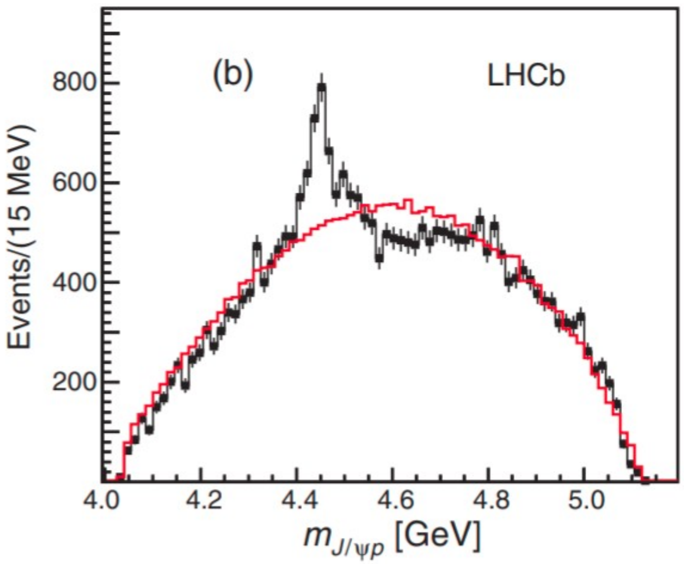
# Predicted molecular states recently found: LHCb pentaquarks, $X_0(2866)$, $\Omega(2012)$

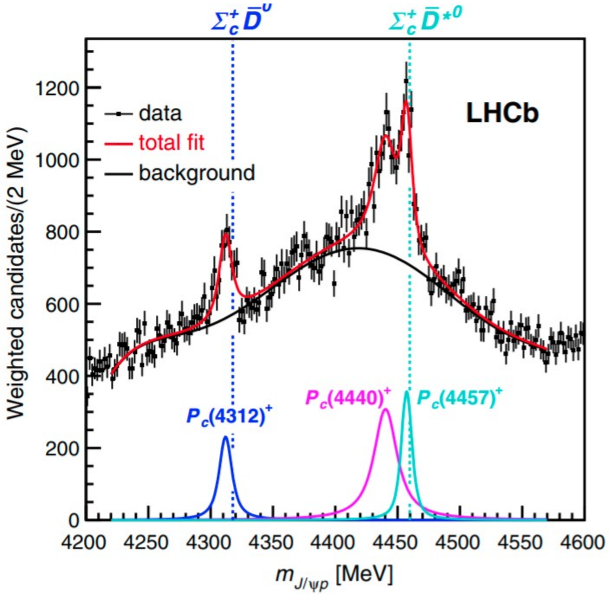
E Oset, IFIC and Departamento de Fisica Teorica, Universidad de Valencia
Raquel Molina, Juan Nieves, Chu Wen Xiao, Natsumi Ikeno, Genaro Toledo




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

Phys. Rev. Lett. 115, 072001

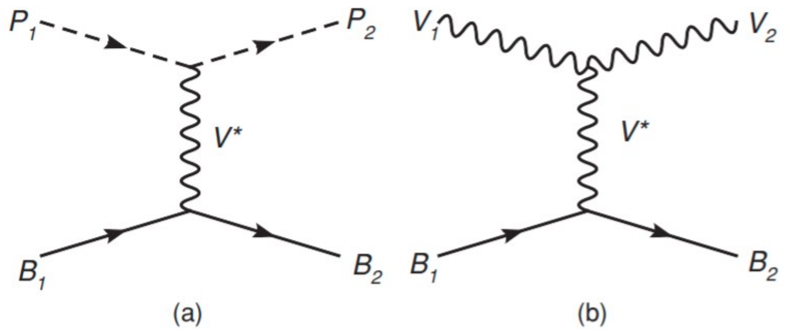
2015




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)




