Pentaquark states

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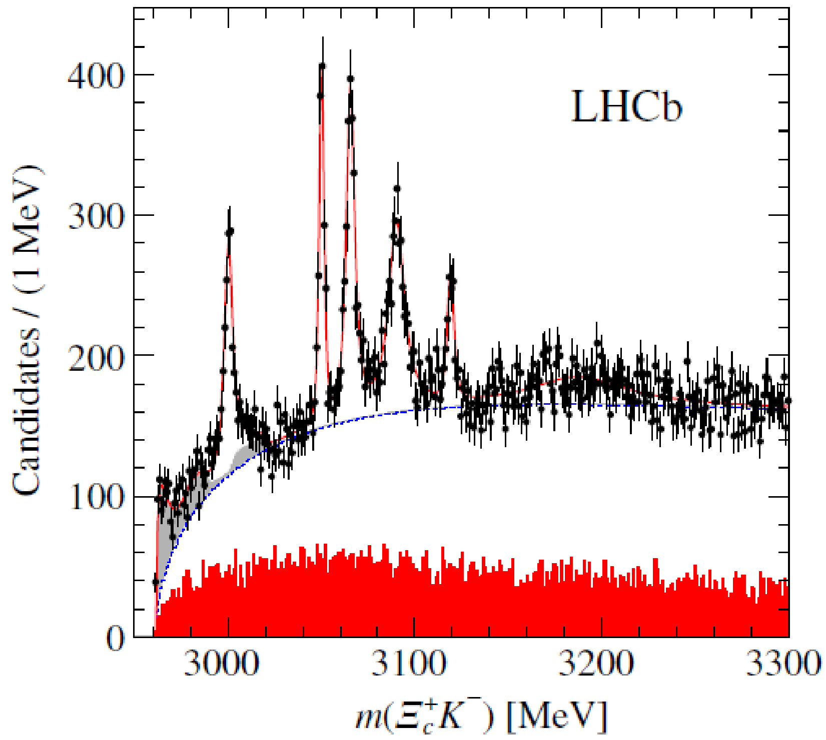
Meson baryon interaction. SU(3) chiral Lagrangians
Local hidden gauge approach
Extension to the charm sector
Ω_c states
Hidden charm pentaquark states
Ξ_{cc} states
Predictions for Ω_b and hidden charm strange states …..

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



The Ξ_c K^- mass spectrum is studied with a sample of pp collision data by LHCb , PRL 017

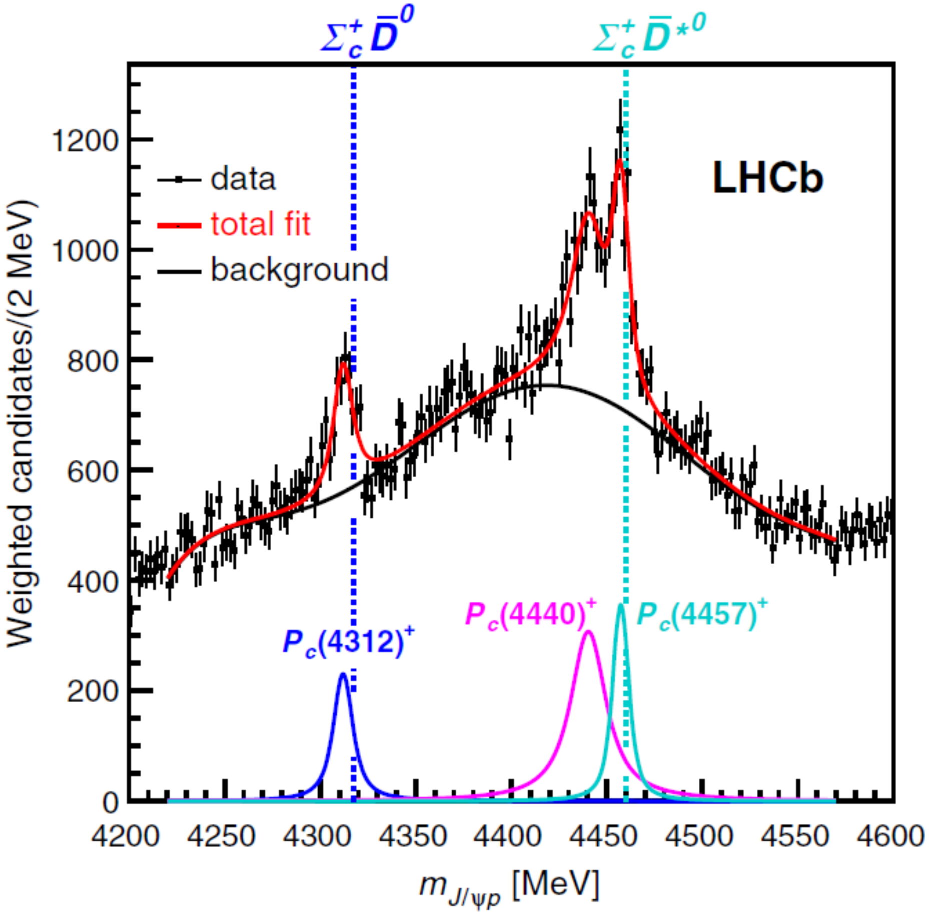
Five clean narrow peaks are obtained

$\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$

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.

