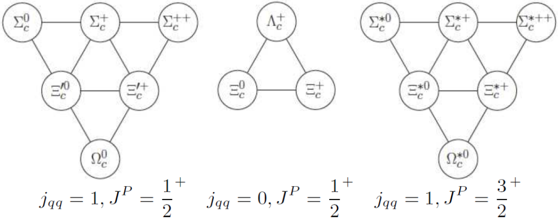
Ω_c^* states. Introduction.

- In $\Omega_c(css)$ system the large difference in mass between the charm quark and the light quarks, provides a natural way to understand the spectrum by using the symmetries provided by the Heavy Quark Effective Theories (HQET).
- In this model, the heavy quark is essentially a spectator and interacts with the diquark which is treated as a single object.
- Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET.



Ω_c^* states. Introduction.

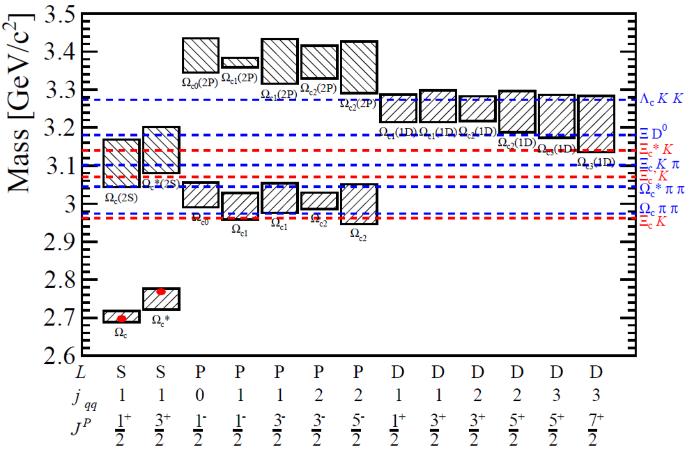
- The SU(3) multiplets containing the ground state charmed baryons, grouped according to the spin *j* of the light diquark and the spin-parity J^P of the baryon.



- All the grounds states have been observed even if the quantum numbers of many of them are not measured.
- Excited states of Λ_c^+, Ξ_c, Σ_c have been reported but no excited Ω_c states have been observed before LHCb measurements.

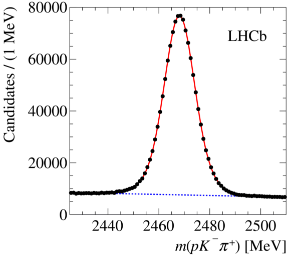
Spectrum of excited Ω_c^0 states.

Mass predictions of the excited Ω_c^0 states. The boxes cover the range of predictions for the masses of each state, and the red dots indicate the measured values.

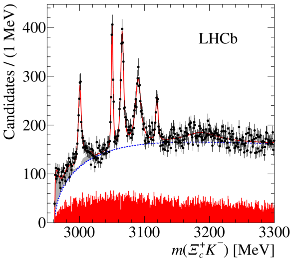


Observation of Ω_c^* states [Phys. Rev. Lett. 118 (2017) 182001]

- Data sample: 1.0 fb^{-1} (7 TeV) + 2.0 fb^{-1} (8 TeV) + 0.3 fb^{-1} (13 TeV) = 3.3 fb^{-1}
- Reconstruct $\Xi_c^+ \to pK^-\pi^+$
- Combine with tight PID K^- and require $p_T > 4.5\ GeV$
- ! Observation of 5 new excited Ω_c states. Two of them are very narrow.



Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		< 1.2 MeV, 95% CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		< 2.6 MeV, 95% CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{fd}$			$190 \pm 70 \pm 20$	



Interpretation of Ω_c^* states

No theory consensus on quantum numbers ([K.-L. Wang, L.-Y. Xiao, X.-H. Zhong, Q. Zhao, Phys. Rev. D95 (2017) 116010]):

TABLE II: Spin-parity (J^P) numbers of the newly observed Ω_c states suggested in various works.

State	[19]	[20]	[21]	[23]	[29]	[25]	[27]	[28]	[32]	[26]	This work
$\Omega_c(3000)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^+$ or $3/2^+$	$1/2^-$		$1/2^-$
$\Omega_c(3050)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$5/2^-$	$3/2^-$	$1/2^-$	$5/2^+$ or $7/2^+$	$3/2^-$		$3/2^-$
$\Omega_c(3066)$	$1/2^+$	$1/2^+$ or $1/2^-$	$3/2^-(5/2^-)$	$3/2^-$	$3/2^-$	$5/2^-$	$3/2^-$	$3/2^-$	$1/2^+$		$3/2^-$
$\Omega_c(3090)$			$3/2^-$ $(1/2^+)$	$3/2^-$	$1/2^-$	$1/2^+$	$3/2^-$	$5/2^-$	$1/2^+$		$5/2^-$
$\Omega_c(3119)$	$3/2^+$	$3/2^+$	$5/2^-$ $(3/2^+)$	$5/2^-$	$3/2^-$	$3/2^+$	$5/2^-$	$5/2^+$ or $7/2^+$	$3/2^+$	$1/2^-$	$1/2^+$ or $3/2^+$

- Either all five P-wave states but why two are so narrow?
- Or three P-wave states and two 2S-states but where are two 1/2 states?
- Chiral QCD approach by M.Praszalowicz, M. Polyakov and H.C.Kim interpret two narrowest states as pentaquarks [Phys.Rev. D96 (2017) no.1, 014009]. Easy to check at LHCb since Ω_c^{**} are predicted to be not "isospin singlet" but "isospin triplets".

Summary and prospects for hadron spectroscopy

- 1 fb^{-1} at 7 TeV and 2 fb^{-1} at 8 TeV
- $\sim$6 fb^{-1} at 13 TeV is expected with $\sigma_{b\bar{b}}(13\,TeV)/\sigma_{b\bar{b}}(7\,TeV) \approx 2$

Analyses expected with full RUNI +RUNII data:

- search for excited B_c states
- properties of Ξ_{cc}^{++}: lifetime, production cross-sections, new decay modes
- searches for Ξ_{cc}^{+}, Ω_{cc}^{+}, Ξ_{bc}^{+}, Ξ_{bc}^{0}

LHCb will be upgraded in 2019, software trigger with 40MHz, PID at the trigger level – great increase ($\sim$2x) of trigger efficiency on full hadronic final states.