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Ω_c excited states with heavy-quark spin symmetry

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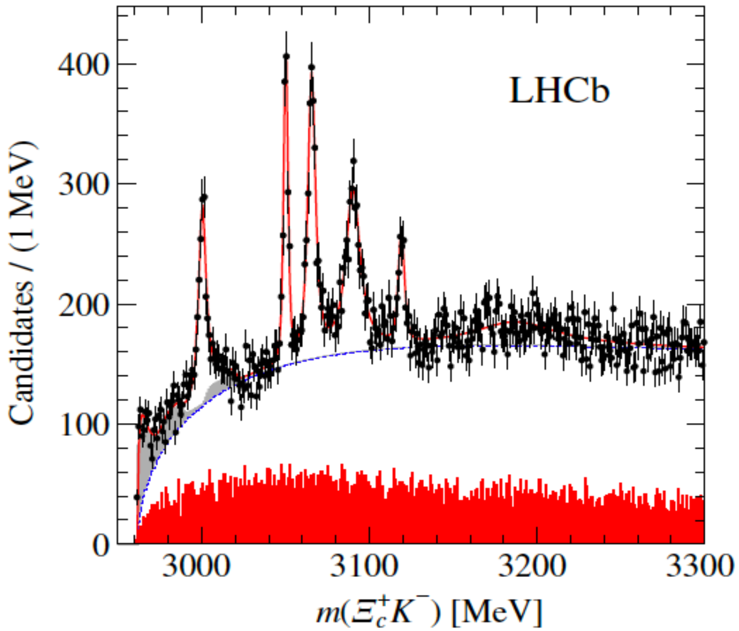
Experimental scenario and theoretical predictions

- five Ω_c with masses between 3 and 3.1 GeV are detected by LHCb analyzing the $\Xi^+_c K^-$ spectrum in pp collisions   Aaij et al '17
- four of them are seen by Belle in $e^- e^+$ collisions   Yelton et al '18



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$
$\Omega_c(3066)^0_{fd}$		
$\Omega_c(3090)^0_{fd}$		
$\Omega_c(3119)^0_{fd}$		

Aaij et al '17

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)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	-	$3199 \pm 9 \pm 4$

Yelton et al '18

Earlier predictions were reported within different approaches, but this discovery has triggered a large activity revisiting conventional quark models, QCD sum-rule schemes, quark-soliton models, lattice QCD and **molecular models**.
Some recent examples of molecular models are:

Montana, Feijoo and Ramos '18

- t-channel vector meson exchange between $1/2^+$ baryons and $0^-,1^-$ mesons
- two states with $J=1/2^-$ identified with $\Omega_c(3050)$ and $\Omega_c(3090)$

Debastiani, Dias, Liang and Oset '18

- local hidden gauge model with $1/2^+,3/2^+$ baryons and $0^-,1^-$ vector mesons
- two states with $J=1/2^-$ identified with $\Omega_c(3050)$ and $\Omega_c(3090)$, and one state $J=3/2^-$ identified with $\Omega_c(3119)$

Wang, Liu, Kang and Guo '18

identification of $1/2^-$ $\Omega_c(3118)$ as superposition of two $D\Xi$ states

Chen, Liu, Hosaka '18

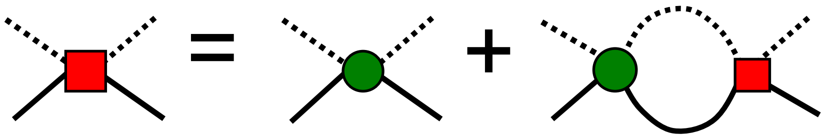
prediction of $3/2^-$ $\Omega_c(3140)$ loosely bound state with large $\Xi^*_c\bar{K}$ component

