Study of the spectra and decay widths of heavy single baryons

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October 17 2023

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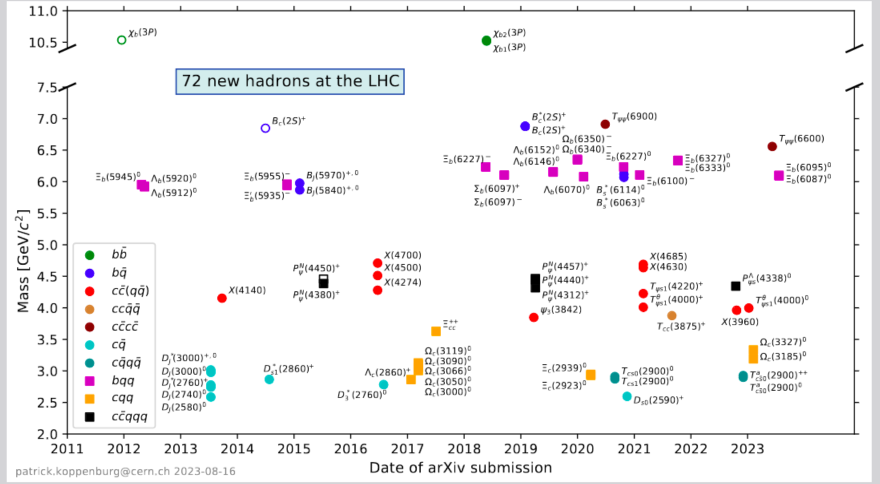
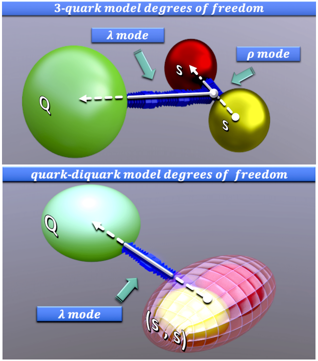
New hadrons discovered at LHC

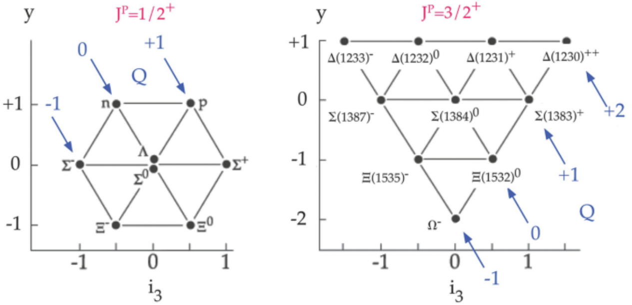


Motivation

- **Physics motivation:**
  - The internal configuration of baryons is still unknown.
  - Number of states depend on the model, i.e. the combination of the quantum numbers.
  - The three-quark model and the effective degrees of freedom
  - The quark-diquark model

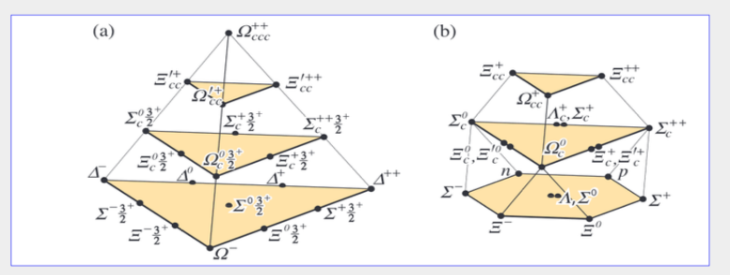


Light baryons in the $SU(3)$ flavor symmetry



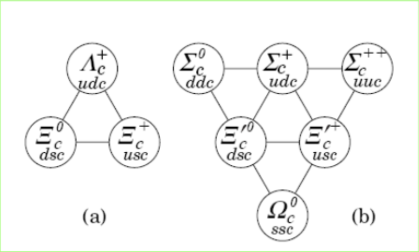
"Baryons can be constructed from quarks by using the combination of (qqq), $(qqqq\bar{q})$ ...", M. Gell-Mann, "A schematic model of baryons and mesons", Phys. Lett. 8 (1964) 214

