Effective theories and resonances

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Chiral Lagrangians. Unitarization of coupled channels interaction

Old generated resonances, $\Lambda(1405) \rightarrow \Lambda(1420), \Lambda(1380)$
$\Lambda(1670)$, $N^*(1535)$, $\Delta(1710)$ ……

A new resonance in the light sector : $\Omega(2012)$

Resonances with charm , Pc, Pcs, Pcc ….

Multihadron states coming

Chiral Lagrangians for P B interaction

G. Ecker, Prog. Part. Nucl. Phys. 35 (1995) 1.
V. Bernard, N. Kaiser and U.G. Meissner, Int. J. Mod. Phys. E 4 (1995) 193.

$$\nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B] ,$$

$$\Gamma_\mu = \tfrac{1}{2}(u^+\partial_\mu u + u\partial_\mu u^+) ,$$

$$U = u^2 = \exp(i\sqrt{2}\Phi/f) ,$$

$$u_\mu = iu^+\partial_\mu U u^+ .$$

$$L_1^{(B)} = \langle \bar{B} i\gamma^\mu \nabla_\mu B\rangle - M_B\langle \bar{B}B\rangle$$

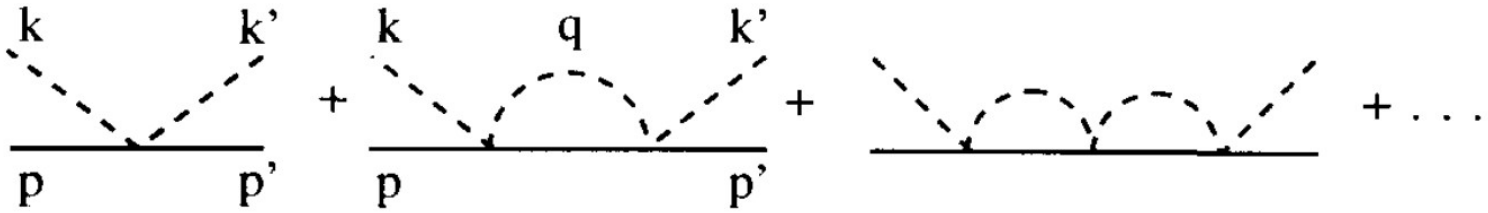
$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix} \qquad B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

$$L_1^{(B)} = \langle \bar{B} i\gamma^\mu \frac{1}{4f^2}[(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi)B - B(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi)]\rangle$$

$$V_{ij} = -C_{ij}\frac{1}{4f^2}\bar{u}(p')\gamma^{\mu}u(p)(k_{\mu}+k'_{\mu}) \qquad V_{ij} = -C_{ij}\frac{1}{4f^2}(k^0+k'^0)$$

C_{ij} coefficients of Eq. (7). $C_{ji} = C_{ij}$

	K^-p	$\bar{K}^0n$	$\pi^0\Lambda$	$\pi^0\Sigma^0$	$\eta\Lambda$	$\eta\Sigma^0$	$\pi^+\Sigma^-$	$\pi^-\Sigma^+$	$K^+\Xi^-$	$K^0\Xi^0$
K^-p	2	1	$\frac{\sqrt{3}}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{\sqrt{3}}{2}$	0	1	0	0
$\bar{K}^0n$		2	$-\frac{\sqrt{3}}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$-\frac{\sqrt{3}}{2}$	1	0	0	0
$\pi^0\Lambda$			0	0	0	0	0	0	$\frac{\sqrt{3}}{2}$	$-\frac{\sqrt{3}}{2}$
$\pi^0\Sigma^0$				0	0	0	2	2	$\frac{1}{2}$	$\frac{1}{2}$
$\eta\Lambda$					0	0	0	0	$\frac{3}{2}$	$\frac{3}{2}$
$\eta\Sigma^0$						0	0	0	$\frac{\sqrt{3}}{2}$	$-\frac{\sqrt{3}}{2}$
$\pi^+\Sigma^-$							2	0	1	0
$\pi^-\Sigma^+$								2	0	1
$K^+\Xi^-$									2	1
$K^0\Xi^0$										2



$$T = V + VGT \qquad\qquad T = [1 - VG]^{-1} V$$

$$G_l = i \int \frac{d^4q}{(2\pi)^4} \frac{M_l}{E_l(\boldsymbol{q})} \frac{1}{k^0 + p^0 - q^0 - E_l(\boldsymbol{q}) + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$

$$= \int \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega_l(q)} \frac{M_l}{E_l(\boldsymbol{q})} \frac{1}{p^0 + k^0 - \omega_l(\boldsymbol{q}) - E_l(\boldsymbol{q}) + i\epsilon},$$

$\Lambda(1380)\ 1/2^-$ $\quad J^P = \frac{1}{2}^-$ $\quad$ Status: $**$

$\Lambda(1405)\ 1/2^-$ $\quad I(J^P) = 0(\frac{1}{2}^-)$ $\quad$ Status: $****$

1429^{+8}_{-7}	[1] MAI	15	DPWA
1434 ± 2	[2] MAI	15	DPWA
1421^{+3}_{-2}	GUO	13	DPWA
1424^{+7}_{-23}	IKEDA	12	DPWA

The case of the Ω(2012)

Similar chiral Lagrangians from the interaction of mesons with baryons of the Δ decuplet
S-wave → $3/2^-$ states
Coupled channels Kbar Ξ*(1530), ηΩ, Kbar Ξ (in D-wave)

J. Hofmann and M. F. M. Lutz, Nucl. Phys. A776, 17 (2006).
S. Sarkar, E. Oset, and M. J. Vicente Vacas, Nucl. Phys. A750, 294 (2005); A780, 90(E) (2006).

$$V = \begin{array}{c} \begin{array}{ccc} \bar{K}\Xi^* & \eta\Omega & \bar{K}\Xi \end{array} \\ \begin{pmatrix} 0 & 3F & \alpha q^2 \\ 3F & 0 & \beta q^2 \\ \alpha q^2 & \beta q^2 & 0 \end{pmatrix} \end{array} \begin{array}{c} \\ \bar{K}\Xi^* \\ \eta\Omega \\ \bar{K}\Xi \end{array}$$

$$F = -\frac{1}{4f^2}(k^0 + k'^0)$$

$$T = [1 - VG]^{-1} V$$

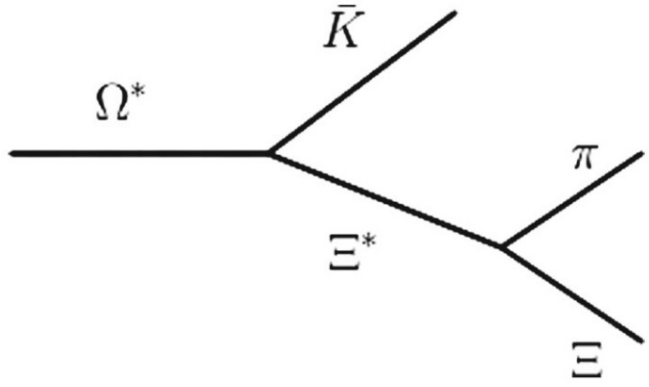
$$G(\sqrt{s}) = \begin{pmatrix} G_{\bar{K}\Xi^*}(\sqrt{s}) & 0 & 0 \\ 0 & G_{\eta\Omega}(\sqrt{s}) & 0 \\ 0 & 0 & G_{\bar{K}\Xi}(\sqrt{s}) \end{pmatrix}$$

$$G_i(\sqrt{s}) = \int_{|\vec{q}|<q_{\max}} \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega_i(\vec{q})} \frac{M_i}{E_i(\vec{q})} \frac{1}{\sqrt{s} - \omega_i(\vec{q}) - E_i(\vec{q}) + i\epsilon},$$

$$G_{\bar{K}\Xi}(\sqrt{s}) = \int_{|\vec{q}|<q'_{\max}} \frac{d^3q}{(2\pi)^3} \frac{(q/q_{on})^4}{2\omega_{\bar{K}}(\vec{q})} \frac{M_\Xi}{E_\Xi(\vec{q})} \frac{1}{\sqrt{s} - \omega_{\bar{K}}(\vec{q}) - E_\Xi(\vec{q}) + i\epsilon}$$

$$m_{\Omega^*}^{\rm exp} = 2012.4 \pm 0.92 \text{ MeV},$$
$$\Gamma_{\Omega^*}^{\rm exp} = 6.4^{+3.0}_{-2.6} \text{ MeV}.$$