Observation of a Narrow Pentaquark State, $P_c(4312)^+$ and of the Two-Peak Structure of the $P_c(4450)^+$

LHCb, PRL 2019



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

bound states [32–34]. The masses of the $P_c(4312)^+$ and $P_c(4457)^+$ states are approximately 5 MeV and 2 MeV below the $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds, respectively, as illustrated in Fig. 6, making them excellent candidates for bound states of these systems. The $P_c(4440)^+$ could be the second $\Sigma_c \bar{D}^*$ state, with about 20 MeV of binding energy, since two states with $J^P = 1/2^-$ and $3/2^-$ are possible. In fact, several papers on hidden-charm states created dynamically by charmed meson-baryon interactions [35–37] were published well before the first observation of the P_c^+ structures [1], and some of these predictions for $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ states [32–34] are consistent with the observed narrow P_c^+ states. Such an interpretation of the $P_c(4312)^+$

[35] J.-J. Wu, R. Molina, E. Oset, and B. S. Zou PRL 2010

[36] J.-J. Wu, R. Molina, E. Oset, and B. S. Zou PRC 2011

[37] C. W. Xiao, J. Nieves, and E. Oset PRD 2013

Meson baryon interaction:

SU(3) Chiral Lagrangian

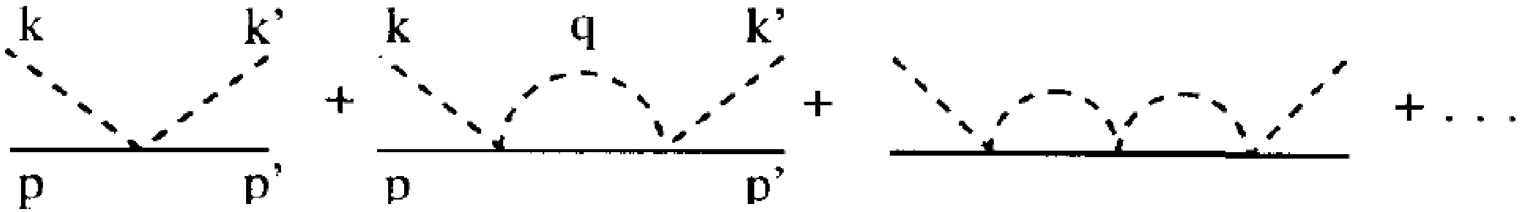
$$\mathcal{L}^B = \frac{1}{4f_\pi^2}\langle \bar{B} i\gamma^\mu [(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi)B - B(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi)]\rangle$$

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

Coupled channels:

$$K^- p \quad \bar{K}^0 n, \pi^0\Lambda, \pi^0\Sigma^0, \pi^+\Sigma^-, \pi^-\Sigma^+, \eta\Lambda, \eta\Sigma^0, K^+\Xi^-, K^0\Xi^0$$

