Results from charm baryon spectroscopy at LHCb, Belle and BESIII

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on behalf of the LHCb collaboration,
with results from Belle and BESIII

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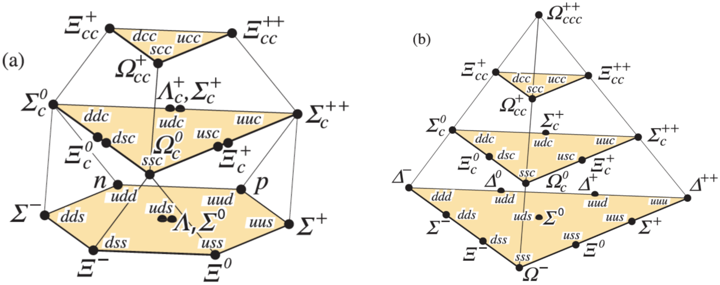
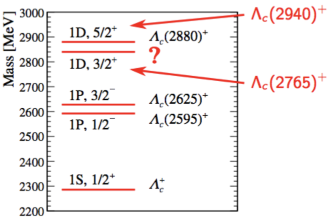
Introduction

- Heavy spectroscopy provides primary tests and inputs to QCD models
- In the last years, many striking results in the spectroscopy sector!
- Concerning conventional c-baryons many states not yet seen and only few excited states observed
  - Λ_c^* states
  - Ω_c^0 baryon lifetime
  - Ω_c^* states
  - Doubly charmed baryons

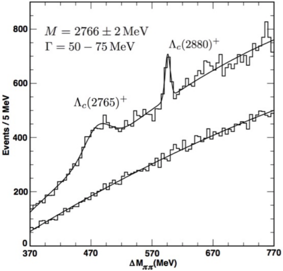


Excited Λ_c^+ states

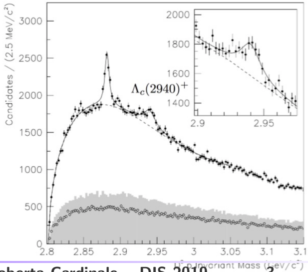
[EPJC A51 (2015) 82]



CLEO, PRL86 4479 (2001)



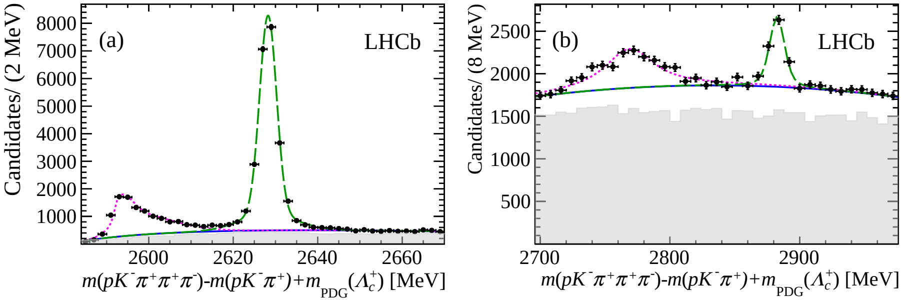
BABAR, PRL 98 012001 (2007)



- Non-relativistic heavy quark-light quark diquark model expectations
- $J^P = 3/2^+$ state (2nd member of the D-wave doublet) is missing in data
- Two experimentally observed states without clear assignment: $\Lambda(2765)^+$ and $\Lambda_c(2940)^+$
- $\Lambda_c(2940)^+$: mass close to the D^*N threshold: possible molecular interpretation

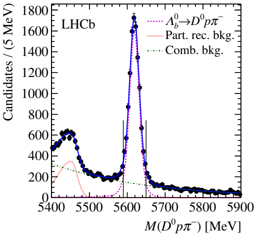
Excited Λ_c^+ in $\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \mu^- \bar{\nu}_\mu X$ [PRD 96, 112005]

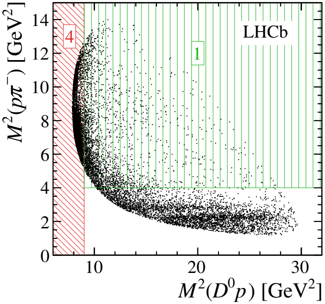
- Determination of the shape of the differential decay rate of $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$
- Clear signal of previously observed $\Lambda_c(2595)^+$ (CLEO), $\Lambda_c(2625)^+$ (ARGUS), $\Lambda_c(2765)^+$ (CLEO) and $\Lambda_c(2880)^+$ (CLEO) with $J^P = 5/2^+$ (Belle) in the $\Lambda_c \pi^+ \pi^-$ invariant mass

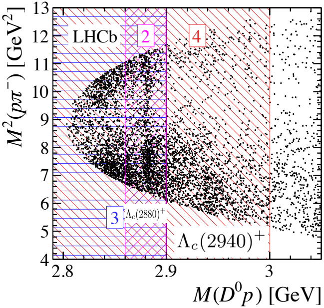


Amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ [JHEP 1705 (2017) 030]

