A meson-baryon molecular interpretation for some Ω_c excited baryons

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arXiv:1709.08737

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Hadron spectroscopy phenomenology
CERN 7/11/2017

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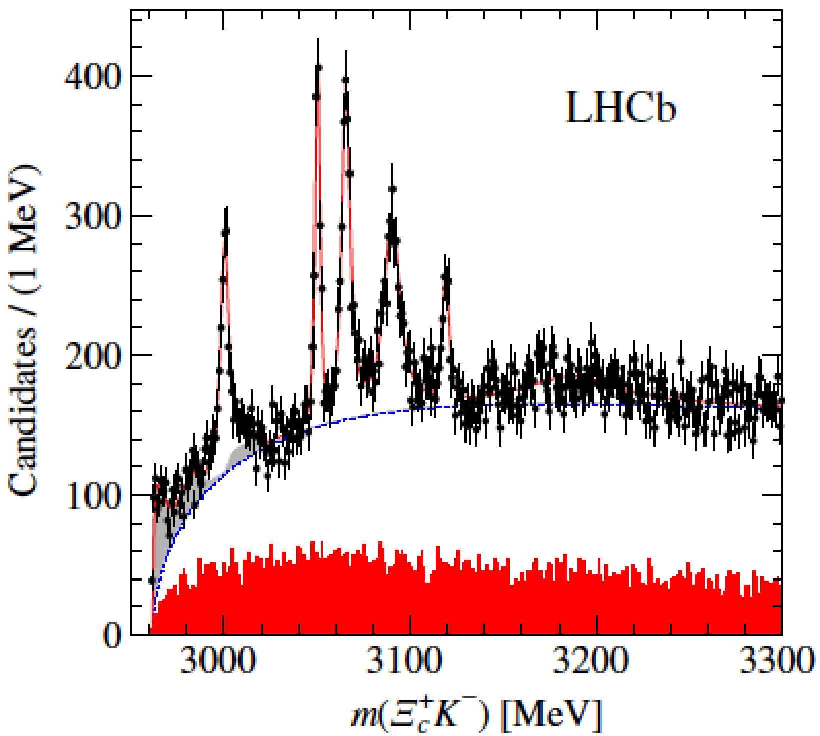
The new Ω_c's seen at LHCb

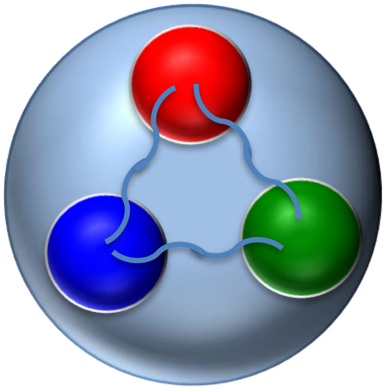
The LHCb collaboration has reported 5 Ω_c states in the invariant mass spectrum of $\Xi_c^+ K^-$ pairs with a sample of pp collision data



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

state	mass	width
$\Omega_c(3000)$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c^0(3050)$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
$\Omega_c^0(3066)$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c^0(3090)$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c^0(3119)$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

Possible interpretation: css states



Quark models have been revisited after the LHCb discovery of the 5 Ω_c states decaying into $K^- \Xi_c^+$ pairs.

1 heavy quark (*c*) and 2 light quarks (*ss*):

→ 1P-wave orbital excitations of the *ss* pair w.r.t. the *c* quark

M.Karliner and J.L.Rosner, PRD95, 114012 (2017)[arXiv:1703.07774 [hep-ph]]
W.Wang and R.L.Zhu, PRD96, 014024 (2017) [arXiv:1704.00179 [hep-ph]]
Z.G.Wang, EPJC 77, 325 (2017 [arXiv:1704.01854 [hep-ph]]
B.Chen and X.Liu [arXiv:1704.02583 [hep-ph]]

$S_{ss} = 1$, $S_c = 1/2$ and P-wave excitation ➔ $J^P = 1/2^-$ (2), $3/2^-$ (2), $5/2^-$ (1)

→ Somes states 1P-wave orbital excitations and some others 2S radial excitations

H.X.Chen, Q.Mao, W.Chen, A.Hosaka, X.Liu and S.L.Zhu, PRD95, 094008 (2017) [arXiv:1703.07703 [hep-ph]]
S.S.Agaev, K.Azizi and H.Sundu, EPL 118, 61001 (2017 [arXiv:1703.07091 [hep-ph]]
S.S.Agaev, K.Azizi and H.Sundu, EPJC77,395 (2017) [arXiv:1704.04928 [hep-ph]]
H.Y.Cheng and C.W~Chiang, PRD95, 094018 (2017) [arXiv:1704.00396 [hep-ph]]
K.L.Wang, L.Y.Xiao, X.H.Zhong and Q.Zhao, PRD95, 116010 (2017 [arXiv:1703.09130 [hep-ph]]

➔ additional J^P possibilities: $1/2^+$, $3/2^+$

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The spin-parity assignment of the 1P-wave orbital excitation quark models seems to be corroborated by a recent **lattice calculation**

M.Padmanath and N.Mathur, PRL119, 042001 (2017) [arXiv:1704.00259 [hep-ph]].