Our molecular model

Romanets, LT, Garcia-Recio, Nieves, Salcedo, Timmermans '12
Nieves, Pavao and LT '18

unitarized coupled-channel model with a $SU(6)_{lsf}$ x HQSS - extended WT meson-baryon interaction

$$V = \frac{K(s)}{4f^2} H_{WT}$$



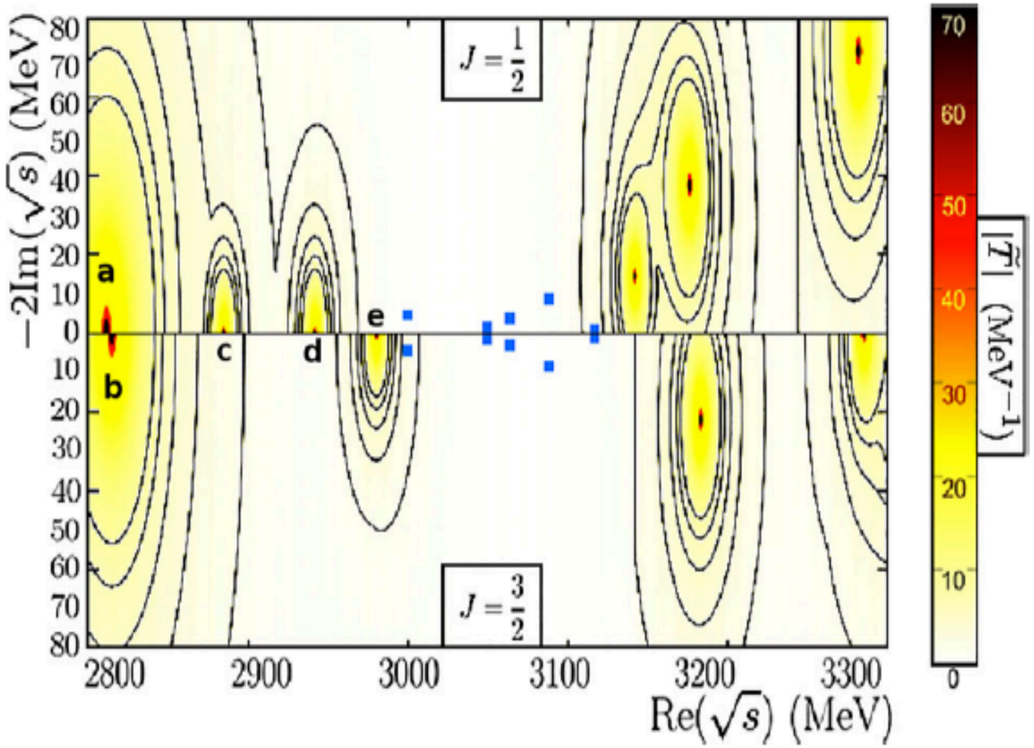
$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

coupling constant

$$T_{ij}(s) \simeq \frac{g_i g_j}{\sqrt{s} - \sqrt{s_R}}$$

mass and width

G_{ij} regularized with one subtraction at certain scale



Ω_c : C=1, S=-2, I=0

Name	M_R (MeV)	Γ_R (MeV)	J
a	2810.9	0	1/2
b	2814.3	0	3/2
c	2884.5	0	1/2
d	2941.6	0	1/2
e	2980.0	0	3/2

Regularization schemes (RS) of the loop function

$$G_i(s) = i2M_i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_i^2 + i\epsilon} \frac{1}{(P-q)^2 - M_i^2 + i\epsilon}$$

$$G_i(s) = \overline{G}_i(s) + G_i(s_{i+}) \quad \text{with} \quad s_{i+} = (m_i + M_i)^2$$

One-subtraction regularization
(one subtraction at certain scale)

$$G_i(\sqrt{s} = \mu) = 0$$

$$G_i^{\mu}(s) = \overline{G}_i(s) - \overline{G}_i(\mu^2)$$

Common cutoff regularization
(use of a common UV cutoff)

$$G_i^{\Lambda}(s) = \overline{G}_i(s) + G_i^{\Lambda}(s_{i+})$$

Note that using channel-dependent cutoffs, the one-subtraction regularization scheme is recovered by choosing Λ_i in each cannel such that

$$G_i^{\Lambda_i}(s_{i+}) = -\overline{G}_i(\mu^2)$$

One-subraction regularization scheme

$$\mu = \sqrt{\alpha \left(m_{th}^2 + M_{th}^2\right)}$$

- for $\alpha=1$, all masses are below 3 GeV, so no identification with LHCb resonances is possible