- Search for excited Λ_c^+ states in exclusive b decays: $\Lambda_b^0 \to D^0 p \pi^-$, $D^0 \to K^- \pi^+$
- Advantages: well-defined initial state, low background
- Detailed study of $D^0 p$ amplitude, including Λ_c^+ resonances

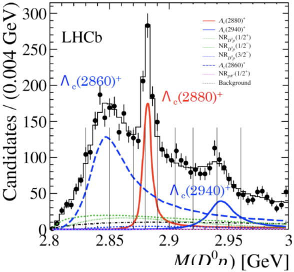




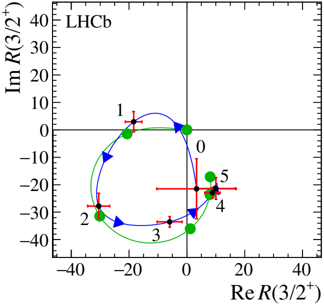


Amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ [JHEP 1705 (2017) 030]

- $\Lambda_c(2880)^+$ preferred spin $J = 5/2^+$
  $m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})$
  $\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})$
  (consistent with Belle)



- $\Lambda_c(2940)^+$ preferred spin $J = 3/2^-$ but $1/2$ and $7/2$ not ruled out
  $m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})$
  $\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.00}(\text{model})$ (First seen by Belle, first constraints on the spin and parity)



- New state at $2860\,\text{MeV}$, could be part of the $J^P = 3/2^+$ doublet
- Threshold enhancement is consistent with a new resonance: rotation of phase for $J^P = 3/2^+$ component $\Lambda(2860)$ wrt. non-resonant amplitude
- Preferred $J^P = 3/2^+$
  $m = 2856.1^{+2.0}_{-1/7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-4.6}(\text{model})$
  $\Gamma = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})$

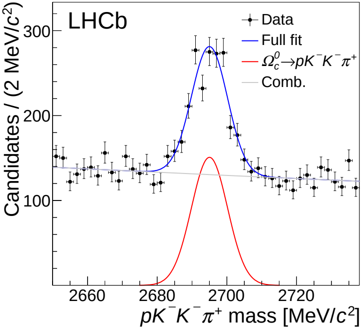
Λ_c decays at BESIII

- In 2014, BESIII collected data above Λ_c^+ pair threshold at $\sqrt{s} = 4.575, 4.580, 4.590$ and $4.599\,\mathrm{GeV}$ with excellent performance: $\sim 100000 \Lambda_c^+ \Lambda_c^-$ pairs
  - Studies of twelve Cabibbo-favoured (CF) Λ_c^+ decay modes with improved precision [Phys. Rev. Lett. 116 052001]
  - First observation of a neutron decay mode $\Lambda_c^+ \to n K_s^0 \pi^+$ [Phys. Rev. Lett. 118 112001]
- Cabibbo-suppressed and neutron modes decays are known with poor precision or not explored yet
  - Measurement of BR of the singly Cabibbo-suppressed (SCS) decays of $\Lambda_c \to pK^+K^-, p\pi^+\pi^-, p\eta$ and $p\pi^0$ decays [Phys. Rev. Lett. 117 232002, Phys. Rev. D 95 111102(R)]
  - First observation of the $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$ [Phys. Lett. B 772 388]
  - First absolute measurement of two W-exchange dominant decay modes $\Lambda_c^+ \to \Xi^0 K^+$ and $\Lambda_c^+ \to \Xi(1530)^0 K^+$ [Phys. Lett. B 783 200]
  - The $\Lambda_c^+ \to \Lambda + X$ is measured with significantly improved precision [Phys. Rev. Lett. 121 062003]
  - Cross section of $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ at $\sqrt{s} = 4.575, 4.580, 4.590$ and $4.599\,\mathrm{GeV}$ [Phys. Rev. Lett. 120 132001]
- In the future, possible to collect Λ_c^+ data at high energies

Ω_c^0 baryon lifetime [PRL 121 (2018) 092003]

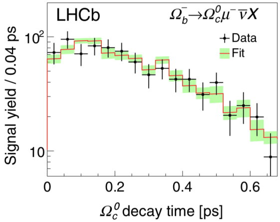
- Charm baryon lifetimes are known much less precisely than charm mesons ones
- Test of HQE and in particular on higher-order terms
- Expected lifetime hierarchy: $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$
- Current measurements are consistent with this hierarchy

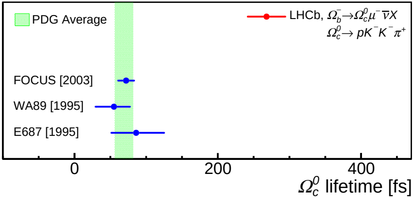
- Using semileptonic $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X$ with $\Omega_c^0 \to pK^-K^-\pi^+$
- Data sample: $1.0\,\mathrm{fb}^{-1}$ (7 TeV) + $2.0\,\mathrm{fb}^{-1}$ (8 TeV)
- Much larger signal wrt previous experiments with (978 $\pm$ 60) candidates
- Measuring the ratio wrt the D^+ lifetime using $D^+ \to K^-\pi^+\pi^+$