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

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

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

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 |

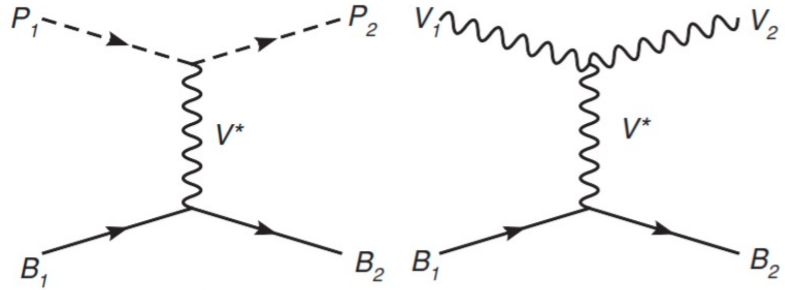
| $(I, S)$ | $z_R$ (MeV) | | $g_a$ |
|---|---|---|---|
| $(1/2, 0)$ | | $\bar{D}^*\Sigma_c$ | $\bar{D}^*\Lambda_c^+$ |
| | 4418 | 2.75 | 0 |

# 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.




(a) (b)

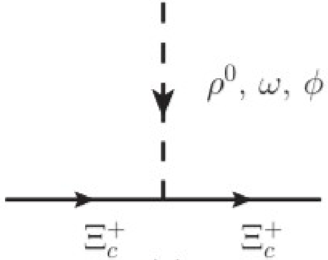
(1) $J = 1/2, I = 1/2$
$\eta_c N, J/\psi N, \bar{D}\Lambda_c, \bar{D}\Sigma_c, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$.
(2) $J = 1/2, I = 3/2$
$J/\psi\Delta, \bar{D}\Sigma_c, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$.
(3) $J = 3/2, I = 1/2$
$J/\psi N, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c^*$.
(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) $J = 5/2, I = 3/2$
$J/\psi\Delta, \bar{D}^*\Sigma_c^*$.

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) $\Xi_c^+$: $\frac{1}{\sqrt{2}}c(us - su)$, and the spin wave function is the mixed antisymmetric, $\chi_{\mathrm{MA}}$, 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, $\chi_{\mathrm{MS}}$, in the last two quarks, At low energies the $\gamma^\mu$ becomes $\gamma^0 \sim 1$



(a)

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

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$^{--}$

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

S=3/2$^{--}$

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

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

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

At 4500-4520 MeV

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 $\Omega_c$ 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

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) $\Lambda$: $\frac{1}{\sqrt{2}}(\phi_{MS}\chi_{MS}+\phi_{MA}\chi_{MA})$
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 $\Xi_c^{*0} : c\,\frac{1}{\sqrt{2}}(ds+sd)\chi_S$,

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** |

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

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

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

This reaction had been suggested in

**Looking for a hidden-charm pentaquark state with strangeness $S = -1$ from $\Xi_b^-$ 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

D. Johnson (CERN), LHC Seminar, $B \to DDh$ decays: A new (virtual) laboratory for exotic particle searches at LHCb p. August 11 (2020)

LHCb finds two states of $J^P = 0^+, 1^-$ decaying to DKbar that offers us the first clear example of an exotic hadron with open heavy flavor, of type cs ubar dbar. The states found are

$$X_0(2866): M = 2866 \pm 7 \quad \text{and} \quad \Gamma = 57.2 \pm 12.9\,\text{MeV},$$
$$X_1(2900): M = 2904 \pm 5 \quad \text{and} \quad \Gamma = 110.3 \pm 11.5\,\text{MeV}$$

R. Molina, T. Branz, and E. Oset PHYSICAL REVIEW D 82, 014010 (2010)

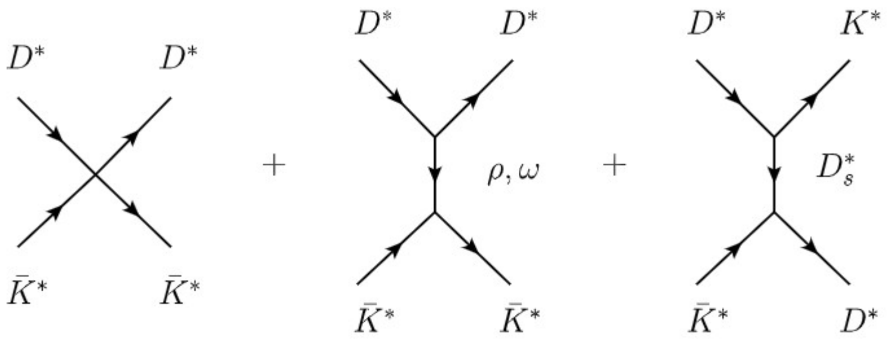
New interpretation for the $D_{s2}$ (2573) and the prediction of novel exotic charmed mesons