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



$$T = V + VGT$$

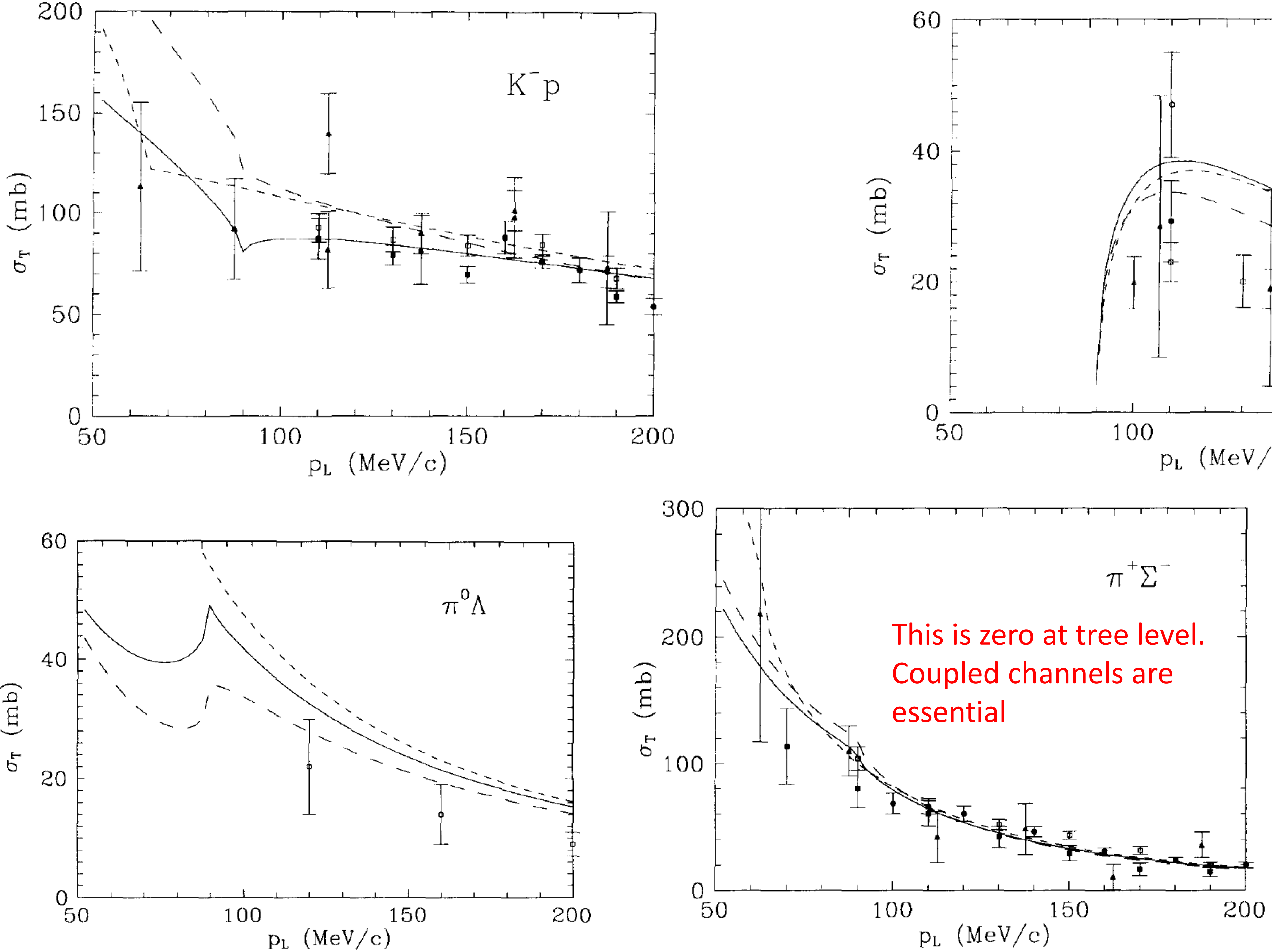
$$T = [1 - VG]^{-1} V$$

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

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

A cut off, q_{max}, is taken to regularize the loops

q_{max}=630 MeV



In addition two Λ(1405) states appear, now supported by many experiments

Equivalent method:
Local hidden gauge
Approach. M. Bando,
Phys. Rept 1988

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

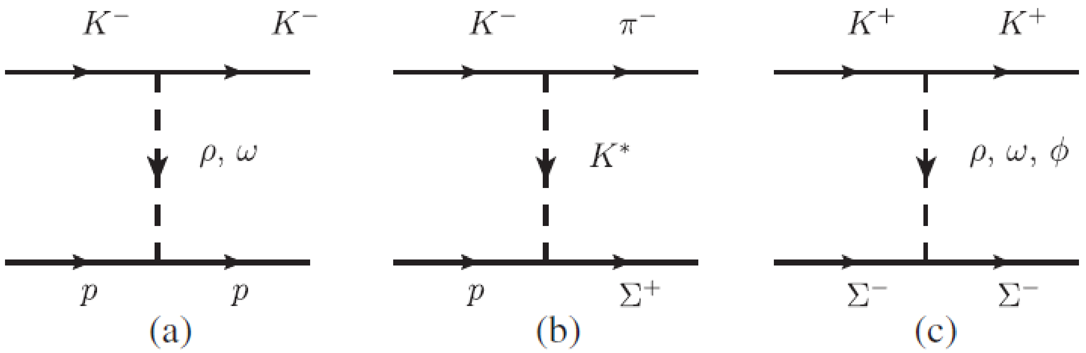
$$\mathcal{L}_{BBV} = g\left(\langle\bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle\right)$$

$g=M_V/2\, f_\pi$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

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

$$V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu$$



Instead of using the Lagrangians, one can use the meson or baryon wave functions with the suitable operators

PPV vertex (Sakai, Roca, E. O, PRD 96 (2107))

$$g' \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), \quad \text{for } \rho^0 \text{ exchange},$$
$$g' \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}), \quad \text{for } \omega \text{ exchange},$$

Operator for ρ_0 exchange

$$-g' \frac{1}{\sqrt{2}}((u\partial_\mu \bar{u} - \partial_\mu u\bar{u}) - (d\partial_\mu \bar{d} - \partial_\mu d\bar{d}))$$

Example in the charm sector:

$$D^+ = c\bar{d}$$

$$-\langle c\bar{d}|g' \frac{1}{\sqrt{2}}((u\partial_\mu \bar{u} - \partial_\mu u\bar{u}) - (d\partial_\mu \bar{d} - \partial_\mu d\bar{d}))|c\bar{d}\rangle$$
$$= -g' \frac{1}{\sqrt{2}}(ip_\mu + ip'_\mu)$$

One does not need to use SU(4). Yet, it is practical to evaluate it using $\mathcal{L}_{\mathrm{VPP}} = -ig\langle[\Phi, \partial_\mu \Phi]V^\mu\rangle$, and the SU(4) matrices

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

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

Lower vertex

BBV

$$\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}),$$
$$\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}),$$
$$\phi = s\bar{s}.$$

approximation of taking $\gamma^\mu \to \gamma^0$

In SU(3)

$$\langle p|g\rho^0|p\rangle \equiv \frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\langle \phi_{\rm MS}\chi_{\rm MS} + \phi_{\rm MA}\chi_{\rm MA}|g\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})| \times \phi_{\rm MS}\chi_{\rm MS} + \phi_{\rm MA}\chi_{\rm MA}\rangle, \quad (10)$$

TABLE I. $J = 1/2$ states chosen and threshold mass in MeV.

States	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
Threshold	2965	3074	3185	3243	3327	3363	3472

TABLE II. $J = 3/2$ states chosen and threshold mass in MeV.

States	$\Xi^*_c \bar{K}$	$\Omega^*_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
Threshold	3142	3314	3327	3363	3401	3472

Note that we do not use SU(4) baryon wave functions, the heavy quark is singled out and flavor-spin symmetry is demanded for the light quarks.

Back to Ω_c states

Molecular Ω_c states generated from coupled meson-baryon channels

Debastiani, Dias, Liang , Oset, PRD 2018

BARYON WAVE FUNCTIONS

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.

Ξ_c^0: the same as Ξ_c^+, changing $(us - su) \to (ds - sd)$.

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

$\Xi_c'^0$: the same as Ξ_c', changing $(us + su) \to (ds + sd)$.

