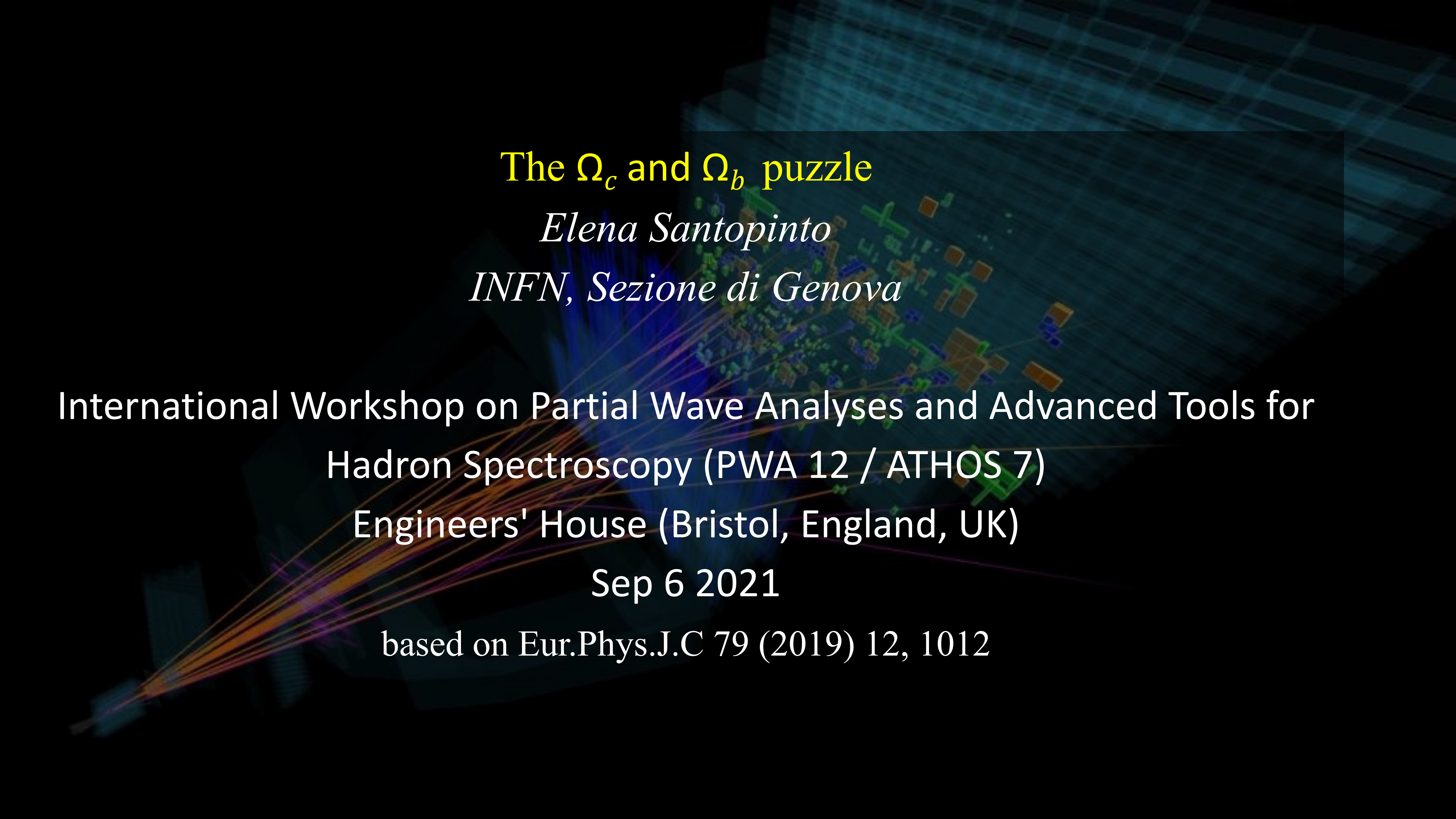

# The $\Omega_c$ and $\Omega_b$ puzzle

*Elena Santopinto*

*INFN, Sezione di Genova*

International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy (PWA 12 / ATHOS 7)

Engineers' House (Bristol, England, UK)

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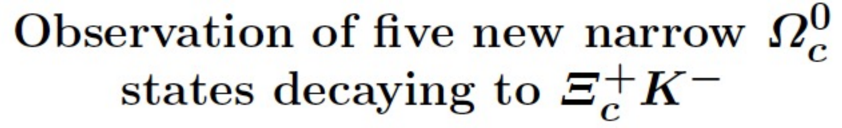
based on Eur.Phys.J.C 79 (2019) 12, 1012

# Outline

- 1) Experimental data
- 2) The $\Omega_c$ puzzle and the predictions of the new $\Omega_b$ later observed by LHCb
- 3) Model
- 4) $\Omega_c$ Mass spectrum and $\Xi_c^+ \, K^-$ decay width results
- 5) Heavy Quark Spin Symmetry with Chiral Tensor Dynamics in Light of the Recent LHCb Pentaquarks

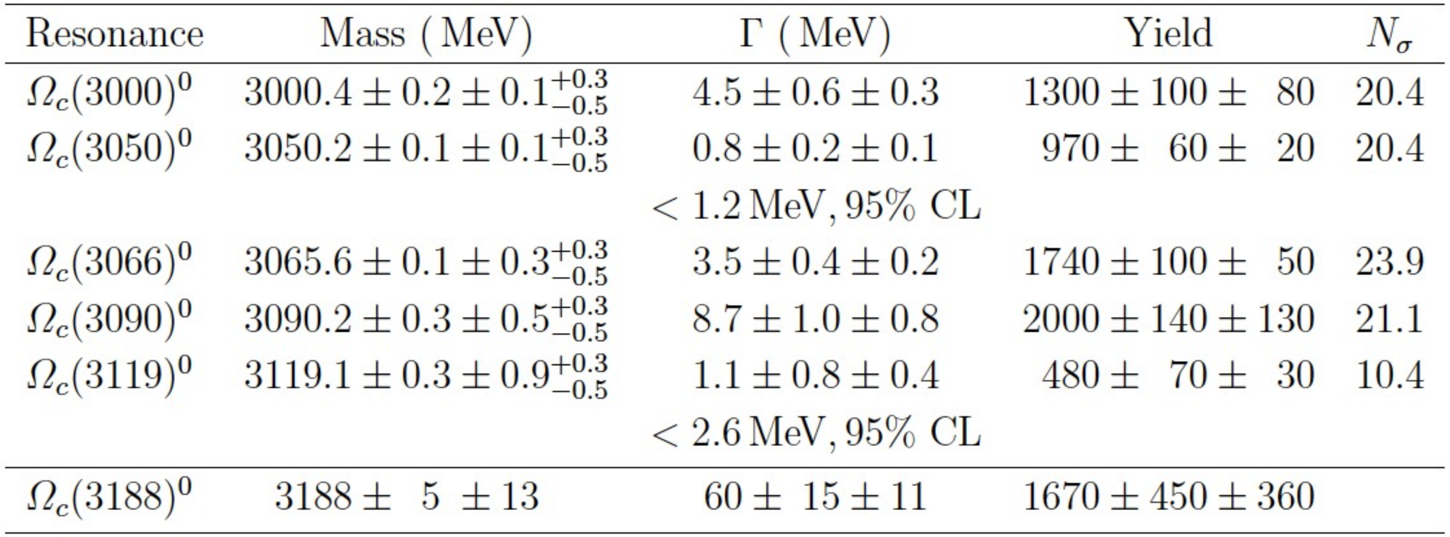
# Experimental background



**Observation of five new narrow $\Omega_c^0$ states decaying to $\Xi_c^+ K^-$**

R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 118 , 182001 (2017)

Mass, width, yield and significance for each resonance.



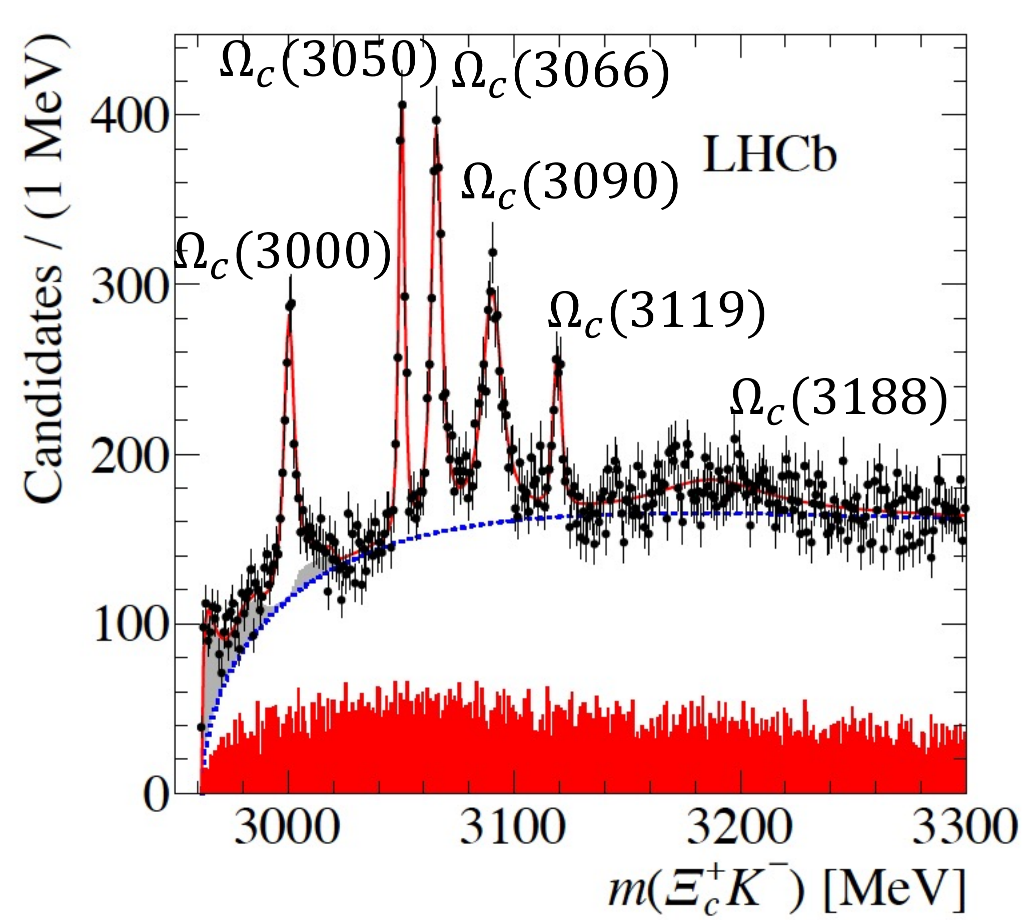
| Resonance | Mass (MeV) | $\Gamma$ (MeV) | Yield | $N_\sigma$ |
|---|---|---|---|---|
| $\Omega_c(3000)^0$ | $3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$ | $4.5 \pm 0.6 \pm 0.3$ | $1300 \pm 100 \pm 80$ | 20.4 |
| $\Omega_c(3050)^0$ | $3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$ | $0.8 \pm 0.2 \pm 0.1$ | $970 \pm 60 \pm 20$ | 20.4 |
| | | $< 1.2\,\mathrm{MeV}, 95\%$ 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 |
| | | $< 2.6\,\mathrm{MeV}, 95\%$ CL | | |
| $\Omega_c(3188)^0$ | $3188 \pm 5 \pm 13$ | $60 \pm 15 \pm 11$ | $1670 \pm 450 \pm 360$ | |

**Quantum numbers not determined**

the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background.

$m_{K^-}$=493.677±0.016 MeV

$m_{\Xi_c^+} = 2467.89^{+0.34}_{-0.50}$ MeV



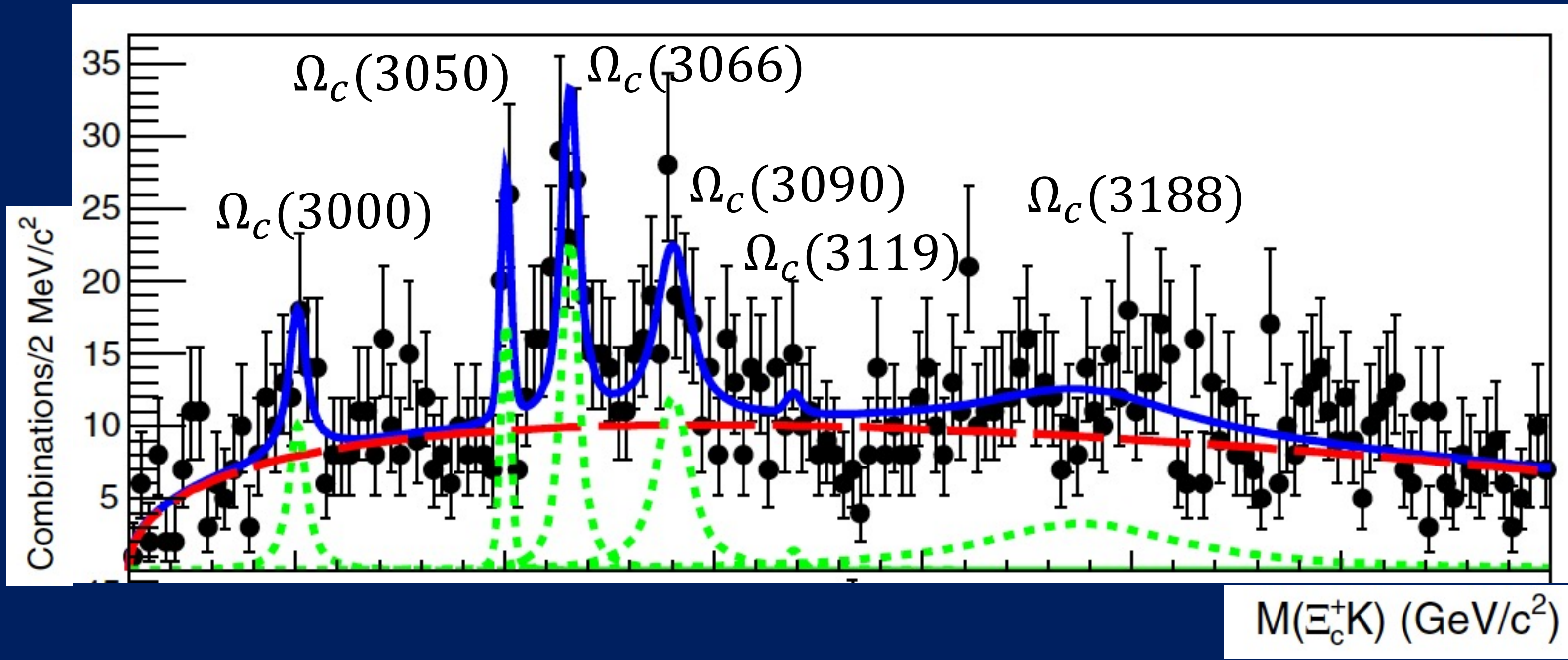
# Experimentaln data

**Observation of excited $\Omega_c$ charmed baryons in $e^+e^-$ collisions**

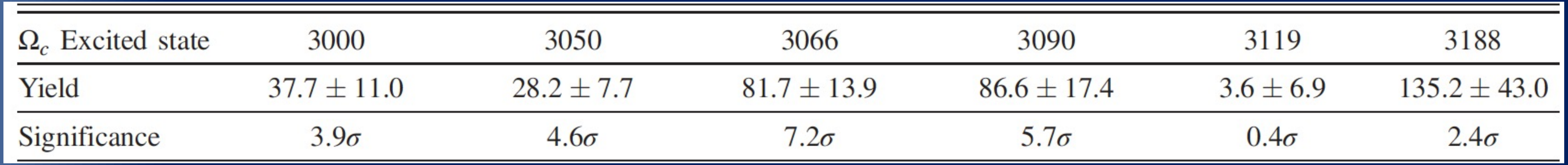
Y. Yelton et al. [Belle Collaboration], Phys. Rev. D 97 , 051102 (2018).

