Double-Strangeness Molecular-Type Pentaquarks from Coupled-Channel Dynamics

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Based on: J.A. Marsé-Valera, V.K. Magas, A. R., *Phys. Rev. Lett.* 130 (2023) 9

Outline

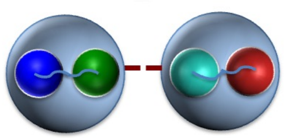
- Introduction to exotic hadrons
- Pentaquarks within a molecular picture
- Model: unitarized t-channel vector exchange interaction: → is there an S=-2 pentaquark?
- Results
- Summary

Exotic hadrons
(anything that goes beyond $q\bar{q}$ and qqq)

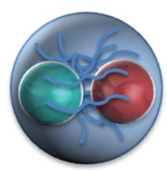
Mesons

compact tetraquark

Glueball



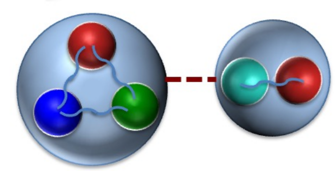
meson-meson molecule



hybrid

Baryons

compact pentaquark



baryon-meson molecule

In spite of the success of the conventional quark model, there are many (excited) hadrons that **do not accommodate** to the $q\bar{q}$ or qqq description:

Mesons	$I^G(J^{PC})$	
$f_0(500)$	$0^+(0^{++})$	➔ the same *orbital* excitation
$a_0(980)$	$1^-(0^{++})$	(only different isospin): $(u\bar{u} \pm d\bar{d})/\sqrt{2}$
$f_0(980)$	$0^+(0^{++})$	➔ $s\bar{s}$
$f_1(1420)$	$0^+(1^{++})$	

Baryons	$I^G(J^P)$	
$N(1440)$	$1/2^+$	➔ *radial* excitation (too low exp. mass)
$N(1535)$	$1/2^-$	➔ *orbital* excitation (too high exp. mass)
$\Lambda(1405)$	$1/2^-$	➔ *orbital* excitation (too low exp. mass)
$\Lambda(1670)$	$1/2^-$	

- Nature gives clues to whether a particular hadron may have an exotic multiquark configuration structure

$f_0(500)$ ➔ appears naturally from chiral $\pi\pi$ interations

$\left.\begin{array}{l} a_0(980) \\ f_0(980) \end{array}\right\}$ ➔ very close to the $K\bar{K}$ threshold

$\Lambda(1405)$ ➔ very close to the $\bar{K}N$ threshold

- A lot of activity for more than 40 years! …

…but disentangling the true nature of a particular hadron is not easy due to the mixing of *conventional* and *exotic* components.

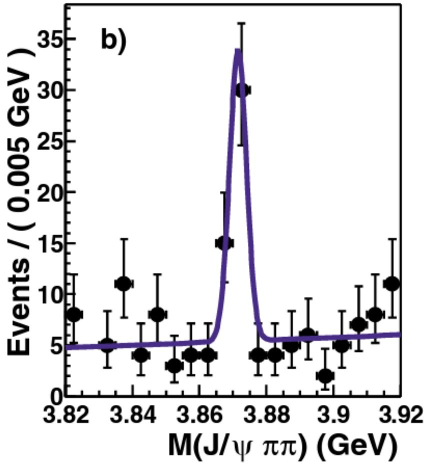
Since the beginning of the millenium, an increasing amount of data in the charm (hidden charm) sector (collected at Belle, BaBar, LHCb and BESIII…), has provided cleaner evidence for many new **exotic** states which appear to be inconsistent with the predictions of the conventional quark model.

Exotic MESONS (hidden charm)