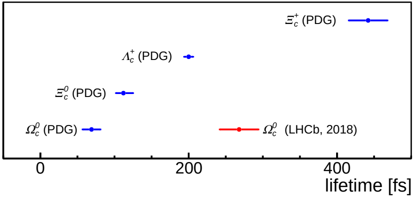
Ω_c^0 baryon lifetime [PRL 121 (2018) 092003]

- Lifetime is measured to be:
  $\tau_{\Omega_c^0} = (268 \pm 21(\mathrm{stat}) \pm 10(\mathrm{syst}) \pm 2(\mathrm{D}^+))\ \mathrm{fs}$
- four times larger than, ad inconsistent with the world average value (69 ± 12) fs
- Necessary to understand better hierarchy of lifetimes for charmed baryon





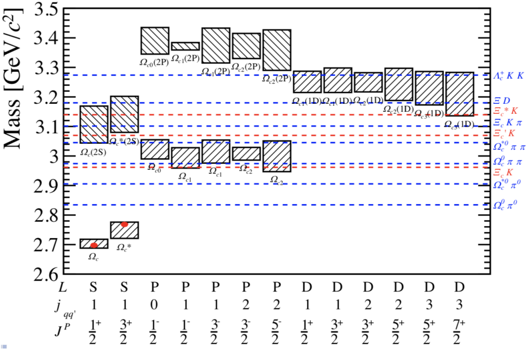
Summary of Ω_c^0 lifetime measurements



Hierarchy of lifetimes for charmed baryons

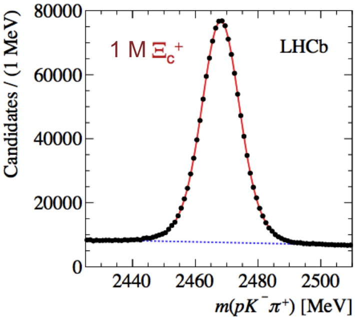
Excited Ω_c^0 states

- Spectroscopy of charmed baryons is intricate
- Spectrum predictions using HQET: precise measurements of the excited heavy meson properties to test of the validity of HQET
- Only two ground states Ω_c^0 $(J^P = 1/2^+)$ and Ω_c^{*0} $(J^P = 3/2^+)$ are known
- Decays to $\Omega_c^0\pi^0$ and $\Omega_c^{*0}\pi^0$ final states are suppressed by isospin-violation
- $\Xi_c K$ is the lowest hadronic threshold



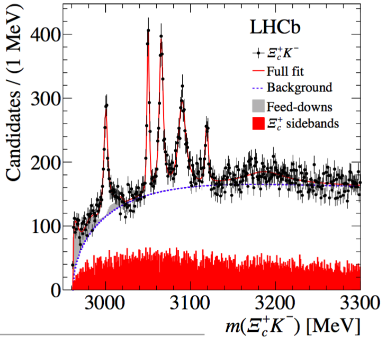
Ξ_c^+ sample [PRL 118 182001]

- $\Xi_c^+ \to pK^-\pi^+$: Cabibbo suppressed $c \to d$ decay
- No hyperons in the final state (tend to decay outside the vertex detector)
- Data sample: $1.0\,\mathrm{fb}^{-1}$ (7 TeV) + $2.0\,\mathrm{fb}^{-1}$ (8 TeV) + $0.3\,\mathrm{fb}^{-1}$ (13 TeV)
- Dedicated trigger in the 13 TeV data (and the larger collision energy): boost of the number of reconstructed Ξ_c^+ candidates in the $13\,\mathrm{TeV}$ sample $(\times 3)$
- Data-driven multivariate selection (vertex χ^2, proton and kaon PID, Ξ_c^+ FD, Ξ_c^+ p_{T}): 83% signal purity



Spectrum of $\Xi_c^+ K^-$ [PRL 118 182001]

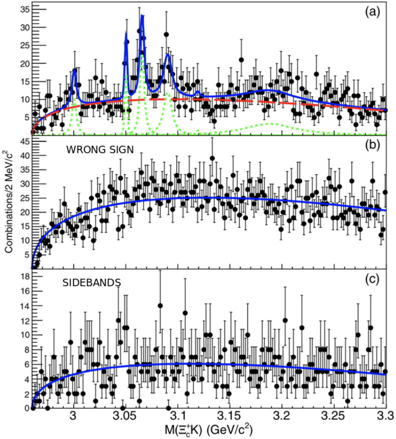
- Ξ_c^+ candidates combined with opposite charge kaons
- 5 narrow peaks in the $\Xi_c^+ K^-$ mass spectrum with significances greater than 5σ
- The broad state could be a superposition of several states
- No peaks in the wrong sign sample $\Xi_c^+ K^+$ and in the Ξ_c^+ sidebands K^- sample



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		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$	

Excited Ω_c at Belle [PRD 97 051102R (2018)]