According to Belle these data unambiguously confirm the existence of $\Omega_c(3066)$ and $\Omega_c(3090)$; Signals of reasonable significance are seen for the $\Omega_c(3000)$ and $\Omega_c(3050)$, but no signal is apparent for the $\Omega_c(3119)$; Belle also see a wide excess, consistent with that found by LHCb, at higher mass ($\Omega_c(3188)$) .

The masses and intrinsic widths of all six states are fixed to the values found by LHCb



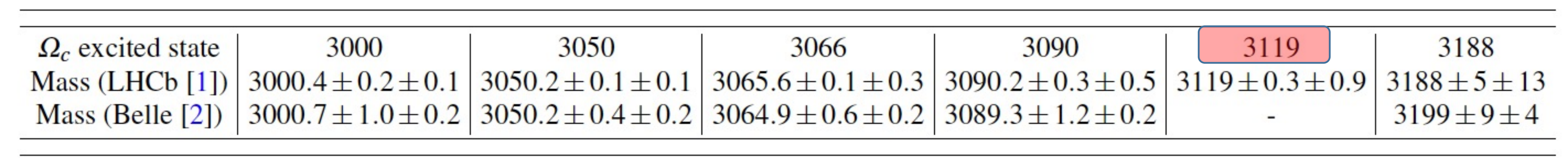
Statistical significance for each state



| $\Omega_c$ Excited state | 3000 | 3050 | 3066 | 3090 | 3119 | 3188 |
|---|---|---|---|---|---|---|
| Yield | $37.7 \pm 11.0$ | $28.2 \pm 7.7$ | $81.7 \pm 13.9$ | $86.6 \pm 17.4$ | $3.6 \pm 6.9$ | $135.2 \pm 43.0$ |
| Significance | $3.9\sigma$ | $4.6\sigma$ | $7.2\sigma$ | $5.7\sigma$ | $0.4\sigma$ | $2.4\sigma$ |

# Experimental background

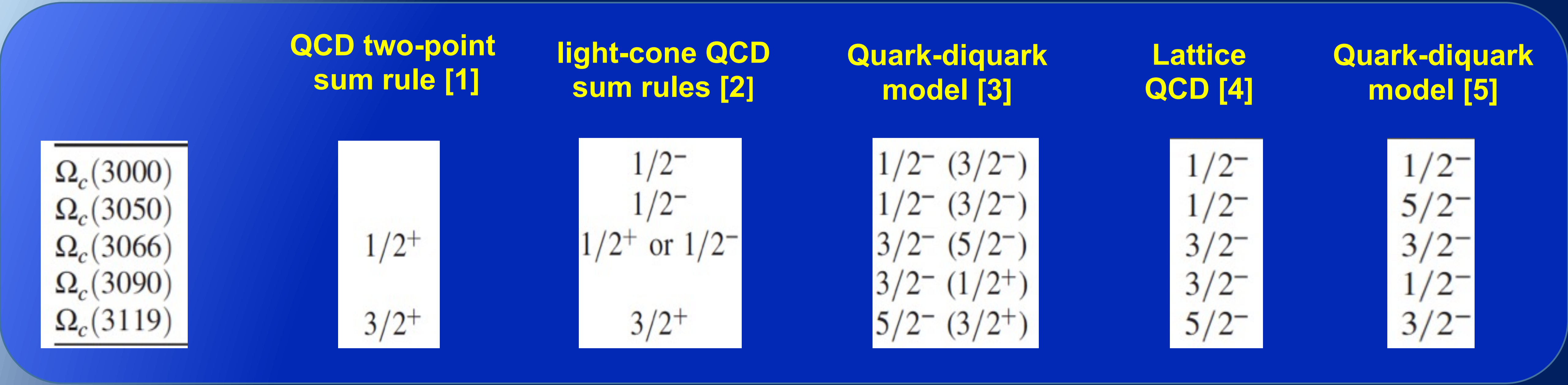
- Both LHCb and Belle were not able to measure the $\Omega_c$ angular momenta and parities;
- $\Omega_c(3119)$ was seen by LHCb and not by Belle



| $\Omega_c$ excited state | 3000 | 3050 | 3066 | 3090 | 3119 | 3188 |
|---|---|---|---|---|---|---|
| Mass (LHCb [1]) | $3000.4 \pm 0.2 \pm 0.1$ | $3050.2 \pm 0.1 \pm 0.1$ | $3065.6 \pm 0.1 \pm 0.3$ | $3090.2 \pm 0.3 \pm 0.5$ | $3119 \pm 0.3 \pm 0.9$ | $3188 \pm 5 \pm 13$ |
| Mass (Belle [2]) | $3000.7 \pm 1.0 \pm 0.2$ | $3050.2 \pm 0.4 \pm 0.2$ | $3064.9 \pm 0.6 \pm 0.2$ | $3089.3 \pm 1.2 \pm 0.2$ | - | $3199 \pm 9 \pm 4$ |

several authors tried to provide different quantum number assignments for these states within several framework

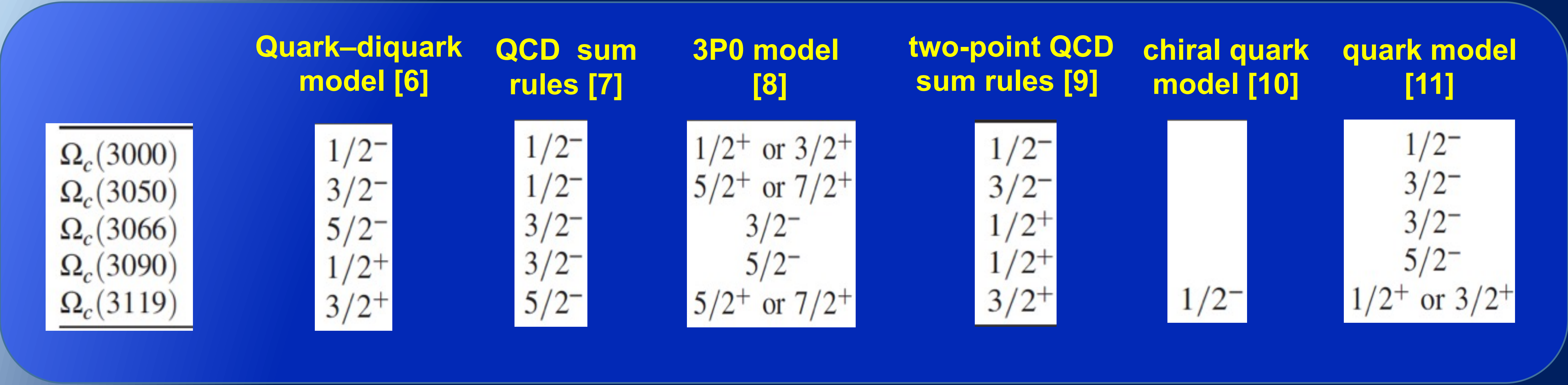
# Many interpretations by different theoretical models



| | QCD two-point sum rule [1] | light-cone QCD sum rules [2] | Quark-diquark model [3] | Lattice QCD [4] | Quark-diquark model [5] |
|---|---|---|---|---|---|
| $\Omega_c(3000)$ | | $1/2^-$ | $1/2^-$ $(3/2^-)$ | $1/2^-$ | $1/2^-$ |
| $\Omega_c(3050)$ | | $1/2^-$ | $1/2^-$ $(3/2^-)$ | $1/2^-$ | $5/2^-$ |
| $\Omega_c(3066)$ | $1/2^+$ | $1/2^+$ or $1/2^-$ | $3/2^-$ $(5/2^-)$ | $3/2^-$ | $3/2^-$ |
| $\Omega_c(3090)$ | | | $3/2^-$ $(1/2^+)$ | $3/2^-$ | $1/2^-$ |
| $\Omega_c(3119)$ | $3/2^+$ | $3/2^+$ | $5/2^-$ $(3/2^+)$ | $5/2^-$ | $3/2^-$ |

1. **S. S. Agaev, K. Azizi, and H. Sundu,** arXiv:1703.07091;
2. H. X. Chen, Q. Mao, W. Chen, A. Hosaka, rX. Liu, and S. L. Zhu, Phys. Rev. D 95, 094008 (2017);
3. M. Karliner and J. L. Rosner, Phys. Rev. D 95, 114012 (2017);
4. M. Padmanath and N. Mathur, Phys. Rev. Lett. 119, 042001 (2017) ;
5. B. Chen and X. Liu, Phys. Rev. D 96, 094015 ( 2017).

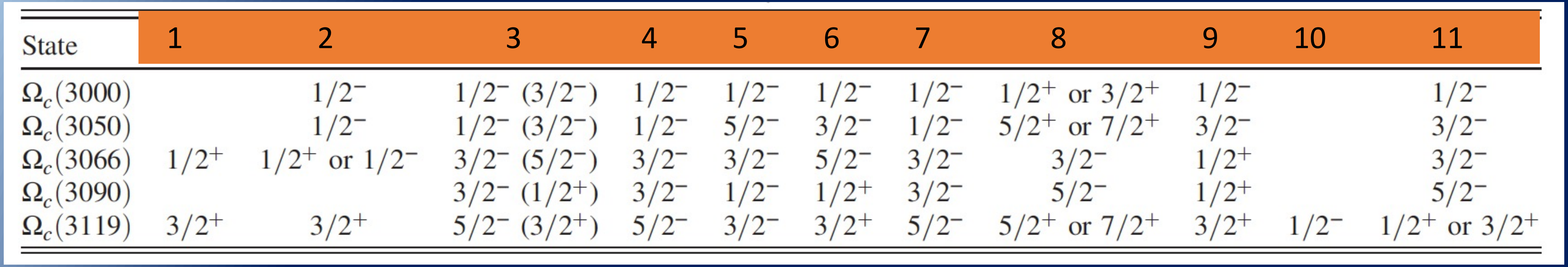
# Many interpretations by the theoretical community



| | Quark–diquark model [6] | QCD sum rules [7] | 3P0 model [8] | two-point QCD sum rules [9] | chiral quark model [10] | quark model [11] |
|---|---|---|---|---|---|---|
| $\Omega_c(3000)$ | $1/2^-$ | $1/2^-$ | $1/2^+$ or $3/2^+$ | $1/2^-$ | | $1/2^-$ |
| $\Omega_c(3050)$ | $3/2^-$ | $1/2^-$ | $5/2^+$ or $7/2^+$ | $3/2^-$ | | $3/2^-$ |
| $\Omega_c(3066)$ | $5/2^-$ | $3/2^-$ | $3/2^-$ | $1/2^+$ | | $3/2^-$ |
| $\Omega_c(3090)$ | $1/2^+$ | $3/2^-$ | $5/2^-$ | $1/2^+$ | | $5/2^-$ |
| $\Omega_c(3119)$ | $3/2^+$ | $5/2^-$ | $5/2^+$ or $7/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^+$ or $3/2^+$ |

6. H. Y. Cheng and C.W. Chiang, Phys. Rev. D 95, 094018 (2017);
7. Z. G. Wang, Eur. Phys. J. C 77, 325 (2017);
8. Z. Zhao, D. D. Ye, and A. Zhang, Phys. Rev. D 95, 114024 (2017);
9. S. S. Agaev, K. Azizi, and H. Sundu, arXiv:1704.04928;
10. H. Huang, J. Ping, and F. Wang, Phys. Rev. D 97, 034027 (2018);
11. Kai-Lei Wang, Li-Ye Xiao, Xian-Hui Zhong, and Qiang Zhao Phys. Rev. D 95, 116010 (2017)

# To summarize:



| State | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Omega_c(3000)$ |  | $1/2^-$ | $1/2^-$ $(3/2^-)$ | $1/2^-$ | $1/2^-$ | $1/2^-$ | $1/2^-$ | $1/2^+$ 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 $3/2^+$ |

1. **S. S. Agaev, K. Azizi, and H. Sundu, On the nature of the newly discovered Ω0c States arXiv:1703.07091**
2. **H. X. Chen, Q. Mao, W. Chen, A. Hosaka, rX. Liu, and S. L. Zhu, Phys. Rev. D 95, 094008 (2017).**
3. **M. Karliner and J. L. Rosner, Very narrow excited Ωc baryons, Phys. Rev. D 95, 114012 (2017)**
4. **M. Padmanath and N. Mathur, Phys. Rev. Lett. 119, 042001 (2017)**
5. **B. Chen and X. Liu, Phys. Rev. D 96, 094015 ( 2017)**
6. **H. Y. Cheng and C.W. Chiang, Phys. Rev. D 95, 094018 (2017).**
7. **Z. G. Wang, Eur. Phys. J. C 77, 325 (2017).**
8. **Z. Zhao, D. D. Ye, and A. Zhang, Phys. Rev. D 95, 114024 (2017)**
9. **S. S. Agaev, K. Azizi, and H. Sundu, arXiv:1704.04928**

**10 H. Huang, J. Ping, and F. Wang, Phys. Rev. D 97, 034027 (2018).**

**11. Kai-Lei Wang, Li-Ye Xiao, Xian-Hui Zhong, and Qiang Zhao Phys. Rev. D 95, 116010 (2017)**

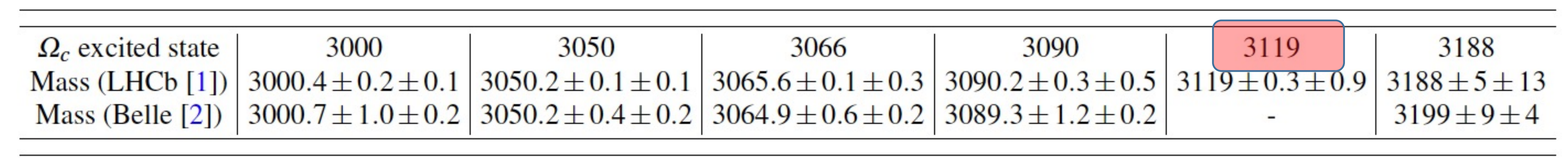
And these are just some examples of a wide literature

# The rise of the $\Omega_c$ puzzle

For each experimental state more than one quantum number assignment was suggested: situation ambiguous;
in the case of the $\Omega_c(3119)$, not only the quantum number assignments are not univocal, but also the quark structure is still unclear, for example in Ref. [10-12-13-14] the authors propose a molecular interpretation for this state.

