The magic role of coupled channels building up molecular states

E. Oset , IFIC . Universidad de Valencia, N. Ikeno, Y.Y. Li , A. Feijoo, W.F. Wang, C.W Xiao, J.J. Wu,J. Nieves, B.S Zou, W. T. Lyu

Coupled channels and the two Λ(1405) states

The case of the Σ(1430)

The Ω(2012)

The Ω(2380)

Back to Pcs states and role of coupled channels

Prediction of a Pcs(4200) and how to observe it in the

$$\Lambda_b \to \phi \eta_c \Lambda \text{ reaction}$$

Pentaquarks of two heavy quarks and strangeness

Version for students. Schroedinger Eqn. $(H_0 + V)|\psi\rangle = E|\psi\rangle$ $H_0|\phi\rangle = E|\phi\rangle$

$$(E - H_0)|\psi - \phi\rangle = V|\psi\rangle,$$

$$|\psi - \phi\rangle = \frac{1}{E - H_0} V|\psi\rangle,$$

$$|\psi\rangle = |\phi\rangle + \frac{1}{E - H_0} V|\psi\rangle$$

define T such that $T|\phi\rangle = V|\psi\rangle$

$$T|\phi\rangle = V|\phi\rangle + V\frac{1}{E - H_0} V|\psi\rangle \qquad T = V + V\frac{1}{E - H_0} T$$

Lippmann Schwinger eqn.

Assume $\langle \boldsymbol{p}'|V|\boldsymbol{p}\rangle = V(\boldsymbol{p}', \boldsymbol{p}) = v\theta(\Lambda - p')\theta(\Lambda - p),$

$$\langle \boldsymbol{p}|T|\boldsymbol{p}'\rangle = \langle \boldsymbol{p}|V|\boldsymbol{p}'\rangle + \int d^3p'' \frac{\langle \boldsymbol{p}|V|\boldsymbol{p}''\rangle}{E - m_1 - m_2 - \boldsymbol{p}''^2/2\mu} \langle \boldsymbol{p}''|T|\boldsymbol{p}'\rangle$$

$$\langle \boldsymbol{p}|T|\boldsymbol{p}'\rangle \equiv \theta(\Lambda - p')\theta(\Lambda - p)t,$$

which has the solution

$$t = v + vGt = \frac{v}{1 - vG} = \frac{1}{v^{-1} - G} \qquad G = \int_{p<\Lambda} d^3p \frac{1}{E - m_1 - m_2 - \boldsymbol{p}^2/2\mu + i\epsilon}$$

Oset, Ramos NPA98

Coupled channels:

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

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

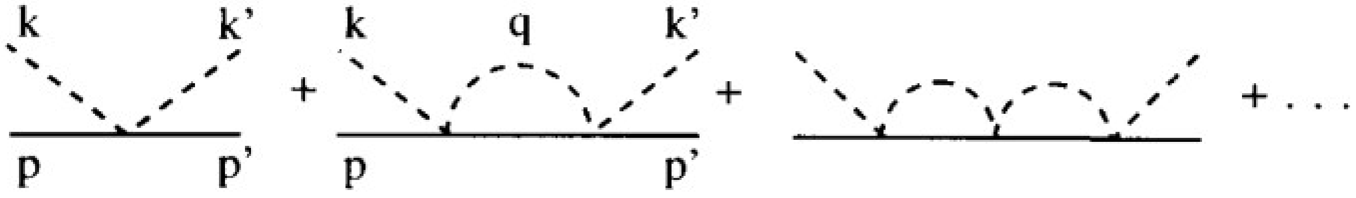
$$T = [1 - VG]^{-1} V$$

$$G_i = i \int \frac{d^4q}{(2\pi)^4} \frac{M_i}{E_i(\vec{q}\,)} \times \frac{1}{k^0 + p^0 - q^0 - E_i(\vec{q}\,) + i\epsilon} \frac{1}{q^2 - m_i^2 + i\epsilon}$$

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

x θ(Λ-q)

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



. Diagrammatic representation of the Lippmann–Schwinger equations, Eq. (15), in $\bar{K}N$ scattering.

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

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

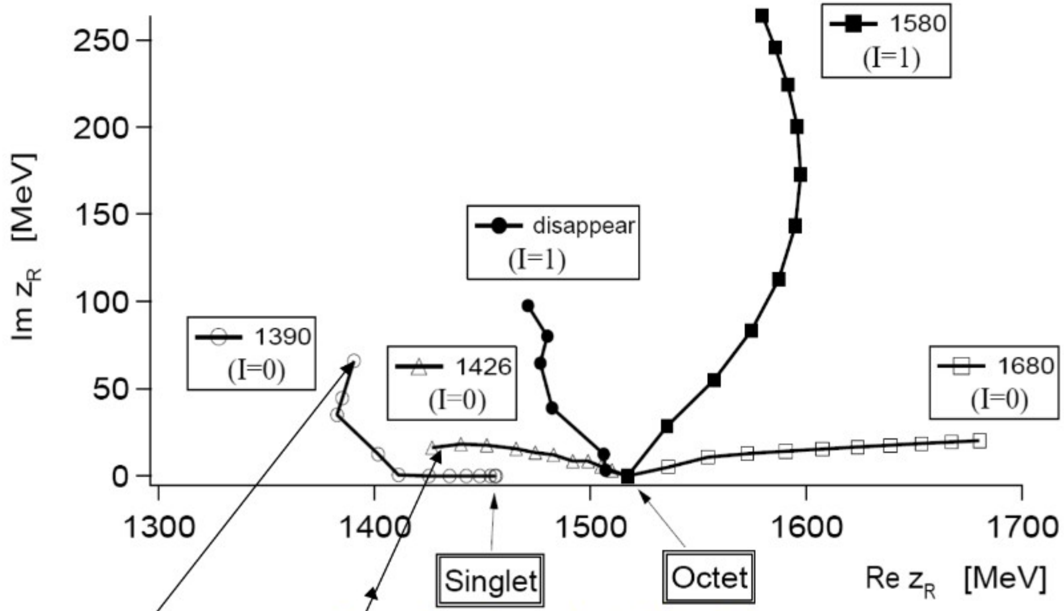
Poles of S=-1 J^P =1/2 $^-$ Resonances

Jido, Oller, Oset, Ramos, Meissner NPA03

$$8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$$

$$M_i(x) = M_0 + x(M_i - M_0),$$
$$m_i^2(x) = m_0^2 + x(m_i^2 - m_0^2),$$
$$a_i(x) = a_0 + x(a_i - a_0),$$