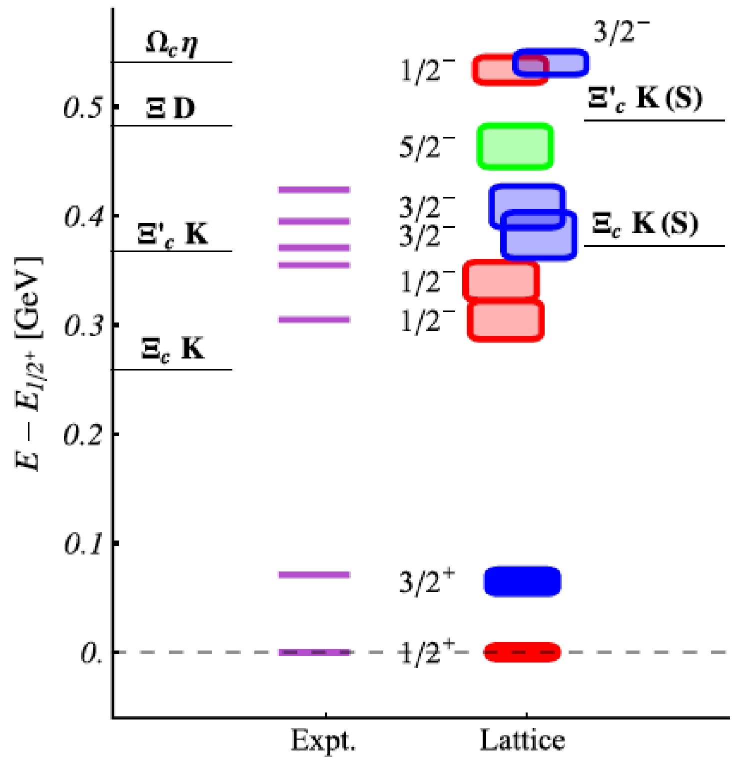
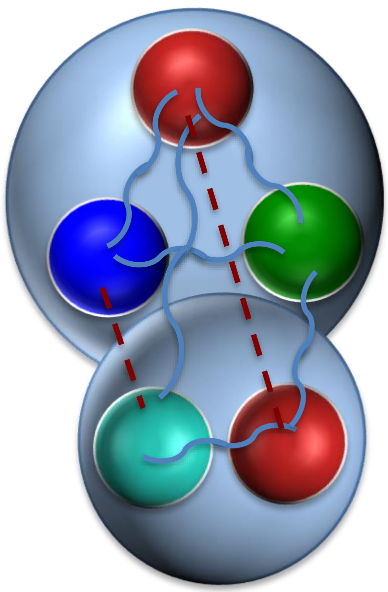


FIG. 4. Comparison plot between experimental and lattice results of Ω_c baryons.

Some pentaquark-type interpretations



Chiral quark model:
constituent quarks interact with each other through one-gluon exchange and Goldstone boson exchange

H. Huang, J.Ping and F.Wang, arXiv:1704.01421 [hep-ph]

➔ The $\Omega_c(3119)$ can be expalined as an S-wave ΞD resonance with $J^P=1/2^-$

C.S.An and H.Chen, PRD96, 034012 (2017) [arXiv:1705.08571 [hep-ph]]

➔ $\Omega_c(3066)$ and $\Omega_c(3090)$: $J^P = 1/2^-$ or $3/2^-$
$\Omega_c(3119)$: $J^P=1/2^-$

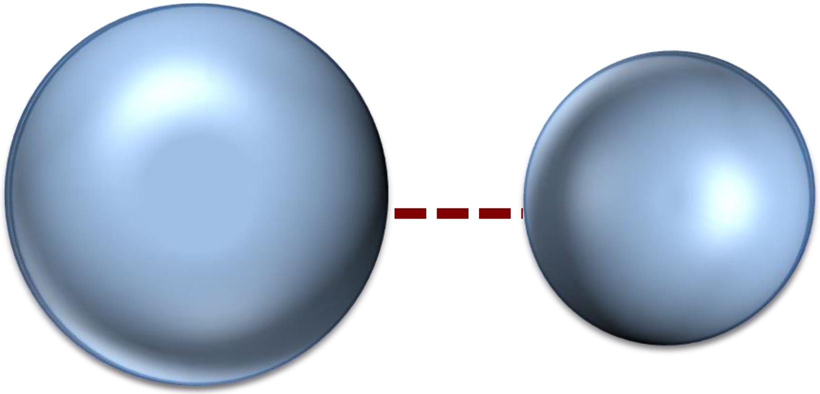
Chiral quark *soliton* model:
c coupled to a "soliton"

H.C.Kim, M.V.Polyakov and M.Praszalowicz, PRD96, 014009 (2017); PRD96, 039902 (2017), [arXiv:1704.04082 [hep-ph]]

➔ $\Omega_c(3000)$: $1/2^-$, $\Omega_c(3066)$: $1/2^-$ and $\Omega_c(3090)$: $3/2^-$ belong to a **6**
$\Omega_c(3050)$: $1/2^+$ and $\Omega_c(3119)$: $3/2^+$ belong to an exotic $\overline{\mathbf{15}}$ (and have I=1!)

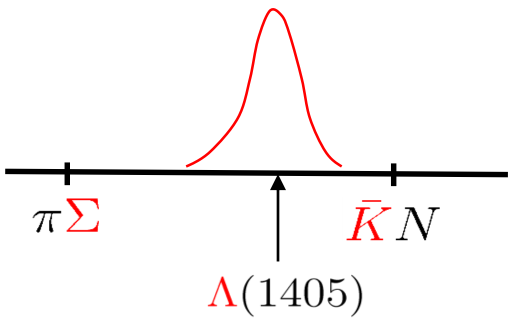
Our work: molecular interpretation

Just as the nucleon-nucleon interaction generates a bound state (the deuteron) we may also find **baryonic resonances** that can be interpreted as **(quasi) bound** systems of a baryon and a meson by virtue of and attractive interaction



A paradigmatic example: The Λ(1405)

- The $\bar{K}N$ interaction in the isospin I=0 channel is able develop a **quasi-bound state**, the Λ(1405), located only 27 MeV below the $\bar{K}N$ threshold



- Idea originally proposed by Dalitz and Tuan in the late 1950's
  R. H. Dalitz and S. F. Tuan, Annals of Phys. 10 (1960) 307
- Reformulated in terms of an effective chiral unitary theory in coupled channels by Kaiser, Siegel and Weise in 1995
  N. Kaiser, P. B. Siegel, and W. Weise, Nucl. Phys. A594 (1995) 325
- Extended to the full coupled-basis by Oset and Ramos in 1998.
  E. Oset and A. Ramos, Nucl. Phys. A635 (1998) 99
- For ten more years (up to ~2006), plenty of theoretical work (NLO Lagrangian, s-channel and u-channel Born terms…,) finding similar features.
  Oller, Meissner, Lutz, Garcia-Recio, Borasoy, Jido, …

- The precise SIDDHARTA measurement of the energy shift ΔE and width Γ of the 1s state in kaonic hydrogen (resolving inconsistencies between KEK and DEAR experiments), has injected a renovated interest in the field

M. Bazzi et al. Phys. Lett. B704 (2011) 113

➔ the parameters of the NLO meson-baryon Lagrangian can be better constrained!