**10. H. Huang, J. Ping, and F. Wang, Phys. Rev. D 97, 034027 (2018);**
**11. Y. Huang, C. j. Xiao, Q. F. Lu, R. Wang, J. He and L. Geng, Phys. Rev. D 97 , 094013 (2018).**
**12 V. R. Debastiani, J. M. Dias, W. H. Liang and E. Oset, Phys. Rev. D 97 , 094035 (2018).**
**13 J. Nieves, R. Pavao and L. Tolos, Eur. Phys. J. C 78 , 114 (2018).**

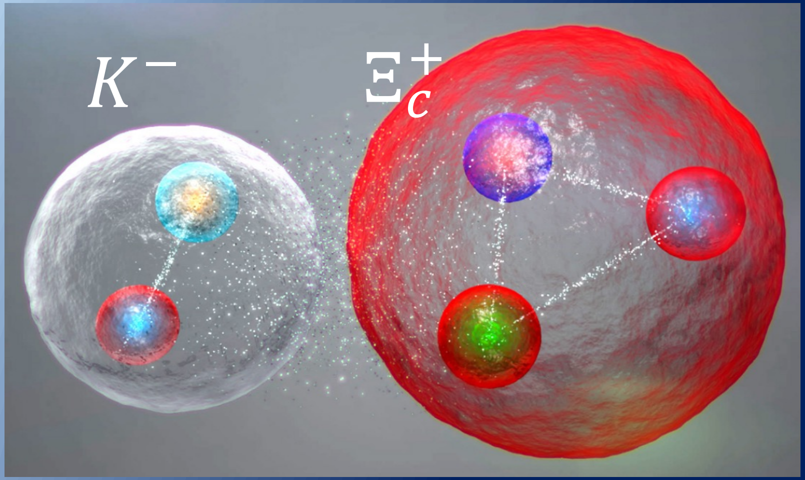
Remember that $\Omega_c(3119)$ was the state not seen by Belle

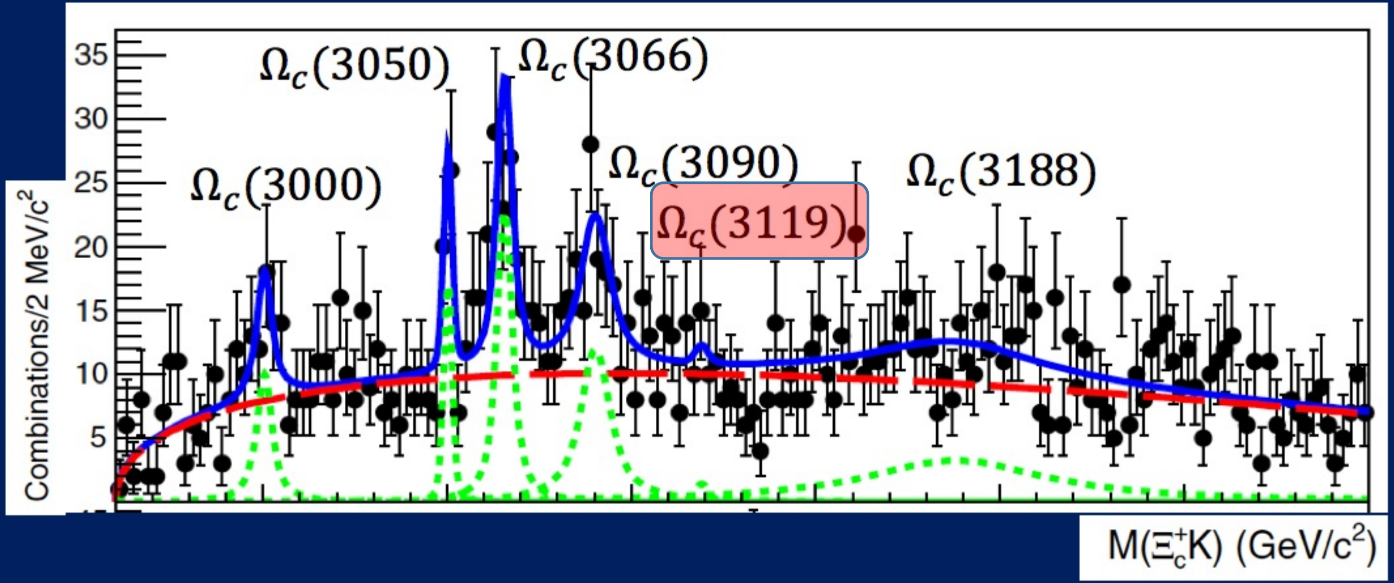


| $\Omega_c$ excited state | 3000 | 3050 | 3066 | 3090 | 3119 | 3188 |
|---|---|---|---|---|---|---|
| Mass (LHCb [1]) | $3000.4 \pm 0.2 \pm 0.1$ | $3050.2 \pm 0.1 \pm 0.1$ | $3065.6 \pm 0.1 \pm 0.3$ | $3090.2 \pm 0.3 \pm 0.5$ | $3119 \pm 0.3 \pm 0.9$ | $3188 \pm 5 \pm 13$ |
| Mass (Belle [2]) | $3000.7 \pm 1.0 \pm 0.2$ | $3050.2 \pm 0.4 \pm 0.2$ | $3064.9 \pm 0.6 \pm 0.2$ | $3089.3 \pm 1.2 \pm 0.2$ | - | $3199 \pm 9 \pm 4$ |

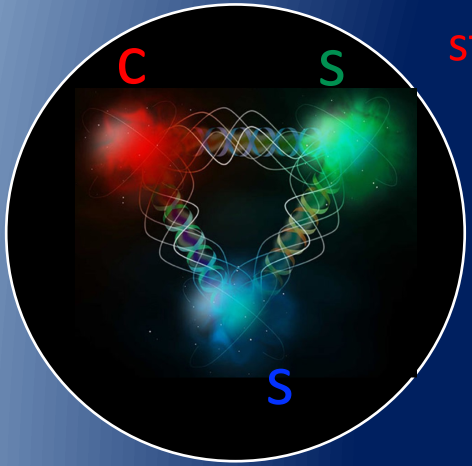
# The rise of the $\Omega_c$ puzzle

1) Is $\Omega_c(3119)$ a $\Xi_c^+ K^-$ molecular state,





or a three-quark state?



Or maybe, since Belle did not see this state, it does not exist at all ?

2) What about the $\Omega_c(3188)$ state which was neglected in most of the theoretical investigation?

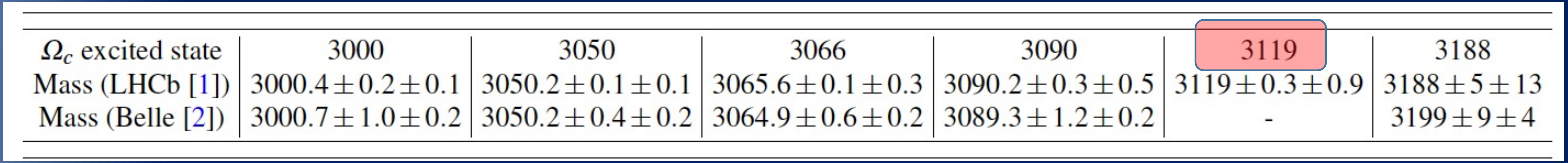
3) What about the quantum numbers of the other states?

# The $\Omega_c$ puzzle

The issues we have to deal with are not restricted to the contrasts between the different interpretations provided in the previous studies, but are also related to the discrepancies on the quantum number assignments within a given study

Is it possible to give a non-ambiguous solution to this puzzle?

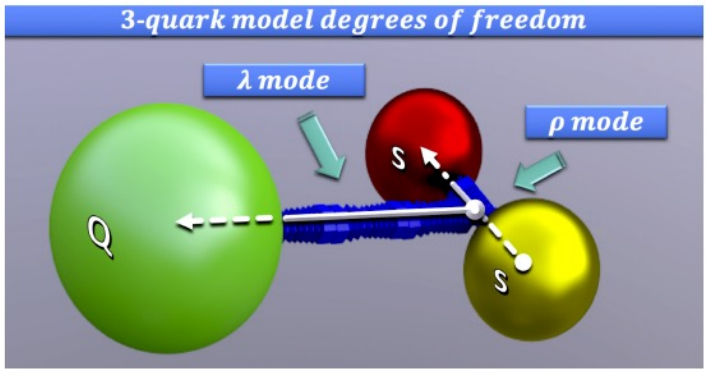
Most of the theoretical investigations take seriously the lighter five states and neglect the heaviest state, $\Omega_c(3188)$, which was seen both by LHCb and Belle, while by contrast the existence of $\Omega_c(3119)$ was not confirmed by Belle:



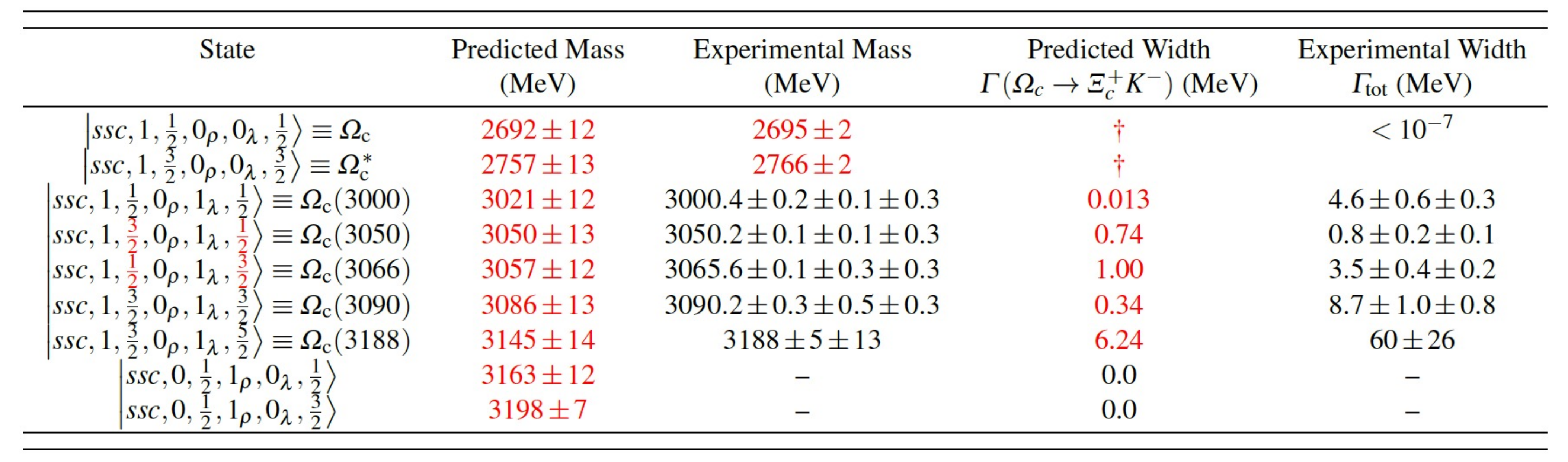
| $\Omega_c$ excited state | 3000 | 3050 | 3066 | 3090 | 3119 | 3188 |
|---|---|---|---|---|---|---|
| Mass (LHCb [1]) | $3000.4 \pm 0.2 \pm 0.1$ | $3050.2 \pm 0.1 \pm 0.1$ | $3065.6 \pm 0.1 \pm 0.3$ | $3090.2 \pm 0.3 \pm 0.5$ | $3119 \pm 0.3 \pm 0.9$ | $3188 \pm 5 \pm 13$ |
| Mass (Belle [2]) | $3000.7 \pm 1.0 \pm 0.2$ | $3050.2 \pm 0.4 \pm 0.2$ | $3064.9 \pm 0.6 \pm 0.2$ | $3089.3 \pm 1.2 \pm 0.2$ | - | $3199 \pm 9 \pm 4$ |

By estimating the P-wave excitations, the spin-orbit , spin-spin, isospin- and flavour-dependent contributions from the well-established charmed baryon mass spectrum, we reproduce quantitatively the spectrum of the $\Omega_c$ states observed both by LHCb and Belle [1].