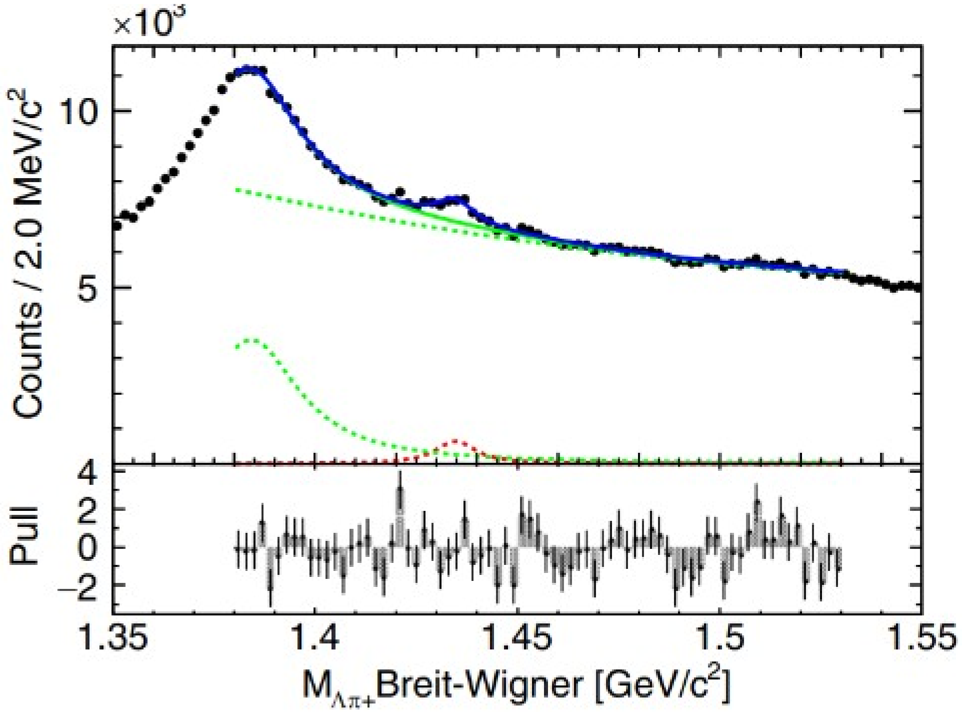
X Є [0,1]



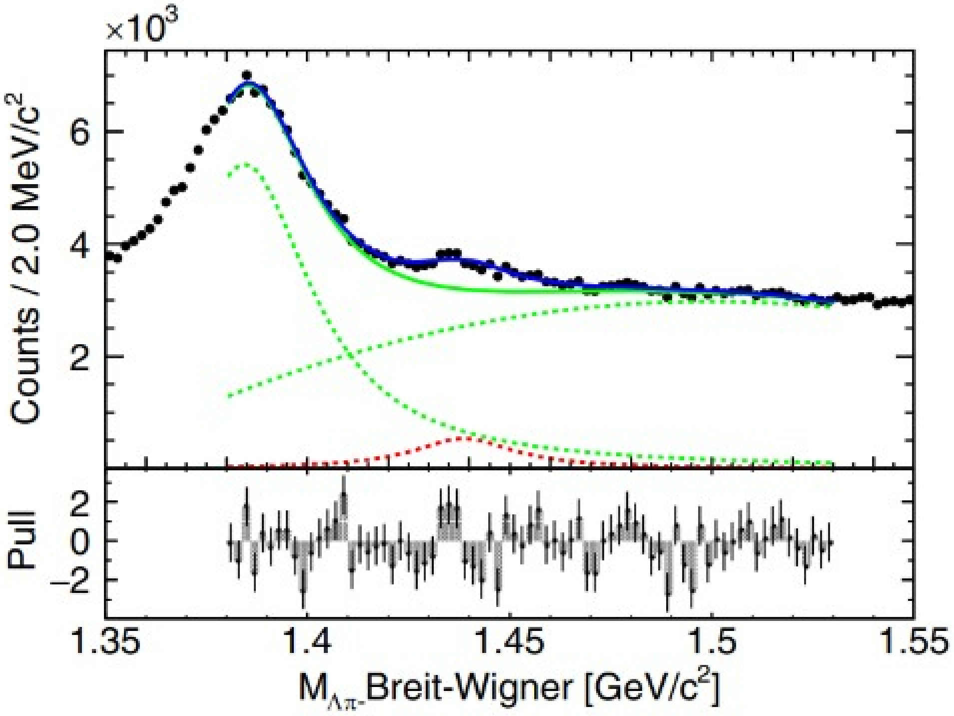
Couples strongly to Kbar N

Couples strongly to pi Sigma

Belle $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ Decay PHYSICAL REVIEW LETTERS 130, 151903 (2023)



(a)



(b)

FIG. 3. Λπ+ (a) and Λπ− (b) invariant mass distribution

How to account for missing channels?