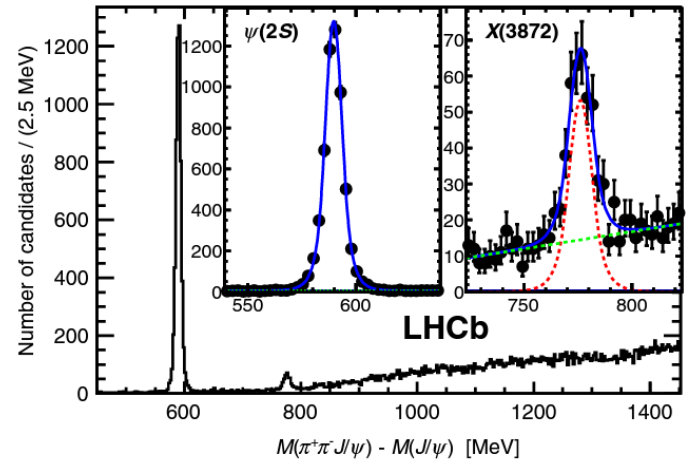
$\chi_{c1}(3872)$

$D^0\overline{D}^{*0}$
$(J^{PC}=1^{++})$

Discovered at Belle, 2003



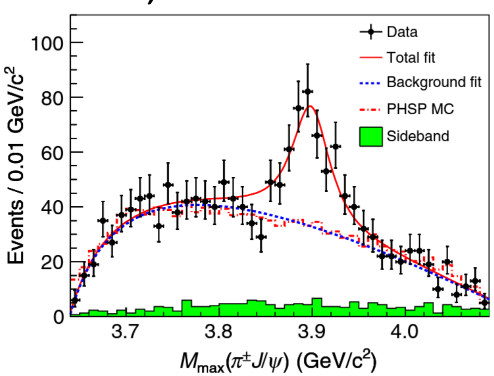
LHCb, PRL 2013



Hidden charm ($c\bar{c}$) but charged (need additional $q\bar{q}$ pair: $u\bar{d}$, $u\bar{s}$)

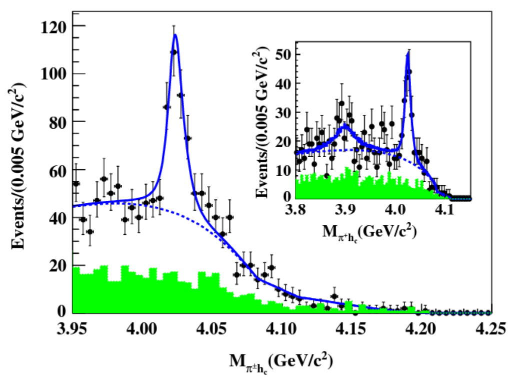
$Z_c(3900)$

BESIII, Belle 2013



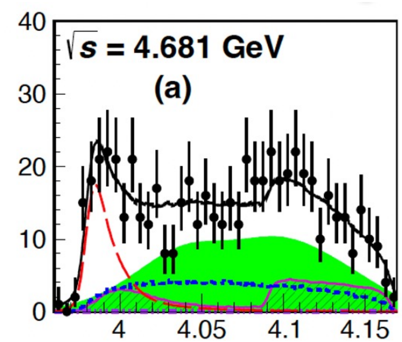
$Z_c(4020)$

BESIII 2013



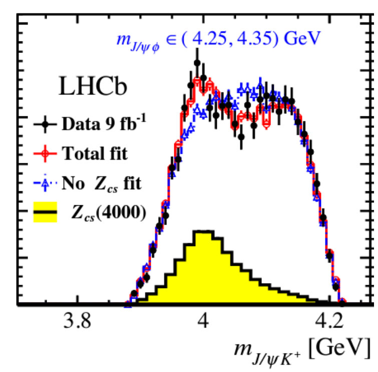
$Z_{cs}(3985)$

BESIII 2021



$Z_{cs}(4000)$

LHCb 2021



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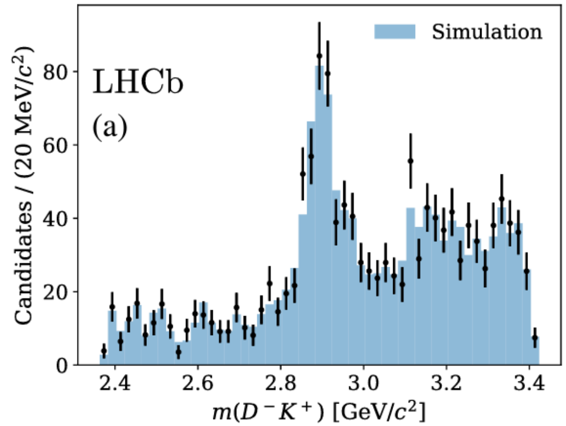
Exotic MESONS (open charm)

LHCb 2021

Charm-strange state (cs): $X_{cs}(2900)$

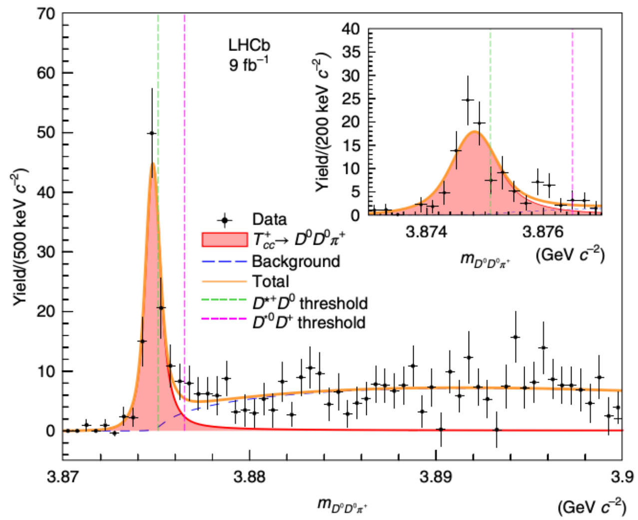
$D^*\overline{K}^*$ molecule?
Molina, Branz, Oset (2010)