- for $\alpha=1.16$, two poles are located close to two experimental resonances: $\Omega_c(3000)$ with dominant $\Xi_c\bar{K}$ component and $\Omega_c(3050)$ with dominant $\Xi^*_c\bar{K}$ one (reconciled with experiment allowing for $\Xi^*_c\bar{K} \to \Xi_c\bar{K}$ d-wave transition)

- we need to explore the impact of different RS in a control manner: employ common UV cutoff within reasonable limits

$\alpha=1$

Name	M_R (MeV)	Γ_R (MeV)	J
a	2810.9	0	1/2
b	2814.3	0	3/2
c	2884.5	0	1/2
d	2941.6	0	1/2
e	2980.0	0	3/2

$\alpha=1.16$

Name	M_R (MeV)	Γ_R (MeV)	J	M_R^{exp}	Γ_R^{exp}
a	2922.2	0	1/2	–	–
b	2928.1	0	3/2	–	–
c	2941.3	0	1/2	–	–
d	2999.9	0.06	1/2	3000.4	4.5
e	3036.3	0	3/2	3050.2	0.8

Common cutoff regularization scheme

first we determine how masses (and widths) of the states change as we adiabatically vary the subtraction constants

$$G_i(s) = \overline{G}_i(s) - (1-x)\overline{G}_i(\mu^2) + xG_i^{\Lambda}(s_{i+})$$

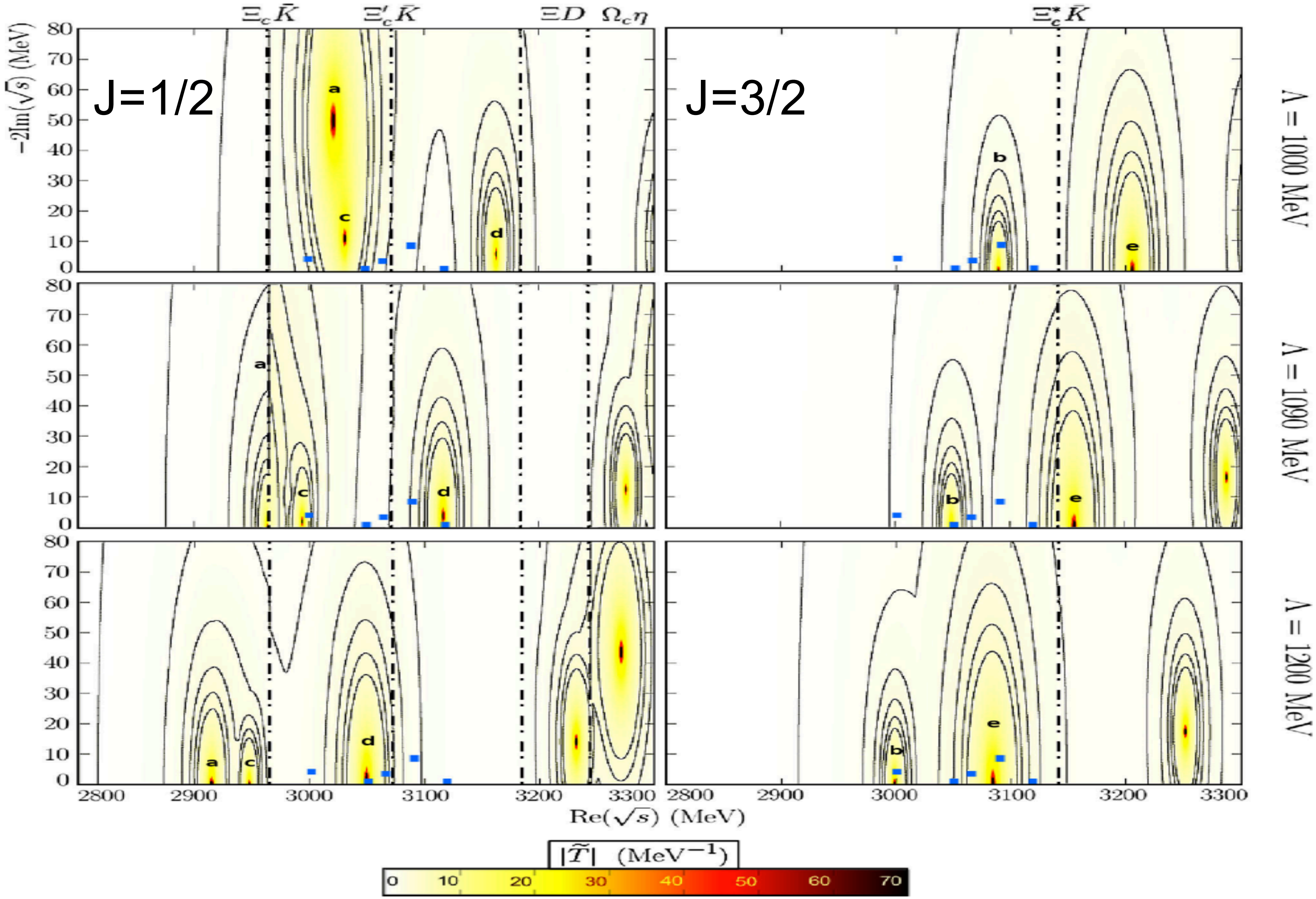
$$x \ \text{ changes from } 0 \text{ to } 1$$