Aceti, Dai, Geng, Zhang
Eur.Phys.J.A 50 (2014) 57

T. Hyodo
Int.J.Mod.Phys.A 28 (2013)1330045

$$v = \begin{pmatrix} v_{11} & v_{12} \\ v_{12} & 0 \end{pmatrix} \qquad T_{11} = \frac{v_{11} + v_{12}^2 G_2}{1 - (v_{11} + v_{12}^2 G_2) G_1}$$

$$V_{\text{eff}} = v_{11} + v_{12}^2 G_2 \qquad T_{\text{eff}} = \frac{V_{\text{eff}}}{1 - V_{\text{eff}} G_1}$$

$$g_{\text{eff}}^2 = \lim \frac{(E - E_0) V_{\text{eff}}}{1 - V_{\text{eff}} G_1} = \frac{V_{\text{eff}}}{-\frac{\partial V_{\text{eff}}}{\partial E} G_1 - V_{\text{eff}} \frac{\partial G_1}{\partial E}}, \qquad (69)$$

which, using the pole condition $1 - V_{\text{eff}} G_1 = 0$, can be rewritten as

$$g_{\text{eff}}^2 = \frac{1}{-G_1^2 \frac{\partial V_{\text{eff}}}{\partial E} - \frac{\partial G_1}{\partial E}}. \qquad (70)$$

Probability of Channel 1

$$-g_{\text{eff}}^2 G_1^2 \frac{\partial V_{\text{eff}}}{\partial E} - g_{\text{eff}}^2 \frac{\partial G_1}{\partial E} = 1$$

Probability of channel 2

Comes from d G_2 / d E

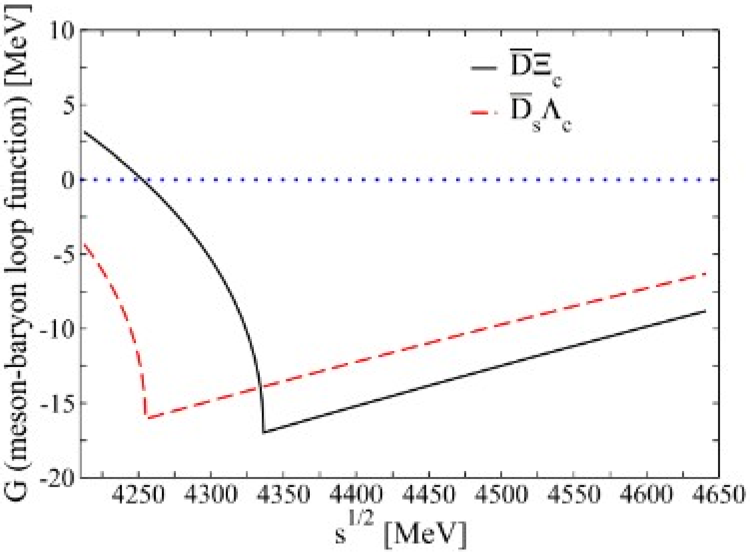


Fig. 2. $\mathrm{Re}G_l(\sqrt{s})$ for the $\bar{D}_s\Lambda_c$ and $\bar{D}\Xi_c$ channels using dimensional regularization.

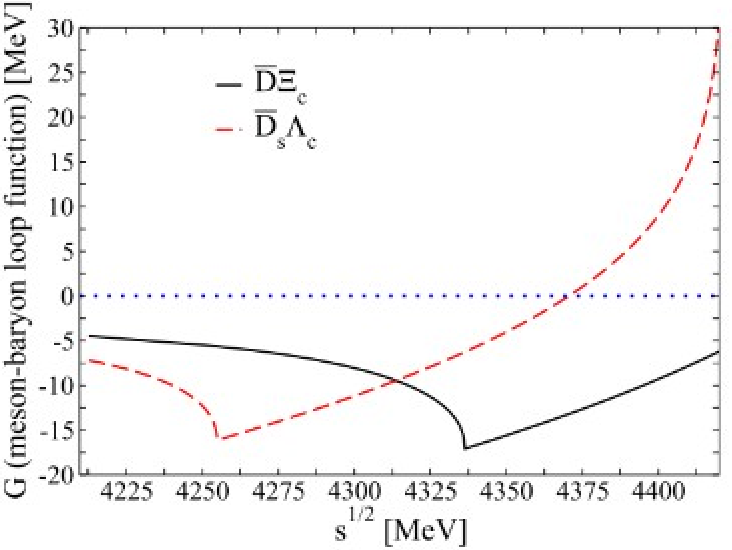


Fig. 1. $\mathrm{Re}G_l(\sqrt{s})$ for the $\bar{D}_s\Lambda_c$ and $\bar{D}\Xi_c$ channels using cut off regularization with $q_{max} = 600$ MeV.