We interpret $\Omega_c$(3000), $\Omega_c$(3050), $\Omega_c$(3065), $\Omega_c$(3090) and $\Omega_c$(3188) as P wave $\lambda$ excitation of ssc -quark states. We suggest a molecular interpretation for the $\Omega_c$ ( 3119) state, which was not observed by Belle.

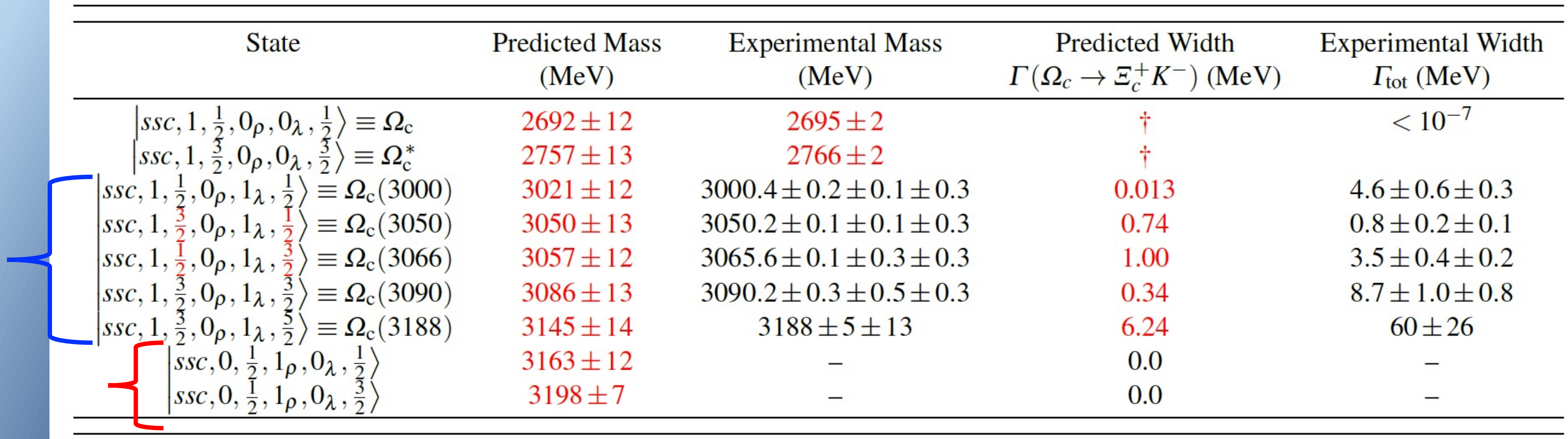


Our results are supported both from the predicted mass spectrum and from the decay width calculations.

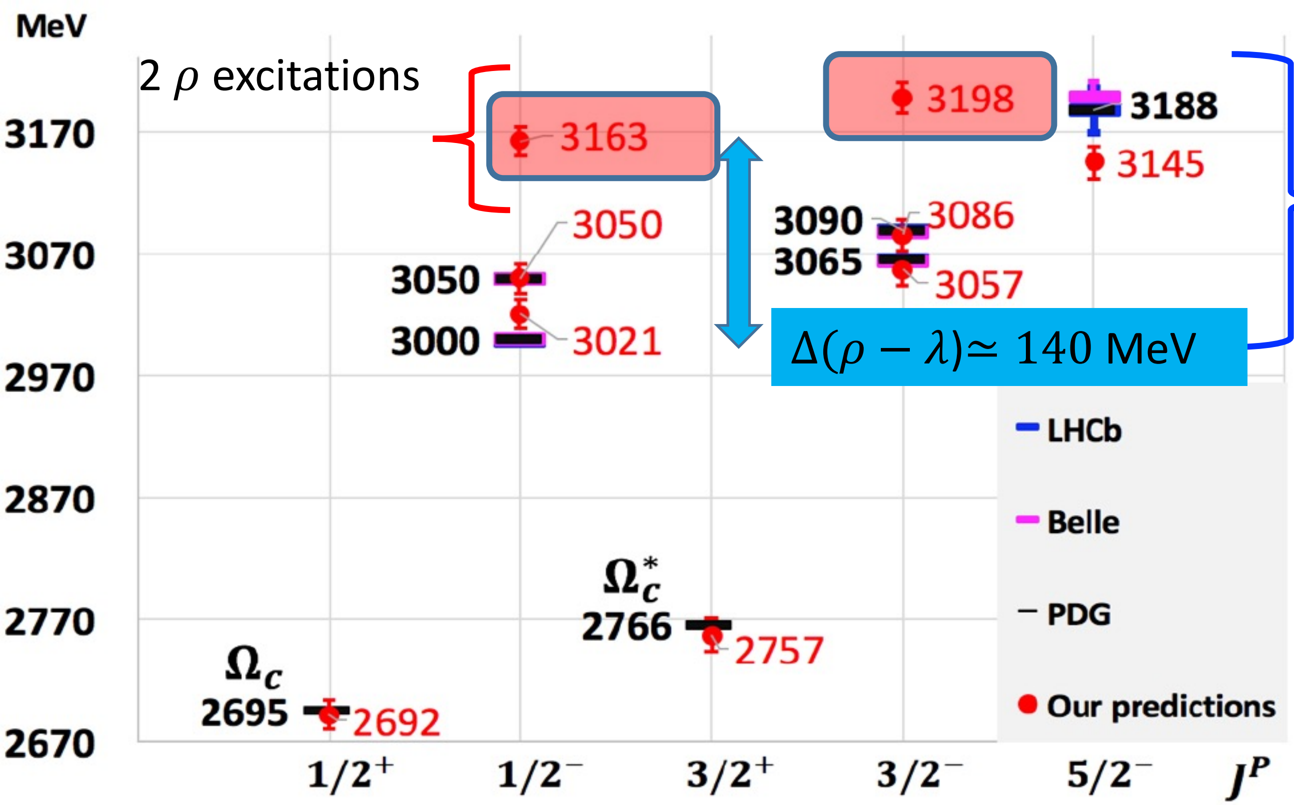


| State | Predicted Mass (MeV) | Experimental Mass (MeV) | Predicted Width $\Gamma(\Omega_c \to \Xi_c^+ K^-)$ (MeV) | Experimental Width $\Gamma_{\text{tot}}$ (MeV) |
|---|---|---|---|---|
| $\lvert ssc, 1, \frac{1}{2}, 0_\rho, 0_\lambda, \frac{1}{2}\rangle \equiv \Omega_c$ | $2692 \pm 12$ | $2695 \pm 2$ | † | $< 10^{-7}$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 0_\lambda, \frac{3}{2}\rangle \equiv \Omega_c^*$ | $2757 \pm 13$ | $2766 \pm 2$ | † | |
| $\lvert ssc, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{1}{2}\rangle \equiv \Omega_c(3000)$ | $3021 \pm 12$ | $3000.4 \pm 0.2 \pm 0.1 \pm 0.3$ | 0.013 | $4.6 \pm 0.6 \pm 0.3$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{1}{2}\rangle \equiv \Omega_c(3050)$ | $3050 \pm 13$ | $3050.2 \pm 0.1 \pm 0.1 \pm 0.3$ | 0.74 | $0.8 \pm 0.2 \pm 0.1$ |
| $\lvert ssc, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{3}{2}\rangle \equiv \Omega_c(3066)$ | $3057 \pm 12$ | $3065.6 \pm 0.1 \pm 0.3 \pm 0.3$ | 1.00 | $3.5 \pm 0.4 \pm 0.2$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{3}{2}\rangle \equiv \Omega_c(3090)$ | $3086 \pm 13$ | $3090.2 \pm 0.3 \pm 0.5 \pm 0.3$ | 0.34 | $8.7 \pm 1.0 \pm 0.8$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{5}{2}\rangle \equiv \Omega_c(3188)$ | $3145 \pm 14$ | $3188 \pm 5 \pm 13$ | 6.24 | $60 \pm 26$ |
| $\lvert ssc, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{1}{2}\rangle$ | $3163 \pm 12$ | – | 0.0 | – |
| $\lvert ssc, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{3}{2}\rangle$ | $3198 \pm 7$ | – | 0.0 | – |

[1] E. Santopinto, A. Giachino, J. Ferretti, H. García-Tecocoatzi, M. A. Bedolla, M R. Bijker, E. Ortiz-Pacheco, Eur.Phys.J.C 79 (2019) 12, 1012



| State | Predicted Mass (MeV) | Experimental Mass (MeV) | Predicted Width $\Gamma(\Omega_c \to \Xi_c^+ K^-)$ (MeV) | Experimental Width $\Gamma_{\text{tot}}$ (MeV) |
|---|---|---|---|---|
| $\lvert ssc, 1, \frac{1}{2}, 0_\rho, 0_\lambda, \frac{1}{2}\rangle \equiv \Omega_c$ | $2692 \pm 12$ | $2695 \pm 2$ | † | $< 10^{-7}$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 0_\lambda, \frac{3}{2}\rangle \equiv \Omega_c^*$ | $2757 \pm 13$ | $2766 \pm 2$ | † | |
| $\lvert ssc, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{1}{2}\rangle \equiv \Omega_c(3000)$ | $3021 \pm 12$ | $3000.4 \pm 0.2 \pm 0.1 \pm 0.3$ | 0.013 | $4.6 \pm 0.6 \pm 0.3$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{1}{2}\rangle \equiv \Omega_c(3050)$ | $3050 \pm 13$ | $3050.2 \pm 0.1 \pm 0.1 \pm 0.3$ | 0.74 | $0.8 \pm 0.2 \pm 0.1$ |
| $\lvert ssc, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{3}{2}\rangle \equiv \Omega_c(3066)$ | $3057 \pm 12$ | $3065.6 \pm 0.1 \pm 0.3 \pm 0.3$ | 1.00 | $3.5 \pm 0.4 \pm 0.2$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{3}{2}\rangle \equiv \Omega_c(3090)$ | $3086 \pm 13$ | $3090.2 \pm 0.3 \pm 0.5 \pm 0.3$ | 0.34 | $8.7 \pm 1.0 \pm 0.8$ |
| $\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{5}{2}\rangle \equiv \Omega_c(3188)$ | $3145 \pm 14$ | $3188 \pm 5 \pm 13$ | 6.24 | $60 \pm 26$ |
| $\lvert ssc, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{1}{2}\rangle$ | $3163 \pm 12$ | – | 0.0 | – |
| $\lvert ssc, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{3}{2}\rangle$ | $3198 \pm 7$ | – | 0.0 | – |



2 $\rho$ excitations

$\Delta(\rho - \lambda) \simeq 140$ MeV

5 $\lambda$ excitations which we identify with the 5 states observed

By calculating the mass splitting between the rho and lambda-mode excitations we provide the experimentalists a new and powerful tool capable to distinguish between three-quark and quark-diquark pictures of baryons

# Classification of ssQ states

A single quark is described by its spin, flavor, and color:

$S=\frac{1}{2}$ $F=3_F$ $C=3_C$

In order to construct an ssQ color singlet state, the light quarks must transform under SUc (3) as the anti-symmetric representation.

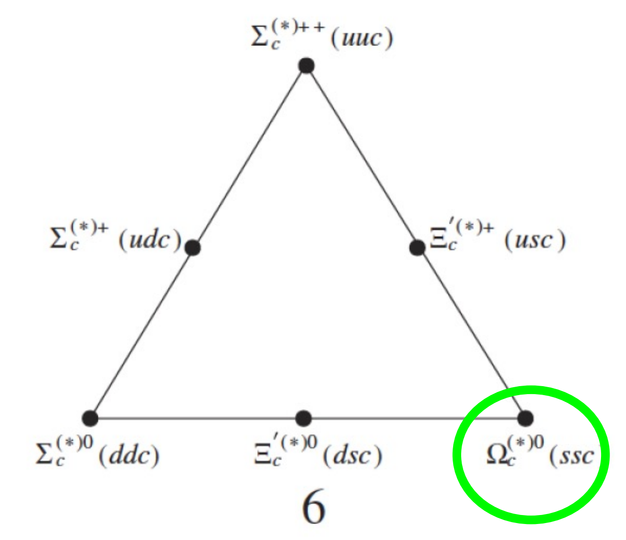
The Pauli principle postulates that the wave function of identical fermions must be anti-symmetric for particle exchange,thus, the ss spin-flavor and orbital wave functions have the same permutation symmetry: symmetric spin-flavor in S-wave or P_lambda , or antisymmetric spin-flavor in antisymmetric P_rho wave.