- $980\,\mathrm{fb}^{-1}$ of e^+e^- annihilation data
- seven Ξ_c^+ decay modes: $\Xi_c^+ \to \Xi^-\pi^+\pi^-$, $\Xi_c^+ \to \Lambda K^-\pi^+\pi^-$, $\Xi_c^+ \to \Xi^0\pi^+$, $\Xi_c^+ \to \Xi^0\pi^+\pi^-\pi^+$, $\Xi_c^+ \to \Sigma^+K^-\pi^+$, $\Xi_c^+ \to \Lambda K_s^0\pi^+$, $\Xi_c^+ \to \Sigma^0 K_s^0\pi^+$
- Masses and width fixed to the LHCb values
- Confirmation of $\Omega_c(3066)$ and $\Omega(3090)$
- Confirmation $(< 5\sigma)$ of $\Omega_c(3000)$ and $\Omega_c(3050)$
- No confirmation for $\Omega_c(3119)$
- Indication of wide excess at higher mass, consistent with LHCb



Ω_c Excited State	3000	3050	3066	3090	3119	3188
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4	3.6 ± 6.9	135.2 ± 43.0
Significance	3.9σ	4.6σ	7.2σ	5.7σ	0.4σ	2.4σ
LHCb Mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle Mass (with fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	-	$3199 \pm 9 \pm 4$

What are they? Why are they so narrow?

- Most of the theoreticians identified these states as the orbitally (L=1) or radial excitations of the Ω_c^0 baryon
- or pentaquarks?
- The narrowness of the states might be a hint that it is difficult to get apart the two s quarks in a c(ss) system. The decays ΞD would have been favored (if allowed kinematically)

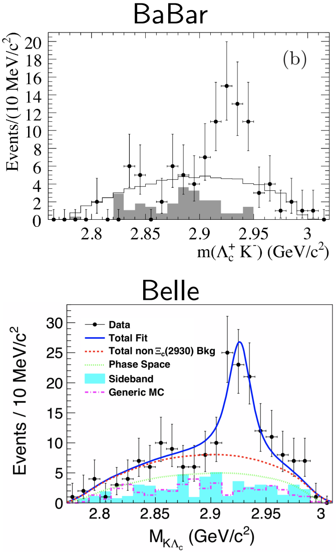
TABLE II: Spin-parity (J^P) numbers of the newly observed Ω_c states suggested in various works.

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 $3/2^+$

[K.-L. Wang, L.-Y. Xiao, X.-H. Zhong, Q. Zhao, Phys. Rev. D95 (2017) 116010]

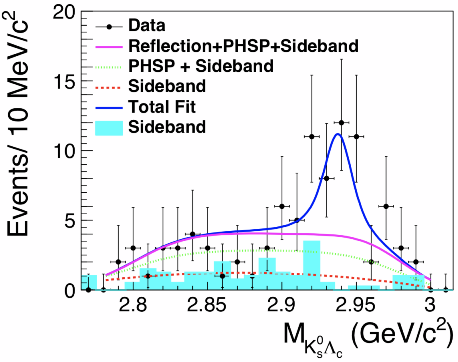
Observation of $\Xi_c(2930)^0$ at Belle [EPJ C78 252 (2018)]

- $\Xi_c(2930)^0$ reported by Babar in the $K^-\Lambda_c^+$ invariant mass in $B^- \to K^-\Lambda_c^+\bar{\Lambda}_c^-$ (no fit and no significance given) [PRD 77 031101 (2008)]
- $711\,\mathrm{fb}^{-1}$ of data at the $\Upsilon(4S)$ resonance
- $\Lambda_c^+ \to pK^-\pi^+, pK_s^0, \Lambda\pi^+ pK_s^0\pi^+\pi^-, \Lambda\pi^+\pi^+\pi^-$
- First observation of $\Xi_c(2930)^0$ with significance $> 5\sigma$
  - $M = (2938.9 \pm 3.0^{+0.9}_{-12.0})\,\mathrm{MeV}$
  - $\Gamma = (19.5 \pm 8.4^{+5.9}_{-7.9})\,\mathrm{MeV}$
  - $\mathcal{B}(B^- \to \Xi_c(2930)^0\Lambda_c^-) \times \mathcal{B}(\Xi_c(2930)^0 \to K^-\Lambda_c^-) = (1.73 \pm 0.45 \pm 0.21) \times 10^{-4})$



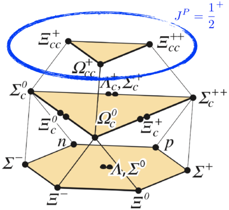
Evidence of $\Xi_c(2930)^+$ at Belle EPJC 78, 928 (2018)]

- $\Xi_c(2930)^+$ in the $K^0_s\Lambda^+_c$ invariant mass in $B^- \to K^0_s\Lambda^+_c\bar{\Lambda}^-_c$ with significance: 4.1σ
- $M = (2942.3 \pm 4.4 \pm 1.5)\,\mathrm{MeV}$ and $\Gamma = (14.8 \pm 8.8 \pm 2.5)\,\mathrm{MeV}$
- $\mathcal{B}(B^- \to \Xi_c(2930)^+\Lambda^-_c) \times \mathcal{B}(\Xi_c(2930)^+ \to \bar{K^0}\Lambda^-_c) = (2.37 \pm 0.51 \pm 0.31) \times 10^{-4})$
- Not able to determine spin-parity due to limited statistics