J. Yelton et al., [Belle Collaboration], Phys. Rev. Lett. 121,052003 (2018)



R. Pavao, E. O, Eur.Phys.J.C 78 (2018) 857

α (10^{-8} MeV^{-3})	β (10^{-8} MeV^{-3})	$q_{\rm max}$ (MeV)	$(m_{\Omega^*}, \Gamma_{\Omega^*})$ (MeV)	$\Gamma(\bar{K}\,\Xi)$ (MeV)	$\Gamma(\pi\,\bar{K}\,\Xi)$ (MeV)
5.0	0.1	735	(2012.19, 6.36)	3.35	3.01
4.0	1.5	735	(2012.4, 6.2)	3.22	2.98
3.0	3.0	735	(2012.36, 6.19)	3.25	2.94
2.0	4.5	735	(2012.26, 6.23)	3.34	2.89

Belle Collaboration, arXiv:2207.03090.

$$\mathcal{R}_{\Xi\bar{K}}^{\Xi\pi\bar{K}} = 0.97 \pm 0.24 \pm 0.07$$

Couplings

$$T_{ij} = \frac{g_i g_j}{\sqrt{s} - z_R}$$

$g_{\bar{K}\Xi^*}$	$g_{\eta\Omega}$	$g_{\bar{K}\Xi}$
$2.01 + i0.02$	$2.84 - i0.01$	$-0.29 + i0.04$

Probabilities approximately

$\left(-g^2 \frac{\partial G(\sqrt{s})}{\partial \sqrt{s}}\right)_{\bar{K}\Xi^*}$	$\left(-g^2 \frac{\partial G(\sqrt{s})}{\partial \sqrt{s}}\right)_{\eta\Omega}$
$0.636 - i0.068$	$0.164 - i0.002$

Related references

J. X. Lu, C. H. Zeng, E. Wang, J. J. Xie, and L. S. Geng, Eur. Phys. J. C 80, 361 (2020).
N. Ikeno, G. Toledo, and E. Oset, Phys. Rev. D 101, 094016

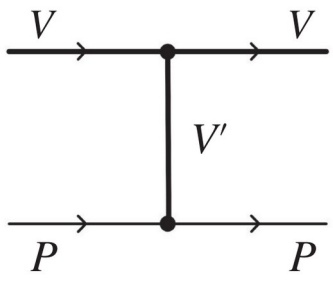
M. P. Valderrama, Phys. Rev. D 98, 054009 (2018).
Y. Huang, M. Z. Liu, J. X. Lu, J. J. Xie, and L. S. Geng, Phys. Rev. D 98, 076012 (2018).
T. Gutsche and V. E. Lyubovitskij, J. Phys. G 48, 025001 (2021).
Y. H. Lin and B. S. Zou, Phys. Rev. D 98, 056013 (2018).

K.~L.~Wang, Q.~F.~L\"u, J.~J.~Xie and X.~H.~Zhong, arXiv:2203.04458

N. Ikeno, W.H. Liang, G. Toledo , E. O, Phys.Rev.D 106 (2022) 3, 034022

VP INTERACTION IN THE LOCAL HIDDEN GAUGE APPROACH

Bando et al Phys Rep. 164



$$\mathcal{L}_{VVV} = ig\langle (V_\mu \partial_\nu V^\mu - \partial_\nu V_\mu V^\mu) V^\nu \rangle$$

Neglecting the k/M_V

$$g = M_V/2f \ (M_V \approx 800 \text{ MeV}, \ f = 93 \text{ MeV})$$

$$\varepsilon_1(\mathbf{k}) = (0, 1, 0, 0)$$

$$\varepsilon_2(\mathbf{k}) = (0, 0, 1, 0)$$

$$\varepsilon_3(\mathbf{k}) = (|\mathbf{k}|, 0, 0, \omega_\mathbf{k})/m_W$$

$$\mathcal{L}_{VPP} = -ig\langle V^\mu [P, \partial_\mu P] \rangle$$

$$-it = -g(V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)_{ij} V^\nu_{ji} \frac{i}{q^2 - M_V^2} V^{\nu'}_{lm} [P, \partial_{\nu'} P]_{ml}$$

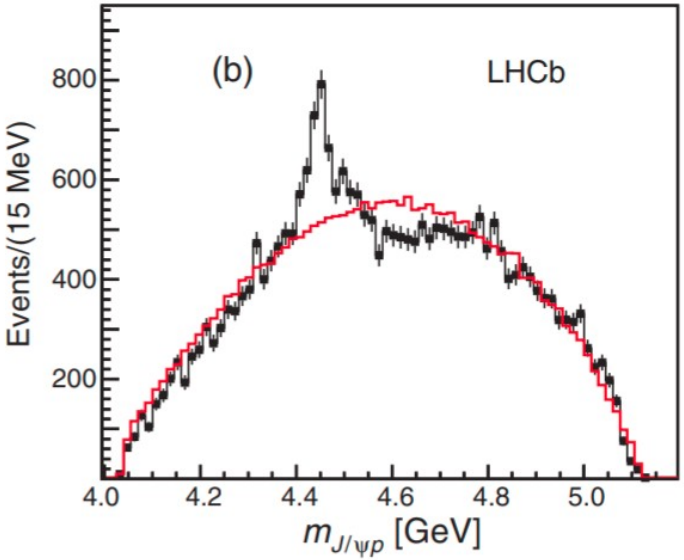
$$\sum_{pol} \epsilon^\nu_{ji} \epsilon^{\nu'}_{lm} = \left(-g^{\nu\nu'} + \frac{q^\nu q^{\nu'}}{M_V^2} \right) \delta_{jl} \delta_{im}$$

$$-it = -i \frac{g^2}{M_V^2} \langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)[P, \partial^\nu P] \rangle$$

$$\mathcal{L} = -\frac{1}{4f^2} \langle [V^\mu, \partial_\nu V^\mu][P, \partial^\nu P] \rangle$$

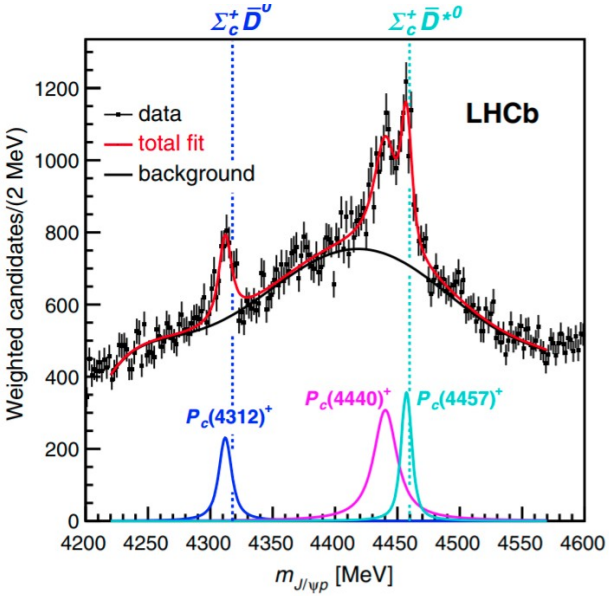
Chiral Lagrangian of M. C. Birse, Z. Phys. A 355, 231 (1996)

Pentaquark Pc



$\Lambda_b^0 \to J/\psi K^- p$ decays.