Heavy baryon with charm quarks



Wave function $\Psi = \sum \omega\psi\phi\chi$
Three particles of spin 1/2
$1/2 \times 1/2 \times 1/2 = 1/2 + 1/2 + 3/2$

Heavy baryon with a single charm quark

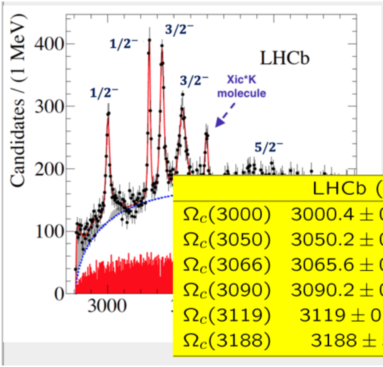


$$\Xi_c^0 := \frac{1}{\sqrt{2}}(|dsc\rangle - |sdc\rangle)$$
$$\Xi_c^+ := \frac{1}{\sqrt{2}}(|usc\rangle - |suc\rangle)$$
$$\Lambda_c^+ := \frac{1}{\sqrt{2}}(|udc\rangle - |duc\rangle)$$

$$\Omega_c := |ssc\rangle$$
$$\Xi_c'^0 := \frac{1}{\sqrt{2}}(|dsc\rangle + |sdc\rangle)$$
$$\Xi_c'^+ := \frac{1}{\sqrt{2}}(|usc\rangle + |suc\rangle)$$
$$\Sigma_c^{++} := |uuc\rangle$$
$$\Sigma_c^0 := |ddc\rangle$$
$$\Sigma_c^+ := \frac{1}{\sqrt{2}}(|udc\rangle + |duc\rangle)$$

Wave function $\Psi = \sum \omega\psi\phi\chi$
Three particles of spin 1/2
$1/2 \times 1/2 \times 1/2 = 1/2 + 1/2 + 3/2$

The Ω_c states observed by LHCb, PRL 118 (2017) 18, 182001



LHCb: proton-proton

BELLE: electron-positron

	LHCb (2017)	BELLE (2018)
$\Omega_c(3000)$	$3000.4 \pm 0.2 \pm 0.1$	$3000.7 \pm 1.0 \pm 0.2$
$\Omega_c(3050)$	$3050.2 \pm 0.1 \pm 0.1$	$3050.2 \pm 0.4 \pm 0.2$
$\Omega_c(3066)$	$3065.6 \pm 0.1 \pm 0.3$	$3064.9 \pm 0.6 \pm 0.2$
$\Omega_c(3090)$	$3090.2 \pm 0.3 \pm 0.5$	$3089.3 \pm 1.2 \pm 0.2$
$\Omega_c(3119)$	$3119 \pm 0.3 \pm 0.9$	not seen
$\Omega_c(3188)$	$3188 \pm 5 \pm 13$	$3199 \pm 9 \pm 4$

Phenomenological model I

- The masses of the heavy single baryon states are calculated as the eigenvalues of the Hamiltonian , E. Santopinto, A. Giachino, J. Ferretti, H. Garcia-Tecocoatzi, M.A. Bedolla, R. Bijker, E. Ortiz-Pacheco, EPJC 79(12), 1012 (2019), which is modeled as:

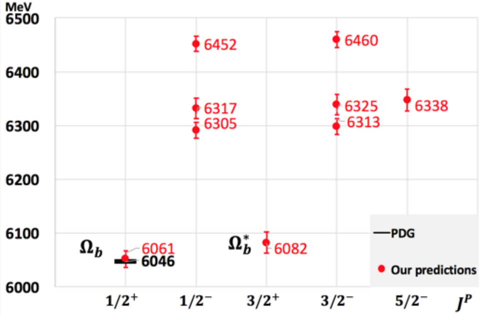
$$H = H_{\mathrm{h.o.}} + P_s\ \mathbf{S}^2 + P_{sl}\ \mathbf{S}\cdot\mathbf{L} + P_I\ \boldsymbol{I}^2 + P_f\ \mathbf{C_2}(\mathrm{SU}(3)_{\mathrm{f}}), \qquad (1)$$

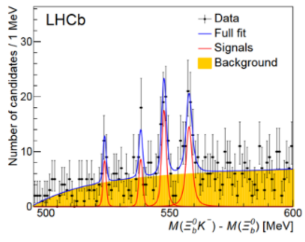
  $\mathbf{S}, \mathbf{L}, \boldsymbol{I}$ and $\mathbf{C_2}(\mathrm{SU}(3)_{\mathrm{f}})$ are the spin, orbital momentum, isospin and Casimir operators, respectively.