Y. Ikeda, T. Hyodo, W. Weise, Nucl.Phys. A881 (2012) 98
Z-H. Guo , J.A. Oller, Phys.Rev. C87 (2013) 3, 035202
M. Mai, U-G. Meissner, Eur. Phys. J. A51 (2015) 3, 30
A. Feijoo, V.K. Magas, A. Ramos, Phys. Rev. C92 (2015) 1, 015206

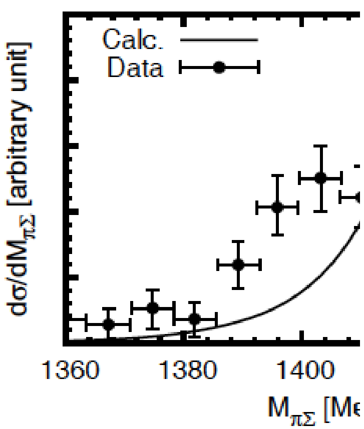


Fig. 6. $\pi\Sigma$ invariant-mass spectra
trary units at 800 MeV/c incident
line denotes the present calculatior
the bubble chamber experiment at K^- momenta between 686
and 844 MeV/c given in ref. [32].

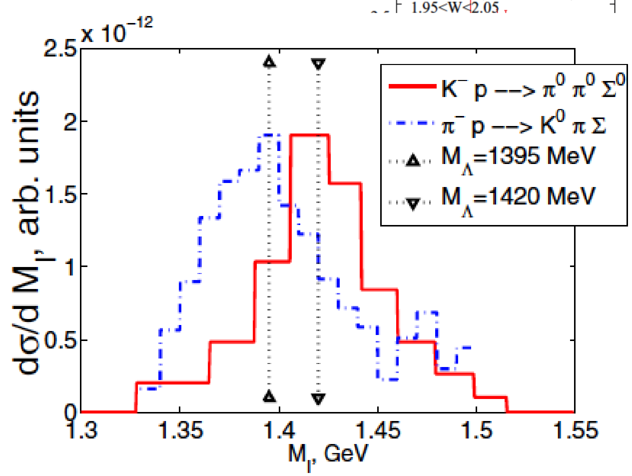


FIG. 5 (color online). Two experimental shapes of the $\Lambda(1405)$ resonance. See text for more details.

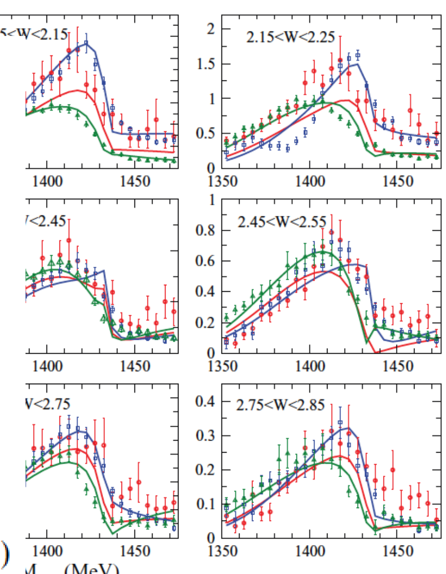


FIG. 2. (Color online) Fit to photoproduction data with fixed unitary amplitudes of $\alpha_i = 1$ and $\beta_i = 1$. Red: $\pi^0\Sigma^0$; blue: $\pi^-\Sigma^+$, green: $\pi^+\Sigma^-$. Experimental data are from Ref. [2].

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C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

POLE STRUCTURE OF THE $\Lambda(1405)$ REGION

Written November 2015 by Ulf-G. Meißner (Bonn Univ. / FZ Jülich) and Tetsuo Hyodo (YITP, Kyoto Univ.).

The $\Lambda(1405)$ resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and systematic approach for the low-energy regime of the strong interactions is chiral perturbation theory (ChPT), see e.g. Ref. 2. A perturbative calculation is, however, not applicable to this sector because of the existence of the $\Lambda(1405)$ just below the $\bar{K}N$ threshold. In this case, ChPT has to be combined with a non-perturbative resummation technique, just as in the case of the nuclear forces. By solving the Lippmann-Schwinger equation with the interaction kernel determined by ChPT and using a particular regularization, in Ref. 3 a successful description of the low-energy K^-p scattering data as well as the mass distribution of the $\Lambda(1405)$ was achieved (for further developments, see Ref. 4 and references therein).

The study of the pole structure was initiated by Ref. 5, which finds two poles of the scattering amplitude in the complex energy plane between the $\bar{K}N$ and $\pi\Sigma$ thresholds. The spectrum in experiments exhibits one effective resonance shape, while the existence of two poles results in the reaction-dependent lineshape [6]. The origin of this two-pole structure is attributed

The acceptance of the $\Lambda(1405)$ as a meson-baryon quasibound state is a real success of the chiral unitary models in coupled channels!

Charm sector

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The $\Lambda_c(2595)$

The $\Lambda_c(2595)$, in the C=1 sector, encounters a similar situation as the $\Lambda(1405)$ in the S=1 sector

A logical approach was to extend the pseudoscalar-baryon chiral unitary method to test the nature of the $\Lambda_c(2595)$.

Several works indeed found the $\Lambda_c(2595)$ as a quasibound state generated dynamically from the interaction of pseudoscalar mesons with baryons in coupled channels:

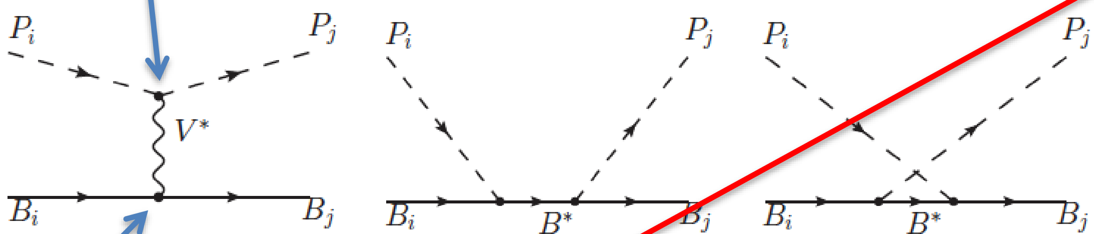
J. Hofmann, M.F.M. Lutz, Nucl. Phys. A 763 (2005) 90

C. E. Jiménez-Tejero, A. Ramos and I. Vidaña, Phys. Rev. C 80, 055206 (2009)

Pseudoscalar – baryon interaction model (S-wave)