Molecular state of D* K*bar

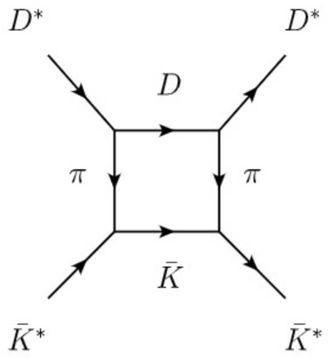
TABLE VI. $C = 1$; $S = -1$; $I = 0$. Mass and width for the states with $J = 0$ and 2.

| $I[J^P]$ | $\sqrt{s}_{\text{pole}}$ (MeV) | Model | $\Gamma$ (MeV) |
|---|---|---|---|
| $0[0^+]$ | 2848 | A, $\Lambda = 1400$ MeV | 23 |
| | | A, $\Lambda = 1500$ MeV | 30 |
| | | B, $\Lambda = 1000$ MeV | 25 |
| | | B, $\Lambda = 1200$ MeV | 59 |
| $0[1^+]$ | 2839 | Convolution | 3 |
| $0[2^+]$ | 2733 | A, $\Lambda = 1400$ MeV | 11 |
| | | A, $\Lambda = 1500$ MeV | 14 |
| | | B, $\Lambda = 1000$ MeV | 22 |
| | | B, $\Lambda = 1200$ MeV | 36 |

# Revision to the light of experimental results   R. Molina, E. O.  Phys.Lett.B 811 (2020) 135870




Decay mode




$$\mathcal{L}_{VVVV} = \frac{1}{2} g^2 \langle [V_\mu, V_\nu] V^\mu V^\nu \rangle,$$

$$\mathcal{L}_{VVV} = ig \langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu) V^\nu ) \rangle \quad (1)$$

$$F(q) = e^{((p_1^0 - q^0)^2 - \vec{q}^{\,2})/\Lambda^2}$$

where $g = M_V / 2 f_\pi$ ($M_V = 800$ MeV, $f_\pi = 93$ MeV) and $V_\mu$ is given by

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

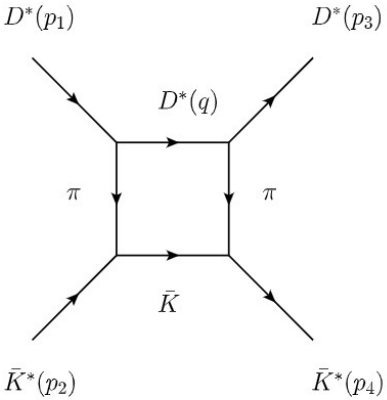
$$\mathcal{P}^{(0)} = \frac{1}{3} \epsilon_\mu \epsilon^\mu \epsilon_\nu \epsilon^\nu$$

$$\mathcal{P}^{(1)} = \frac{1}{2} (\epsilon_\mu \epsilon_\nu \epsilon^\mu \epsilon^\nu - \epsilon_\mu \epsilon_\nu \epsilon^\nu \epsilon^\mu)$$

$$\mathcal{P}^{(2)} = \{ \frac{1}{2} (\epsilon_\mu \epsilon_\nu \epsilon^\mu \epsilon^\nu + \epsilon_\mu \epsilon_\nu \epsilon^\nu \epsilon^\mu) - \frac{1}{3} \epsilon_\mu \epsilon^\mu \epsilon_\nu \epsilon^\nu \}$$

Tree level amplitudes for $D^*\bar{K}^*$ in $I=0$. The last column shows the value of $V$ at threshold.

| $J$ | Amplitude | Contact | V-exchange | $\sim$ Total |
|---|---|---|---|---|
| 0 | $D^*\bar{K}^* \to D^*\bar{K}^*$ | $4g^2$ | $-\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D_s^*}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} - \frac{3}{m^2_\rho})(p_1+p_3).(p_2+p_4)$ | $-9.9g^2$ |
| 1 | $D^*\bar{K}^* \to D^*\bar{K}^*$ | 0 | $\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D_s^*}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} - \frac{3}{m^2_\rho})(p_1+p_3).(p_2+p_4)$ | $-10.2g^2$ |
| 2 | $D^*\bar{K}^* \to D^*\bar{K}^*$ | $-2g^2$ | $-\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D_s^*}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} - \frac{3}{m^2_\rho})(p_1+p_3).(p_2+p_4)$ | $-15.9g^2$ |




$$\mathcal{L} = \frac{iG'}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\langle\delta_\mu V_\nu \delta_\alpha V_\beta P\rangle$$