Ω_c^0: css, and the spin wave function χ_{MS} in the last two quarks, like that for Ξ_c'.

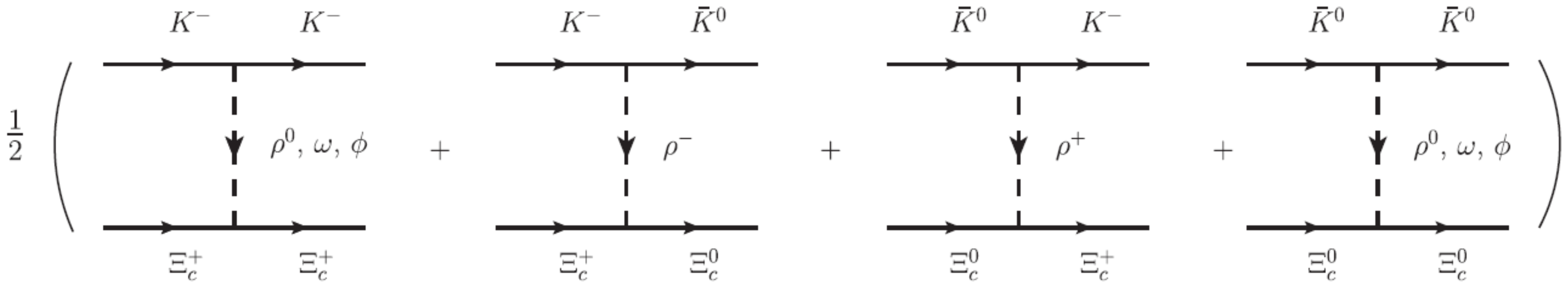


FIG. 3. Diagrams in the $\bar{K}\Xi_c \to \bar{K}\Xi_c$ transition.

Upper vertex

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

$$-it_{K^-\to K^-}\begin{pmatrix}\rho^0\\ \omega\\ \phi\end{pmatrix} = gV_\mu(-ip^\mu - ip'^\mu)\begin{pmatrix}1/\sqrt{2}\\ 1/\sqrt{2}\\ -1\end{pmatrix},$$

$$-it_{K^-\to\bar{K}^0\rho^-} = g\rho^{+\mu}(-ip^\mu - ip'^\mu),$$

$g=m_V/2\,f$,
f=93 MeV

Lower vertex

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

$$=\begin{pmatrix}\frac{1}{\sqrt{2}}g\\ \frac{1}{\sqrt{2}}g\\ g\end{pmatrix}.$$

No need to invoke SU(4)

With light vector exchange the heavy quarks are spectators. Nothing depends upon them. Heavy quark symmetry is automatically implemented

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

The exchange of heavy vectors is penalized

$$\frac{1}{(q^0)^2 - |\mathbf{q}|^2 - m_{D_s^*}^2} \approx \frac{1}{(m_D - m_K)^2 - m_{D_s^*}^2},$$

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

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

$$T = [1 - VG]^{-1}V, \qquad G_l^{II} = G_l^I + i\frac{2M_l q}{4\pi\sqrt{s}}, \qquad T_{ij} = \frac{g_i g_j}{\sqrt{s} - z_R}$$

Exp (MeV)
M Γ

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.

Exp (MeV) M, Γ	$3054.05 + i0.44$	$\Xi_c \bar{K}$	$\Xi_c' \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi_c' \bar{K}^*$
3050, 0.8	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^*	$\Xi_c \bar{K}^*$	$\Xi_c' \bar{K}^*$
3090, 8.7	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.

Exp (MeV) M, Γ	3124.84	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi_c' \bar{K}^*$
3119, 1.1	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
	$3290.31 + i0.03$	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi_c' \bar{K}^*$
	g_i	$0.01 + i0.02$	$0.31 + i0.01$	0	0	$6.22 - i0.04$	0
	$g_i G_i^{II}$	$-0.62 - i0.18$	$-5.25 - i0.18$	0	0	$-31.08 + i0.20$	0

We get three states in very good agreement with experiment, both mass and width

Related work:

[15] J. Hofmann and M. F. M. Lutz, Nucl. Phys. **A763**, 90 (2005).
[16] C. E. Jimenez-Tejero, A. Ramos, and I. Vidana, Phys. Rev. C **80**, 055206 (2009).

[17] O. Romanets, L. Tolos, C. Garcia-Recio, J. Nieves, L. L. Salcedo, and R. G. E. Timmermans, Phys. Rev. D **85**, 114032 (2012).

Revisions made after experiment to fit some parameter

[41] G. Montaña, A. Feijoo, and A. Ramos, Eur. Phys. J. A **54**, 64 (2018).

Uses SU(4) : matrix elements exchanging light vectors are equal. Results similar to ours, but only two states, since they study $1/2^-$ states only

J.~Nieves, R.~Pavao and L.~Tolos, Omega _c excited states within a SU(6)}_ HQSS model, Eur. Phys. J. C 78 114 (2018)

Better results than in [17] but the widths and the positions not so good as in the works of Montaña and present work .