The vertices are described via effective Lagrangians, obtained from the hidden gauge formalism and assuming SU(4) symmetry:

$$\mathcal{L}_{VPP}^{SU(4)} = ig \left\langle [\partial_\mu \phi, \phi] V^\mu \right\rangle$$



(a) t-channel. (b) s-channel. (c) u-channel.

neglected (minor S-wave contribution)

$$\mathcal{L}_{BBV}^{SU(4)} = \frac{g}{2} \sum_{i,j,k,l=1}^{4} \bar{B}_{ijk} \gamma^\mu \left(V_{\mu,l}^{k} B^{ijl} + 2 V_{\mu,l}^{j} B^{ilk} \right)$$

$$g = \frac{m_V}{2f} \qquad f = 93 \text{ MeV}$$

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$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta + \frac{1}{\sqrt{3}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta + \frac{1}{\sqrt{3}}\eta' & K^0 & D^- \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta + \frac{1}{\sqrt{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$

$$V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}(\rho^0+\omega) & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{1}{\sqrt{2}}(-\rho^0+\omega) & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

$$B^{121} = p, \quad B^{122} = n, \quad B^{132} = \frac{1}{\sqrt{2}}\Sigma^0 - \frac{1}{\sqrt{6}}\Lambda,$$

$$B^{213} = \sqrt{\frac{2}{3}}\Lambda, \quad B^{231} = \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda, \quad B^{232} = \Sigma^-,$$

$$B^{233} = \Xi^-, \quad B^{311} = \Sigma^+, \quad B^{313} = \Xi^0,$$

$$B^{141} = -\Sigma_c^{++}, \quad B^{142} = \frac{1}{\sqrt{2}}\Sigma_c^+ + \frac{1}{\sqrt{6}}\Lambda_c, \quad B^{143} = \frac{1}{\sqrt{2}}\Xi_c'^+ - \frac{1}{\sqrt{6}}\Xi_c^+,$$

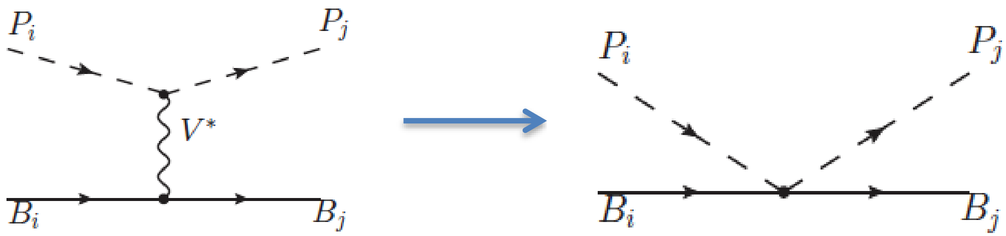
$$B^{241} = \frac{1}{\sqrt{2}}\Sigma_c^+ - \frac{1}{\sqrt{6}}\Lambda_c, \quad B^{242} = \Sigma_c^0, \quad B^{243} = \frac{1}{\sqrt{2}}\Xi_c'^0 + \frac{1}{\sqrt{6}}\Xi_c^0,$$

$$B^{341} = \frac{1}{\sqrt{2}}\Xi_c'^+ + \frac{1}{\sqrt{6}}\Xi_c^+, \quad B^{342} = \frac{1}{\sqrt{2}}\Xi_c'^0 - \frac{1}{\sqrt{6}}\Xi_c^0, \quad B^{343} = \Omega_c,$$

$$B^{124} = \sqrt{\frac{2}{3}}\Lambda_c, \quad B^{234} = \sqrt{\frac{2}{3}}\Xi_c^0, \quad B^{314} = \sqrt{\frac{2}{3}}\Xi_c^+,$$

$$B^{144} = \Xi_{cc}^{++}, \quad B^{244} = -\Xi_{cc}^+, \quad B^{344} = \Omega_{cc},$$

In the zero-range limit:



kernel: $$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s}-M_i-M_j)\sqrt{\frac{E_i+M_i}{2M_i}}\sqrt{\frac{E_j+M_j}{2M_j}}$$

Coupled channels for the $\Lambda_c(2595)$ (I=0, C=1, S=0, $J^P=1/2^-$):

	$\pi\Sigma_c$	DN	$\eta\Lambda_c$	$K\Xi_c$	$K\Xi'_c$	$D_s\Lambda$	$\eta'\Lambda_c$
$\pi\Sigma_c$	4	$\sqrt{\frac{3}{2}}\kappa_c$	0	0	$\sqrt{3}$	0	0
DN		3	$-\frac{1}{\sqrt{2}}\kappa_c$	0	0	$-\sqrt{3}$	$-\kappa_c$
$\eta\Lambda_c$			0	$-\sqrt{3}$	0	$-\sqrt{\frac{2}{3}}\kappa_c$	0
$K\Xi_c$				2	0	$-\frac{1}{\sqrt{2}}\kappa_c$	0
$K\Xi'_c$					2	$-\sqrt{\frac{3}{2}}\kappa_c$	0
$D_s\Lambda$						1	$\frac{1}{\sqrt{3}}\kappa_c$
$\eta'\Lambda_c$							0

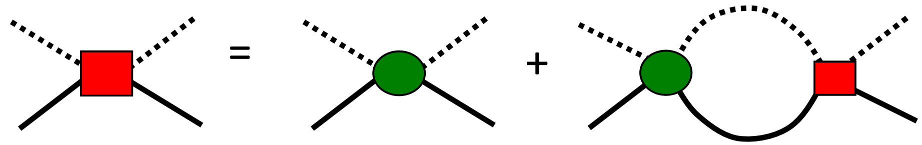
κ_c ~ 1/4

(suppression factor accounting for the heavier mass of the exchanged meson)

Unitarization:

N/D, Bethe-Salpeter, …

(on-shell approach)



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

The meson-baryon loop

$$G_l = i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$

is calculated in dimensional regularization

$$\begin{aligned} G_l \;=\; & \frac{2M_l}{16\pi^2} \left\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln\frac{m_l^2}{M_l^2} + \right. \\ & + \frac{\bar{q}_l}{\sqrt{s}} \left[\ln(s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right. \\ & \left.\left. - \ln(-s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right] \right\} \end{aligned}$$