Two equal flavour quarks are necessarily in the $6_F$ flavor-symmetric state.

$$\mathbf{S}_{tot} = \mathbf{S}_\rho + \tfrac{1}{2}$$

$$\mathbf{J} = \mathbf{l}_\rho + \mathbf{l}_\lambda + \mathbf{S}_{tot}$$

$$|ssQ, \mathbf{S}_\rho, \mathbf{S}_{tot}, \mathbf{l}_\rho, \mathbf{l}_\lambda, \mathbf{J}\rangle$$



The two ground states with spin 1/2 and 3/2

$$|ssQ, 1, \tfrac{1}{2}, 0_\rho, 0_\lambda, \tfrac{1}{2}\rangle \equiv \Omega_Q$$
$$|ssQ, 1, \tfrac{3}{2}, 0_\rho, 0_\lambda, \tfrac{3}{2}\rangle \equiv \Omega_Q^*$$

The 5 $\lambda$ excitations

$$|ssc, 1, \tfrac{1}{2}, 0_\rho, 1_\lambda, \tfrac{1}{2}\rangle$$
$$|ssc, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{1}{2}\rangle$$
$$|ssc, 1, \tfrac{1}{2}, 0_\rho, 1_\lambda, \tfrac{3}{2}\rangle$$
$$|ssc, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{3}{2}\rangle$$
$$|ssc, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{5}{2}\rangle$$

The 2 $\rho$ excitations

$$|ssc, 0, \tfrac{1}{2}, 1_\rho, 0_\lambda, \tfrac{1}{2}\rangle$$
$$|ssc, 0, \tfrac{1}{2}, 1_\rho, 0_\lambda, \tfrac{3}{2}\rangle$$

We predicted spectrum and decay widths of the first $\Omega_b$ excitations six months before the observation by LHCb of $\Omega_b\,(6316), \Omega_b\,(6330), \Omega_b\,(6340)$ and $\Omega_b\,(6350)$ in $\Xi_b^0\,K^-$ channel (Phys.Rev.Lett. 124 (2020) 8, 082002)

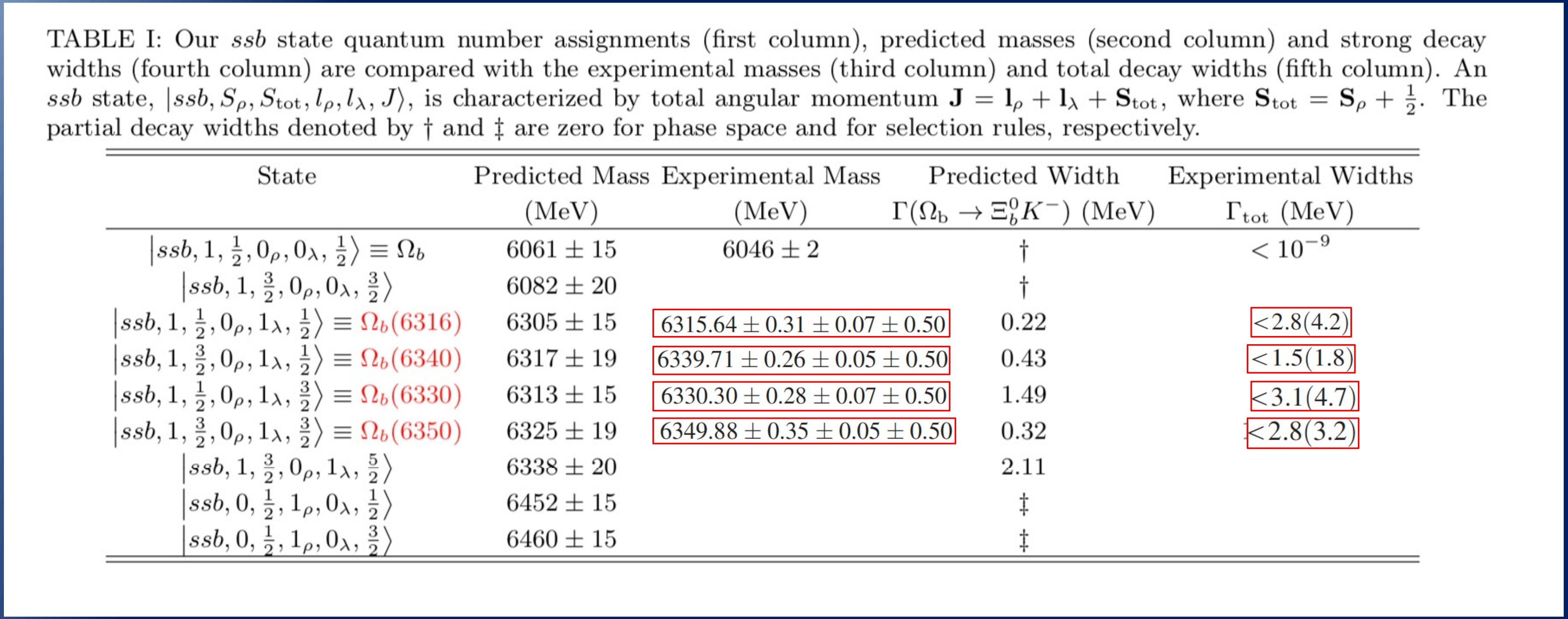


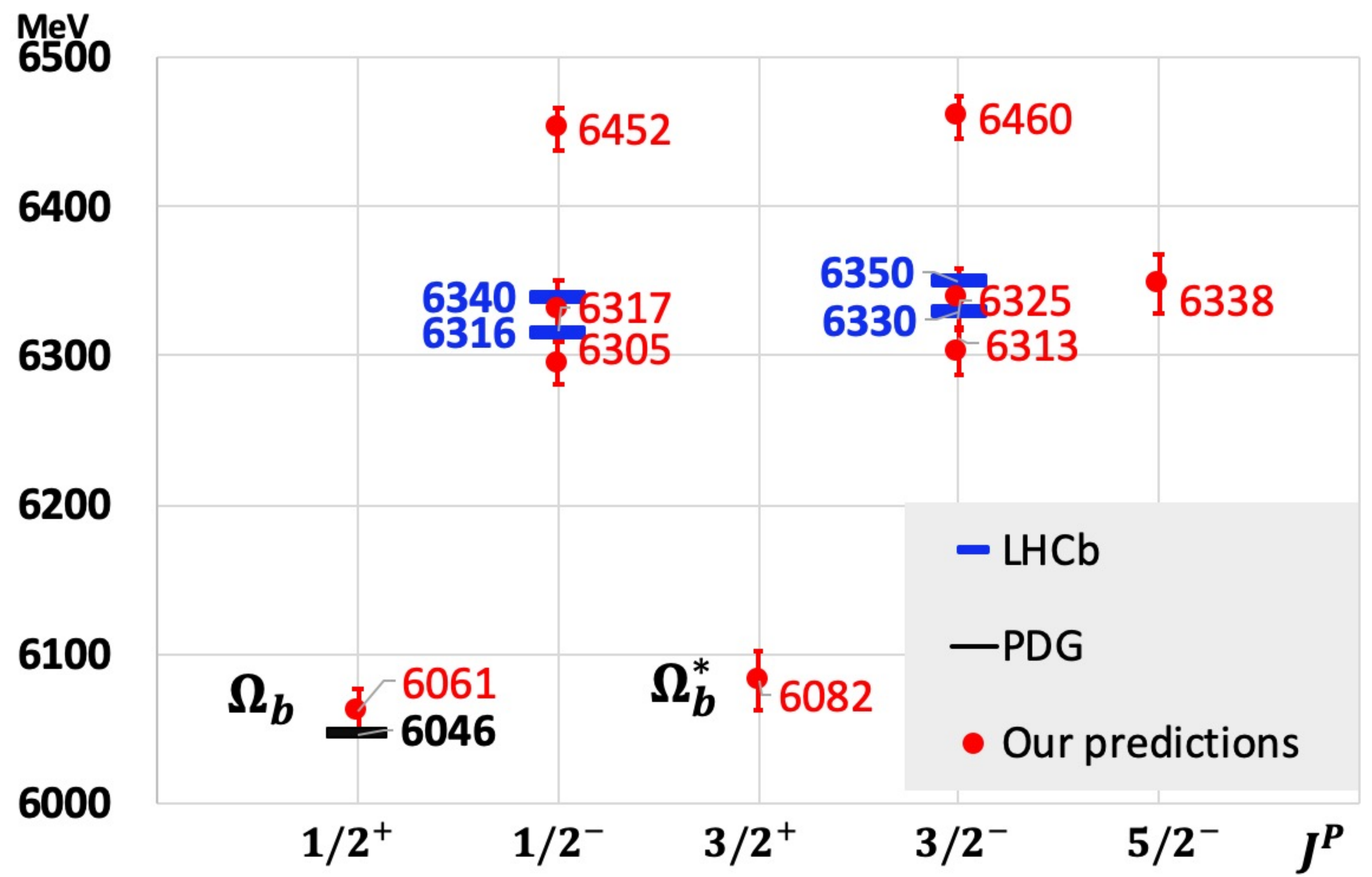
TABLE I: Our $ssb$ state quantum number assignments (first column), predicted masses (second column) and strong decay widths (fourth column) are compared with the experimental masses (third column) and total decay widths (fifth column). An $ssb$ state, $|ssb, S_\rho, S_{\rm tot}, l_\rho, l_\lambda, J\rangle$, is characterized by total angular momentum $\mathbf{J} = \mathbf{l}_\rho + \mathbf{l}_\lambda + \mathbf{S}_{\rm tot}$, where $\mathbf{S}_{\rm tot} = \mathbf{S}_\rho + \frac{1}{2}$. The partial decay widths denoted by † and ‡ are zero for phase space and for selection rules, respectively.

| State | Predicted Mass (MeV) | Experimental Mass (MeV) | Predicted Width $\Gamma(\Omega_b \to \Xi_b^0 K^-)$ (MeV) | Experimental Widths $\Gamma_{\rm tot}$ (MeV) |
|---|---|---|---|---|
| $\left\|ssb, 1, \frac{1}{2}, 0_\rho, 0_\lambda, \frac{1}{2}\right\rangle \equiv \Omega_b$ | $6061 \pm 15$ | $6046 \pm 2$ | † | $< 10^{-9}$ |
| $\left\|ssb, 1, \frac{3}{2}, 0_\rho, 0_\lambda, \frac{3}{2}\right\rangle$ | $6082 \pm 20$ | | † | |
| $\left\|ssb, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{1}{2}\right\rangle \equiv \Omega_b(6316)$ | $6305 \pm 15$ | $6315.64 \pm 0.31 \pm 0.07 \pm 0.50$ | 0.22 | $<2.8(4.2)$ |
| $\left\|ssb, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{1}{2}\right\rangle \equiv \Omega_b(6340)$ | $6317 \pm 19$ | $6339.71 \pm 0.26 \pm 0.05 \pm 0.50$ | 0.43 | $<1.5(1.8)$ |
| $\left\|ssb, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{3}{2}\right\rangle \equiv \Omega_b(6330)$ | $6313 \pm 15$ | $6330.30 \pm 0.28 \pm 0.07 \pm 0.50$ | 1.49 | $<3.1(4.7)$ |
| $\left\|ssb, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{3}{2}\right\rangle \equiv \Omega_b(6350)$ | $6325 \pm 19$ | $6349.88 \pm 0.35 \pm 0.05 \pm 0.50$ | 0.32 | $<2.8(3.2)$ |
| $\left\|ssb, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{5}{2}\right\rangle$ | $6338 \pm 20$ | | 2.11 | |
| $\left\|ssb, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{1}{2}\right\rangle$ | $6452 \pm 15$ | | ‡ | |
| $\left\|ssb, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{3}{2}\right\rangle$ | $6460 \pm 15$ | | ‡ | |

States in red are the four $\Omega_b$ excitations reported by LHCb

All the predicted decay widths are compabitble with experimental data and also the observed peaks are in well agreement with our predictions for excited $\Omega_b$ resonances.

The comparison between our mass predictions and the later observed $\Omega_b$ peaks is reported below:



The red states are our theoretical mass predictions and the blue states are the experimental masses of the four $\Omega_b$ excitations observed six month later by LHCb

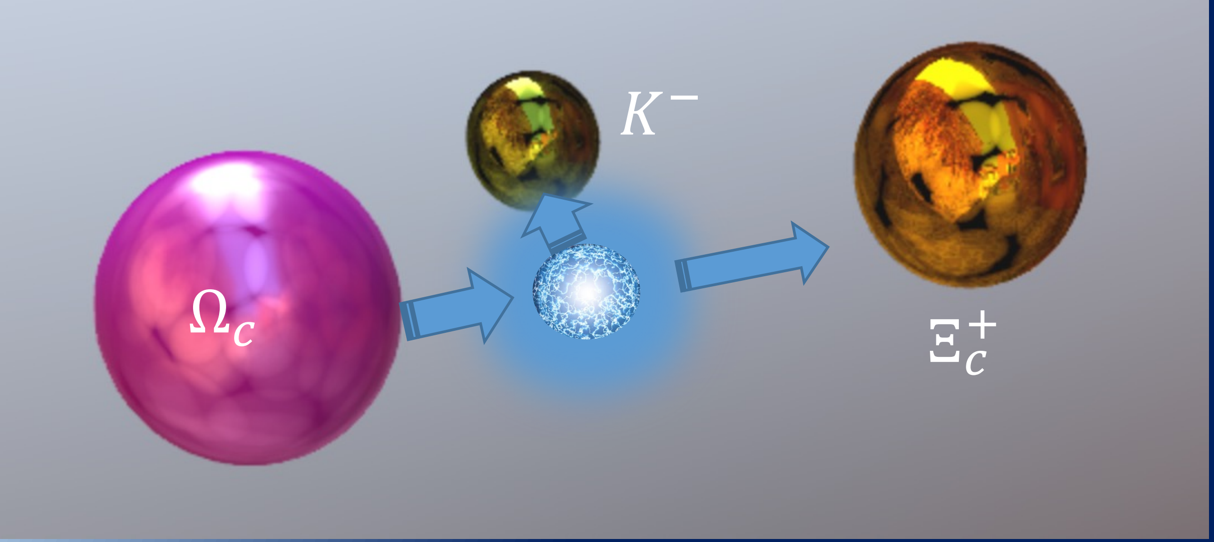
# The model

Harmonic Oscillator Hamiltonian plus a perturbation term given by **spin-orbit, spin, isospin and flavour-dependent contributions**

- The spin-orbit interaction, which is mysteriously small in light baryons [1,2], turns out to be fundamental to describe the heavy-light baryon mass patterns;

- The spin-, isospin-, and flavour-dependent interactions are necessary to reproduce the masses of charmed baryon ground states, as observed by E. S. and A. Giachino in Phys. Rev. D 96 , 014014 (2017).