E. Jenkins, A.V. Manohar, Phys. Lett. B 259 (1991) 353

E.E. Kolomeitsev, M.F.M. Lutz, Phys. Lett. B 585 (2004) 243,

S. Sakar, E. Oset and M.J.Vicente-Vacas, Nucl.Phys.A 750 (2005) 294-323,

$$10 \otimes 8 = 8 \oplus 10 \oplus 27 \oplus 35$$

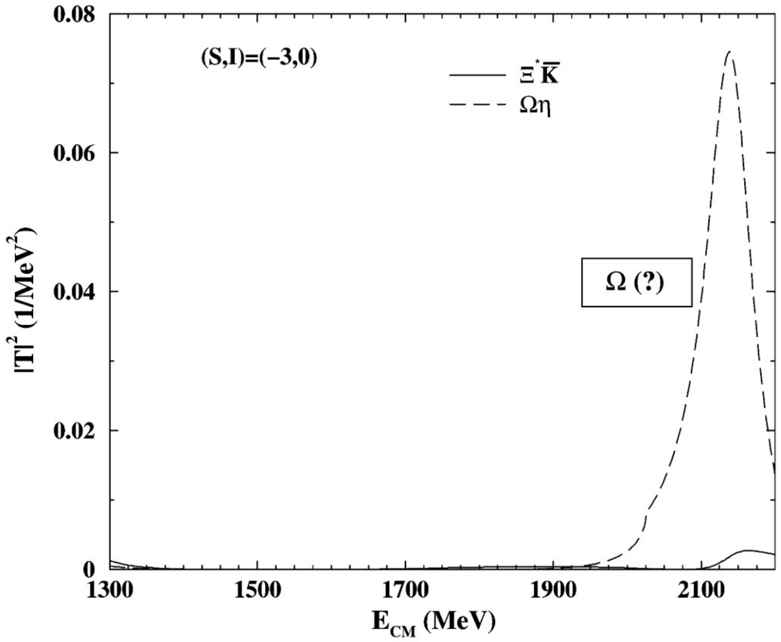
0^- 3/2^+ in s-wave $\rightarrow$ 3/2^- states

Many states of $3/2^-$ are dynamically generated from the interaction with coupled channels:

$N^*(1520)$ $\Delta(1700)$

$\Lambda(1520)$ $\Sigma(1670)$

$\Sigma(1940)$ $\Xi(1820)$



The Ω state around 2100 MeV has been confirmed recently, by Belle and called Ω(2012)
J. Yelton et al. (Belle Collaboration), Phys. Rev. Lett. 121, 052003 (2018)

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

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

$\bar{K}\Xi^*$, $\eta\Omega$ and $\bar{K}\Xi$ channels

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

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

arXiv:2207.03090 [hep-ex]

and it was concluded that “this ratio is consistent with the molecular interpretation of the Ω(2012)”

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

Natsumi Ikeno and E. O.

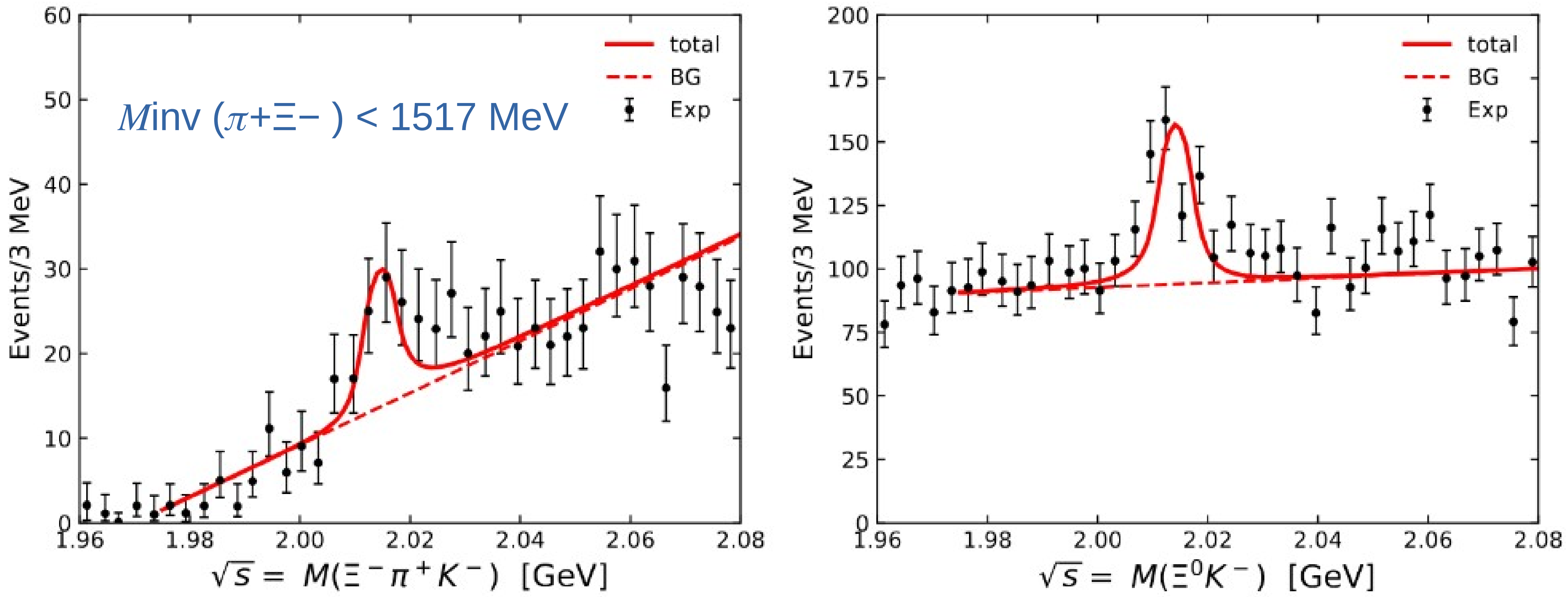


FIG. 3. Events in the decay of $H \to K^-\pi^+\Xi^-$ (Left) and to $K^-\Xi^0$ (Right) as a function of the energy $\sqrt{s}$. The peaks correspond to the production and posterior decay of the doorway state H.