- We describe the observed excited states of Ω_c, Σ_c, Λ_c, Ξ_c, and Ξ'_c at the same time, PRD107 034031 (2023)
- We recently study the Ω_b, Σ_b, Λ_b, Ξ_b, and Ξ'_b states
- We work within the quark-model framework H. Garcia-Tecocoatzi, A. Giachino, A. Ramirez-Morales, A. Rivero-Acosta, E. Santopinto, and C. Vaquera e-Print: 2307.00505 [hep-ph] (2023)

Predictions of Ω_b excited states

First Observation of Excited Ωb States by LHCb collaboration, PRL 124, 082002 (2020)
In agreement with our predictions
Eur.Phys.J. C79 (2019) no.12, 1012





Mass	Width (MeV)	
6316	< 2.8 (4.2)	0.50
6330	< 3.1 (4.7)	2.79
6340	< 1.5 (1.8)	1.14
6350	< 2.8 (3.2)	0.62

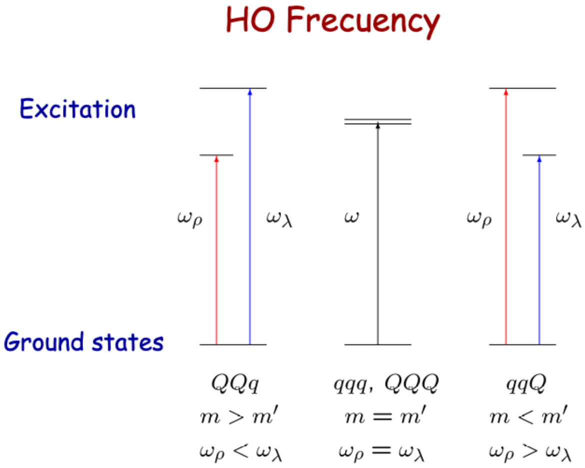
The Hamiltonian of three quark model

- The Hamiltonian of the harmonic oscillator is given:

$$H_{\mathrm{h.o.}} = \sum_{i=1}^{3} m_i + \frac{\mathbf{p}_\rho^2}{2m_\rho} + \frac{\mathbf{p}_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\rho \omega_\rho^2 \boldsymbol{\rho}^2 + \frac{1}{2} m_\lambda \omega_\lambda^2 \boldsymbol{\lambda}^2 \tag{2}$$

- It is written in terms of Jacobi coordinates, $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$, and their conjugated momenta, $\mathbf{p}_\rho$ and $\mathbf{p}_\lambda$, whose eigenvalues are $\sum_{i=1}^{3} m_i + \omega_\rho\, n_\rho + \omega_\lambda n_\lambda$,
- Will we observe all the predicted states?

Mass splitting due to ρ and λ excitations



Diquark description

- When $\mathbf{p}_\rho = 0$, the three-quark Hamiltonian becomes

$$H_{\text{h.o.}} = m_D + m_Q + \frac{\mathbf{p}_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\lambda \omega_\lambda^2 \boldsymbol{\lambda}^2. \tag{3}$$

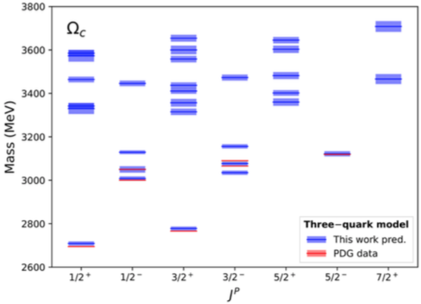
- The quark-diquark Hamiltonian depends on the relative coordinate $\boldsymbol{r}$ and the momentum $\mathbf{p}_r$ and is

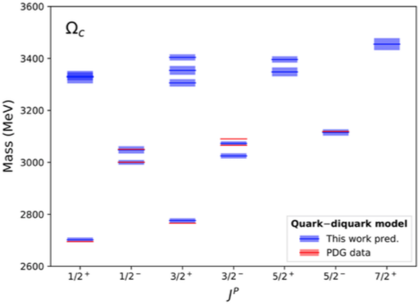
$$H_D = m_D + m_Q + \frac{p_r^2}{2\mu} + \frac{1}{2} \mu \omega_\lambda^2 \mathbf{r}^2, \tag{4}$$