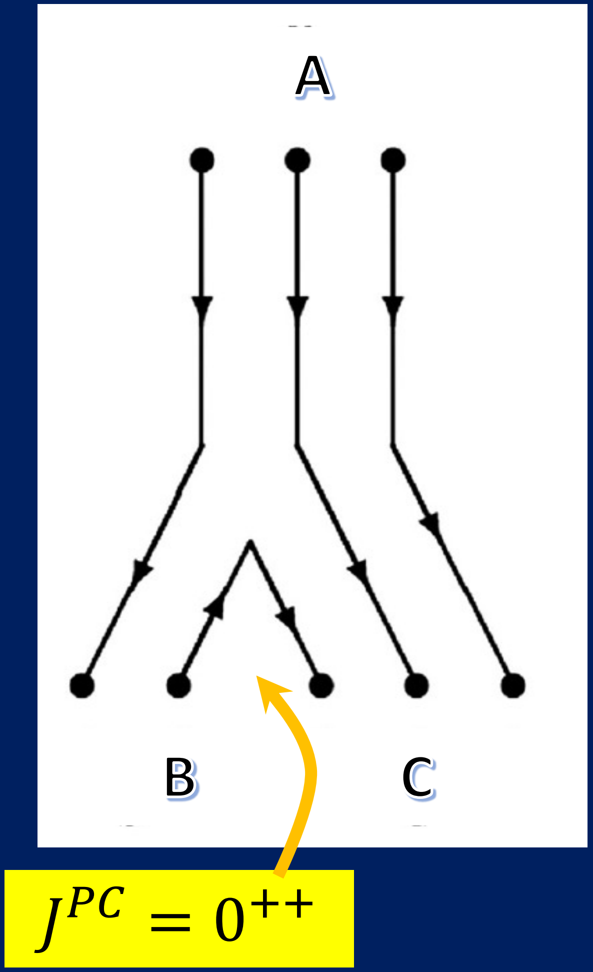
[1] S. Capstick and N. Isgur, Phys. Rev. D 34 , 2809 (1986).
[2] D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Lett. B 659 , 612 (2008).

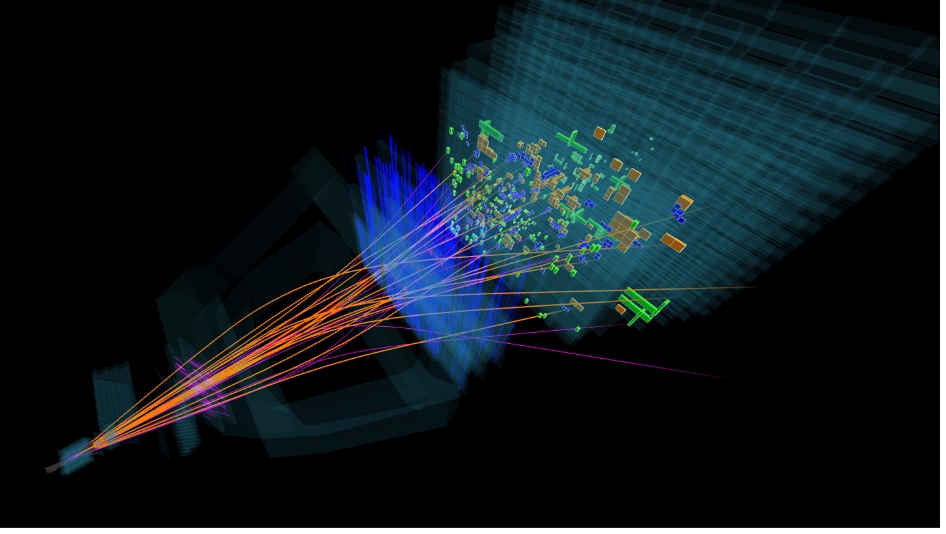


# Calculation of strong decay width in $\Xi_c^+ \, K^-$ channel

The 3P0 pair-creation is an effective model introduced by Micu in 1968 to describe the open-flavor strong decays (**Nucl.Phys. B10 (1969) 521-526** )

In this model a baryon decay proceeds via the creation of additional quark-antiquark pair from the QCD vacuum with the vacuum quantum numbers $J^{PC} = 0^{++}$





# Calculation of strong decay width in $\Xi_c^+ K^-$ channel

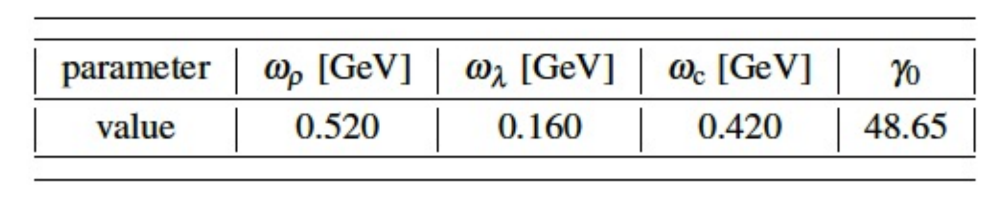
For a $A \rightarrow B + C$ decay process the final state, $B + C$ , is characterized by the relative orbital angular momentum between B and C, $l$, and a total angular momentum $J = J_B + J_C + l$

Final state momentum in A baryon reference system

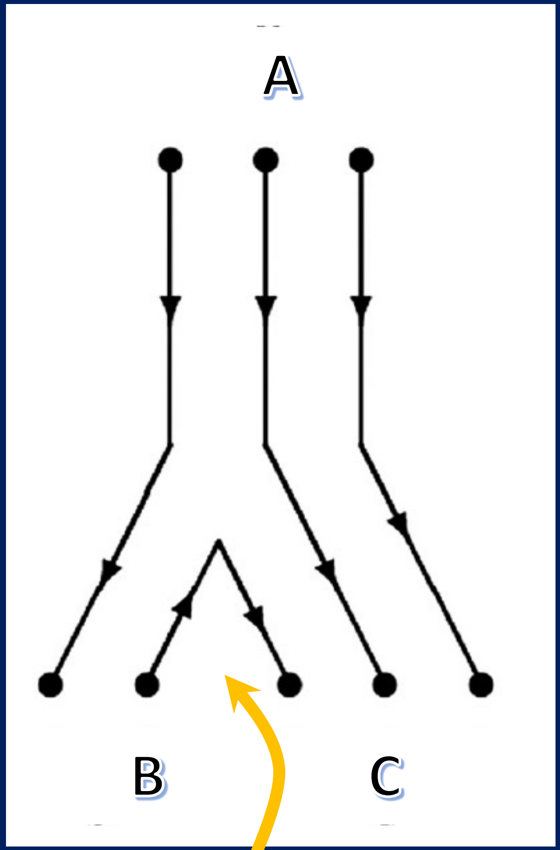
The decay amplitude can be expressed as:

$$\Gamma_{A\to BC} = \Phi_{A\to BC}(\boxed{q_0}) \sum \left|\langle BC \boxed{q_0}\, \ell J|\, T^\dagger\, |A\rangle\right|^2 .$$

We used harmonic oscillator wave Functions depending on two single oscillator parameters $\omega_\rho$ and $\omega_\lambda$ for baryons and on $\omega_c$ for mesons



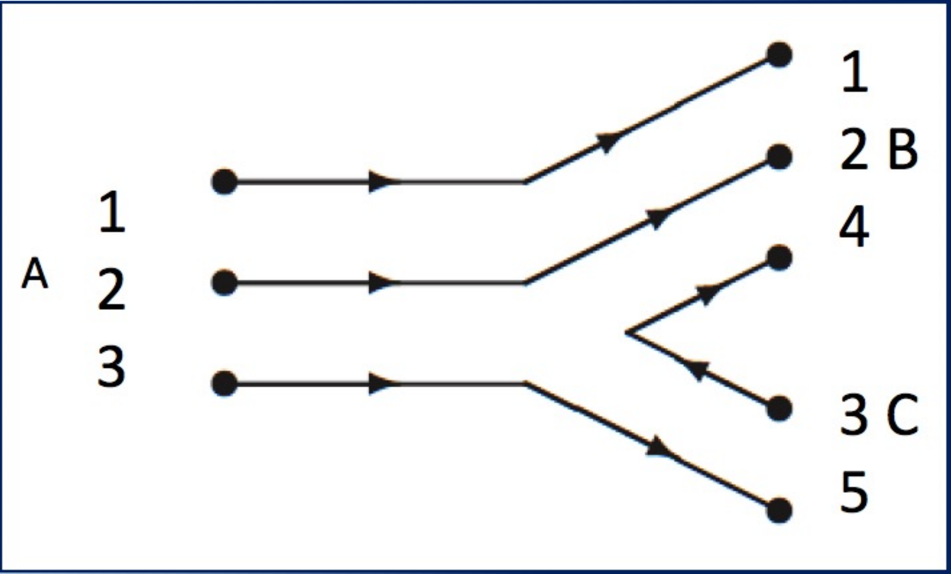
| parameter | $\omega_\rho$ [GeV] | $\omega_\lambda$ [GeV] | $\omega_c$ [GeV] | $\gamma_0$ |
|---|---|---|---|---|
| value | 0.520 | 0.160 | 0.420 | 48.65 |



$J^{PC} = 0^{++}$

[1] R. Bijker, J. Ferretti, G. Galatà, H. García Tecocoatzi E. Santopinto, **Phys.Rev. D94 (2016) no.7, 074040**

# Calculation of strong decay width in $\Xi_c^+ K^-$ channel



$$\Gamma_{A\to BC} = \Phi_{A\to BC}(q_0)\sum\left|\langle BC q_0\,\ell J|\,T^\dagger\,|A\rangle\right|^2 .$$

Relativistic phase space factor

$$\Phi_{A\to BC}(q_0) = 2\pi q_0 \frac{E_b(q_0)E_c(q_0)}{M_a} ,$$

Transition operator

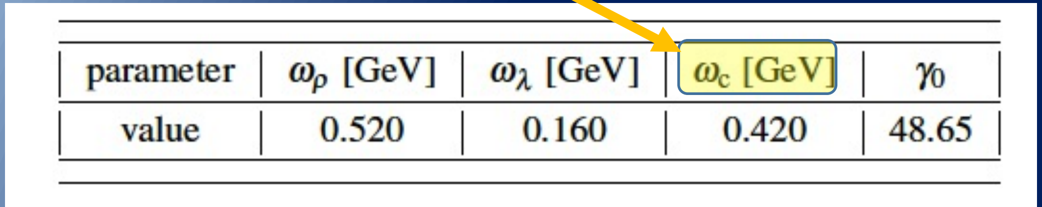
$$T^\dagger = -3\gamma_0\int d\vec{p}_4\, d\vec{p}_5\,\delta(\vec{p}_4+\vec{p}_5)\,C_{45}\,F_{45}\,V(\vec{p}_4-\vec{p}_5)\,[\chi_{45}\times\mathcal{Y}_1(\vec{p}_4-\vec{p}_5)]_0^{(0)}\,b_4^\dagger(\vec{p}_4)\,d_5^\dagger(\vec{p}_5)\ . \qquad (23)$$

- $\gamma_0 = 48.65$ is the pair-creation strength;
- $b^+(\vec{p}_4)$ and $d^+(\vec{p}_5)$ are the creation operators for a quark and an antiquark with momenta $\vec{p}_4$ and $\vec{p}_5$, respectively;
- The $q\,\bar{q}$ pair is characterized by a color-singlet wave function, $F_{45}$, a spin-triplet wave function $\chi_{45}$ with spin S = 1; and a solid spherical harmonic $\Upsilon_1(\vec{p}_4-\vec{p}_5)$ since the quark and antiquark are in a relative P –wave

- $V(\vec{p}_4-\vec{p}_5) = e^{-\alpha_d^2(\vec{p}_4-\vec{p}_5)^2/8}$ is the pair-creation vertex or quark form factor; in this work we used $\alpha_d = 0$.

# Calculation of strong decay width in $\Xi_c^+ K^-$ channel

From literature [1]

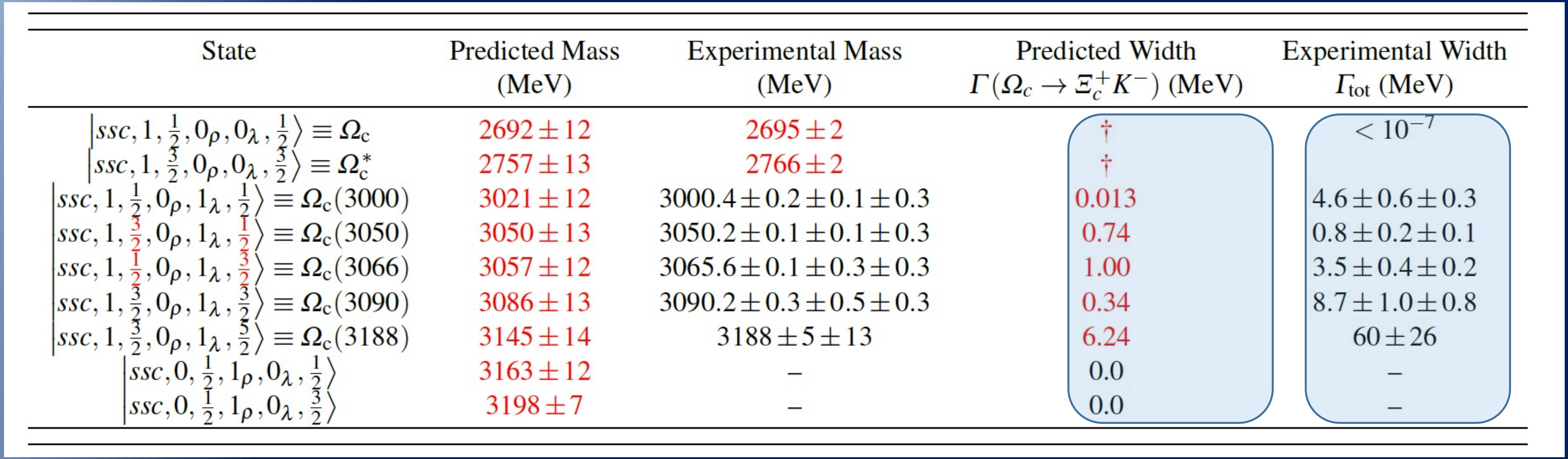


| parameter | $\omega_\rho$ [GeV] | $\omega_\lambda$ [GeV] | $\omega_c$ [GeV] | $\gamma_0$ |
|---|---|---|---|---|
| value | 0.520 | 0.160 | 0.420 | 48.65 |

As a check of the parameters used we calculate the decay width of $\Sigma_c$ in $\Lambda_c$ and pion and we could reproduce the experimental decay width (PDG):

$$\Gamma(\Sigma_c^{++} \to \Lambda_c^+ \pi^+) = 1.89^{+0.09}_{-0.18}\ \mathrm{MeV}$$

The decay width were calculated by using the experimental masses of the $\Omega_c$ states