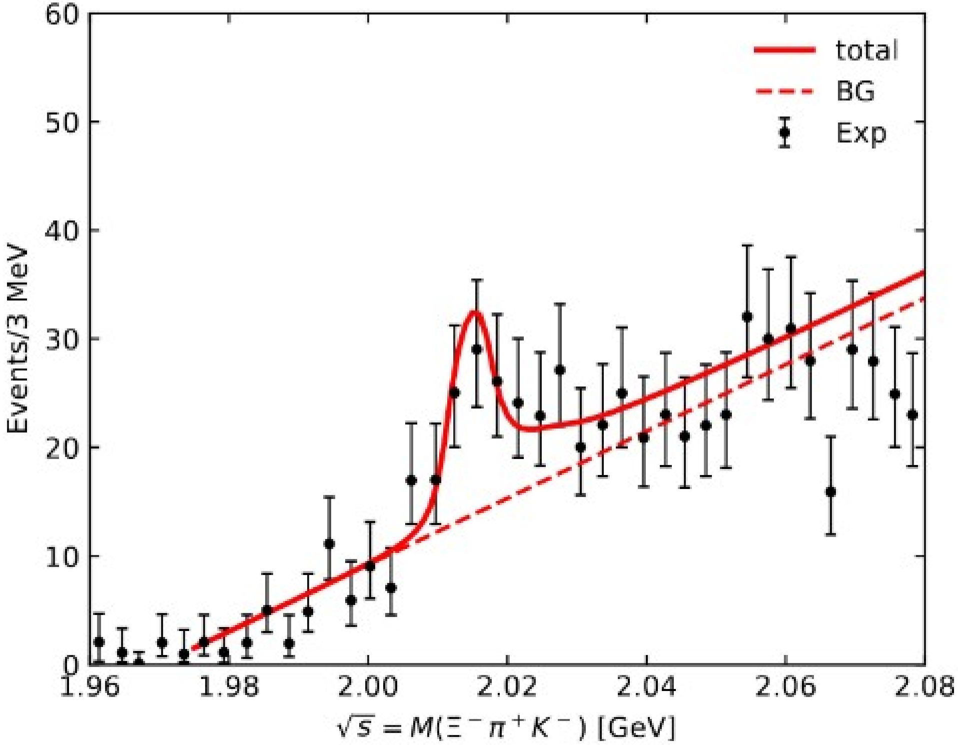
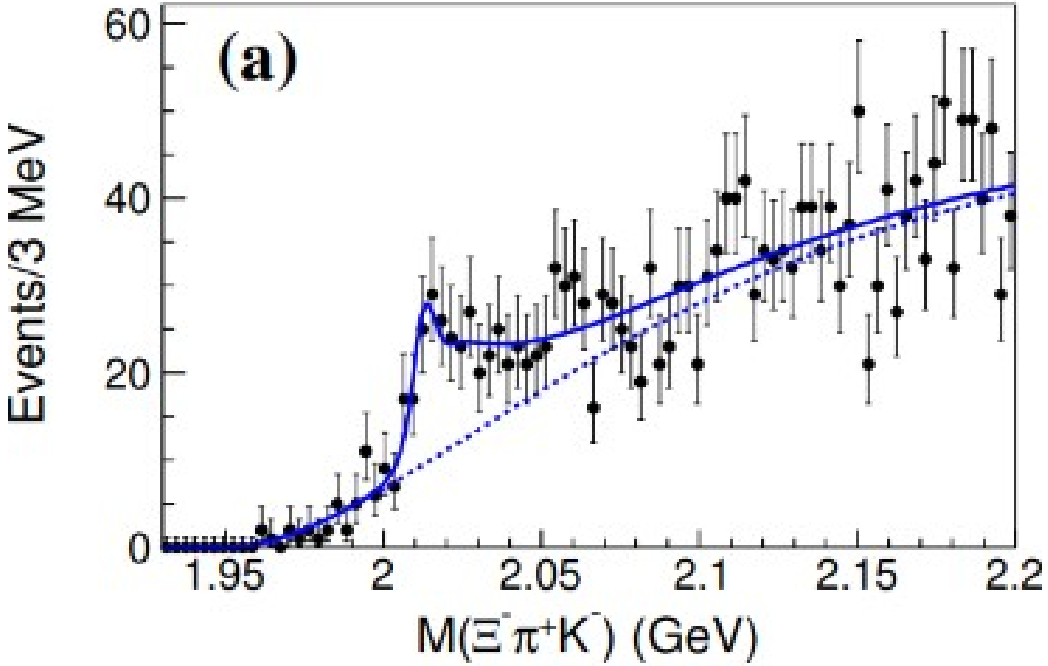


FIG. 4. The same as Fig. 3 (Left) except with the cut $M_{\text{inv}}(\pi^+\Xi^-) <$ 1530 MeV.

Minv (π+Ξ−) < 1517 MeV



S. Jia et al. (Belle), Phys. Lett. B 860, 139224 (2025)

Data have cut, but blue line of experimental analysis has not

Yi-Yao Li,[1,2,3,4,*] Albert Feijoo,[5,†] and Eulogio Oset[4,6,‡]

$\Omega(2380)^-$

Status: $**$

OMITTED FROM SUMMARY TABLE

$\Omega(2380)^-$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2380 OUR ESTIMATE					
$2384 \pm 9 \pm 8$	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
26 ± 23	45	BIAGI	86B	SPEC	SPS Ξ^- beam

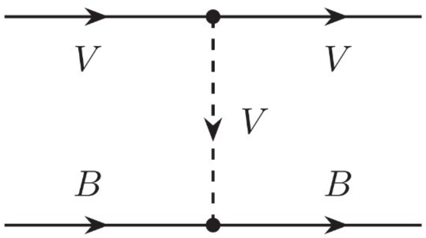
$\Omega(2380)^-$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^- \pi^+ K^-$	
Γ_2	$\Xi(1530)^0 K^-$	seen
Γ_3	$\Xi^- \overline{K}^*(892)^0$	

We extend the work of the pseudoscalar-baryon of decuplet to
Vector-baryon of decuplet