(μ=1000 MeV) $a_l(\mu) \simeq -2$

(equivalent to “cut-off” values of 800-1000 MeV)

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Resonance:

➔ it is given by a pole of the unitarized amplitude

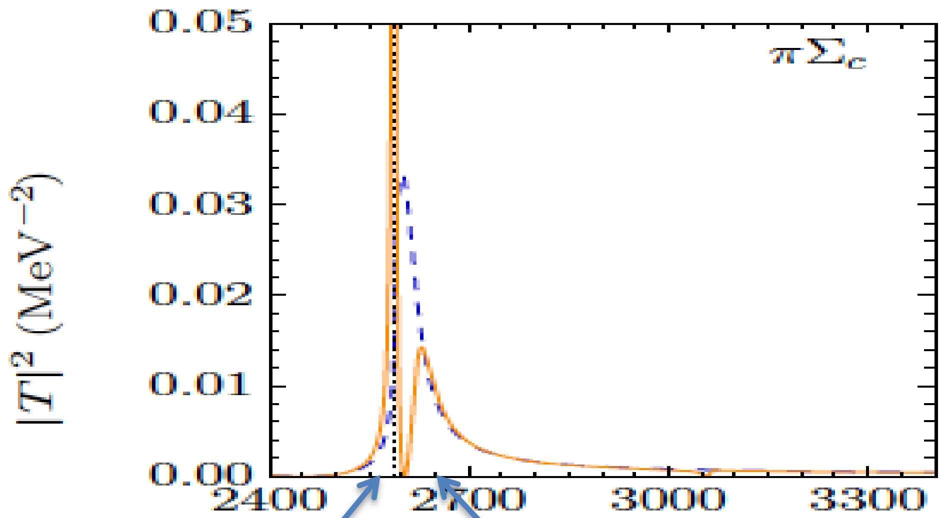
$$T_{ij}(z) \sim \frac{g_i g_j}{z - z_p} \qquad \begin{aligned} M &= \mathrm{Re}\, z_p \\ \Gamma &= -2\mathrm{Im}\, z_p \end{aligned}$$

Compositeness:

➔ the amount of the meson-baryon component of the resonance

$$X_i = -g_i^2 \left(\frac{\partial G}{\partial E} \right) \Bigg|_{z_p}$$

This simple model (and many others alike) generates the $\Lambda_c(2595)$ having as a double pole structure



G. Montaña, master thesis, Barcelona 2017

I=0, C=1, S=0, $J^P=1/2^-$

Channels \ Poles	Coupling constants (g_i) 2588.054 + i 0.000	2618.019 + i 19.033	2814.088 + i 0.014	3060.790 + i 7.213
$\pi\Sigma_c$	**0.941 + i 0.000**	**−1.308 − i 1.070**	0.005 + i 0.008	−0.188 − i 0.345
DN	**4.254 + i 0.000**	**3.632 − i 1.523**	−0.064 − i 0.014	−0.220 − i 0.255
$\eta\Lambda_c$	−0.183 + i 0.000	−0.191 + i 0.058	**−1.291 + i 0.000**	0.102 + i 0.048
$K\Xi_c$	0.007 + i 0.000	0.025 + i 0.005	**2.526 + i 0.001**	0.085 + i 0.016
$K\Xi'_c$	0.129 + i 0.000	−0.434 − i 0.282	−0.004 + i 0.003	**1.701 − i 0.212**
$D_s\Lambda$	**−2.037 + i 0.000**	**−2.257 + i 0.608**	0.334 + i 0.009	**−1.122 + i 0.199**
$\eta'\Lambda_c$	−0.199 + i 0.000	−0.220 + i 0.059	0.024 + i 0.001	−0.011 + i 0.012

Can we conclude that the Λ_c**(2595)** is essentially a DN bound state?

Not in this case! In dealing with hadrons with a heavy quark, one must deal with **Heavy Quark Spin Symmetry** (HQSS), according to which the spin interactions vanish for infinitely heavy quark masses.

(M_D ~ 1870 MeV M_{D*} ~ 2010 MeV)

➔ SU(8) model (including **vector** mesons and **decuplet** baryons):

C. García-Recio et al., Phys. Rev. D 79, 054004 (2009)

$I = 0, J = 1/2$		
M_R	Γ_R	Couplings to main channels
2595.4	0.58	$g_{\Sigma_c \pi} = \mathbf{0.36}$, $g_{ND} = 3.69$, $g_{ND^*} = 5.70$, $g_{\Lambda D_s} = 1.42$, $g_{\Lambda D_s^*} = 2.94$
2610.0	70.9	$g_{\Sigma_c \pi} = \mathbf{2.25}$, $g_{ND} = 1.47$, $g_{ND^*} = 1.81$, $g_{\Sigma_c \rho} = 1.22$

➔ coupling pseudoscalar–baryon with vector–baryon channels (Box diagrams)

W.H. Liang, T. Uchino, C.W. Xiao and E. Oset, Eur. Phys. J. A (2015) 51: 16

$2592.26 + i0.56$	DN	$\pi\Sigma_c$	$\eta\Lambda_c$	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	$\mathbf{8.18 + i0.61}$	$\mathbf{0.54 + i0.00}$	$-0.40 - i0.03$	$\mathbf{9.81 + i0.77}$	$-0.45 - i0.04$	$0.42 + i0.0$	$-0.59 - i0.05$