Heavy quark spin symmetric molecular states from $\bar{D}^{(*)}\Sigma_c^{(*)}$ and other coupled channels in the light of the recent LHCb pentaquarks

C. W. Xiao,[1] J. Nieves,[2] and E. Oset[2,3] PRD (2019)

$$I = 1/2,\ \eta_c N,\ \ J/\psi N,\ \bar{D}\Lambda_c,\ \bar{D}\Sigma_c,\ \bar{D}^*\Lambda_c,\ \bar{D}^*\Sigma_c,\ \bar{D}^*\Sigma_c^* \text{ for spin parity } J^P = 1/2^-$$

$$J/\psi N,\ \bar{D}^*\Lambda_c,\ \bar{D}^*\Sigma_c,\ \ \bar{D}\Sigma_c^*,\ \bar{D}^*\Sigma_c^* \text{ for } J^P = 3/2^-$$

$$T = [1 - V\,G]^{-1}\,V$$

HQSS tells that the interaction cannot depend on the spin of the heavy quarks. Then one rewrites the physical states in terms of a basis of states where the spin of the light quarks and the heavy ones are separated.

One uses the Wigner Eckart theorem to write matrix elements in terms of a few reduced matrix elements

This produces symmetries in the matrix elements of the interaction.

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

$$
\begin{array}{ccccccc}
\eta_c N & J/\psi N & \bar{D}\Lambda_c & \bar{D}\Sigma_c & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c & \bar{D}^*\Sigma_c^*
\end{array}
$$

$$
\left(\begin{array}{ccccccc}
\mu_1 & 0 & \frac{\mu_{12}}{2} & \frac{\mu_{13}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{13} \\
0 & \mu_1 & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & -\frac{\mu_{12}}{2} & \frac{5\mu_{13}}{6} & \frac{\sqrt{2}\mu_{13}}{3} \\
\frac{\mu_{12}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & \mu_2 & 0 & 0 & \frac{\mu_{23}}{\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{23} \\
\frac{\mu_{13}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & 0 & \frac{1}{3}(2\lambda_2+\mu_3) & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2-\mu_3)}{3\sqrt{3}} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3-\lambda_2) \\
\frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{12}}{2} & 0 & \frac{\mu_{23}}{\sqrt{3}} & \mu_2 & -\frac{2\mu_{23}}{3} & \frac{\sqrt{2}\mu_{23}}{3} \\
-\frac{\mu_{13}}{2\sqrt{3}} & \frac{5\mu_{13}}{6} & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2-\mu_3)}{3\sqrt{3}} & -\frac{2\mu_{23}}{3} & \frac{1}{9}(2\lambda_2+7\mu_3) & \frac{1}{9}\sqrt{2}(\mu_3-\lambda_2) \\
\sqrt{\frac{2}{3}}\mu_{13} & \frac{\sqrt{2}\mu_{13}}{3} & \sqrt{\frac{2}{3}}\mu_{23} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3-\lambda_2) & \frac{\sqrt{2}\mu_{23}}{3} & \frac{1}{9}\sqrt{2}(\mu_3-\lambda_2) & \frac{1}{9}(\lambda_2+8\mu_3)
\end{array}\right)_{I=1/2}
$$

- $J=3/2,\ I=1/2$

$$
\begin{array}{c}
\begin{array}{ccccc} J/\psi N & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c & \bar{D}\Sigma_c^* & \bar{D}^*\Sigma_c^* \end{array} \\
\left(\begin{array}{ccccc}
\mu_1 & \mu_{12} & \frac{\mu_{13}}{3} & -\frac{\mu_{13}}{\sqrt{3}} & \frac{\sqrt{5}\mu_{13}}{3} \\
\mu_{12} & \mu_2 & \frac{\mu_{23}}{3} & -\frac{\mu_{23}}{\sqrt{3}} & \frac{\sqrt{5}\mu_{23}}{3} \\
\frac{\mu_{13}}{3} & \frac{\mu_{23}}{3} & \frac{1}{9}(8\lambda_2+\mu_3) & \frac{\lambda_2-\mu_3}{3\sqrt{3}} & \frac{1}{9}\sqrt{5}(\mu_3-\lambda_2) \\
-\frac{\mu_{13}}{\sqrt{3}} & -\frac{\mu_{23}}{\sqrt{3}} & \frac{\lambda_2-\mu_3}{3\sqrt{3}} & \frac{1}{3}(2\lambda_2+\mu_3) & \frac{1}{3}\sqrt{\frac{5}{3}}(\lambda_2-\mu_3) \\
\frac{\sqrt{5}\mu_{13}}{3} & \frac{\sqrt{5}\mu_{23}}{3} & \frac{1}{9}\sqrt{5}(\mu_3-\lambda_2) & \frac{1}{3}\sqrt{\frac{5}{3}}(\lambda_2-\mu_3) & \frac{1}{9}(4\lambda_2+5\mu_3)
\end{array}\right)_{I=1/2}
\end{array}
$$

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

$$\bar{D}^*\Sigma_c^*:\ (\lambda_2)_{I=1/2}$$

The different terms are evaluated using an extensión of the local hidden gauge approach, with the exchange of vector mesons.

$$\mu_1 = 0, \quad \mu_{23} = 0, \quad \lambda_2 = \mu_3, \quad \mu_{13} = -\mu_{12},$$
$$\mu_2 = \frac{1}{4f^2}(k^0 + k'^0), \quad \mu_3 = -\frac{1}{4f^2}(k^0 + k'^0),$$
$$\mu_{12} = -\sqrt{6}\,\frac{m_\rho^2}{p_{D^*}^2 - m_{D^*}^2}\,\frac{1}{4f^2}\,(k^0 + k'^0),$$

f= f_π=93 MeV, k^0, k'^0 are the energies of the external mesons

The only free parameter is the subtraction constant in the regularization of the meson baryon loops. We take it such that the average mass of our states agrees with experiment.