LHCb 2022

Double-charm (cc): $T_{cc}(2900)$

$D^{*+}D^0$



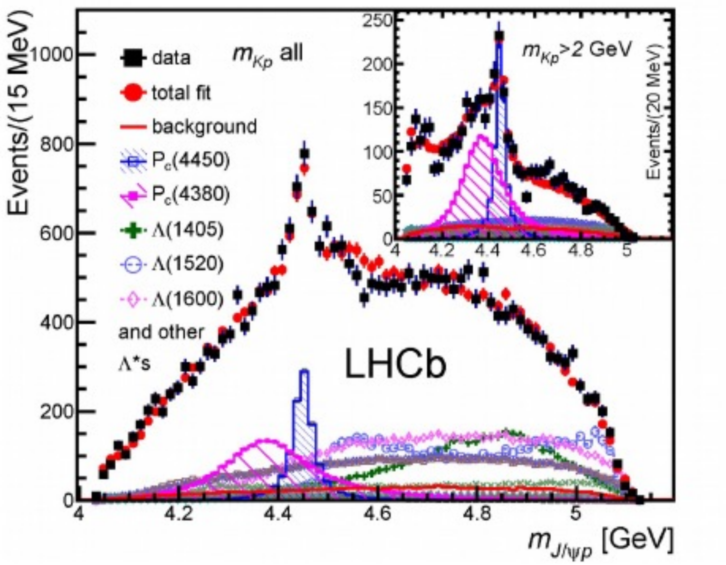
Exotic BARYONS

S=0 $(c\bar{c}qqq)$ $\quad q = u, d$

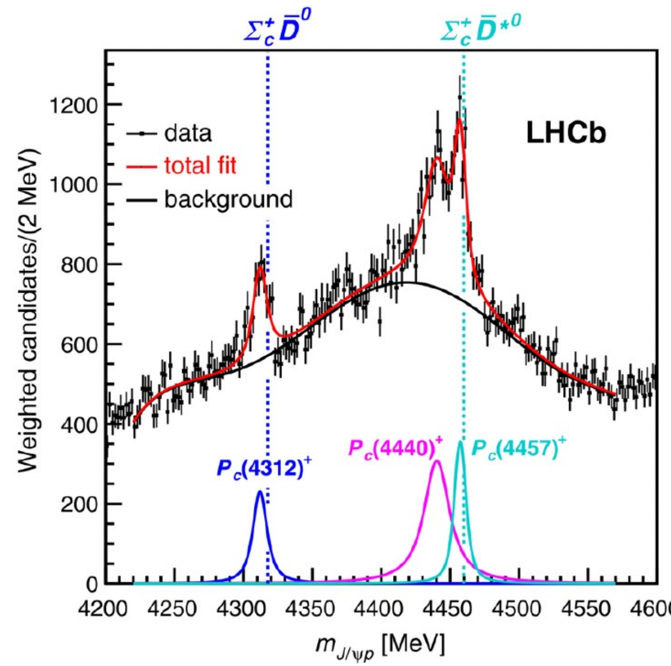
P_c (or P_ψ^N)

$$\Lambda_b \to J/\psi\ p\ K^-$$

LHCb, Run 1, 2015



LHCb, Run 1+Run 2, 2019



P_c(4380)

P_c(4450) ⟶

New state: **P_c(4312)**

Broad **P_c(4380)** ?

P_c(4440), P_c(4457)

- The flavor content of the $P_c(4310)$, $P_c(4440)$, $P_c(4457)$ states is not exotic (uud) but the high mass and the observation from J/ψ p pairs makes them to be unambiguous pentaquark candidates ($c\bar{c}uud$).

In fact, these states find a natural explanation as baryon-meson molecules:

$\bar{D}^0\Sigma_c^+$ threshold: 4318 MeV → **$P_c(4312)$**

$\bar{D}^{*0}\Sigma_c^+$ threshold: : 4460 MeV (J=1/2, 3/2) → **$P_c(4440)$, $P_c(4457)$**

and were already predicted in 2010!

J.J.Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010); Phys. Rev. C 84, 015202 (2011).