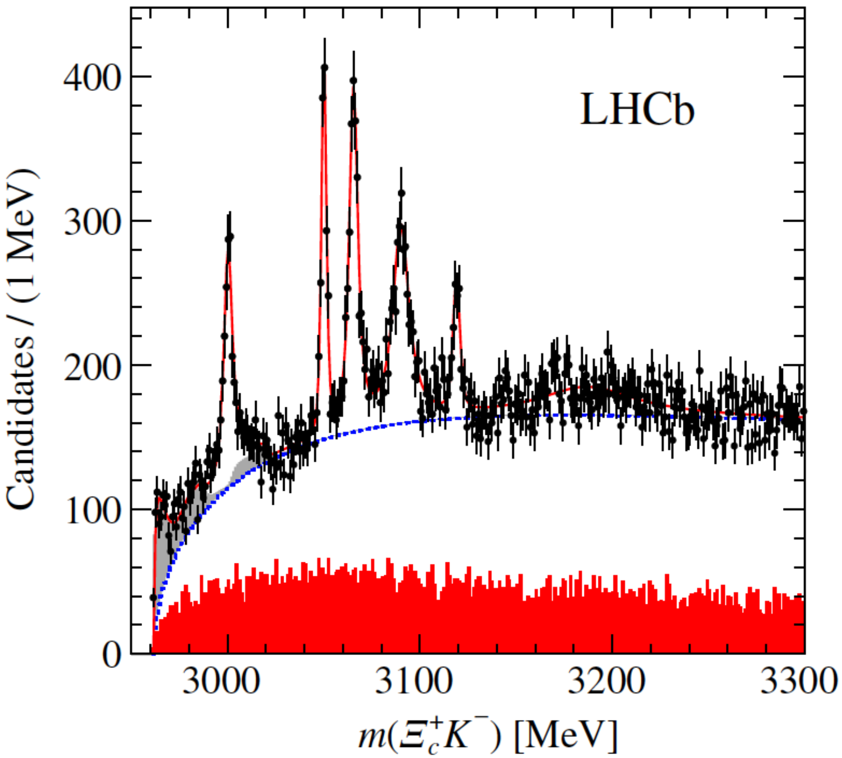
$2611.06 + i53.35$	DN	$\pi\Sigma_c$	$\eta\Lambda_c$	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	$0.08 - i1.81$	$\mathbf{1.78 + i1.40}$	$0.03 - i0.09$	$-1.56 + i1.38$	$0.09 - i0.05$	$-0.08 + i0.05$	$0.11 - i0.07$

➔ The coupling DN – D*N plays an important role

➔ The Λ_c(2595) is a DN – D*N molecule!

The new Ω_c's seen at LHCb

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



C=1, S=-2

state	mass	width
$\Omega_c(3000)$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c^0(3050)$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
$\Omega_c^0(3066)$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c^0(3090)$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c^0(3119)$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

Similarly as the P_c pentaquarks, it is plausible that some Ω_c's can be obtained by adding a $u\bar{u}$ pair to the natural ssc content ➔ the hadronization of the 5q system could lead to *meson-baryon bound states*.

➔ Moreover, the $\bar{K}\Xi_c$ and $\bar{K}\Xi_c'$ thresholds, 2964 Mev and 3070 MeV, are in the energy range of interest.

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Some earlier theoretical works already gave predictions for Ω_c resonances being meson-baryon molecules:

SU(8) model: O. Romanets et al., Phys. Rev. D85 (2012) 114032

TABLE VI. Ω_c and Ω_c^* resonances.

M_R	Γ_R	Couplings to main channels	J
2810.9	0.0	$g_{\Xi D} = 3.3$, $g_{\Xi D^*} = 1.7$, $g_{\Xi_c \bar{K}^*} = 0.9$, $g_{\Xi^* D^*} = 4.8$, $g_{\Omega_c \eta'} = 0.9$, $g_{\Omega D_s^*} = 4.2$	1/2
2814.3	0.0	$g_{\Xi D^*} = 3.7$, $g_{\Xi^* D} = 3.1$, $g_{\Xi^* D^*} = 3.8$, $g_{\Omega D_s} = 2.7$, $g_{\Omega_c^* \eta'} = 0.9$, $g_{\Omega D_s^*} = 3.4$	3/2
2884.5	0.0	$g_{\Xi_c \bar{K}} = 2.1$, $g_{\Xi D^*} = 1.7$, $g_{\Xi_c' \bar{K}^*} = 1.5$, $g_{\Xi_c^* \bar{K}^*} = 1.8$, $g_{\Omega_c \phi} = 0.9$, $g_{\Omega_c^* \phi} = 1.1$	1/2
2941.6	0.0	$g_{\Xi_c' \bar{K}} = 1.9$, $g_{\Xi D} = 1.5$, $g_{\Omega_c \eta} = 1.7$, $g_{\Xi_c \bar{K}^*} = 1.4$, $g_{\Xi_c' \bar{K}^*} = 1.1$, $g_{\Omega_c \phi} = 1.0$, $g_{\Omega D_s^*} = 0.9$	1/2
2980.0	0.0	$g_{\Xi_c^* \bar{K}} = 1.9$, $g_{\Omega_c^* \eta} = 1.6$, $g_{\Xi D^*} = 1.4$, $g_{\Xi_c \bar{K}^*} = 1.6$, $g_{\Xi_c^* \bar{K}^*} = 1.3$, $g_{\Omega_c^* \phi} = 1.2$	3/2

But these Ω_c states are much more bound than the LHCb ones

SU(4) finite range model: J. Hofmann, M.F.M. Lutz, Nucl. Phys. A 763 (2005) 90

➔ 3 Ω_c states (below 2953 MeV)

C. E. Jiménez-Tejero, A. Ramos, and I. Vidaña, Phys. Rev. C 80, 055206 (2009)

TABLE VI. Masses, widths, and couplings of the resonances in the $(I, S, C) = (0, -2, 1)$ sector.

M [MeV]	2959	2966	3117
Γ [MeV]	0.	1.1	16
	$\|g_i\|$	$\|g_i\|$	$\|g_i\|$
$\bar{K}\,\Xi_c(2964)$	1.36	0.43	0.51
$\bar{K}\,\Xi'_c(3070)$	2.04	4.49	0.27
$D\,\Xi(3189)$	2.03	1.68	5.34
$\eta\Omega_c(3246)$	1.67	3.69	0.24
$\eta'\Omega_c(3656)$	0.10	0.07	0.35
$D_s\Omega_{cc}(5528)$	0.17	1.17	0.19
$\eta_c\Omega_c(5678)$	0.28	0.21	1.03

The only model that gives a prediction above 3 GeV !

We have employed the above described methodology to investigate what meson-baryon molecules we predict in the C=1, S=-2 sector.