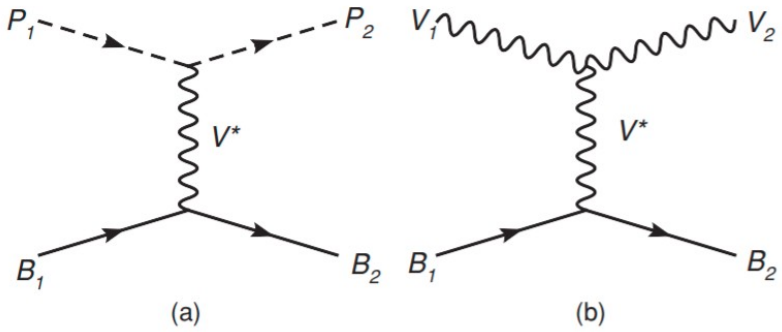
Phys. Rev. Lett. 115, 072001 2015



R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 122,222001 (2019).

$$M_{P_{c1}} = (4311.9 \pm 0.7^{+6.8}_{-0.6})\ \text{MeV},$$
$$\Gamma_{P_{c1}} = (9.8 \pm 2.7^{+3.7}_{-4.5})\ \text{MeV},$$
$$M_{P_{c2}} = (4440.3 \pm 1.3^{+4.1}_{-4.7})\ \text{MeV},$$
$$\Gamma_{P_{c2}} = (20.6 \pm 4.9^{+8.7}_{-10.1})\ \text{MeV},$$
$$M_{P_{c3}} = (4457.3 \pm 0.6^{+4.1}_{-1.7})\ \text{MeV},$$
$$\Gamma_{P_{c3}} = (6.4 \pm 2.0^{+5.7}_{-1.9})\ \text{MeV}.$$

Jia-Jun Wu, R. Molina, E. Oset, and B. S. Zou, PHYSICAL REVIEW C 84, 015202 (2011)



$$T = [1 - VG]^{-1} V$$

$$\mathcal{L}_{VVV} = ig\langle V^\mu [V^\nu, \partial_\mu V_\nu]\rangle,$$
$$\mathcal{L}_{PPV} = -ig\langle V^\mu [P, \partial_\mu P]\rangle,$$
$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu [V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$$G_l = i\int \frac{d^4q}{(2\pi)^4} \frac{M_l}{E_l(\mathbf{q})} \frac{1}{k^0 + p^0 - q^0 - E_l(\mathbf{q}) + i\epsilon} \frac{1}{\mathbf{q}^2 - m_l^2 + i\epsilon}$$

These Lagrangians in SU(3) were extrapolated to SU(4)

Coupled channels

$J = 1/2, I = 1/2$

$\eta_c N, J/\psi N, \bar{D}\Lambda_c, \bar{D}\Sigma_c, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$

(I, S)	z_R (MeV)		g_a
$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$
	4269	2.85	0

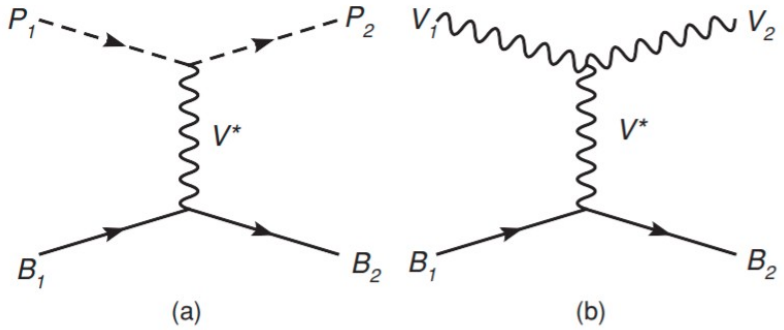
(I, S)	z_R (MeV)		g_a
$(1/2, 0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$
	4418	2.75	0

Modern formulation

C. W. Xiao, J. Nieves and E. Oset

PHYSICAL REVIEW D 100, 014021 (2019)

We use heavy quark spin symmetry and the transition potentials are calculated in terms of a few parameters. These parameters are obtained using and extension of the Local hidden gauge approach (exchange of vector mesons). Then we have only a cut off to regulate the loops as a free parameter, fitted to the bulk of the data.



We do not use SU(4). Meson states are simple. Baryon states single out the heavy quark and the symmetry is imposed on the light quarks.

Int. J. Mod. Phys. A 23, 2817 (2008), by W Roberts et al

(1) $J = 1/2, I = 1/2$
$\eta_c N, J/\psi N, \bar{D}\Lambda_c, \bar{D}\Sigma_c, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*.$

(2) $J = 1/2, I = 3/2$
$J/\psi\Delta, \bar{D}\Sigma_c, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*.$

(3) $J = 3/2, I = 1/2$
$J/\psi N, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c^*.$

(4) $J = 3/2, I = 3/2$
$\eta_c\Delta, J/\psi\Delta, \bar{D}^*\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c^*.$

(5) $J = 5/2, I = 1/2$
$\bar{D}^*\Sigma_c^*.$

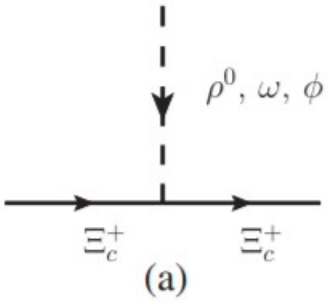
(6) $J = 5/2, I = 3/2$
$J/\psi\Delta, \bar{D}^*\Sigma_c^*.$

(1) Ξ_c^+: $\frac{1}{\sqrt{2}}c(us - su)$, and the spin wave function is the mixed antisymmetric, χ_{MA}, for the two light quarks.

$\Xi_c'^+$: $\frac{1}{\sqrt{2}}c(us + su)$, and now the spin wave function for the three quarks is the mixed symmetric, χ_{MS}, in the last two quarks,

$$\chi_{\mathrm{MS}} = \begin{cases} \frac{1}{\sqrt{6}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow - 2\downarrow\uparrow\uparrow), & \text{for } S_z = 1/2, \\ -\frac{1}{\sqrt{6}}(\downarrow\uparrow\downarrow + \downarrow\downarrow\uparrow - 2\uparrow\downarrow\downarrow), & \text{for } S_z = -1/2. \end{cases}$$

$$\chi_{\mathrm{MA}} = \begin{cases} \frac{1}{\sqrt{2}}\uparrow(\uparrow\downarrow - \downarrow\uparrow), & \text{for } S_z = 1/2, \\ \frac{1}{\sqrt{2}}\downarrow(\uparrow\downarrow - \downarrow\uparrow), & \text{for } S_z = -1/2. \end{cases}$$



At low energies the γ^μ becomes $\gamma^0 \sim 1$

$$\frac{1}{\sqrt{2}}\langle (us-su)| \begin{pmatrix} g\frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d}) \\ g\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d}) \\ gs\bar{s} \end{pmatrix} |\frac{1}{\sqrt{2}}(us-su)\rangle = \begin{pmatrix} \frac{1}{\sqrt{2}}g \\ \frac{1}{\sqrt{2}}g \\ g \end{pmatrix}$$

One can see that the heavy quarks are spectators if we exchange light vectors. Then heavy quark spin symmetry is automatically fulfilled. The exchange of light vectors gives the dominant terms.