- We can find a match as follows: $\frac{p_\lambda^2}{2m_\lambda} \to \frac{p_r^2}{2\mu}$ and $\frac{1}{2} m_\lambda \omega_\lambda^2 \boldsymbol{\lambda}^2 \to \frac{1}{2} \mu \omega_\lambda^2 \mathbf{r}^2$, where $\mu = \frac{m_D m_Q}{m_D + m_Q}$ is the reduced mass, $\mathbf{p}_r = \frac{m_Q \mathbf{p}_D - m_D \mathbf{p}_Q}{m_D + m_Q}$

Results for Ω_c,PRD107 034031 (2023)

Three-quark model vs quark-diquark model

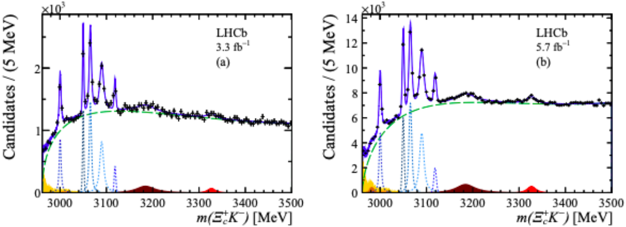




H. Garcia-Tecocoatzi, A. Giachino, J. Li, A. Ramirez-Morales, and E. Santopinto, PRD107 034031 (2023)

New Ω_c states observed by LHCb, PRL131 131902(2023

New state $\Omega_c(3327)$ with mass=3327.1 ± 1.2 MeV and $\Gamma = 20 \pm 5$ MeV



$\|l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	${}^2D_{3/2}$	3315^{+15}_{-14}	3306^{+14}_{-14}	†	11^{+5}_{-5}
$\|l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	${}^2D_{5/2}$	3360^{+17}_{-16}	3348^{+17}_{-17}	†	24^{+12}_{-12}
$\|l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	${}^4D_{1/2}$	3330^{+25}_{-25}	3328^{+24}_{-23}	†	16^{+8}_{-8}
$\|l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	${}^4D_{3/2}$	3357^{+18}_{-19}	3354^{+17}_{-17}	†	30^{+15}_{-15}
$\|l_\lambda = 2, l_\rho = 0, k_\lambda = 0, k_\rho = 0\rangle$	${}^4D_{5/2}$	3402^{+13}_{-13}	3396^{+12}_{-12}	†	62^{+31}_{-31}

H. Garcia-Tecocoatzi, A. Giachino, J. Li, A. Ramirez-Morales, and E. Santopinto, PRD107 034031 (2023)

Results for Ξ_c' and Ξ_c, PRD107 034031 (2023)

$\Xi_c'(snc)$ $\mathcal{F} = \mathbf{6}_f$	$^{2S+1}L_J$	Three-quark predicted mass (MeV)	Quark-diquark predicted mass (MeV)	Experimental mass (MeV)	Predicted Γ_{tot} (MeV)	Experimental Γ (MeV)
$N=0$						
$\vert l_\lambda=0, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2S_{1/2}$	2571^{+8}_{-8}	2577^{+10}_{-10}	2578.0 ± 0.9 (*)	0	†
$\vert l_\lambda=0, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4S_{3/2}$	2640^{+7}_{-7}	2650^{+9}_{-9}	2645.9 ± 0.71 (*)	$0.4^{+0.2}_{-0.2}$	2.25 ± 0.41 (*)
$N=1$						
$\vert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	2893^{+9}_{-9}	2893^{+11}_{-11}	†	7^{+4}_{-3}	†
$\vert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4P_{1/2}$	2935^{+14}_{-15}	2941^{+14}_{-14}	2923.0 ± 0.35	5^{+2}_{-3}	7.1 ± 2.0
$\vert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	2920^{+9}_{-9}	2919^{+13}_{-13}	2938.5 ± 0.3	28^{+14}_{-14}	15 ± 9
$\vert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4P_{3/2}$	2962^{+9}_{-9}	2966^{+10}_{-10}	2964.9 ± 0.33 (*)	19^{+9}_{-9}	14.1 ± 1.6 (*)
$\vert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^4P_{5/2}$	3007^{+12}_{-12}	3009^{+14}_{-14}	†	43^{+21}_{-21}	†
$\vert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	3040^{+10}_{-9}	††	3055.9 ± 0.4 (*)	157^{+80}_{-80}	7.8 ± 1.9 (*)
$\vert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	3067^{+10}_{-10}	††	3078.6 ± 2.8 (*)	100^{+47}_{-48}	4.6 ± 3.3 (*)