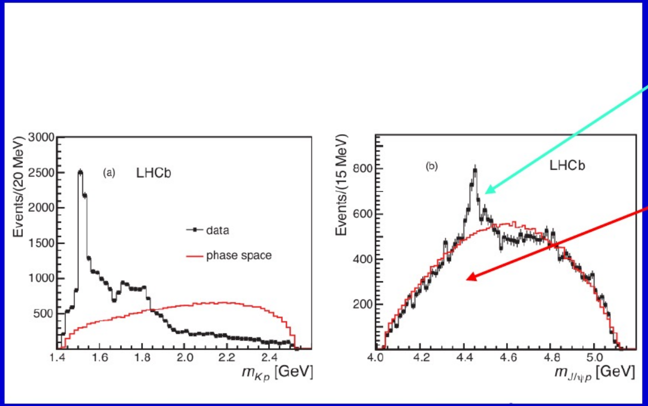
| State | Predicted Mass (MeV) | Experimental Mass (MeV) | Predicted Width $\Gamma(\Omega_c \to \Xi_c^+ K^-)$ (MeV) | Experimental Width $\Gamma_{\text{tot}}$ (MeV) |
|---|---|---|---|---|
| $\left\lvert ssc, 1, \frac{1}{2}, 0_\rho, 0_\lambda, \frac{1}{2} \right\rangle \equiv \Omega_c$ | $2692 \pm 12$ | $2695 \pm 2$ | † | $< 10^{-7}$ |
| $\left\lvert ssc, 1, \frac{3}{2}, 0_\rho, 0_\lambda, \frac{3}{2} \right\rangle \equiv \Omega_c^*$ | $2757 \pm 13$ | $2766 \pm 2$ | † | |
| $\left\lvert ssc, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{1}{2} \right\rangle \equiv \Omega_c(3000)$ | $3021 \pm 12$ | $3000.4 \pm 0.2 \pm 0.1 \pm 0.3$ | 0.013 | $4.6 \pm 0.6 \pm 0.3$ |
| $\left\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{1}{2} \right\rangle \equiv \Omega_c(3050)$ | $3050 \pm 13$ | $3050.2 \pm 0.1 \pm 0.1 \pm 0.3$ | 0.74 | $0.8 \pm 0.2 \pm 0.1$ |
| $\left\lvert ssc, 1, \frac{1}{2}, 0_\rho, 1_\lambda, \frac{3}{2} \right\rangle \equiv \Omega_c(3066)$ | $3057 \pm 12$ | $3065.6 \pm 0.1 \pm 0.3 \pm 0.3$ | 1.00 | $3.5 \pm 0.4 \pm 0.2$ |
| $\left\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{3}{2} \right\rangle \equiv \Omega_c(3090)$ | $3086 \pm 13$ | $3090.2 \pm 0.3 \pm 0.5 \pm 0.3$ | 0.34 | $8.7 \pm 1.0 \pm 0.8$ |
| $\left\lvert ssc, 1, \frac{3}{2}, 0_\rho, 1_\lambda, \frac{5}{2} \right\rangle \equiv \Omega_c(3188)$ | $3145 \pm 14$ | $3188 \pm 5 \pm 13$ | 6.24 | $60 \pm 26$ |
| $\left\lvert ssc, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{1}{2} \right\rangle$ | $3163 \pm 12$ | – | 0.0 | – |
| $\left\lvert ssc, 0, \frac{1}{2}, 1_\rho, 0_\lambda, \frac{3}{2} \right\rangle$ | $3198 \pm 7$ | – | 0.0 | – |

the predicted partial decay amplitudes are all lower than the total measured decay widths so our results are compatible with experimental data.

[1] C. Chen, X. L. Chen, X. Liu,W. Z. Deng and S. L. Zhu, Phys. Rev. D 75 , 094017 (2007).

# Experimental background

**LHCb**
**Phys. Rev. Lett.115(2015) 072001**



M _$P_c^+$(4450) = (4449.8 ± 8 ± 29)MeV
Γ = (39 ± 5 ± 19) MeV

M_$P_c^+$(4380) = (4380 ± 1.7 ± 2.5)MeV

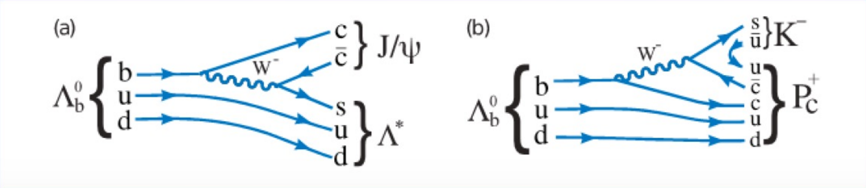
Γ =(205±18±86 )MeV

**statistic significance greater then 9 sigma !**

$P_c\ (uudc\bar{c})$

$$\Lambda_b^0 \longrightarrow J/\psi + \Lambda^*, \Lambda^* \longrightarrow K^- + p$$

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



The LHCb observation [1] was further supported by another two articles by the same group [2,3]:

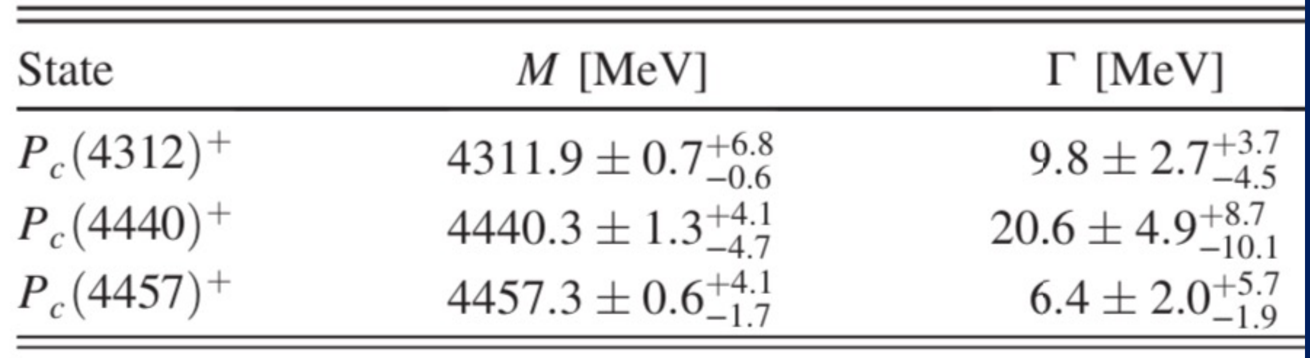
[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001
[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082002
[3] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **117** (2016) no.8, 082003

# Why pentaquark states?

## Experimental background

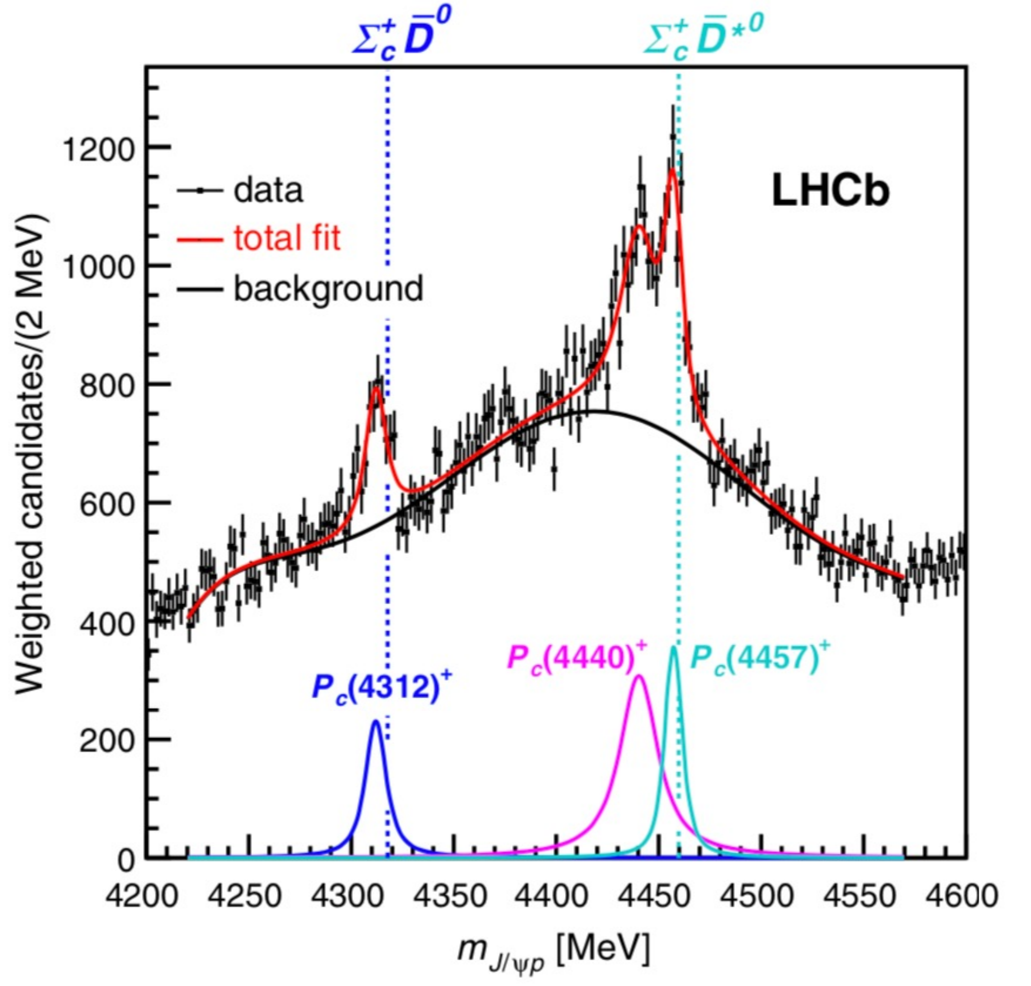
**As well as revealing the new $P_c(4312)$ state, the LHCb 2019 analysis also uncovered a more complex structure of $P_c(4450)$, consisting of two narrow nearby separate peaks, $P_c(4440)$ and $P_c(4457)$ with the two-peak structure hypothesis having a statistical significance of 5.4 sigma with respect to the single-peak structure hypothesis.**

The masses and widths of the three narrow pentaquark states are as follows



| State | $M$ [MeV] | $\Gamma$ [MeV] |
|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+3.7}_{-4.5}$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+8.7}_{-10.1}$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+5.7}_{-1.9}$ |

[*] R. Aaij et al. (LHCb), Phys. Rev. Lett. 122, 222001 (2019).

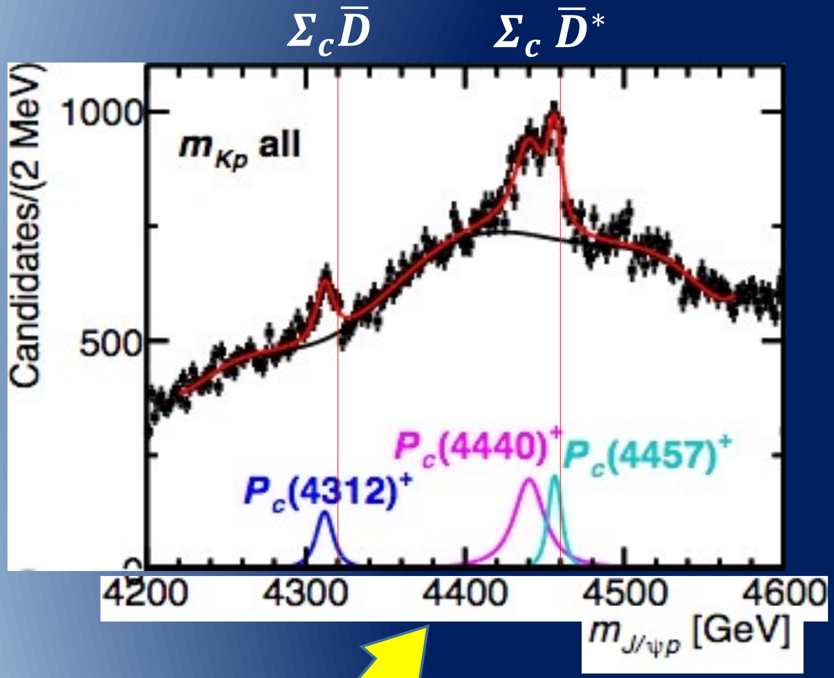


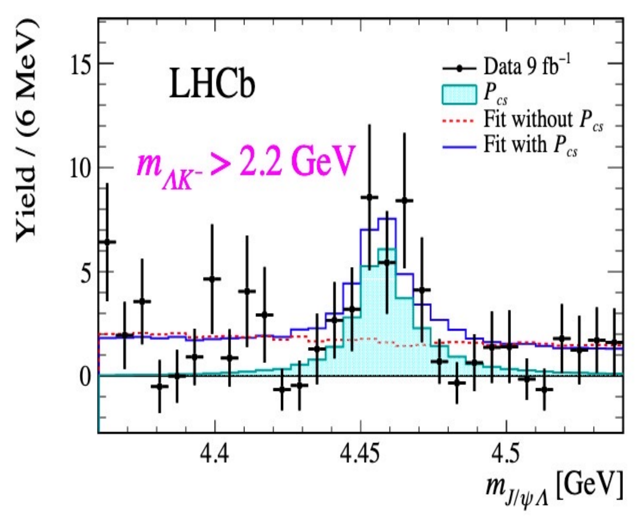
Number of events versus J/Psi p invariant mass [*]. The mass thresholds for the $\Sigma_c \bar{D}$ and $\Sigma_c \bar{D}^*$ final states are superimposed.

# 2021 Experimental background

▷ $P_c$ $(\boldsymbol{uudc\bar{c}})$, $P_{cs}$ $(\boldsymbol{udsc\bar{c}})$

LHCb PRL**115**(2015)072001, PRL**122**(2019)222001, (2021) LHCb, arXiv: 2012.10380





Significance of $\boldsymbol{P^0_{cs}(4459)}$ exceeds 3 $\sigma$ after considering all the systematic uncertainties.

New narrow $P_c(4312)^+$ observed in 2019 at LHCb, $P_c(4450)^+$ is resolved to two states. (with 10 times statistics)

Mass of $P_{cs}(4459)^0$ 19 MeV below the $\Xi_c^0\bar{D}^{*0}$ threshold, similar to $P_c(4440)^+$ and $P_c(4457)^+$ pentaquark states.