S. Sarkar, B.-X. Sun, E. Oset, and M. J. Vicente Vacas, Eur. Phys. J. A 44, 431 (2010).

channels are $\bar{K}^{*}\Xi^{*}(1530)$, $\omega\Omega$, $\phi\Omega$



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

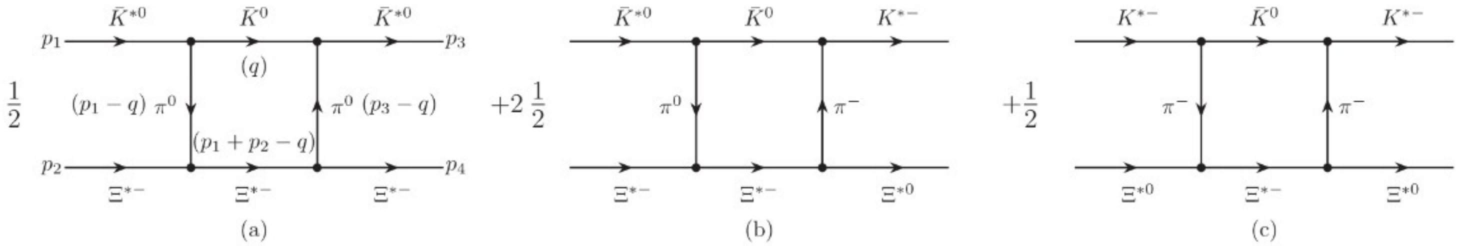
$$\tilde{\mathcal{L}}_{\rm VBB} = gq\bar{q}\gamma^{\nu'}V_{\nu'}$$

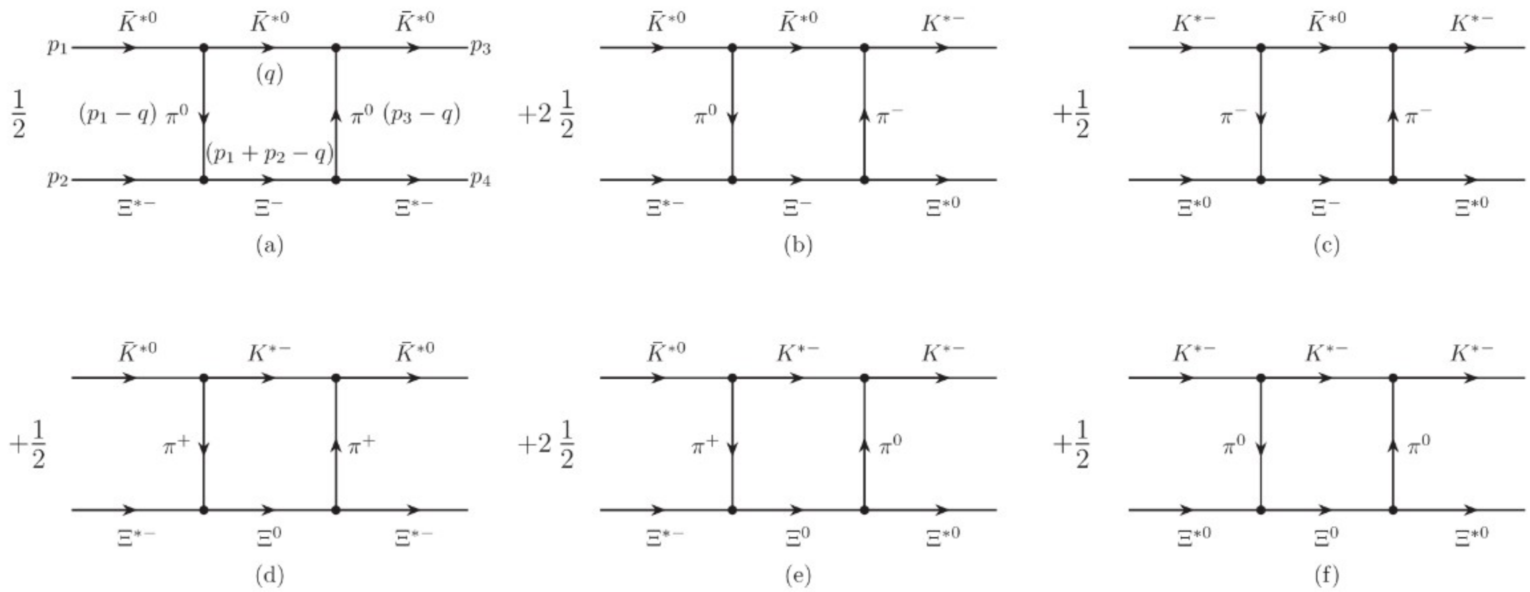
$$V_{ij} = \frac{1}{4f_{\pi}^{2}} C_{ij}(k^{0}+k'^{0})\vec{\epsilon}\,\vec{\epsilon}',$$

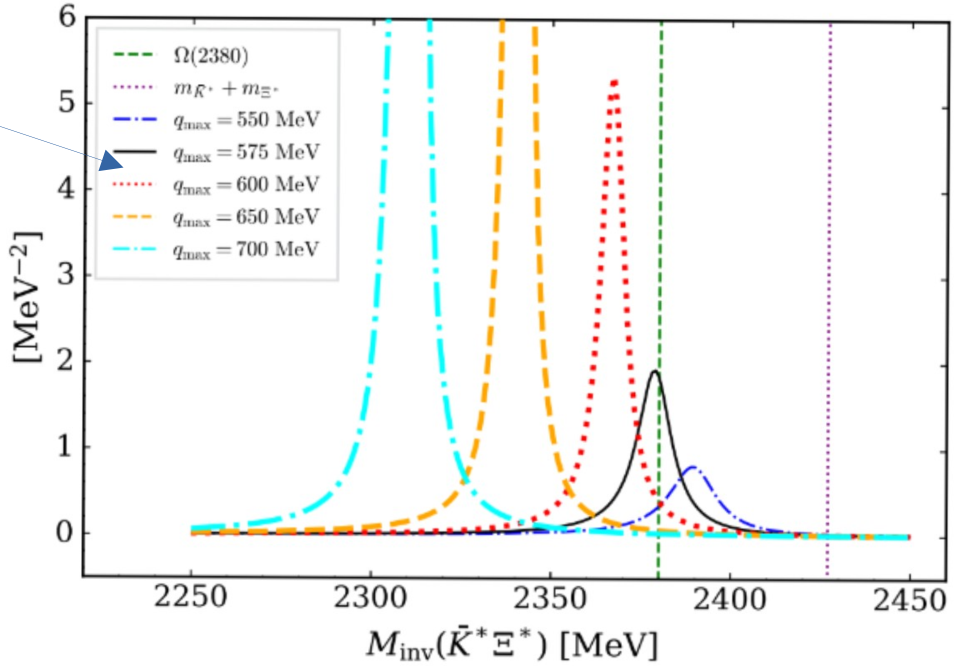
$$V = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

$$C_{ij} = \begin{pmatrix} 0 & \sqrt{3} & -\sqrt{6} \\ & 0 & 0 \\ & & 0 \end{pmatrix}$$