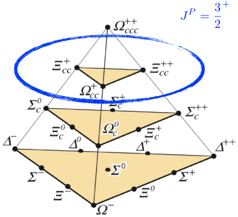


Double-charmed baryons

- Doubly charmed baryons predicted by quark model
- Provide a new and unique system for testing QCD with two heavy constituent quarks
- Ground states are $\Xi_{cc}^{++}(ccu)$, $\Xi_{cc}^{+}(ccd)$ and $\Omega_{cc}^{+}(ccs)$
- Theoretical predictions of masses [PRD70 (2004) 094004, PRD73 (2006) 094022, PRD78 (2008) 094007, EPJA37 (2008) 217, E2PJA45 (2010) 267,...]
  - $m(\Xi_{cc}^{+}) \simeq m(\Xi_{cc}^{++})$
  - $m(\Omega_{cc}^{+}) \sim m(\Xi_{cc}^{++})$ +100 MeV
  - $\sim 3.5\text{-}3.7\,\mathrm{GeV/c^2}$
- Different theoretical predictions are available also for the lifetime showing a large ambiguity: 100 - 1550 fs [PRD98(2018) 113004, PRD60 (1999) 014007, EPJC9(1999) 213, PRD66(2002) 014007, PRD90 (2014) 094007, ...]
  - $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$
  - $\tau(\Xi_{cc}^{++}) \sim 3/4 \times \tau(\Xi_{cc}^{+})$



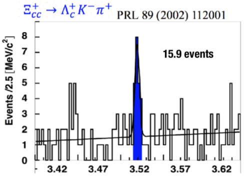
$J^P = 1/2^+$ baryons decay weakly to other flavours

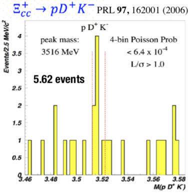


$J^P = 3/2^+$ baryons decay via strong interactions to $J^P = 1/2^+$

Double-charmed baryons: Ξ_{cc} system

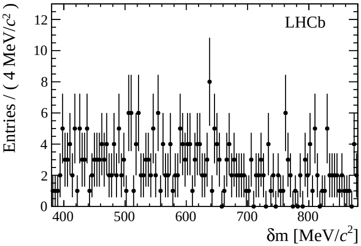
- Ξ_{cc}^{+} state observed (6.3 σ) by SELEX experiment in $\Lambda_c^+ K^- \pi^+$ (4.8σ in $D^+ K^- p$) [PRL 89 (2002) 112001, PRL97 (2006) 162001]:
  - $M = 3518.7 \pm 1.7\,\mathrm{MeV}$
  - Unexpected short lifetime: $\tau < 33\,\mathrm{fs}$ @ 90% CL





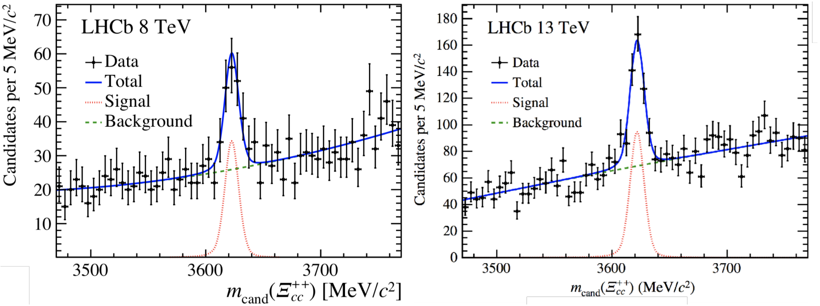
- Not confirmed by Focus [Nucl.Phys.Proc.Suppl 115 (2003)33], BaBar [PRD 74 (2006) 011103], Belle [PRL 97(2006) 162001] nor LHCb [JHEP 12 (2013) 090]

$$\delta m \equiv m(\Lambda_c^+ K \pi) - m(\Lambda_c^+) - m(K) - m(\pi)$$



Observation of Ξ_{cc}^{++} [PRL 119 (2017) 112001]

- Search in LHCb using $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ with $\Lambda_c^+ \to p K^- \pi^+$
- Data sample: $2.0\,\mathrm{fb}^{-1}$ at 8 TeV (2012) + $1.7\,\mathrm{fb}^{-1}$ at 13 TeV (2016)



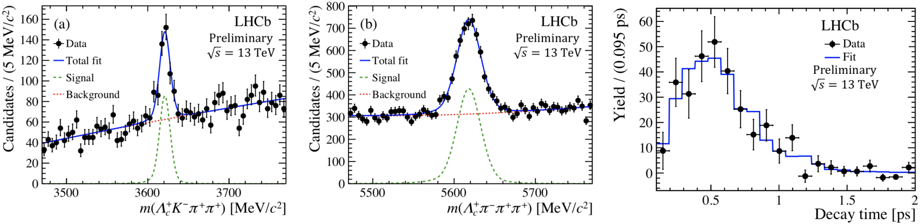
- Highly significant peaks: 7.6σ (2012), 12.9σ (2016)
  Yields: 313 ± 33 (2016) and 113 ± 21 (2012)
- Mass measured with the 2016 sample:

$$m(\Xi_c^{++}) = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c^+)\,\mathrm{MeV/c^2}$$

consistent with theoretical range of predictions, not consistent with Ξ_{cc}^+ SELEX measurement (100 MeV above SELEX Ξ_{cc}^+ peaks)