G. Montaña, A. Feijoo, A. Ramos, arXiv:1709.08737

We consider the following pseudoscalar-baryon coupled channels:

$$\bar{K}\Xi_c(2964),\ \bar{K}\Xi'_c(3070),\ D\Xi(3189),\ \eta\Omega_c(3246),\ \eta'\Omega_c(3656),\ \bar{D}_s\Omega_{cc}(5528),\ \eta_c\Omega_c(5678)$$

double charm (neglected)

	$\bar{K}\Xi_c$	$\bar{K}\Xi'_c$	$D\Xi$	$\eta\Omega_c^0$	$\eta'\Omega_c^0$
$\bar{K}\Xi_c$	1	0	$\sqrt{\frac{3}{2}}\kappa_c$	0	0
$\bar{K}\Xi'_c$		1	$\frac{1}{\sqrt{2}}\kappa_c$	$-\sqrt{6}$	0
$D\Xi$			2	$-\frac{1}{\sqrt{3}}\kappa_c$	$-\sqrt{\frac{2}{3}}\kappa_c$
$\eta\Omega_c^0$				0	0
$\eta'\Omega_c^0$					0

TABLE I: The C_{ij} coefficients for the $I=0$, $C=1$, $S=-2$ sector of the PB interaction.

strong attraction in the DΞ channel

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s}-M_i-M_j)\sqrt{\frac{E_i+M_i}{2M_i}}\sqrt{\frac{E_j+M_j}{2M_j}}$$

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Model 1: Subtraction constants in the dimensional regularization loops chosen so as to make it coincide with cut-off loop (Λ=800 MeV)

	$a_{\bar{K}\Xi_c}$	$a_{\bar{K}\Xi'_c}$	$a_{D\Xi}$	$a_{\eta\Omega_c}$	$a_{\eta'\Omega_c}$
Model 1	-2.19	-2.26	-1.90	-2.31	-2.26
Λ (MeV)	800	800	800	800	800

$$a_l(\mu) = \frac{16\pi^2}{2M_l}\left(G_l^{\rm cut}(\Lambda) - G_l(\mu, a_l = 0)\right)$$

$0^- \oplus \frac{1}{2}^+$ interaction in $(I,S,C)=(0,-2,1)$ sector	Model 1			
M [MeV]	3051.6		3103.3	
Γ [MeV]	0.45		17	
	$\lvert g_i \rvert$	$-g_i^2 dG/dE$	$\lvert g_i \rvert$	$-g_i^2 dG/dE$
$\bar{K}\Xi_c(2964)$	0.11	$0.00 + i\,0.00$	0.58	$0.01 + i\,0.03$
$\bar{K}\Xi'_c(3070)$	1.67	$0.54 + i\,0.01$	0.30	$0.01 - i\,0.01$
$D\Xi(3189)$	1.10	$0.05 - i\,0.01$	4.08	$0.90 - i\,0.05$
$\eta\Omega_c(3246)$	2.08	$0.23 + i\,0.00$	0.44	$0.01 + i\,0.01$
$\eta'\Omega_c(3656)$	0.04	$0.00 + i\,0.00$	0.28	$0.00 + i\,0.00$

The state at 3051 MeV mainly composed by $\bar{K}\Xi_c'$ and $\eta\Omega_c$

The state at 3103 MeV clearly qualifies as a $D\Xi$ bound state

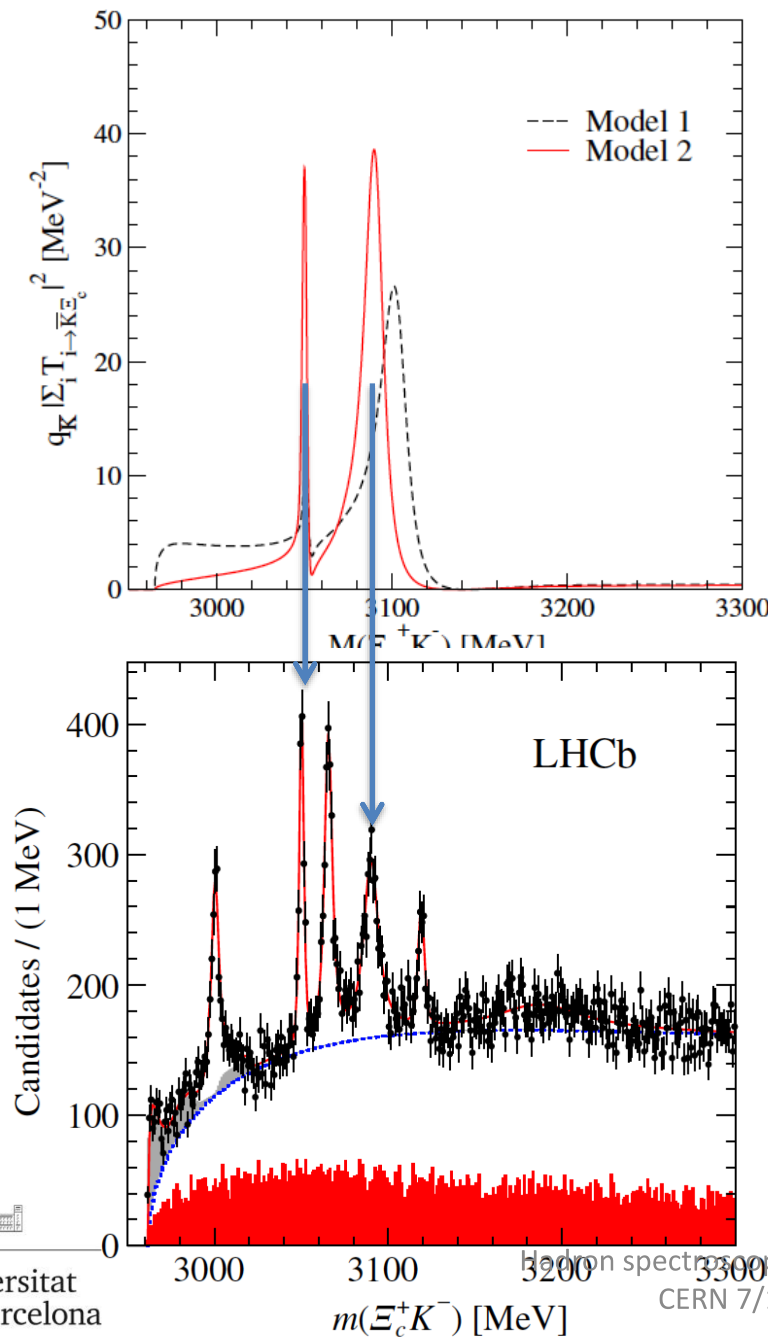
➔ 10 MeV too heavy and too wide…

$$M = 3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}\ \text{MeV}$$
$$\Gamma = 8.7 \pm 1.0 \pm 0.8\ \text{MeV}.$$