Box diagrams considered for the width







$$\Gamma \approx 51.5 \text{ MeV}$$

$$\Gamma_{\rm exp} = 26 \pm 23 \text{ MeV}$$

$$\mathrm{Br}[\bar{K}\Xi^*] = \Gamma_{\bar{K}\Xi^*}/\Gamma_{\bar{K}\Xi\pi} = 0.53,$$

$$\mathrm{Br}[\bar{K}^*\Xi] = \Gamma_{\bar{K}^*\Xi}/\Gamma_{\bar{K}\Xi\pi} = 0.47.$$

$$T_{ij} = g_i\, g_j \,/\, (M_{\rm inv} - M_R + i\Gamma/2)$$

TABLE I. Moduli of the coupling constants ($|g_i|$) and wave functions at the origin ($g_i G_i$ in MeV) of the three channels.

	$\lvert g_i \rvert$	$g_i G_i$
$\bar{K}^*\Xi^*$	2.84	$-27.79 - i2.01$
$\omega\Omega$	2.25	-18.72
$\phi\Omega$	3.36	11.31

A new look at the P_{cs} states from a molecular perspective

Albert Feijoo[a,*], Wen-Fei Wang[a,b], Chu-Wen Xiao[c,d], Jia-Jun Wu[e], Eulogio Oset[a], Juan Nieves[a], Bing-Song Zou[e,f] PLB 839, 137760

New perspective on the Pcs states

The large transition matrix element sqrt(2) is not present in the Pc states

$$
\begin{array}{ccc}
J/\psi N & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c \\
\left(\begin{array}{ccc}
\mu_1 & \mu_{12} & \frac{\mu_{13}}{3} \\
\mu_{12} & \mu_2 & \frac{\mu_{23}}{3} \\
\frac{\mu_{13}}{3} & \frac{\mu_{23}}{3} & \frac{1}{9}(8\lambda_2+\mu_3)
\end{array}\right. & &
\end{array}
$$

$$\mu_{23} = 0,$$

Table 1
Coefficients C_{ij} for the PB sector with $J^P = \frac{1}{2}^-$ and $I = 0$.

	$\eta_c\Lambda$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
$\eta_c\Lambda$	0	$-\frac{1}{\sqrt{3}}\lambda$	$\frac{1}{\sqrt{6}}\lambda$	$-\frac{1}{\sqrt{2}}\lambda$
$\bar{D}_s\Lambda_c$		0	$-\sqrt{2}$	0
$\bar{D}\Xi_c$			-1	0
$\bar{D}\Xi_c'$				-1

Table 2
Coefficients C_{ij} for the VB sector with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ and $I = 0$.

	$J/\psi\Lambda$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
$J/\psi\Lambda$	0	$-\frac{1}{\sqrt{3}}\lambda$	$\frac{1}{\sqrt{6}}\lambda$	$-\frac{1}{\sqrt{2}}\lambda$
$\bar{D}_s^*\Lambda_c$		0	$-\sqrt{2}$	0
$\bar{D}^*\Xi_c$			-1	0
$\bar{D}^*\Xi_c'$				-1

Poles		$\eta_c \Lambda$	$\bar{D}_s \Lambda_c$	$\bar{D} \Xi_c$	$\bar{D} \Xi'_c$
$4198.94 + i0.11$	g_i	$0.12 - i0.00$	$3.01 - i0.01$	$\mathbf{4.85 + i0.01}$	$0.01 - i0.03$
	$g_i G_i^{II}$	$-0.35 + i1.01$	$-19.24 + i0.05$	$\mathbf{-20.35 - i0.07}$	$-0.03 + i0.09$
$4422.79 + i7.75$	g_i	$0.71 - i0.08$	$0.05 + i0.00$	$-0.06 + i0.04$	$\mathbf{2.79 - i0.35}$
	$g_i G_i^{II}$	$1.14 + i10.71$	$0.76 + i1.82$	$-0.43 - i1.53$	$\mathbf{-26.54 + i0.64}$

The novelty is the prediction of a Pcs state around 4200 MeV.

Table 4
The same as in Table 3, but for the $VB(1/2^+)$ sector with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$.