Lifetime measurement [PRL 121 (2018) 052002]

- Measuring its lifetime is crucial to establish the weak nature of its decay and for comparison with theoretical predictions
- Using the $\Xi_c^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay relative to the control channel $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ ($\sim 1.7\,\mathrm{fb}^{-1}$ - $13\,\mathrm{TeV}$)
- Unbinned maximum likelihood fit of the background-subtracted Ξ_{cc}^{++} decay time distribution

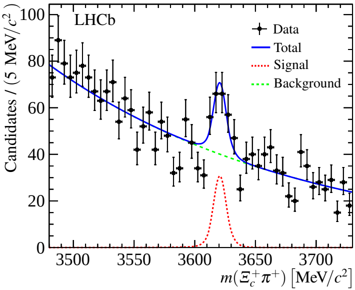


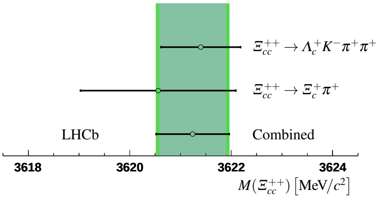
$$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.224}_{-0.022}(stat) \pm 0.014(syst)\,\mathrm{ps}$$

Weak decay confirmed!

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ PRL 121 (2018) 162002

- Searching for new decay modes is critical to understand the decay dynamics
- Search for $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ with $\Xi_c^+ \to pK^-\pi^+$
- Data sample: $1.7\,\text{fb}^{-1}$ (13 TeV)
- Yield: 91 ± 20
- Significance: 5.9σ
- Normalisation channel: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- Mass measurement consistent with previous result:
  $m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65(\text{stat}) \pm 0.31(\text{syst})$
- Ratio of branching fraction measurement:

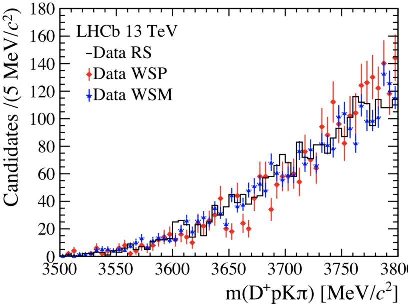




$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009(\text{stat}) \pm 0.003(\text{syst})$$

$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ [LHCb-PAPER-2019-011 (in preparation)]

- Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ with $D^+ \to K^- \pi^+ \pi^+$
- Data sample: $1.7\,\text{fb}^{-1}$ (13 TeV)
- Motivations
  - Excellent trigger for $D^+ \to K^- \pi^+ \pi^+$
  - $\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+) \sim \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)$ (similar tree level amplitudes)
- Normalizing channel: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



No signal observed in $[3300 \div 3800]\,\text{MeV}$

$$\frac{\Xi_{cc}^{++} \to D^+ p K^- \pi^+}{\Xi_{cc}^{++} \to \Lambda_{cc}^{++} K^- \pi^+ \pi^+} < 1.7(2.1) \times 10^{-2} \text{ at 90\% (95\%) CL}$$

- Difference of two order of magnitude between the two Ξ_{cc}^{++} decay modes?
  - Better understanding of resonant and non-resonant contributions
  - Dynamical effect or spin constraints in the resonance structures can suppress the decay

Conclusions

- Great interest into spectroscopy
- Experiments are very active in filling the gaps in charm spectra: unprecedented opportunities for discovering new states and measuring their properties
- Good experimental prospects with increasing LHC(b) data size and its upgrade program, with Belle II and with a new run at Λ_c^+ pair threshold

Spare Slides

Λ_c^* interpretations

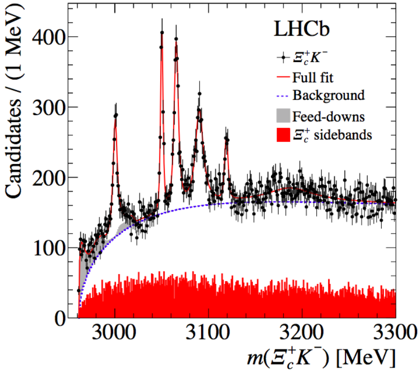
- $\Lambda_c(2860)^+$ fits well into Λ_c spectrum as 1D state (nonrelativistic heavy quark-light diquark model [arXiv:1609.07967]/QCD sum rules in the HQET framework [PRD94 (2016) 114016])
- $\Lambda_c(2940)^+$ consistent with molecular interpretation [PRD89 (2014) 096006, PLB 718 (213) 1381, 1405.0919] or radial 2P excitation [EPJ A51 (2015) 82].