S=1/2^{--}

	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
	$(4306.38 + i7.62)$ MeV						
g_i	$0.67 + i0.01$	$0.46 - i0.03$	$0.01 - i0.01$	$\mathbf{2.07 - i0.28}$	$0.03 + i0.25$	$0.06 - i0.31$	$0.04 - i0.15$
$\lvert g_i \rvert$	0.67	0.46	0.01	2.09	0.25	0.31	0.16
	$(4452.96 + i11.72)$ MeV						
g_i	$0.24 + i0.03$	$0.88 - 0.11$	$0.09 - i0.06$	$0.12 - i0.02$	$0.11 - i0.09$	$\mathbf{1.97 - i0.52}$	$0.02 + i0.19$
$\lvert g_i \rvert$	0.25	0.89	0.11	0.13	0.14	2.03	0.19
	$(4520.45 + i11.12)$ MeV						
g_i	$0.72 - i0.10$	$0.45 - i0.04$	$0.11 - i0.06$	$0.06 - i0.02$	$0.06 - i0.05$	$0.07 - i0.02$	$\mathbf{1.84 - i0.56}$
$\lvert g_i \rvert$	0.73	0.45	0.13	0.06	0.08	0.08	1.92

S=3/2⁻⁻

$(4374.33 + i6.87)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.73 - i0.06$	$0.11 - i0.13$	$0.02 - i0.19$	**$1.91 - i0.31$**	$0.03 - i0.30$
$\lvert g_i \rvert$	0.73	0.18	0.19	1.94	0.30
$(4452.48 + i1.49)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.30 - i0.01$	$0.05 - i0.04$	**$1.82 - i0.08$**	$0.08 - i0.02$	$0.01 - i0.19$
$\lvert g_i \rvert$	0.30	0.07	1.82	0.08	0.19
$(4519.01 + i6.86)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.66 - i0.01$	$0.11 - i0.07$	$0.10 - i0.3$	$0.13 - i0.02$	**$1.79 - i0.36$**
$\lvert g_i \rvert$	0.66	0.13	0.10	0.13	1.82

TABLE III. Identification of some of the $I = 1/2$ resonances found in this work with experimental states.

Mass [MeV]	Width [MeV]	Main channel	J^P	Experimental state
4306.4	15.2	$\bar{D}\Sigma_c$	$1/2^-$	$P_c(4312)$
4453.0	23.4	$\bar{D}^*\Sigma_c$	$1/2^-$	$P_c(4440)$
4452.5	3.0	$\bar{D}^*\Sigma_c$	$3/2^-$	$P_c(4457)$

Similar results obtained using single channels in

M. Z. Liu, Y. W. Pan, F. Z. Peng,
M. S. Sanchez, L. S. Geng,
A. Hosaka, and M. P. Valderrama,
Phys. Rev. Lett. 122,242001 (2019)

And in coupled channels in Du, Baru, Guo, Hanhart, Meissner
Phys.Rev.Lett. 124 (2020) 7, 072001 (also spectrum done)

Note state around 4380 MeV !!!

Another state

$J = 5/2,\ I = 1/2$

At 4500-4520 MeV

$\bar{D}^*\Sigma_c^*$

Side comment: We do not use SU(4) symmetry

Some people use SU(4) instead, Lutz, Ramos….

It does not matter: the dominant terms come from the exchange of light vectors and one projects over SU(3) automatically.

In the study of Ω_c states

G. Montaña, A. Feijoo, and A. Ramos, Eur. Phys. J. A 54, 64 (2018) use SU(4)

V. R. Debastiani, J. M. Dias, W. H. Liang and E. Oset PHYSICAL REVIEW D 97, 094035 (2018)

The results are practically indistinguishable

Talk given by M. Z. Wang, on behalf of the LHCb Collaboration at Implications workshop 2020

In the reaction $\Xi_b^- \to J/\psi \Lambda K^-$

Sci.Bull. 66 (2021) 1278-1287 • e-Print: 2012.10380

$$M = 4458.8 \pm 2.9^{+4.7}_{-1.2}\text{MeV}, \quad \Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}\text{MeV}$$

This reaction had been suggested in

Looking for a hidden-charm pentaquark state with strangeness $S = -1$ from Ξ_b^- decay into $J/\psi K^- \Lambda$

Hua-Xing Chen(BeiHang U.), Li-Sheng Geng, Wei-Hong Liang, Eulogio Oset, En Wang

PHYSICAL REVIEW C **93**, 065203 (2016)

Can the newly $P_{cs}(4459)$ be a strange hidden-charm $\Xi_c \bar{D}^*$ molecular pentaquarks?

Rui Chen E-Print: 2011.07214

In the work of Wu and Molina there were predictions about hidden charm and strange pentaquark molecules. An update using HQSS is done in

Xiao, Nieves, Oset Phys.Lett.B 799 (2019) 135051

i) $J=1/2,\ I=0$
$\eta_c\Lambda,\ J/\psi\Lambda,\ \bar{D}\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}\Xi_c',\ \bar{D}^*\Xi_c,\ \bar{D}_s^*\Lambda_c,\ \bar{D}^*\Xi_c',\ \bar{D}^*\Xi_c^*.$

ii) $J=3/2,\ I=0$
$J/\psi\Lambda,\ \bar{D}^*\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}^*\Xi_c',\ \bar{D}\Xi_c^*,\ \bar{D}^*\Xi_c^*.$

In addition, $\bar{D}^*\Xi_c^*$ could also couple to $J=5/2$ in $S-$wave.

1) Λ: $\frac{1}{\sqrt{2}}(\phi_{MS}\chi_{MS}+\phi_{MA}\chi_{MA})$
2) $\Lambda_c^+ : c\,\frac{1}{\sqrt{2}}(ud-du)\chi_{MA}$,
3) $\Xi_c^+ : c\,\frac{1}{\sqrt{2}}(us-su)\chi_{MA}$ and $\Xi_c^0 : c\,\frac{1}{\sqrt{2}}(ds-sd)\chi_{MA}$,
4) $\Xi_c'^+ : c\,\frac{1}{\sqrt{2}}(us+su)\chi_{MS}$ and $\Xi_c'^0 : c\,\frac{1}{\sqrt{2}}(ds+sd)\chi_{MS}$
5) $\Xi_c^{*+} : c\,\frac{1}{\sqrt{2}}(us+su)\chi_S$ and $\Xi_c^{*0} : c\,\frac{1}{\sqrt{2}}(ds+sd)\chi_S$,

experiment

Dimensionless coupling constants of the $(I=0, J^P=1/2^-)$ poles found in this work.

	$\eta_c\Lambda$	$J/\psi\Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c'$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}^*\Xi_c^*$
$4276.59+i7.67$									
g_i	$0.17-i0.03$	$0.29-i0.07$	$\mathbf{2.93+i0.08}$	$0.76+i0.31$	$0.00+i0.01$	$0.01+i0.02$	$0.01+i0.04$	$0.01-i0.02$	$0.01-i0.03$
$\lvert g_i\rvert$	0.17	0.30	**2.93**	0.82	0.01	0.02	0.05	0.02	0.03
$4429.84+i7.92$									
g_i	$0.29-i0.11$	$0.17-i0.07$	$0.00-i0.00$	$0.00-i0.00$	$0.15-i0.26$	$\mathbf{2.78+i0.01}$	$0.66+i0.32$	$0.01+i0.05$	$0.01+i0.03$
$\lvert g_i\rvert$	0.31	0.18	0.00	0.00	0.30	**2.78**	0.73	0.05	0.04
$4436.70+i1.17$									
g_i	$0.24+i0.03$	$0.14+0.01$	$0.00-i0.00$	$0.00-i0.00$	$\mathbf{1.72-i0.04}$	$0.22-i0.31$	$0.06-i0.01$	$0.01-i0.04$	$0.01-i0.03$
$\lvert g_i\rvert$	0.24	0.14	0.00	0.00	**1.72**	0.38	0.07	0.04	0.03
$4580.96+i2.44$									
g_i	$0.12-i0.00$	$0.37-i0.04$	$0.02-i0.01$	$0.02-i0.01$	$0.03-i0.00$	$0.02-i0.02$	$0.03-i0.02$	$\mathbf{1.57-i0.17}$	$0.00+i0.02$
$\lvert g_i\rvert$	0.12	0.37	0.02	0.02	0.03	0.03	0.03	**1.58**	0.02
$4650.86+i2.59$									
g_i	$0.32-i0.05$	$0.19-i0.03$	$0.02-i0.01$	$0.03-i0.02$	$0.02-i0.00$	$0.01-i0.01$	$0.02-i0.01$	$0.01-i0.00$	$\mathbf{1.41-i0.23}$
$\lvert g_i\rvert$	0.32	0.19	0.03	0.04	0.02	0.02	0.02	0.02	**1.43**

Same as Table 1 for $J^P=3/2^-$.