Poles		$J/\psi \Lambda$	$\bar{D}_s^* \Lambda_c$	$\bar{D}^* \Xi_c$	$\bar{D}^* \Xi'_c$
$4337.98 + i0.12$	g_i	$0.11 - i0.00$	$3.17 - i0.01$	$\mathbf{5.07 + i0.01}$	$0.00 - i0.04$
	$g_i G_i^{II}$	$-0.13 + i1.07$	$-18.57 + i0.06$	$\mathbf{-19.94 - i0.07}$	$-0.01 + i0.10$
$4565.73 + i15.58$	g_i	$0.70 - i0.16$	$0.09 - i0.03$	$-0.10 + i0.09$	$\mathbf{2.84 - i0.72}$
	$g_i G_i^{II}$	$6.24 + i21.04$	$2.07 + i3.40$	$-1.37 - i2.81$	$\mathbf{-26.31 + i1.15}$

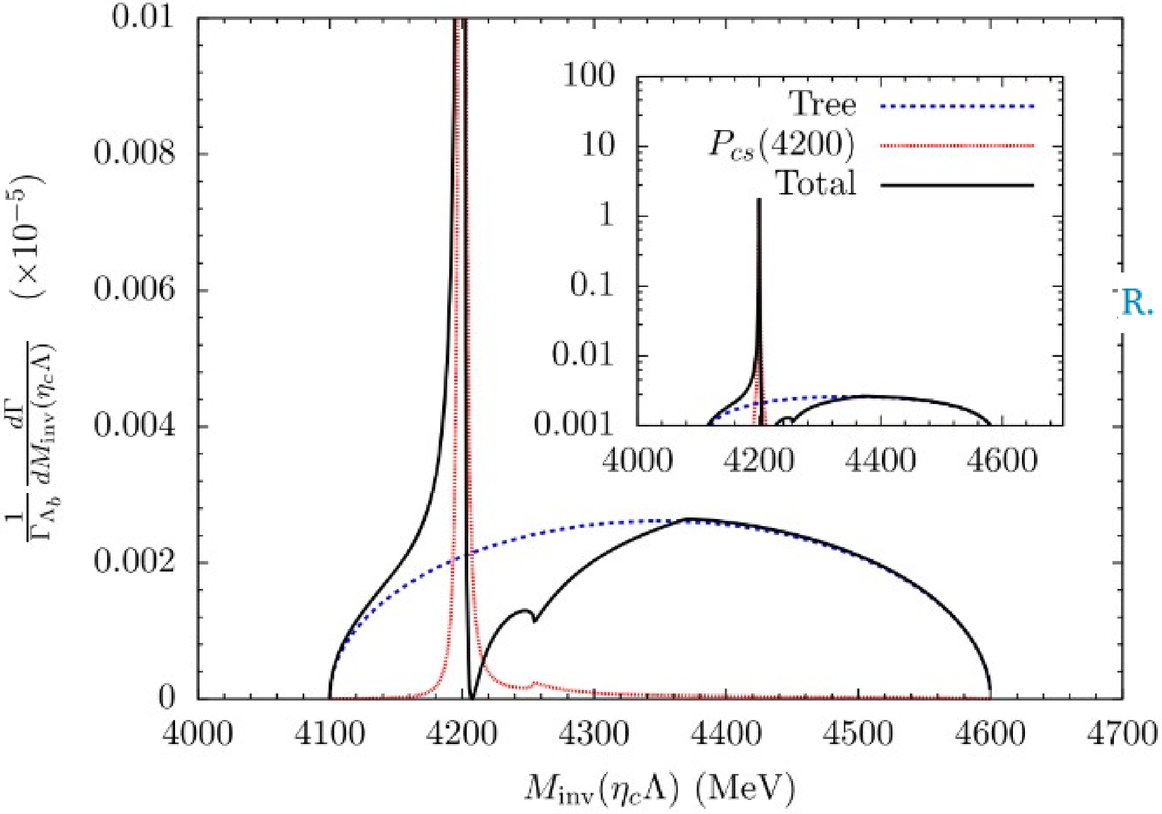
Expe: 4338 MeV (In analogy to Pc states would be Dbar Xic) ,

4459 MeV (in analogy to Pc states would be D*bar Xic)

Searching for a $P_{cs}(4200)$ state in the $\Lambda_b \to \phi\eta_c\Lambda$ reaction

Wen-Tao Lyu[a,b,*], Eulogio Oset[b]

Phys. Lett. B 877 (2026) 140452



$\Lambda_b^0 \to \phi D_s^- \Lambda_c^+$

R. Aaij, et al.[LHCb], Phys. Rev. D 112 (5) (2025) 052013.

The BR of this reaction allows us to determine the BR for the peak of η_c Λ mass distribution of the

$\Lambda_b \to \phi\eta_c\Lambda$ reaction

10^{-5},

A.~Feijoo and E.~Oset,
%``Predicted Exotic Doubly Heavy-Strange Pentaquarks,''
[arXiv:2605.25918 [hep-ph]].

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

C_{ij}

	$\Omega_{cc}^{+}\pi^{+}$	$\Xi_{cc}^{++}\bar{K}^{0}$	$\Xi_{c}^{+}D^{+}$	$\Xi_{c}^{\prime +}D^{+}$
$\Omega_{cc}^{+}\pi^{+}$	0	-1	$\frac{\sqrt{3}}{2\sqrt{2}}\lambda_1$	$\frac{1}{2\sqrt{2}}\lambda_1$
$\Xi_{cc}^{++}\bar{K}^{0}$		0	$\frac{-\sqrt{3}}{2\sqrt{2}}\lambda_2$	$\frac{1}{2\sqrt{2}}\lambda_2$
$\Xi_{c}^{+}D^{+}$			$-\lambda_3$	0
$\Xi_{c}^{\prime +}D^{+}$				$-\lambda_3$

We predict exotic doubly heavy–strange pentaquarks with minimal quark content $u\bar{d}sQQ'$ ($QQ' = cc, bc, bb$)

Conclusions

Coupled channels play a very important role in hadron dynamics
They collaborate to build up emblematic resonances like the two $\Lambda(1405)$

The predicted $\Sigma(1430)$ from pseudoscalar-baryon interaction has been recently found by the Belle Collaboration

We show the role of two coupled channels producing a bound sate, when none of the channels binds individually.

A predicted Ω state by the chiral unitary approach has been found as the $\Omega(2012)$

The partner of the $\Omega(2012)$ in the vector-baryon sector has been identified as the $\Omega(2380)$

We present a new perspective on the Pcs states and predict a new one at 4200 MeV

We also show how double heavy strange pentaquarks can be produced