Fit model

- 6 RBW convolved with Gaussian PDF (resolution 0.7-$1.7\,\mathrm{MeV}$)
- 3 feed-downs due to $\Omega_c^0 \to \Xi_c^{'+} K^-$ with $\Xi_c^{'+} \to \Xi_c^+ \gamma$
  - States with masses $M > m(\Xi_c^{'}) + m(K)$ could decay also to $\Xi_c^{'} K^-$ and appear into $\Xi_c K^-$ as partially reconstructed decays (i.e. feed-downs)
- Wrong-sign sample to study combinatorial background parameterisation

$$B(m) = \begin{cases} P(m) e^{a_1 m + a_2 m^2} & \text{for } m < m_0, \\ P(m) e^{b_0 + b_1 m + b_2 m^2} & \text{for } m > m_0, \end{cases}$$

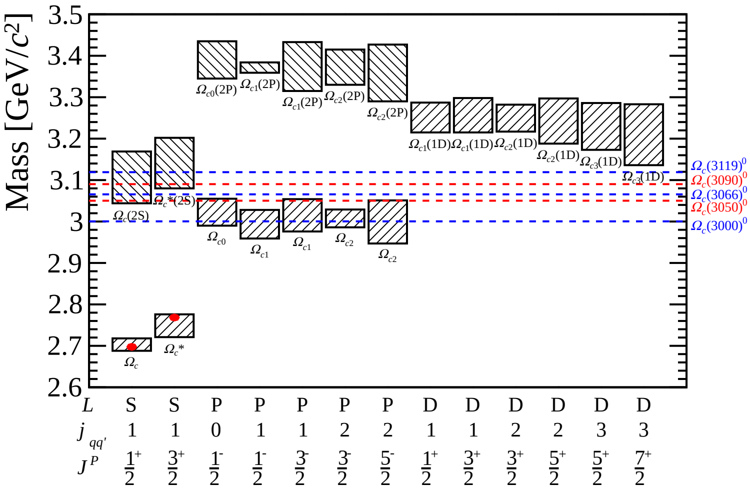
where $P(m)$ is a two-body phase-space factor, m_0, a and b are free parameters



Results

- Observation of 5 new excited Ω_c states with significances greater than 5σ
- The broad state could be a superposition of several states
- The largest systematic uncertainty is due to possible interference
- Feed-down shift has a sizeable effect only on $\Omega_c(3000)^0$ parameters

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
		$< 1.2\,\text{MeV}, 95\%$ 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
		$< 2.6\,\text{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\text{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\text{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\text{fd}}$			$190 \pm 70 \pm 20$	



Mass [GeV/c^2]
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
Ω_{c0}(2P)
Ω_{c1}(2P)
Ω_{c1}(2P)
Ω_{c2}(2P)
Ω_{c2}(2P)
Ω_{c1}(1D)
Ω_{c1}(1D)
Ω_{c2}(1D)
Ω_{c2}(1D)
Ω_{c3}(1D)
Ω_{c3}(1D)
Ω_c(2S)
Ω_c*(2S)
Ω_{c0}
Ω_{c1}
Ω_{c1}
Ω_{c2}
Ω_{c2}
Ω_c
Ω_c*
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
L S S P P P P P D D D D D D
$j_{qq'}$ 1 1 0 1 1 2 2 1 1 2 2 3 3
J^P $\frac{1}{2}^+$ $\frac{3}{2}^+$ $\frac{1}{2}^-$ $\frac{1}{2}^-$ $\frac{3}{2}^-$ $\frac{3}{2}^-$ $\frac{5}{2}^-$ $\frac{1}{2}^+$ $\frac{3}{2}^+$ $\frac{3}{2}^+$ $\frac{5}{2}^+$ $\frac{5}{2}^+$ $\frac{7}{2}^+$

E687 Ω_c^0 lifetime measurement

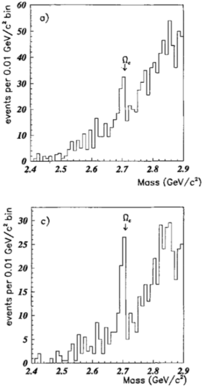


Fig. 1. (a) The mass distribution for the combined sample; (b) the mass distribution for the combined sample for proper times greater than −50 fs; (c) the mass distribution for the combined sample for positive proper times.

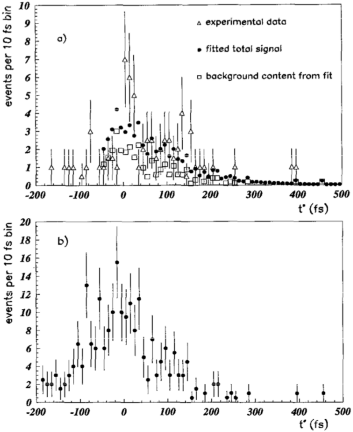


Fig. 2. The observed proper time (t^*) distributions for the combined sample: (a) in the signal region. The solid circles are the total signal obtained from the fit while the squares are the background contribution. Note that the fit results start from $t^* > -50$ fs, corresponding to the final choice of $t^*_{\rm cut}$ (see text); (b) in the sidebands. (The sizes of the sidebands are given in the text).

WA89 Ω_c^0 lifetime measurement

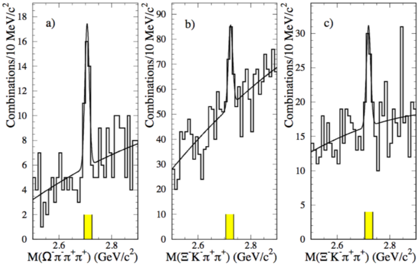


Figure 3: Mass distributions for three different final states: a) $\Omega^-\pi^+\pi^-\pi^+$, b) $\Xi^-K^-\pi^+\pi^+$ from carbon, c) $\Xi^-K^-\pi^+\pi^+$ from all targets with positively RICH identified kaon. The shaded region denotes the signal band.