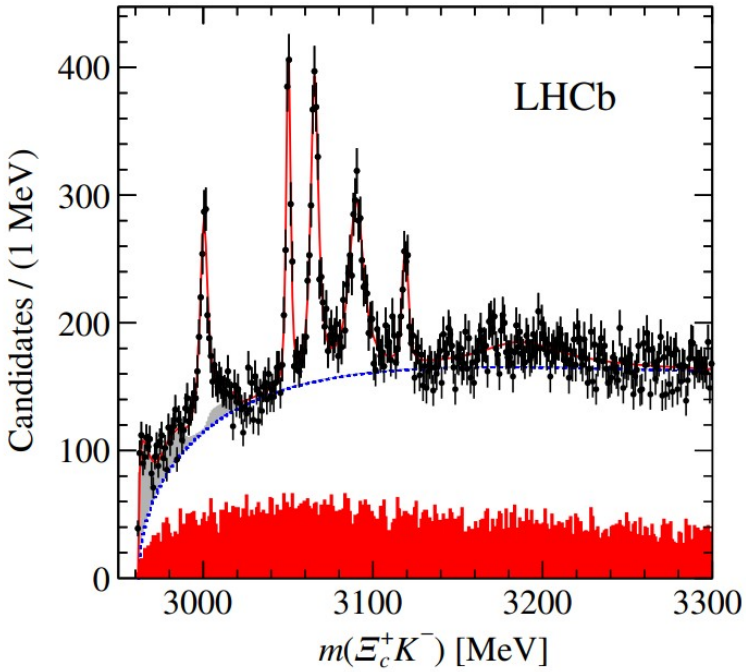
	$J/\psi\Lambda$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}\Xi_c^*$	$\bar{D}^*\Xi_c^*$
$4429.52+i7.67$						
g_i	$0.31-i0.10$	$\mathbf{2.77-i0.02}$	$0.67+i0.32$	$0.00+i0.0.02$	$0.00-i0.06$	$0.00+i0.0.04$
$\lvert g_i\rvert$	0.32	**2.77**	0.74	0.02	0.06	0.04
$4506.99+i1.03$						
g_i	$0.27-i0.02$	$0.02-i0.03$	$0.02-i0.02$	$0.00-i0.03$	$\mathbf{1.56-i0.07}$	$0.00-i0.05$
$\lvert g_i\rvert$	0.27	0.03	0.03	0.03	**1.56**	0.05
$4580.96+i0.34$						
g_i	$0.14-i0.01$	$0.01-i0.01$	$0.01-i0.01$	$\mathbf{1.54-i0.02}$	$0.02-i0.00$	$0.00-i0.04$
$\lvert g_i\rvert$	0.14	0.01	0.02	**1.54**	0.02	0.04
$4650.58+i1.48$						
g_i	$0.29-i0.02$	$0.02-i0.01$	$0.03-i0.02$	$0.03-i0.01$	$0.03-i0.00$	$\mathbf{1.40-i0.13}$
$\lvert g_i\rvert$	0.29	0.03	0.03	0.03	0.03	**1.41**

Related works

J.~A.~M.~Valera, I, V.~K.~Magas and A.~Ramos,
%``Double strangeness molecular-type pentaquarks from coupled channel dynamics,"
[arXiv:2210.02792 [hep-ph]].

C.~W.~Shen, Y.~h.~Lin and U.~G.~Mei\ss{}ner,
%``P_{cc}^N states in a unitarized coupled-channel approach,"
[arXiv:2208.10865 [hep-ph]].

Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+ K^-$



LHCb PRL 118, 182001 (2017)

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.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

$$V_{ij} = D_{ij} \frac{1}{4f_\pi^2} (p^0 + p'^0)$$

Debastiani, Dias , Liang , E. O.
Phys.Rev.D 97 (2018) 9, 094035

TABLE III. D_{ij} coefficients of Eq. (23) for the meson-baryon states coupling to $J^P = 1/2^-$ in s-wave.

$J = 1/2$	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
$\Xi_c \bar{K}$	-1	0	$-\frac{1}{\sqrt{2}}\lambda$	0	0	0	0
$\Xi'_c \bar{K}$		-1	$\frac{1}{\sqrt{6}}\lambda$	$-\frac{4}{\sqrt{3}}$	0	0	0
ΞD			-2	$\frac{\sqrt{2}}{3}\lambda$	0	0	0
$\Omega_c \eta$				0	0	0	0
ΞD^*					-2	$-\frac{1}{\sqrt{2}}\lambda$	$\frac{1}{\sqrt{6}}\lambda$
$\Xi_c \bar{K}^*$						-1	0
$\Xi'_c \bar{K}^*$							-1

$$\lambda \equiv \frac{-m_V^2}{(m_D - m_K)^2 - m_{D_s^*}^2} \approx 0.25$$

$$T = [1 - VG]^{-1} V$$

Poles searched in the second Riemann sheet

$$G_l^{II} = G_l^I + i\frac{2M_l q}{4\pi\sqrt{s}}$$

Couplings defined as

$$T_{ij} = \frac{g_i g_j}{\sqrt{s} - z_R}$$

Three states in very good agreement with experiment

TABLE VI. The coupling constants to various channels for the poles in the $J^P = 1/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_i G_i^{II}$ in MeV.

$3054.05 + i0.44$	$\Xi_c\bar{K}$	$\Xi_c'\bar{K}$	ΞD	$\Omega_c\eta$	ΞD^*	$\Xi_c\bar{K}^*$	$\Xi_c'\bar{K}^*$
g_i	$-0.06 + i0.14$	$1.94 + i0.01$	$-2.14 + i0.26$	$1.98 + i0.01$	0	0	0
$g_i G_i^{II}$	$-1.40 - i3.85$	$-34.41 - i0.30$	$9.33 - i1.10$	$-16.81 - i0.11$	0	0	0

$3091.28 + i5.12$	$\Xi_c\bar{K}$	$\Xi_c'\bar{K}$	ΞD	$\Omega_c\eta$	ΞD^*	$\Xi_c\bar{K}^*$	$\Xi_c'\bar{K}^*$
g_i	$0.18 - i0.37$	$0.31 + i0.25$	$5.83 - i0.20$	$0.38 + i0.23$	0	0	0
$g_i G_i^{II}$	$5.05 + i10.19$	$-9.97 - i3.67$	$-29.82 + i0.31$	$-3.59 - i2.23$	0	0	0

TABLE VIII. The coupling constants to various channels for the poles in the $J^P = 3/2^-$ sector, with $q_{\max} = 650$ MeV, and $g_i G_i^{II}$ in MeV.