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

$(4306.38 + i7.62)$ 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	$0.67 + i0.01$	$0.46 - i0.03$	$0.01 - i0.01$	$\mathbf{2.07 - i0.28}$	$0.03 + i0.25$	$0.06 - i0.31$	$0.04 - i0.15$
$\|g_i\|$	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	$0.24 + i0.03$	$0.88 - 0.11$	$0.09 - i0.06$	$0.12 - i0.02$	$0.11 - i0.09$	$\mathbf{1.97 - i0.52}$	$0.02 + i0.19$
$\|g_i\|$	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	$0.72 - i0.10$	$0.45 - i0.04$	$0.11 - i0.06$	$0.06 - i0.02$	$0.06 - i0.05$	$0.07 - i0.02$	$\mathbf{1.84 - i0.56}$
$\|g_i\|$	0.73	0.45	0.13	0.06	0.08	0.08	1.92

TABLE II. Same as Table I for $J^P = 3/2^-$.

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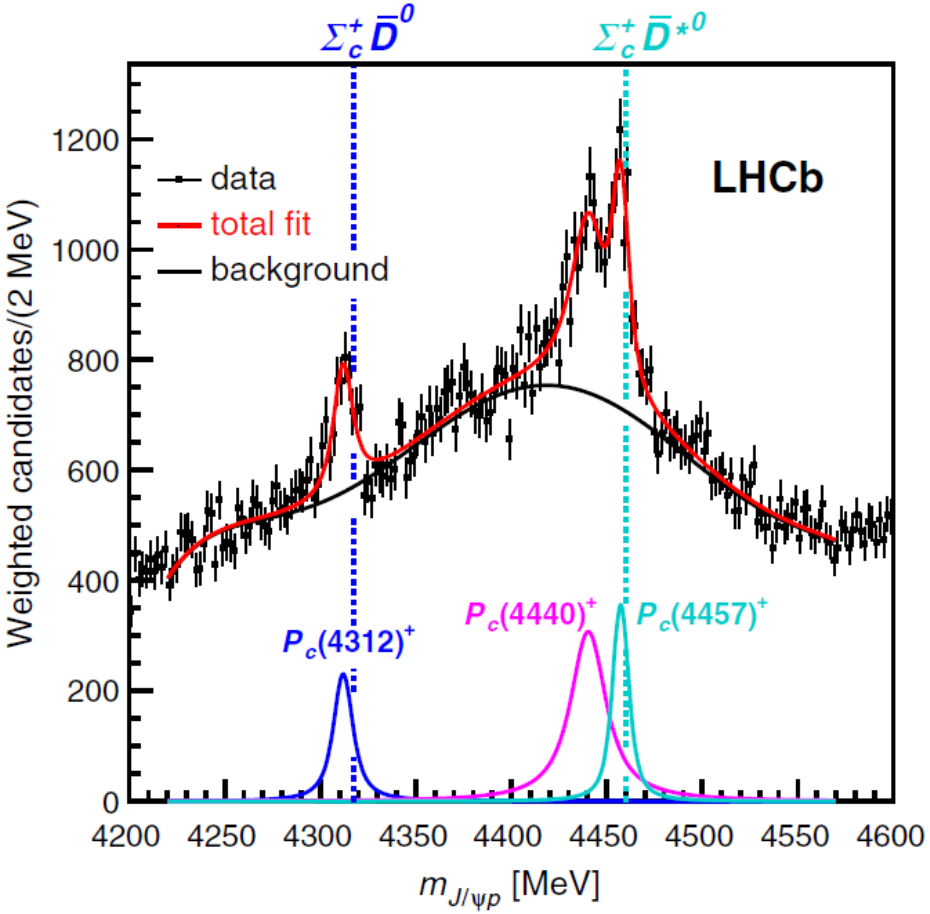
$(4374.33 + i6.87)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.73 - i0.06$	$0.11 - i0.13$	$0.02 - i0.19$	$\mathbf{1.91 - i0.31}$	$0.03 - i0.30$
$\lvert g_i \rvert$	0.73	0.18	0.19	1.94	0.30
$(4452.48 + i1.49)$ MeV	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
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

And a state at : 4519.23 MeV and a zero width for the single channel $\bar{D}^*\Sigma_c^*$ with $J = 5/2^-$

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	$\bar{D}^*\Sigma_c$	$3/2^-$	$P_c(4457)$



$\Sigma_c^+ \bar{D}^0$
$\Sigma_c^+ \bar{D}^{*0}$
data
total fit
background
LHCb
$P_c(4312)^+$
$P_c(4440)^+$
$P_c(4457)^+$
Weighted candidates/(2 MeV)
0
200
400
600
800
1000
1200
4200
4250
4300
4350
4400
4450
4500
4550
4600
$m_{J/\psi p}$ [MeV]

M.Z. Liu, Y.W. Pang, F.Z. Peng, M. Sanchez-Sanchez, L.S. Geng, A. Hosaka, M. Pavon-Valderrama
Arxiv 1903.11560 , PRL 2019
Similar conclusions based on single channels.

All these papers, written after the LHCb paper, claim these seven states of molecular nature.