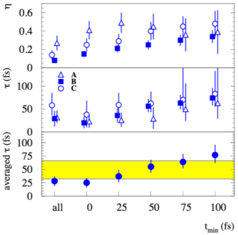


Figure 7: Results of the likelihood fits (see text) for the different samples and their dependence on the lower decay time cut t_{min} used in the fit. The shaded area represents the size of the full systematic error. Sample A) denotes $\Omega^-\pi^+\pi^-\pi^+$, sample B) $\Xi^-K^-\pi^+\pi^+$ from the carbon target and sample C) $\Xi^-K^-\pi^+\pi^+$ with identified K^-.

FOCUS Ω_c^0 lifetime measurement

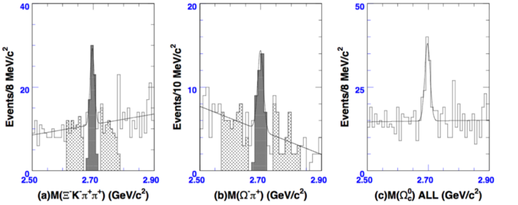
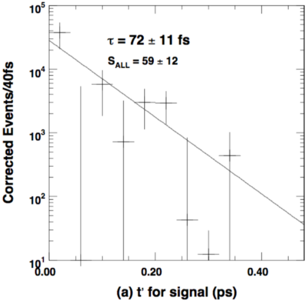


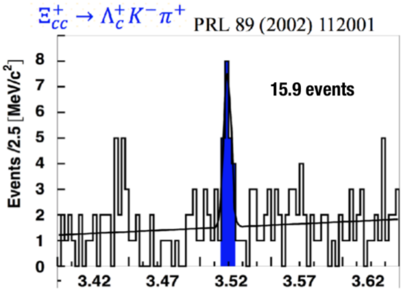
FIG. 1: Invariant mass distributions for Ω_c^0 candidates: (a) Reconstructed mass of $\Xi^- K^- \pi^+ \pi^+$. There are 38 ± 9 events at a mass of 2696.5 ± 1.9 MeV/c^2. (b) Reconstructed mass of $\Omega^- \pi^+$. There are 23 ± 7 events at a mass of 2699.4 ± 3.4 MeV/c^2. (c) Combined invariant mass distribution. There are 64 ± 14 events at a mass of 2697.5 ± 2.2 MeV/c^2. We define the signal region (hatched area) to be within $2\,\sigma$ of the fitted mass value and the two sideband regions (dotted area) are 4–12 σ from the fitted mass value.



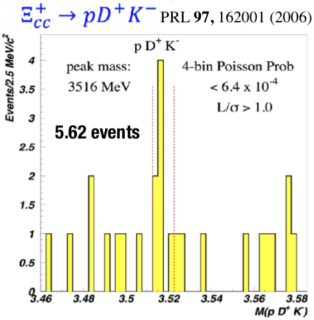
Ω_c^0 lifetime: theoretical issue

SELEX Ξ_{cc}^{+}

Using collisions of a hyperon beam on fixed nuclear targets



6.3σ



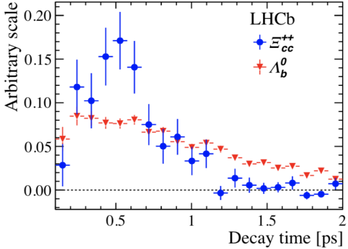
4.8σ

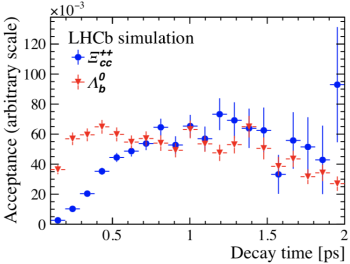
Future prospect for Ξ_{cc}^{++}

- Ξ_{cc}^{++}
  - Other decay mode to further understand the dynamics of weakly decaying doubly heavy baryons which may differ significantly from those of singly heavy hadrons due to interference effects between decay amplitudes of the two heavy quarks
    - $\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+$
    - ...
  - Production cross-section $\sigma(pp \to \Xi_{cc}^{++} + X)$
- Other double-charmed states
  - Ξ_{cc}^{+}
    - Update on $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$
    - Search for $\Xi_{cc}^{+} \to \Xi_c^+ \pi^+ \pi^-$
  - Ω_{cc}^{+}
- Establishing quantum numbers
- Search for excited Ξ_{cc}^{*} and Ω_{cc}^{*} states

Ξ_{cc}^{++} lifetime

$$f_{\Xi_{cc}^{++}}(t) = H_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times exp(\frac{t}{\tau(\Lambda_b^0)} - \frac{t}{\tau(\Xi_{cc}^{++})})$$





Ξ_{cc}^{++} lifetime: systematic uncertainties

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014