3124.84	$\Xi_c^*\bar{K}$	$\Omega_c^*\eta$	ΞD^*	$\Xi_c\bar{K}^*$	$\Xi^* D$	$\Xi_c'\bar{K}^*$
g_i	1.95	1.98	0	0	-0.65	0
$g_i G_i^{II}$	-35.65	-16.83	0	0	1.93	0

Description of the Ξ_c and Ξ_b states as molecular states

Eur. Phys. J. C (2019) 79:167

Table 10 Poles in the $J^P = 1/2^-$ sector from pseudoscalar-baryon interaction (all units are in MeV)

q_{max}	600	650	700
	$2684.23 + i89.72$	$2679.71 + i76.48$	$2673.49 + i64.54$
	$2800.72 + i100.03$	$2801.80 + i86.16$	$2803.28 + i72.06$
	$2880.76 + i10.31$	$2842.47 + i10.13$	$\mathbf{2791.30 + i3.63}$
	$2896.57 + i1.34$	$2870.10 + i10.64$	$2850.70 + i16.38$
	$2969.50 + i3.30$	$2955.62 + i5.10$	$\mathbf{2937.15 + i7.31}$
	$3171.55 + i32.48$	$3160.12 + i37.77$	$3148.11 + i41.88$

The bold numbers indicate the poles that can be associated with the experimental data

Experiment

Mass	JP	Γ [MeV]
2790	1/2-	8.9+-1
2930	?	10.2+-1.4

Q. X. Yu, R. Pavao, V.R. Debastiani, and E.O.

Ξc states

Table 15 The poles in the $J^P = 1/2^-, 3/2^-$ sector from the vector-baron interaction (all units are in MeV)

q_{max}	600	650	700	750	800
	3055.63	3016.46	**2973.76**	2928.28	2880.75
	3117.37	3094.39	**3068.21**	3040.89	3013.14
	3121.75	3115.67	**3109.04**	3100.55	3090.16
	3234.03+i0.22	3204.98	3174.50	3143.09	3111.43

The bold numbers indicate the poles that can be associated with the experimental data

3080	?	5.6+-2.2
3123	?	4+-4

Table 11 The coupling constants to various channels and $g_i G_i^{II}$ for the pole at $2191.30 + i3.63$ MeV in the $J^P = 1/2^-$ sector with $q_{max} = 700$ MeV (all units are in MeV)

2791.30 + *i*3.63	$\Xi_c\pi$	$\Xi_c'\pi$	$\Lambda_c\bar{K}$	$\Sigma_c\bar{K}$	ΛD
g_i	$-0.01 - i0.03$	$0.39 - i0.44$	$-0.09 - i0.05$	$1.05 - i0.47$	$1.91 - i0.09$
$g_i G_i^{II}$	$0.78 + i0.53$	$-3.98 + i14.85$	$2.70 + i0.73$	$-11.27 + i4.95$	$-7.45 + i0.27$

	$\Xi_c\eta$	ΣD	$\Xi_c'\eta$	$\Omega_c K$	ΞD_s
g_i	$0.23 + i0.03$	$\mathbf{8.82 + i0.38}$	$0.49 - i0.17$	$0.21 - i0.26$	$5.44 + i0.20$
$g_i G_i^{II}$	$-2.00 - i0.26$	$\mathbf{-29.16 - i1.48}$	$-3.53 + i1.19$	$-1.42 + i1.74$	$-11.96 - i0.49$

The bold numbers indicate the channel with largest coupling

Description of the Ξ_c and Ξ_b states as molecular states

Eur. Phys. J. C (2019) 79:167

Q. X. Yu, R. Pavao, V.R. Debastiani, and E.O.

Table 20 The coupling constants to various pseudoscalar-baryon channels and $g_i G_i^{II}$ for the poles in the $J^P = 1/2^-$ sector with $q_{max} = 650$ MeV (all units are in MeV)

6220.30 + i12.60	$\Xi_b\pi$	$\Xi'_b\pi$	$\Lambda_b\bar{K}$	$\Sigma_b\bar{K}$	$\Lambda\bar{B}$
g_i	$0.01 + i0.02$	$0.34 - i0.91$	$0.01 - i0.01$	$\mathbf{3.53 - i0.14}$	$-1.03 + i0.61$
$g_i G_i^{II}$	$-0.60 + i0.05$	$10.08 + i25.84$	$0.42 + i0.15$	$\mathbf{-44.85 - i0.67}$	$1.47 - i0.78$

	$\Xi_b\eta$	$\Sigma\bar{B}$	$\Xi'_b\eta$	$\Omega_b K$	ΞB_s
g_i	$-0.00 + i0.04$	$-2.09 + i4.72$	$1.80 + i0.02$	$0.09 - i0.65$	$-1.93 + i2.81$
$g_i G_i^{II}$	$0.02 - i0.38$	$2.54 - i5.25$	$-13.14 - i0.55$	$-0.74 + i4.33$	$1.45 - i2.02$

LHCb

Observation of a new Ξ_b^0 state

PHYSICAL REVIEW D **103,** 012004 (2021)

$$m(\Xi_b(6227)^0) = 6227.1^{+1.4}_{-1.5} \pm 0.5 \text{ MeV} \quad \text{and} \quad \Gamma(\Xi_b(6227)^0) = 18.6^{+5.0}_{-4.1} \pm 1.4 \text{ MeV}$$

More molecular baryonic states

J.~M.~Dias, Q.~X.~Yu, W.~H.~Liang, Z.~F.~Sun, J.~J.~Xie and E.~Oset,
%``Ξ_{bb} and Ω_{bbb} molecular states,''
Chin. Phys. C \textbf{44}, no.6, 064101 (2020)

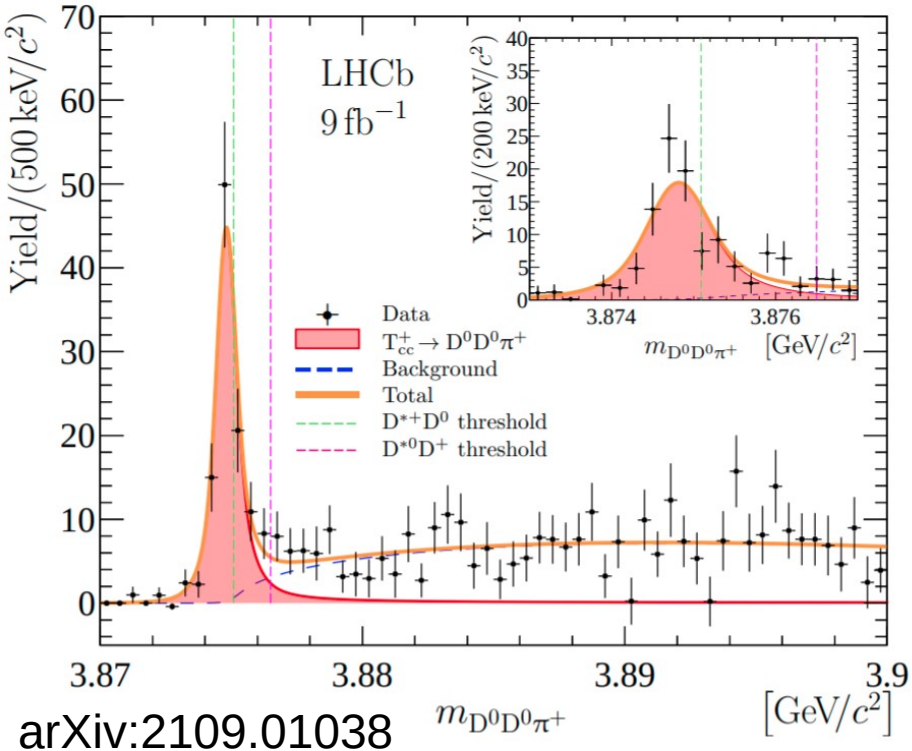
J.~M.~Dias, V.~R.~Debastiani, J.~J.~Xie and E.~Oset,
%``Doubly charmed Ξ_{cc} molecular states from meson-baryon interaction,''
Phys. Rev. D \textbf{98}, no.9, 094017 (2018)