- two $J=1/2^-$ and one $J=3/2^-$ can be identified with three experimental states due to closeness in energy and also because of the important contribution of $\Xi'_c\bar{K}$, $\Xi_c\bar{K}$ (note that couple predominantly to $\Xi'_c\bar{K}$, ΞD and $\Xi^*_c\bar{K}$, respectively).

- need to assess the cutoff dependence of our results

$\Lambda = 1090$ MeV

Name	M_R (MeV)	Γ_R (MeV)	J	M_R^{exp}	Γ_R^{exp}
a	2963.95	0.0	1/2	–	–
c	2994.26	1.85	1/2	3000.4	4.5
b	3048.7	0.0	3/2	3050.2	0.8
d	3116.81	3.72	1/2	3119.1/ 3090.2	1.1/ 8.7
e	3155.37	0.17	3/2	–	–



- for Λ<1000 MeV or Λ>1300 MeV no identification is possible
- a maximum number of three states can be identified

Comparison with other recent molecular models

Montana, Feijoo and Ramos '18

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our model identifies $J=1/2^-$ $\Omega_c(3000)$, $\Omega_c(3119/3090)$ and $J=3/2^-$ $\Omega_c(3050)$ for $\Lambda=1090$ MeV due to a different regularization scheme and different interaction matrices (in particular for D, D* and light vector mesons)

Wang, Liu, Kang and Guo '18

identification of $1/2^-$ $\Omega_c(3118)$ as superposition of two Ξ D states

Chen, Liu, Hosaka '18

prediction of $3/2^-$ $\Omega_c(3140)$ loosely bound state with large $\Xi^*_c\bar{K}$ component

no identification is possible in our model: $\Omega_c(3118)$ comes from less attractive representation and $\Omega_c(3140)$ is not seen as we incorporate $\Xi^{(*)}$ $D^{(*)}$

Summary

- We study the C=1, S=-2, I=0 sector, where five Ω_c with masses between 3 and 3.1 GeV have been observed by the LHCb (four corroborated by Belle), using a unitarized coupled-channel approach with a $SU(6)_{lsf}$xHQSS - extended WT meson-baryon interaction.

- We analyze two different regularization schemes: one-subtraction regularization and cutoff regularization

- We find that a maximum of three Ω_c with energies between 3 and 3.1 GeV can be identified experimentally. In particular, for Λ=1090 MeV we find $J=1/2^-$ $\Omega_c(3000)$, $\Omega_c(3119/3090)$ and $J=3/2^-$ $\Omega_c(3050)$ that couple predominantly to $\Xi'_c\bar{K}$, ΞD and $\Xi^*_c\bar{K}$, respectively.

- We conclude that some (probably at least three) of the experimental states will have odd parity and spins J = 1/2 and J = 3/2. Moreover, our $J=1/2^-$ $\Omega_c(3119/3090)$ and $J=3/2^-$ $\Omega_c(3050)$ belong to the same $SU(6)_{lsf}$xHQSS multiplets as $\Lambda_c(2595)$ and $\Lambda_c(2625)$[1], or $\Lambda_b(5912)$ and $\Lambda_b(5920)$[2].

[1] Romanets, LT, Garcia-Recio, Nieves, Salcedo, Timmermans '12
[2] Garcia-Recio, Nieves, Romanets, Salcedo, LT '13