with $G' = \frac{3g'}{4\pi^2 f}$; $g' = -\frac{G_V m_\rho}{\sqrt{2}f^2}$, $G_V \simeq 55$ MeV,

| $I(J^P)$ | $M$[MeV] | $\Gamma$[MeV] | Coupled channels | state |
|---|---|---|---|---|
| $0(2^+)$ | 2775 | 38 | $D^*\bar{K}^*$ | ? |
| $0(1^+)$ | 2861 | 20 | $D^*\bar{K}^*$ | ? |
| $0(0^+)$ | 2866 | 57 | $D^*\bar{K}^*$ | $X_0(2866)$ |

No D Kbar decay

No D* Kbar decay

Belle

PHYSICAL REVIEW LETTERS 121, 052003 (2018)

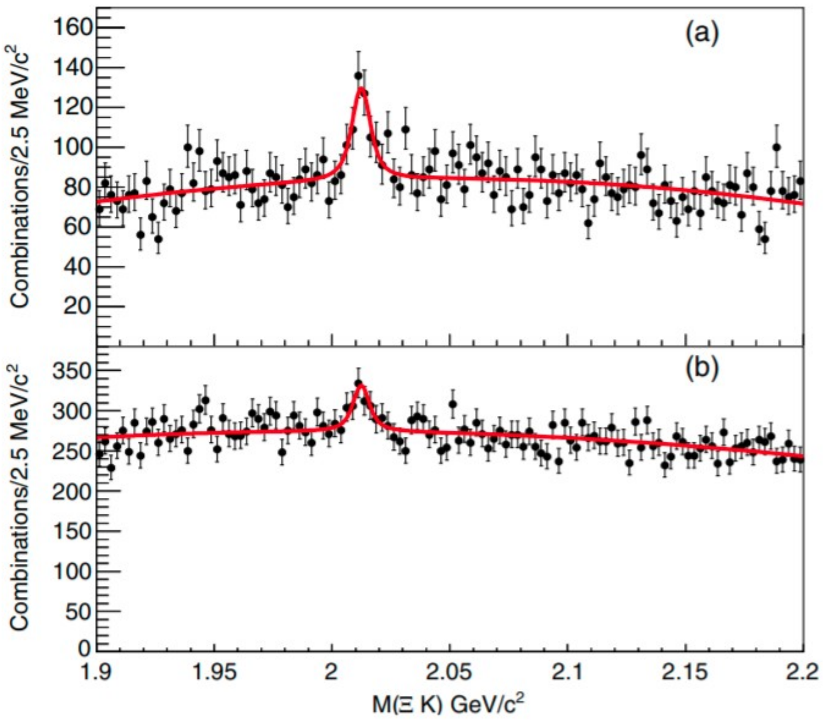



FIG. 2. The (a) $\Xi^0 K^-$ and (b) $\Xi^- K^0_S$ invariant mass distributions in data taken at the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonance energies.

$\Omega^{*-}$ decaying into $\Xi^0 K^-$ and $\Xi^- K^0_S$

$$2012.4 \pm 0.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})\ \mathrm{MeV}/c^2$$

$$\Gamma = 6.4^{+2.5}_{-2.0}(\mathrm{stat}) \pm 1.6(\mathrm{syst})\ \mathrm{MeV}$$

Sourav Sarkar, E. Oset, M.J. Vicente Vacas

Nuclear Physics A 750 (2005) 294–323

Baryonic resonances from baryon decuplet-meson octet interaction

Couplings of the resonance with $S = -3$ and $I = 0$ to various channels

| $z_R$ | $2141 - i38$ | |
|---|---|---|
| | $g_i$ | $\lvert g_i \rvert$ |
| $\Xi^* \bar{K}$ | $1.1 - i0.8$ | 1.4 |
| $\Omega \eta$ | $3.3 + i0.4$ | 3.4 |

# Molecular works triggered by the discovery

Only Kbar Ξ* state :

[7] Y. H. Lin and B. S. Zou, Phys. Rev. D 98, 056013 (2018).

Coupled channels: Kbar Ξ*, ηΩ

[8] M. P. Valderrama, Phys. Rev. D 98, 054009 (2018).

[9] Y. Huang, M. Z. Liu, J. X. Lu, J. J. Xie, and L. S. Geng, Phys. Rev. D 98, 076012 (2018).