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Prediction of hidden charm strange molecular baryon states with heavy quark spin symmetry

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

To be observed
In J/ψ Λ

$\eta_c\Lambda,\ J/\psi\Lambda,\ \bar{D}\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}\Xi_c',\ \bar{D}^*\Xi_c,\ \bar{D}_s^*\Lambda_c,\ \bar{D}^*\Xi_c',\ \bar{D}^*\Xi_c^*$ 1/2$^-$

$J/\psi\Lambda,\ \bar{D}^*\Xi_c,\ \bar{D}_s^*\Lambda_c,\ \bar{D}^*\Xi_c'\ ,\ \bar{D}\Xi_c^*,\ \bar{D}^*\Xi_c^*$ in $3/2^-$ and $\bar{D}^*\Xi_c^*$ in $5/2^-$

TABLE I. 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	$0.17-i0.03$	$0.29-i0.07$	**$2.93+i0.08$**	$0.76+i0.31$	$0.00+i0.01$	$0.01+i0.02$	$0.01+i0.04$	$0.01-i0.02$	$0.01-i0.03$
$\|g_i\|$	0.17	0.30	**2.93**	0.82	0.01	0.02	0.05	0.02	0.03
$4429.84+i7.92$									
g_i	$0.29-i0.11$	$0.17-i0.07$	$0.00-i0.00$	$0.00-i0.00$	$0.15-i0.26$	**$2.78+i0.01$**	$0.66+i0.32$	$0.01+i0.05$	$0.01+i0.03$
$\|g_i\|$	0.31	0.18	0.00	0.00	0.30	**2.78**	0.73	0.05	0.04
$4436.70+i1.17$									
g_i	$0.24+i0.03$	$0.14+0.01$	$0.00-i0.00$	$0.00-i0.00$	**$1.72-i0.04$**	$0.22-i0.31$	$0.06-i0.01$	$0.01-i0.04$	$0.01-i0.03$
$\|g_i\|$	0.24	0.14	0.00	0.00	**1.72**	0.38	0.07	0.04	0.03
$4580.96+i2.44$									
g_i	$0.12-i0.00$	$0.37-i0.04$	$0.02-i0.01$	$0.02-i0.01$	$0.03-i0.00$	$0.02-i0.02$	$0.03-i0.02$	**$1.57-i0.17$**	$0.00+i0.02$
$\|g_i\|$	0.12	0.37	0.02	0.02	0.03	0.03	0.03	**1.58**	0.02
$4650.86+i2.59$									
g_i	$0.32-i0.05$	$0.19-i0.03$	$0.02-i0.01$	$0.03-i0.02$	$0.02-i0.00$	$0.01-i0.01$	$0.02-i0.01$	$0.01-i0.00$	**$1.41-i0.23$**
$\|g_i\|$	0.32	0.19	0.03	0.04	0.02	0.02	0.02	0.02	**1.43**

TABLE II. Same as Table I 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	$0.31 - i0.10$	$\mathbf{2.77 - i0.02}$	$0.67 + i0.32$	$0.00 + i0.0.02$	$0.00 - i0.06$	$0.00 + i0.0.04$
$\|g_i\|$	0.32	**2.77**	0.74	0.02	0.06	0.04
$4506.99 + i1.03$						
g_i	$0.27 - i0.02$	$0.02 - i0.03$	$0.02 - i0.02$	$0.00 - i0.03$	$\mathbf{1.56 - i0.07}$	$0.00 - i0.05$
$\|g_i\|$	0.27	0.03	0.03	0.03	**1.56**	0.05
$4580.96 + i0.34$						
g_i	$0.14 - i0.01$	$0.01 - i0.01$	$0.01 - i0.01$	$\mathbf{1.54 - i0.02}$	$0.02 - i0.00$	$0.00 - i0.04$
$\|g_i\|$	0.14	0.01	0.02	**1.54**	0.02	0.04
$4650.58 + i1.48$						
g_i	$0.29 - i0.02$	$0.02 - i0.01$	$0.03 - i0.02$	$0.03 - i0.01$	$0.03 - i0.00$	$\mathbf{1.40 - i0.13}$
$\|g_i\|$	0.29	0.03	0.03	0.03	0.03	**1.41**

Conclusions

Extension of chiral unitary theory to the heavy sector, using the exchange of vectors in the hidden gauge approach, together with unitarity in coupled channels leads to neat predictions for molecular states

The important terms in the interaction come from light vector Exchange -> 1) heavy quaks are spectators and matrix elements do not depend upon them HEAVY QUARK SYMMETRY AUTOMATICALLY FULFILLED.
2) One does not have to invoke SU(4) to evaluate matrix elements.

Recent results for Ω_c states and the new pentaquarks states of hidden charm, are giving support to these molecular pictures.

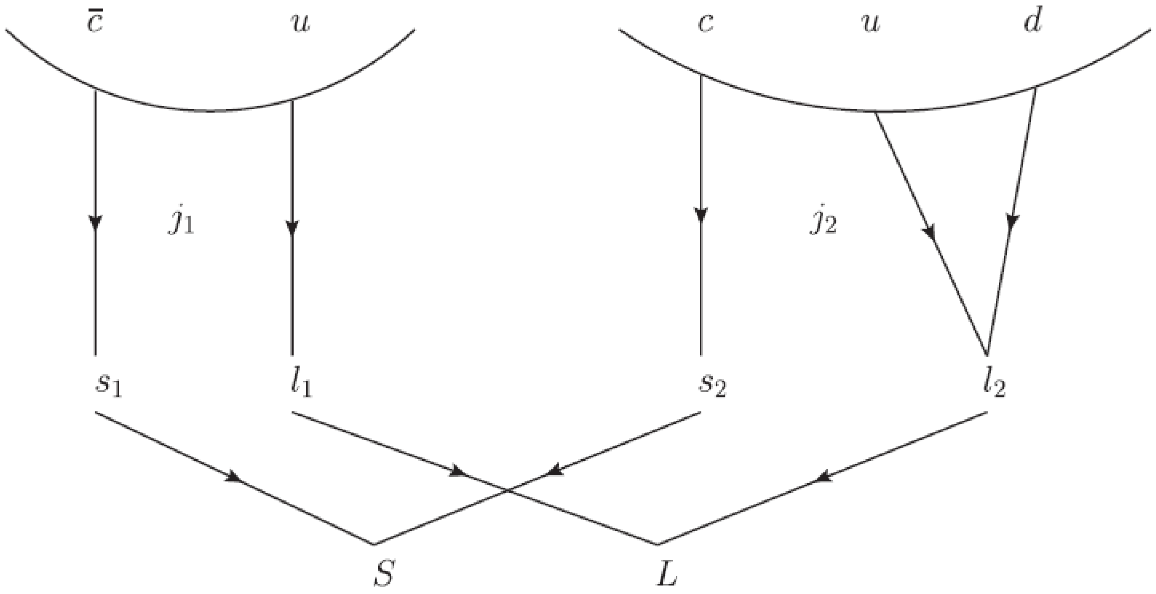
Reliable predictions are made for many states likely to be observed in the near future. LHCb has the key to them