$\Xi_c(snc)$ $\bar{\mathbf{3}}_f$	$^{2S+1}L_J$	Three-quark predicted mass (MeV)	Quark-diquark predicted mass (MeV)	Experimental mass (MeV)	Predicted Γ_{tot} (MeV)	Experimental Γ (MeV)
$N=0$						
$\vert l_\lambda=0, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2S_{1/2}$	2466^{+10}_{-10}	2473^{+10}_{-10}	2469.42 ± 1.77 (*)	0	≈ 0
$N=1$						
$\vert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	2788^{+10}_{-10}	2789^{+9}_{-9}	2793.3 ± 0.28 (*)	3^{+2}_{-2}	9.5 ± 2.0 (*)
$\vert l_\lambda=1, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	2815^{+10}_{-10}	2814^{+9}_{-9}	2818.49 ± 2.07 (*)	5^{+2}_{-2}	2.48 ± 0.5 (*)
$\vert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{1/2}$	2935^{+12}_{-12}	††	†	17^{+9}_{-8}	†
$\vert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^4P_{1/2}$	2977^{+20}_{-20}	††	2968.6 ± 3.3	13^{+6}_{-6}	20 ± 3.5
$\vert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^2P_{3/2}$	2962^{+12}_{-12}	††	†	89^{+45}_{-45}	†
$\vert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^4P_{3/2}$	3004^{+17}_{-17}	††	†	56^{+29}_{-31}	†
$\vert l_\lambda=0, l_\rho=1, k_\lambda=0, k_\rho=0\rangle$	$^4P_{5/2}$	3049^{+18}_{-19}	††	†	122^{+59}_{-60}	†
$N=2$						
$\vert l_\lambda=2, l_\rho=0, k_\lambda=0, k_\rho=0\rangle$	$^2D_{3/2}$	3118^{+14}_{-14}	3113^{+14}_{-14}	3122.9 ± 1.23	50^{+24}_{-25}	4 ± 4

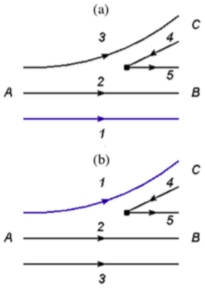
Strong decay widths

We can use the decay properties to identify baryons

- Open-flavor strong decays
- Study of the decay channels
- At the moment, there is no decay model from first principles, i.e., a QCD decay model.
- There are many models inspired by QCD, such as the flux tube, the elementary emission model, effective Lagrangians, or $^3P_0$, none of them, of course, correspond to QCD!

$^{3}P_{0}$ decay model

- The $q\bar{q}$ pair is created with the vacuum quantum numbers: 0^{++}
- Due to parity conservation, the pair is created in P-wave
- The spin should be $S = 1$ to couple to $J = 0$
- It has only one coupling constant



Decay widths

- The decay widths are calculated with the predicted masses and their predicted quantum numbers
- The $^3P_0$ model is used for calculating the strong-decay widths of a charm baryon A into a charm baryon B plus a meson C, or a charm baryon A into a light baryon B plus a charm meson C, $A \to BC$

$$\Gamma = \frac{2\pi\gamma_0^2}{2J_A+1}\,\Phi_{A\to BC}(q_0)\sum_{M_{J_A},M_{J_B}}\left|\mathcal{M}^{M_{J_A},M_{J_B}}\right|^2 \tag{5}$$

- The error propagation was obtained using the bootstrap method.