W.~H.~Liang, J.~M.~Dias, V.~R.~Debastiani and E.~Oset,
%``Molecular Ω_b states,''
Nucl. Phys. B \textbf{930}, 524-532 (2018)

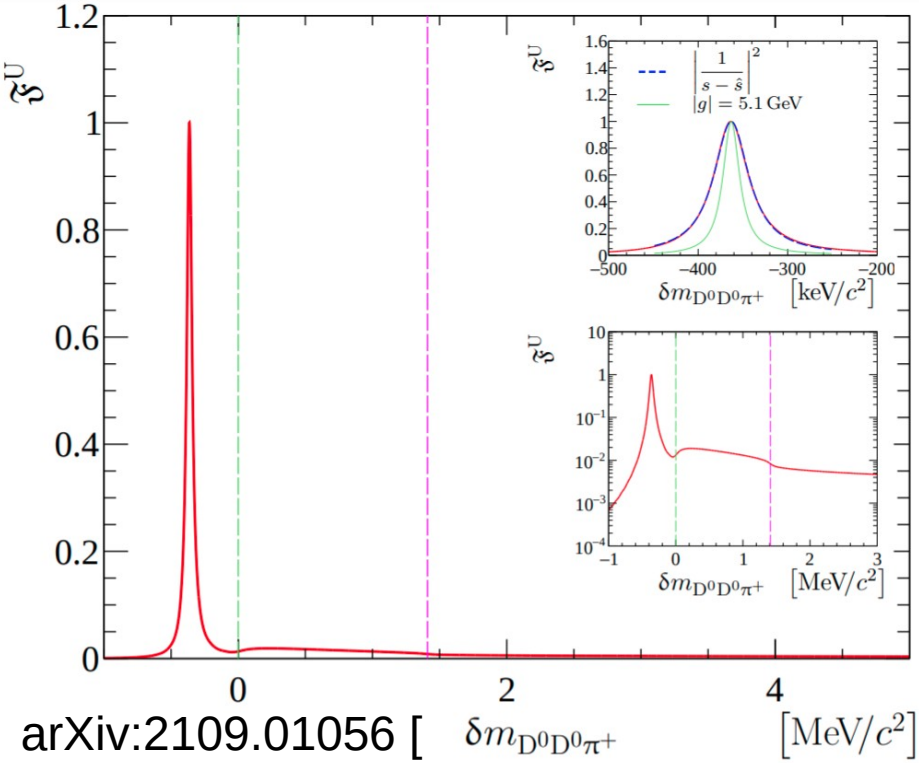
Q.~X.~Yu, J.~M.~Dias, W.~H.~Liang and E.~Oset,
%``Molecular $\Xi _{bc}$ states from meson-baryon interaction,''
Eur. Phys. J. C \textbf{79}, no.12, 1025 (2019)

W.~F.~Wang, A.~Feijoo, J.~Song and E.~Oset,
%``Molecular Ω_{cc} , Ω_{bb} and Ω_{bc} states,''
[arXiv:2208.14858 [hep-ph]].

The Tcc discovery by the LHCb collaboration



arXiv:2109.01038



arXiv:2109.01056 [

Spectra without correction by experimental resolution

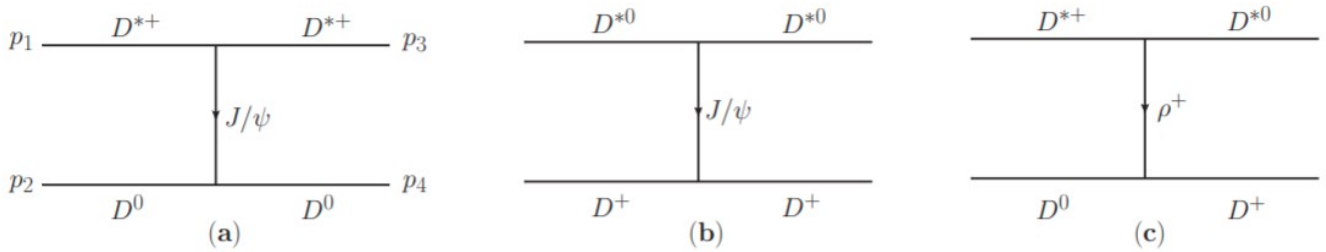
$$m_{\rm exp} = 3875.09\ {\rm MeV} + \delta m_{\rm exp},$$

$$\delta m_{\rm exp} = -273 \pm 61 \pm 5^{+11}_{-14}\ {\rm keV}. \quad \Gamma = 410 \pm 165 \pm 43^{+18}_{-38}\ {\rm keV}$$

Spectra corrected by resolution and analyzed with a unitary amplitude

$$\delta m_{\rm exp} = -360 \pm 40^{+4}_{-0}\ {\rm keV}, \quad \Gamma = 48 \pm 2^{+0}_{-14}\ {\rm keV}.$$

A. Feijoo, W.H. Liang, Eulogio Oset, Phys.Rev.D 104 (2021) 11, 114015



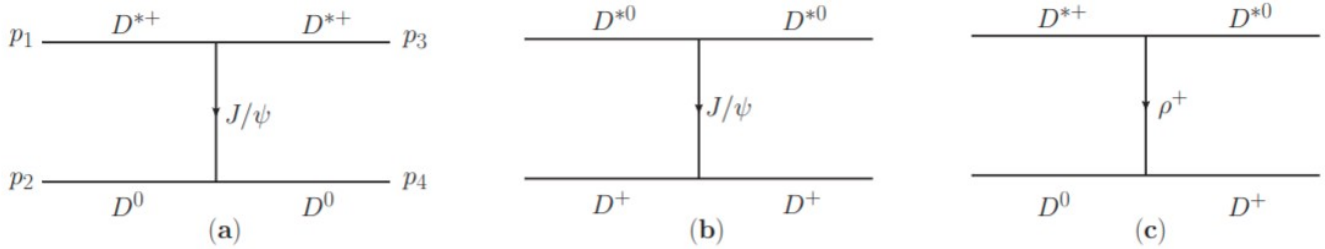
$$\mathcal{L}_{VPP} = -ig\,\langle [P, \partial_\mu P] V^\mu \rangle,$$
$$\mathcal{L}_{VVV} = ig\,\langle (V^\nu \partial_\mu V_\nu - \partial_\mu V^\nu V_\nu) V^\mu \rangle,$$
$$g = \frac{M_V}{2\,f}, \quad (M_V = 800 \text{ MeV}, \; f = 93 \text{ MeV}).$$

$$P = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix} \qquad V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

$D^{*+}D^0, D^{*0}D^+$ the 1, 2 channels, the interaction that we obtain is

$$V_{ij} = C_{ij}\, g^2\, (p_1+p_3)\cdot(p_2+p_4)\, \vec{\epsilon}\cdot\vec{\epsilon}\,'$$
$$\to C_{ij}\, g^2\, \frac{1}{2}[3s - (M^2+m^2+M'^2+m'^2)$$
$$-\frac{1}{s}(M^2-m^2)(M'^2-m'^2)]\, \vec{\epsilon}\cdot\vec{\epsilon}\,',$$

$$C_{ij} = \begin{pmatrix} \frac{1}{M^2_{J/\psi}} & \frac{1}{m^2_\rho} \\ \frac{1}{m^2_\rho} & \frac{1}{M^2_{J/\psi}} \end{pmatrix} \qquad T = [1 - VG]^{-1}\, V,$$



$$|D^*D, I=0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+),$$
$$|D^*D, I=1, I_3=0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+),$$

$$C_{00} = \frac{1}{M^2_{J/\psi}} - \frac{1}{m^2_\rho}; \quad C_{11} = \frac{1}{M^2_{J/\psi}} + \frac{1}{m^2_\rho}; \quad C_{01} = 0;$$

There is attraction in I=0, repulsion in I=1, but due to different masses there is a bit of isospin breaking

Convolution of the G function:
Origin of the width.