Model 2: Let the subtraction constants in the dimensional regularization loops vary to reproduce the experimental data

	$a_{\bar{K}\Xi_c}$	$a_{\bar{K}\Xi'_c}$	$a_{D\Xi}$	$a_{\eta\Omega_c}$	$a_{\eta'\Omega_c}$
Model 2	-1.69	-2.09	-1.93	-2.46	-2.42
Λ (MeV)	320	620	830	980	980

$0^- \oplus \frac{1}{2}^+$ interaction in $(I,S,C)=(0,-2,1)$ sector				
	Model 2			
M [MeV]	3050.3		3090.8	
Γ [MeV]	0.44		12	
	$\lvert g_i \rvert$	$-g_i^2 dG/dE$	$\lvert g_i \rvert$	$-g_i^2 dG/dE$
$\bar{K}\Xi_c(2964)$	0.11	$0.00 + i\,0.00$	0.49	$-0.02 + i\,0.01$
$\bar{K}\Xi'_c(3070)$	1.80	$0.61 + i\,0.01$	0.35	$0.02 - i\,0.02$
$D\Xi(3189)$	1.36	$0.07 - i\,0.01$	4.28	$0.91 - i\,0.01$
$\eta\Omega_c(3246)$	1.63	$0.14 + i\,0.00$	0.39	$0.01 + i\,0.01$
$\eta'\Omega_c(3656)$	0.06	$0.00 + i\,0.00$	0.28	$0.00 + i\,0.00$



Preliminary comparison using:

$$q_{\overline{K}}\, |\Sigma_i\, T_{i\to\overline{K}\Xi_c}|^2\ [\mathrm{MeV}^{-2}]$$

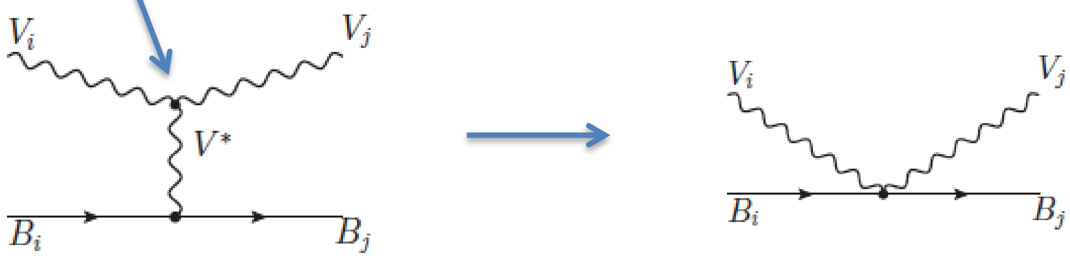
The states at 3050 MeV and 3090 MeV are in very good agreement with experiment.

If these states are interpreted as pseudoscalar meson-baryon molecules, their spin-parity can be predicted to be $1/2^-$.

Vector – baryon interaction model

$$\mathcal{L}_{VVV} = ig\,\langle [V^\mu, \partial_\nu V_\mu] V^\nu \rangle$$

E. Oset, A. Ramos, Eur.Phys.J. A44 (2010) 445-454.



➔ **kernel:** $$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}\vec{\epsilon}_i\vec{\epsilon}_j$$

➔ **coupled-channels:**

$$D^*\Xi(3326),\quad \bar{K}^*\Xi_c(3363),\quad \bar{K}^*\Xi'_c(3470),\quad \omega\Omega_c(3480),\ \phi\Omega_c(3717)$$

➔ **coefficients:** the same as pseudoscalar-baryon with the transformations:

$$\pi \to \rho,\ K \to K^*,\ \bar{K} \to \bar{K}^*,\ D \to D^*,\ \bar{D} \to \bar{D}^*,$$

$$\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' \to \omega \qquad \text{and} \quad -\sqrt{\frac{2}{3}}\eta + \frac{1}{\sqrt{3}}\eta' \to \phi$$

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vector – baryon resonances

	$a_{D^*\Xi}$	$a_{\bar{K}^*\Xi_c}$	$a_{\bar{K}^*\Xi'_c}$	$a_{\omega\Omega_c}$	$a_{\phi\Omega_c}$
	-1.97	-2.15	-2.20	-2.27	-2.26
Λ (MeV)	800	800	800	800	800

$J^P=3/2^-$

$1^- \oplus \frac{1}{2}^+$ interaction in $(I,S,C)=(0,-2,1)$ sector				
M [MeV]	3231.19		3419.25	
Γ [MeV]	0.0		4.8	
	$\lvert g_i\rvert$	$-g_i^2 dG/dE$	$\lvert g_i\rvert$	$-g_i^2 dG/dE$
$D^*\Xi(3326)$	4.30	$0.90 - i0.00$	0.24	$0.00 + i0.00$
$\bar{K}^*\Xi_c(3363)$	0.64	$0.03 - i0.00$	0.13	$0.00 + i0.00$
$\bar{K}^*\Xi'_c(3470)$	0.26	$0.00 - i0.00$	1.83	$0.42 + i0.02$
$\omega\Omega_c(3480)$	0.34	$0.01 - i0.00$	1.56	$0.28 + i0.00$
$\phi\Omega_c(3717)$	0.00	$0.00 - i0.00$	2.31	$0.22 + i0.00$

These states cannot be identified with any of the seen Ω_c states.

The model does not give us how they couple to the $\Xi_c^+ K^-$ pairs.
➔ incomplete!
(see next talk by V.R. Debastiani)

Summary

There are quite a few baryons than can be naturally described as meson-baryon molecules, generated by the interaction of their hadronic constituents (just as the Deuteron is a bound state of two nucleons)

➔ The $\Lambda(1405)$ is a well tested nice example!

The pattern is naturally reproduced in the charm sector (eg. the $\Lambda_c(2595)$)

➔ In the C=1, S=-2 sector we have identified two states having a pseudoscalar-baryon molecular nature among the 5 Ω_c states measured at LHCb, and hence we can predict their spin-parity to be $J^P=1/2^-$

A combined theoretical/experimental effort to find reactions that help in establishing the nature of hadrons, especially in the prolific charm sector, is very much needed!

Thank you for your attention

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