# Heavy Quark Spin Symmetry with Chiral Tensor Dynamics in the Light of the Recent LHCb Pentaquarks

In Refs. [1] , [2] we studied the hidden-charm pentaquarks by coupling the $\Lambda_c \bar{D}^{(*)}$ and $\Sigma_c^*$ $\bar{D}^{(*)}$ meson-baryon channels to a $uudc\bar{c}$ compact core with a meson-baryon binding interaction satisfying the heavy quark and chiral symmetries. This studies followed two previous investigations of the pentaquark states thought as purely $uudc\bar{c}$ five quark states [3] and as meson-baryon molecules in a coupled channel approach [4].

The predicted pentaquark masses and widths are consistent with the new data by LHCb [*] with the following quantum number assignments: $J^P\left(P_c(4312)\right) = \frac{1}{2}^-$ , $J^P\left(P_c(4440)\right) = \frac{3}{2}^-$ and $J^P\left(P_c(4457)\right) = \frac{1}{2}^-$.

We find that the dominant components of these states are the nearby threshold channels: $P_c(4312)$ is dominated by $\Sigma_c \bar{D}$ , $P_c(4440)$ and $P_c(4457)$ are both dominated by $\Sigma_c \bar{D}^*$

**[*]** R. Aaij *et al.* (LHCb Collaboration) Phys. Rev. Lett. **122**, 22200

**[1]** Y.Yamaguchi, H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, Phys.Rev.D **101** (2020) 091502(R)

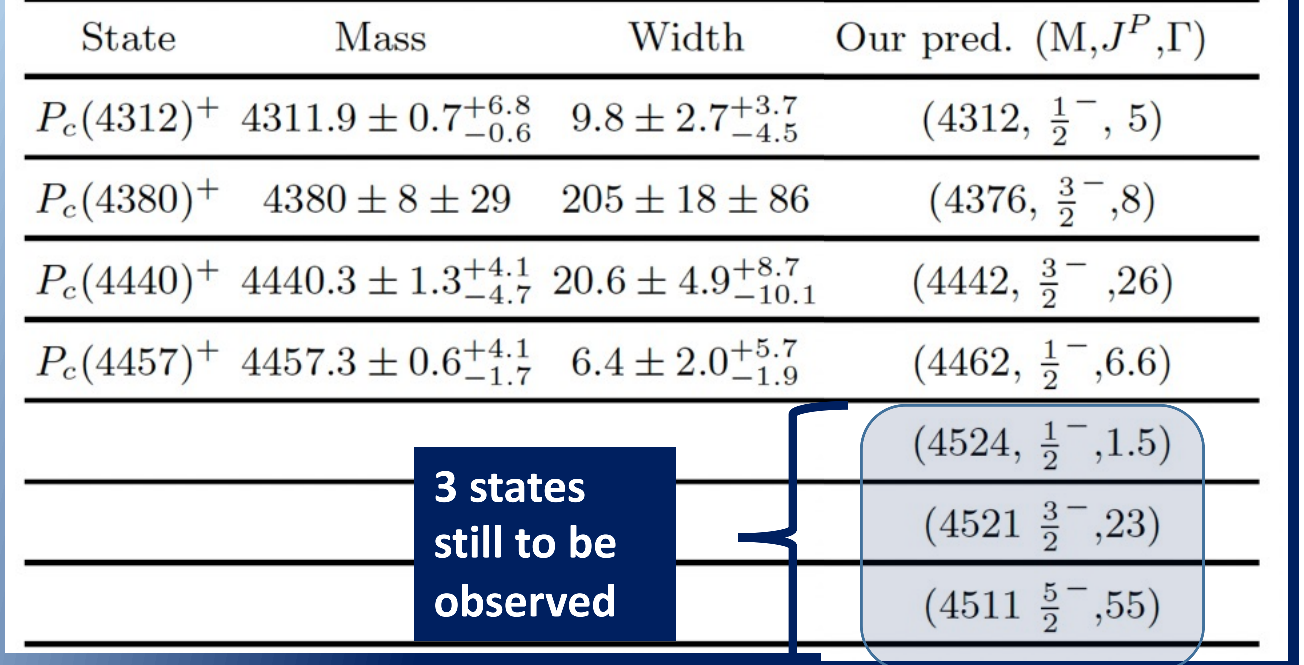
**[2]** Y.Yamaguchi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, PRD **96** (2017) 114031(R) Phys.Rev. **D96** (2017**)** 114031

**[3]** E. Santopinto and A. Giachino in Phys. Rev. D 96 , 014014 (2017)

**[4]** Y. Yamaguchi and E. Santopinto Phys.Rev.D 96 (2017) 1, 014018

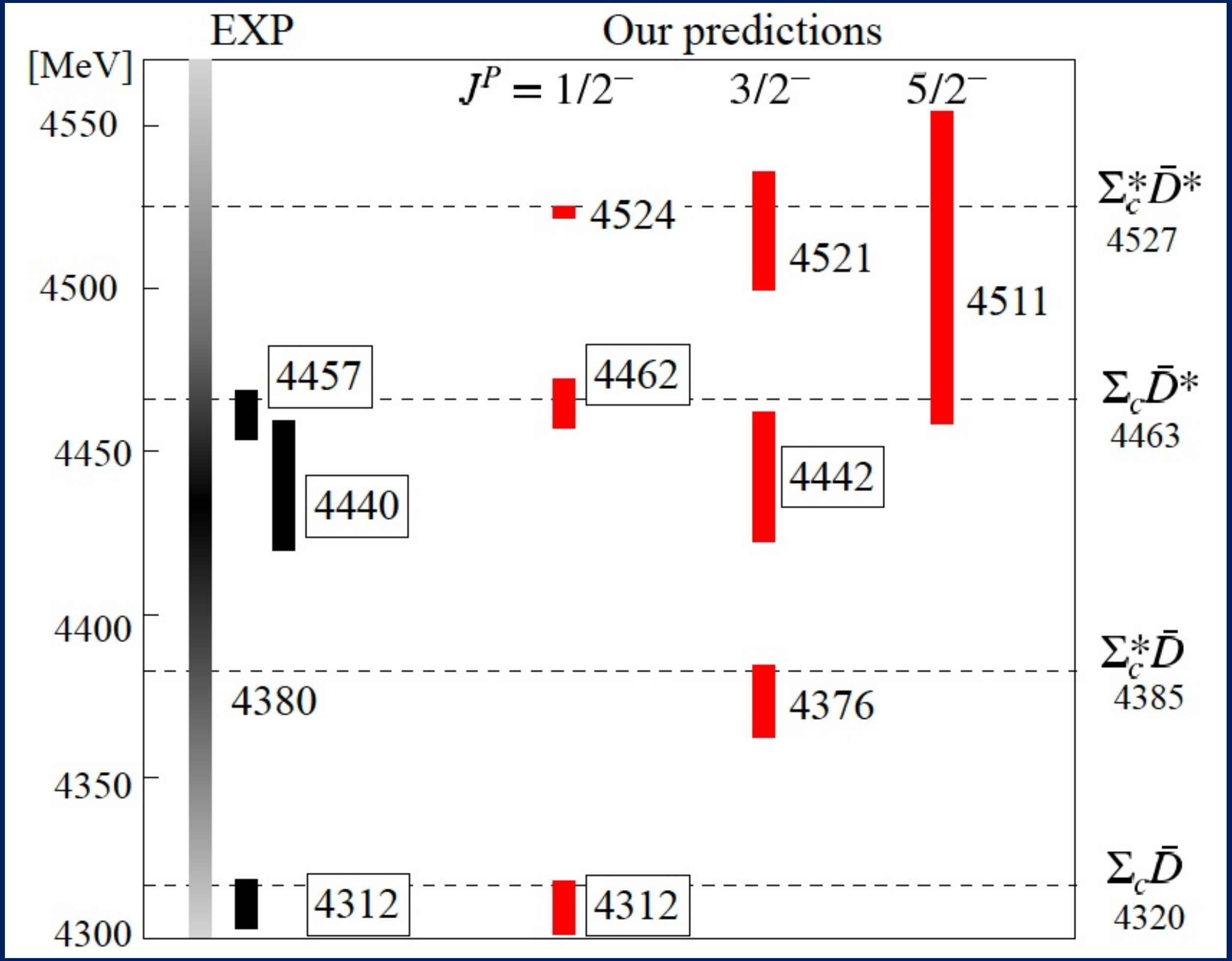
# results

Y. Yamaguchi, H. Garcia-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi and M. Takizawa Phys.Rev.D **101** (2020) 091502 (R)



| State | Mass | Width | Our pred. (M,$J^P$,Γ) |
|---|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+3.7}_{-4.5}$ | (4312, $\frac{1}{2}^-$, 5) |
| $P_c(4380)^+$ | $4380 \pm 8 \pm 29$ | $205 \pm 18 \pm 86$ | (4376, $\frac{3}{2}^-$,8) |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+8.7}_{-10.1}$ | (4442, $\frac{3}{2}^-$ ,26) |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+5.7}_{-1.9}$ | (4462, $\frac{1}{2}^-$,6.6) |
| | | | (4524, $\frac{1}{2}^-$,1.5) |
| | | | (4521 $\frac{3}{2}^-$,23) |
| | | | (4511 $\frac{5}{2}^-$,55) |

**3 states still to be observed**



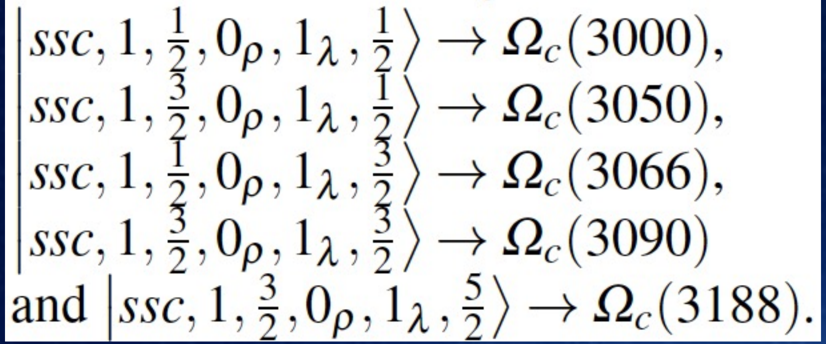
**agreement with the experimental masses and decay widths**

**Cited by PDG2020!** Togheter with Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, PRD **96** (2017) 114031.

# CONCLUSION

- We calculated the $\Omega_c$ masses and $\Xi_c^+ K^-$ strong decay widths in a parameter-free way, with the exception of $\Omega_c(3000)$ which was used to set the harmonic oscillator scale.

- By means of these mass and decay width predictions, we proposed an univocal assignment to the five $\Omega_c$ states observed both by LHCb and Belle



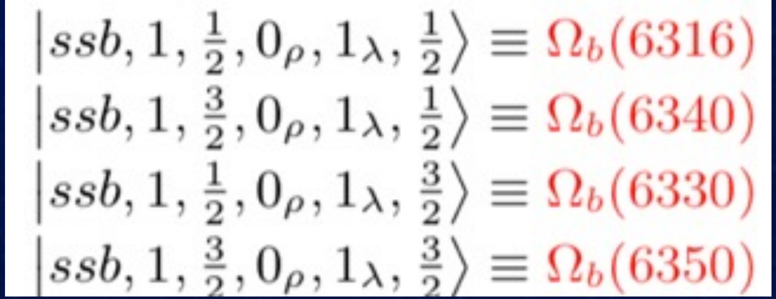
$$\begin{aligned}
&\left|ssc, 1, \tfrac{1}{2}, 0_\rho, 1_\lambda, \tfrac{1}{2}\right\rangle \rightarrow \Omega_c(3000),\\
&\left|ssc, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{1}{2}\right\rangle \rightarrow \Omega_c(3050),\\
&\left|ssc, 1, \tfrac{1}{2}, 0_\rho, 1_\lambda, \tfrac{3}{2}\right\rangle \rightarrow \Omega_c(3066),\\
&\left|ssc, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{3}{2}\right\rangle \rightarrow \Omega_c(3090)\\
&\text{and } \left|ssc, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{5}{2}\right\rangle \rightarrow \Omega_c(3188).
\end{aligned}$$

and we suggest a molecular interpretation of the $\Omega_c$ ( 3119) state, which was not observed by Belle.

- We calculated the mass splitting between the $\rho$ and $\lambda$ mode excitations of the $\Omega_c$ resonances, about 150 MeV; this large mass difference between these two excitation modes could be the key to access the nature of the effective degrees of freedom involved in heavy-light baryon spectroscopy

# CONCLUSION

- We predicted spectrum and decay widths of the first $\Omega_b$ excitations six months before the observation by LHCb $\Omega_b\,(6316), \Omega_b\,(6330), \Omega_b\,(6340)$ and $\Omega_b\,(6350)$



$$\left|ssb, 1, \tfrac{1}{2}, 0_\rho, 1_\lambda, \tfrac{1}{2}\right\rangle \equiv \Omega_b(6316)$$
$$\left|ssb, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{1}{2}\right\rangle \equiv \Omega_b(6340)$$
$$\left|ssb, 1, \tfrac{1}{2}, 0_\rho, 1_\lambda, \tfrac{3}{2}\right\rangle \equiv \Omega_b(6330)$$
$$\left|ssb, 1, \tfrac{3}{2}, 0_\rho, 1_\lambda, \tfrac{3}{2}\right\rangle \equiv \Omega_b(6350)$$

- We studied the hidden-charm pentaquarks by coupling the $\Lambda_c\overline{D}^{(*)}$ and $\Sigma_c^*\,\overline{D}^{(*)}$ meson-baryon channels to a $uudc\bar{c}$ compact core with a meson-baryon binding interaction satisfying the heavy quark and chiral symmetries; the predicted pentaquark masses and widths are consistent with the new data by LHCb with the following quantum number assignments: $J^P\big(P_c(4312)\big) = \frac{1}{2}^-$, $J^P\big(P_c(4440)\big) = \frac{3}{2}^-$ and $J^P\big(P_c(4457)\big) = \frac{1}{2}^-$.

*Thanks for your attention*