Spectral function
Mass distribution

$$\mathrm{Im}[D(s_V)] = \mathrm{Im}\left(\frac{1}{s_V - M_V^2 + iM_V\Gamma_V}\right)$$

$$G(\sqrt{s}, M_k, m_k) = \frac{\int_{(M_V-2\Gamma_V)^2}^{(M_V+2\Gamma_V)^2} ds_V\, G(\sqrt{s}, \sqrt{s_V}, m_k) \times \mathrm{Im}[D(s_V)]}{\int_{(M_V-2\Gamma_V)^2}^{(M_V+2\Gamma_V)^2} ds_V\, \mathrm{Im}[D(s_V)]}$$

$$G_l = i \int \frac{d^4q}{(2\pi)^4} \frac{M_l}{E_l(\mathbf{q})} \frac{1}{k^0 + p^0 - q^0 - E_l(\mathbf{q}) + i\epsilon}$$

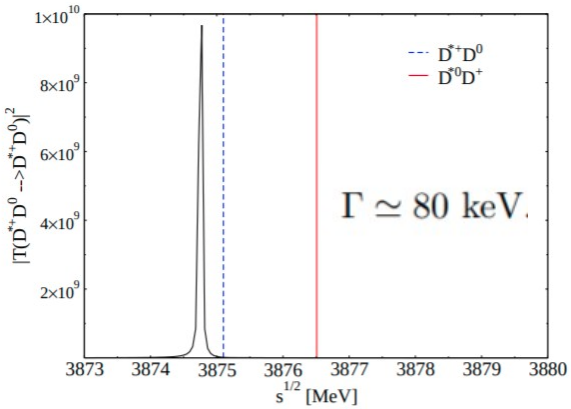
$$\Gamma_{D^{*+}}(M_{\mathrm{inv}}) = \Gamma(D^{*+}) \left(\frac{m_{D^{*+}}}{M_{\mathrm{inv}}}\right)^2 \cdot \left[\frac{2}{3}\left(\frac{p_\pi}{p_{\pi,\mathrm{on}}}\right)^3 + \frac{1}{3}\left(\frac{p'_\pi}{p'_{\pi,\mathrm{on}}}\right)^3\right]$$

where p_π is the π^+ momentum in $D^{*+} \to D^0\pi^+$ decay

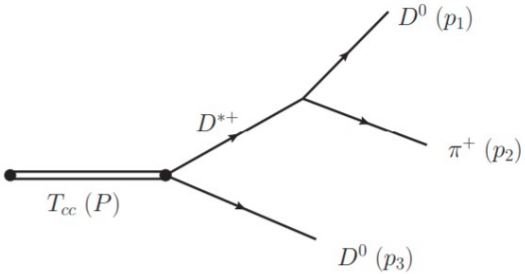
$p'_\pi, p'_{\pi,\mathrm{on}}$ are the same magnitudes for $D^{*+} \to D^+\pi^0$.

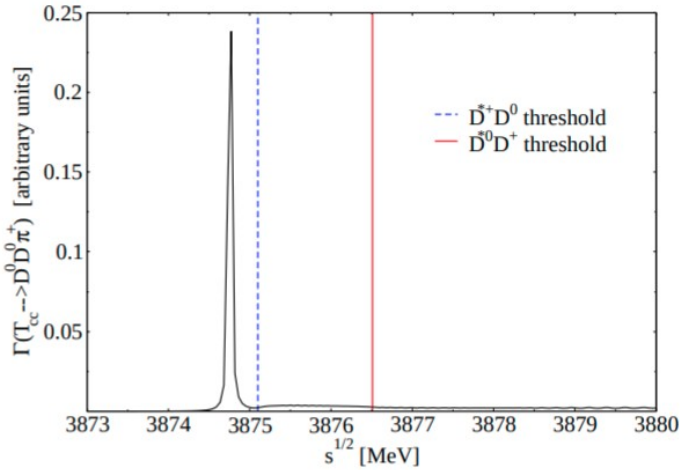
$$\Gamma_{D^{*0}}(M_{\mathrm{inv}}) = \Gamma(D^{*0}) \left(\frac{m_{D^{*0}}}{M_{\mathrm{inv}}}\right)^2 \cdot \left[0.647\left(\frac{p_\pi}{p_{\pi,\mathrm{on}}}\right)^3 + 0.353\right]$$

$D^{*0} \to D^0\pi^0$ $\quad$ $D^{*0} \to D^0\gamma$

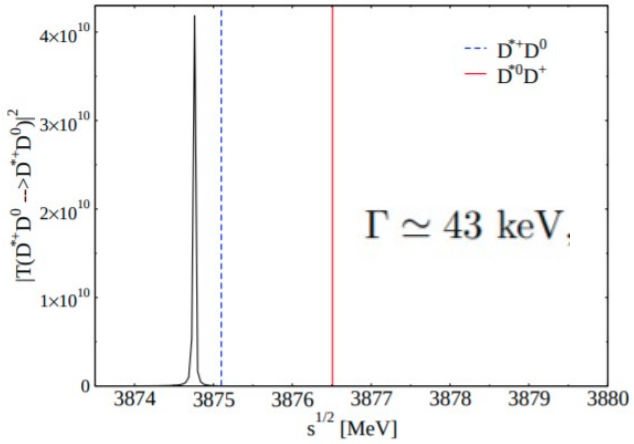


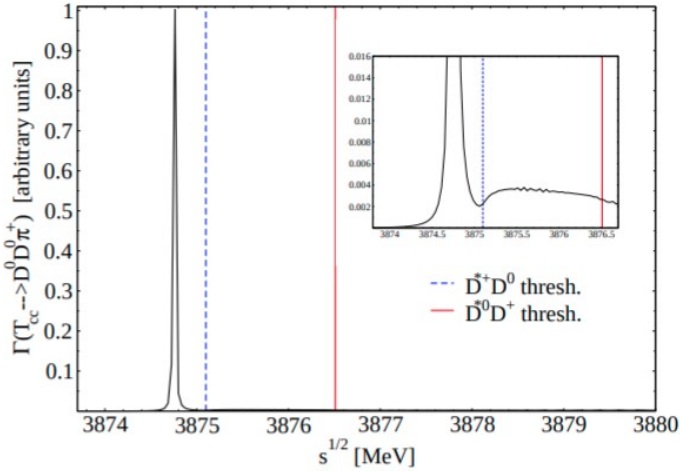
With mass of experimental raw data





With mass from unitary reanalysis of LHCb data , Mikhasenko





Works along the molecular structure of Tcc

L. Meng, G. J. Wang, B. Wang and S. L. Zhu, Phys. Rev. D 104, 051502 (2021)

Xi-Zhe Ling, Ming-Zhu Liu, Li-Sheng Geng, En Wang, Ju-Jun Xie, Phys.Lett.B 826 (2022) 136897

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Hong-Wei Ke, Xiao-Hai Liu, Xue-Qian Li, Eur.Phys.J.C 82 (2022) 2, 144

Xiang-Kun Dong, Feng-Kun Guo, Bing-Song Zou, Commun.Theor.Phys. 73 (2021) 12, 125201

…….

Multihadron states coming:

One baryon and two mesons

Three mesons

Many mesons ……

A. Martinez Torres, K. P. Khemchandani, L. Roca, and E. Oset. Few-body systems consisting of mesons. Few Body Syst., 61(4):35, 2020.

Tian-Wei Wu, Ya-Wen Pan, Ming-Zhu Liu, and Li-Sheng Geng. Multi-hadron molecules: status and prospect. Sci. Bull., 67:1735–1738, 2022.

“Meson number is not conserved, but flavor is conserved in strong interactions. Multimeson states with different flavors can be relatively stable → a periodic table of multihadron states is anticipated “