LOWEST ORDER HQSS CONSTRAINTS

HQSS predicts that all types of spin interactions vanish for infinitely massive quarks: The dynamics is unchanged under arbitrary transformations of the spin of the heavy quark (Q). The spin-dependent interactions are proportional to the chromomagnetic moment of the heavy quark, and hence they are of the order of $1/m_Q$. The total angular momentum $\vec{J}$ of the hadron is always a conserved quantity, but in this case the spin of the heavy quark $\vec{S}_Q$ is also conserved in the $m_Q \to \infty$ limit. Consequently, the spin of the light degrees of freedom $\vec{S}_l = \vec{J} - \vec{S}_Q$ is a conserved quantity in that limit. Thus, heavy hadrons come in

$$|l_1 s_1 j_1; l_2 s_2 j_2; JM\rangle = \sum_{S,L} [(2S+1)(2L+1)(2j_1+1)(2j_2+1)]^{1/2} \begin{Bmatrix} l_1 & l_2 & L \\ s_1 & s_2 & S \\ j_1 & j_2 & J \end{Bmatrix} |l_1 l_2 L; s_1 s_2 S; JM\rangle,$$

$$\begin{array}{llllllllll} \text{generic:} & l_1 & l_2 & s_1 & s_2 & j_1 & j_2 & L & S & J \\ \text{HQSS:} & \ell_M\left(\frac{1}{2}\right) & \ell_B & \frac{1}{2} & \frac{1}{2} & J_M(0,1) & J_B\left(\frac{1}{2},\frac{3}{2}\right) & \mathcal{L} & S_{c\bar{c}} & J\left(\frac{1}{2},\frac{3}{2},\frac{5}{2}\right). \end{array}$$



$${}_{(\ell'_M,\ell'_B)}\langle S'_{c\bar{c}}, \mathcal{L}'; J', \alpha' | H^{\text{QCD}} | S_{c\bar{c}}, \mathcal{L}; J, \alpha\rangle_{(\ell_M,\ell_B)} = \delta_{\alpha\alpha'}\delta_{JJ'}\delta_{S'_{c\bar{c}}S_{c\bar{c}}}\delta_{\mathcal{L}\mathcal{L}'}\langle \ell'_M \ell'_B \mathcal{L}; \alpha || H^{\text{QCD}} || \ell_M \ell_B \mathcal{L}; \alpha\rangle$$

$$
\begin{aligned}
&\text{(i)} && |S_{c\bar{c}} = 0,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=0,\ell_B=\frac{1}{2})}, \\
& && |S_{c\bar{c}} = 0,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=1/2,\ell_B=0)}, \\
& && |S_{c\bar{c}} = 0,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=1/2,\ell_B=1)}, \\
&\text{(ii)} && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=0,\ell_B=\frac{1}{2})}, \\
& && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=1/2,\ell_B=0)}, \\
& && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=1/2,\ell_B=1)}, \\
&\text{(iii)} && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{3}{2}\rangle_{(\ell_M=0,\ell_B=\frac{1}{2})}, \\
& && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{3}{2}\rangle_{(\ell_M=1/2,\ell_B=0)}, \\
& && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{1}{2}; J = \tfrac{3}{2}\rangle_{(\ell_M=1/2,\ell_B=1)}, \\
&\text{(iv)} && |S_{c\bar{c}} = 0,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{3}{2}\rangle_{(\ell_M=0,\ell_B=\frac{3}{2})}, \\
& && |S_{c\bar{c}} = 0,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{3}{2}\rangle_{(\ell_M=1/2,\ell_B=1)}, \\
&\text{(v)} && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=0,\ell_B=\frac{3}{2})}, \\
& && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{1}{2}\rangle_{(\ell_M=1/2,\ell_B=1)}, \\
&\text{(vi)} && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{3}{2}\rangle_{(\ell_M=0,\ell_B=\frac{3}{2})}, \\
& && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{3}{2}\rangle_{(\ell_M=1/2,\ell_B=1)}, \\
&\text{(vii)} && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{5}{2}\rangle_{(\ell_M=0,\ell_B=\frac{3}{2})}, \\
& && |S_{c\bar{c}} = 1,\ \mathcal{L} = \tfrac{3}{2}; J = \tfrac{5}{2}\rangle_{(\ell_M=1/2,\ell_B=1)}.
\end{aligned}
$$