Results, partial-decay widths PRD107 034031 (2023)

$\Omega_c(ssc)$ $\mathcal{F}=\mathbf{6}_f$	$\Xi_c K$	$\Xi'_c K$	$\Xi^*_c K$	$\Xi_c K^*$	$\Xi'_c K^*$	$\Xi^*_c K^*$	$\Omega_c \eta$	$\Omega^*_c \eta$	$\Omega_c \phi$	$\Omega^*_c \phi$	$\Omega_c \eta'$	$\Omega^*_c \eta'$	$\Xi_8 D$	$\Xi_{10} D$	Predicted Γ_{tot}
$\Omega_c(2709)^2S_{1/2}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\Omega_c(2778)^4S_{3/2}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\Omega_c(3008)^2P_{1/2}$	4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	4.1
$\Omega_c(3050)^4P_{1/2}$	7.5	0.1	0	0	0	0	0	0	0	0	0	0	0	0	7.6
$\Omega_c(3035)^2P_{3/2}$	26.3	0	0	0	0	0	0	0	0	0	0	0	0	0	26.3
$\Omega_c(3077)^4P_{3/2}$	6.3	0.4	0	0	0	0	0	0	0	0	0	0	0	0	6.7
$\Omega_c(3122)^4P_{5/2}$	40.9	8.9	0.3	0	0	0	0	0	0	0	0	0	0	0	50.1
$\Omega_c(3129)^2P_{1/2}$	—	8.9	5.5	0	0	0	0	0	0	0	0	0	0	0	14.4
$\Omega_c(3156)^2P_{3/2}$	—	61.1	10.5	0	0	0	0	0	0	0	0	0	0	0	71.6
$\Omega_c(3315)^2D_{3/2}$	1.9	1.8	2.3	0	0	0	0.3	—	0	0	0	0	4.3	0	10.6
$\Omega_c(3360)^2D_{5/2}$	5.4	5.1	0.5	0	0	0	1.2	—	0	0	0	0	12.2	0	24.4
$\Omega_c(3330)^4D_{1/2}$	0.2	0.2	3.3	0	0	0	0.1	0.1	0	0	0	0	12.3	0	16.2
$\Omega_c(3357)^4D_{3/2}$	2.0	0.5	5.2	0.2	0	0	0.2	0.6	0	0	0	0	21.7	0	30.4
$\Omega_c(3402)^4D_{5/2}$	5.0	1.2	5.0	1.6	0	0	0.3	1.2	0	0	0	0	46.9	1.1	62.3
$\Omega_c(3466)^4D_{7/2}$	7.8	2.0	5.0	2.6	0	0	0.8	0.9	0	0	0	0	83.2	20.9	123.2
$\Omega_c(3342)^2S_{1/2}$	0.2	0.3	0.1	0	0	0	0.1	—	0	0	0	0	0.5	0	1.2
$\Omega_c(3411)^4S_{3/2}$	0.2	0.1	0.4	0.2	0	0	—	0.1	0	0	0	0	2.1	0.2	3.3
$\Omega_c(3585)^2S_{1/2}$	0.3	1.0	0.7	3.0	11.6	0.1	1.1	0.5	0	0	0	0	—	—	18.3
$\Omega_c(3654)^4S_{3/2}$	0.1	0.1	1.2	2.8	1.0	17.2	0.2	1.4	0	0	—	0	—	—	24.0
$\Omega_c(3437)^2D_{3/2}$	—	6.5	107.0	53.5	0	0	4.0	27.0	0	0	0	0	—	—	198.0

Summary

- We calculated the mass spectra of the heavy single baryons (ρ and λ mode excitations up to the D-wave.
- We calculated the strong-decay widths of ground- and excited-heavy baryon into the single heavy baryon-(vector/pseudoscalar) meson pairs and the (octet/ decuplet) baryon-(pseudoscalar/vector) heavy meson pairs.
- The uncertainties are treated rigorously and propagated in full to the parameters of the model using a Monte Carlo bootstrap method.
- The identification of the states is a complex task
- The future experiments will help us to understand the structure of the hadrons
- The $^3P_0$ can describe the trend of the data with only one parameter.
- Single bottom baryons H. Garcia-Tecocoatzi, A. Giachino, , A. Ramirez-Morales, A. Rivero-Acosta, E. Santopinto, and C. Vaquera e-Print: 2307.00505 [hep-ph] (2023)

Thanks for listening!