[10] R. Pavao and E. Oset, Eur. Phys. J. C 78, 857 (2018).

[11] M. V. Polyakov, H. D. Son, B. D. Sun, and A. Tandogan, Phys. Lett. B 792, 315 (2019).

# The molecular picture was challenged in

S. Jia et al. (Belle Collaboration), Phys. Rev. D 100, 032006(2019).

$$\frac{\Gamma_{\Omega}(\pi\bar{K}\Xi)}{\Gamma_{\Omega,\bar{K}\Xi}} < 11.9\%$$

“”The result strongly disfavors the molecular interpretation of [7] and is in tension with [8-11] “”

# Molecular picture for the Ω(2012) revisited

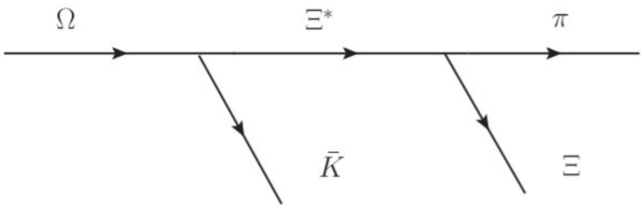
Natsumi Ikeno, Genaro Toledo and Eulogio Oset PHYSICAL REVIEW D 101, 094016 (2020)

$\bar{K}\Xi^*$, $\eta\Omega$($s$-wave), and $\bar{K}\Xi$($d$-wave)

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

$$F = -\frac{1}{4f^2}(k^0 + k'^0); \qquad q_{\rm on} = \frac{\lambda^{1/2}(s, m_{\bar{K}}^2, m_{\Xi}^2)}{2\sqrt{s}}$$

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




$$q_{\max} = 735\ \text{MeV}; \qquad q_{\max}(\eta\Omega) = 750\ \text{MeV};$$

$$\alpha = -11.0 \times 10^{-8}\ \text{MeV}^{-3}; \qquad \beta = 20.0 \times 10^{-8}\ \text{MeV}^{-3}$$

$$\text{(a)} \quad \Gamma_{\Omega^*,\text{non}} = 8.2\ \text{MeV},$$

$$\text{(c)} \quad \Gamma_{\Omega^*,\text{con(Edep)}} = 9.1\ \text{MeV},$$

$$M_{\Omega^*} = 2012.6\ \text{MeV},$$

$$\frac{\Gamma_{\Omega^* \to \pi \bar{K}\Xi(\text{cut})}}{\Gamma_{\Omega^*,\text{non}}} = 11\%$$

| | $\bar{K}\Xi^*$ (2027) | $\eta\Omega$ (2220) | $\bar{K}\Xi$ (1812) |
|---|---|---|---|
| $g_i$ | $1.88 + i0.04$ | $3.55 - i0.67$ | $-0.42 + i0.22$ |
| $\lvert\tilde{g}_i\rvert$ | 1.77 | 3.42 | 0.44 |
| $\lvert g_{i,\text{conv}}\rvert$ | 1.75 | 3.38 | 0.45 |
| $\text{wf}_i(g_i G_i)$ | $-34.37 - i2.42$ | $-31.99 + i5.63$ | … |
| $-g_i^2 \frac{\partial G_i}{\partial\sqrt{s}}$ | $0.57 + i0.16$ | $0.26 - i0.09$ | … |

Similar results in J. Lu, C. Zeng, E. Wang, J. Xie, and L. Geng Eur.\ Phys.\ J.\ C {\bf 80}, 361 (2020)

# Conclusions

In the recently observed states in the LHCb, Belle, Babar, BesIII, there are many states which qualify as dynamically generated from the interaction of hadron components: molecular states

Many of these states were predicted before. The experiment has served to fine tune some parameters which allow to make more refined predictions for other states not yet found.

The chiral unitary approach in the SU(3) sector has proved to be quite accurate to study the interaction of hadrons and eventually find poles in the t-matrix that correspond to states

The local hidden gauge aproach, with the exchange of vector mesons, is equivalent to the chiral unitary approach in SU(3). An extension of the LHGA has been done to the charm and bottom sectors, which respects heavy quark symmetry and turns out rather accurate interpreting results and making predictions.

More predictions have been made. We hope that they can be tested in the near future.

Attention must also be payed to hybrids of q qbar or qqq and molecular components. J. Nieves, F. K. Guo, David Rodriguez Entem …...