This work also predicted **S=-1** states at **4209 MeV** ($\bar{D}\Xi_c$), **4394 MeV** ($\bar{D}\Xi_c'$)
4368 MeV ($\bar{D}^*\Xi_c$), **4544 MeV** ($\bar{D}^*\Xi_c'$)

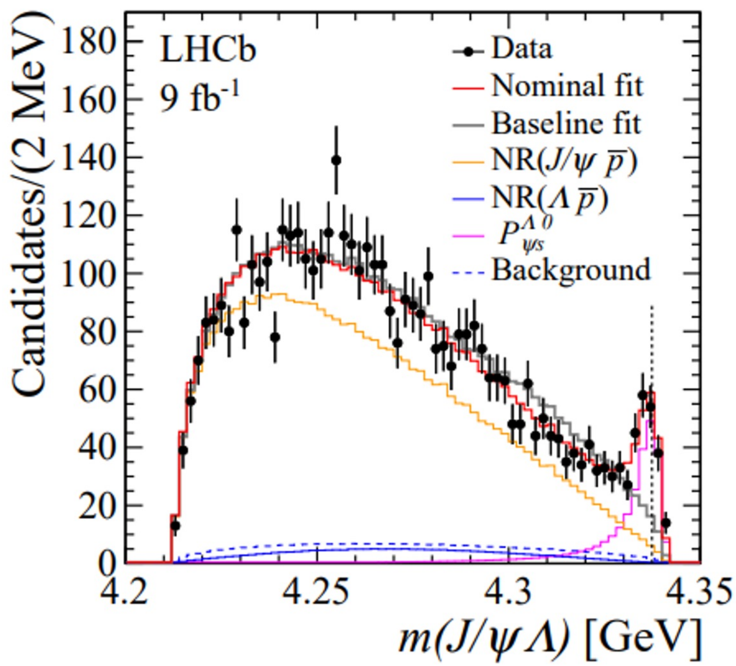
Exotic BARYONS

S=-1 $(c\bar{c}qqs)$ $q = u, d$

P_{cs} (or $P^{\Lambda}_{\psi s}$)

$B^- \to J/\psi \Lambda \bar{p}$

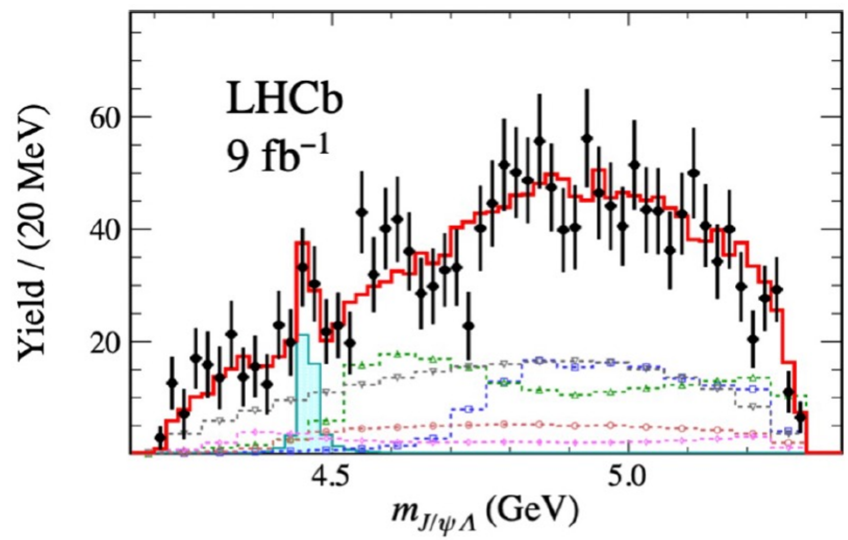
LHCb, arXiv:2210.10346 (Oct 2022)



$P_{cs}(4338)$

$\Xi_b^- \to J/\psi \Lambda K^-$

LHCb, Sci. Bull. 66 (2021) 1278



$P_{cs}(4459)$

S=-2 pentaquarks?

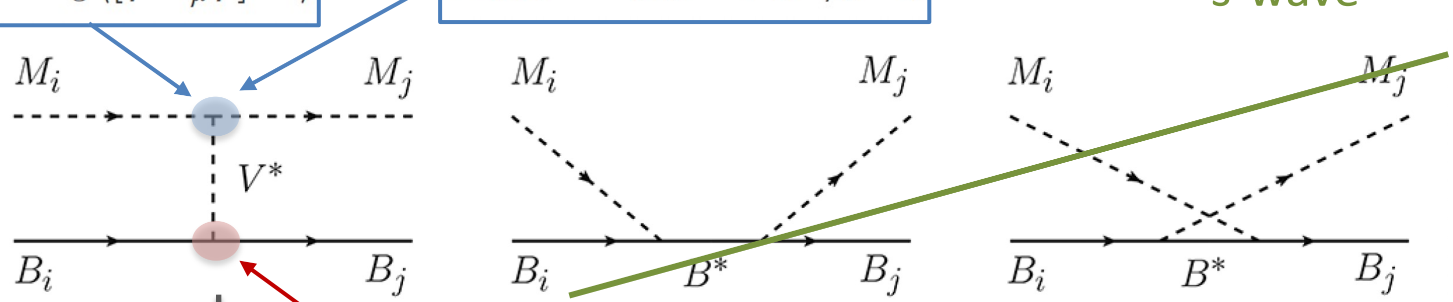
P_{css} (or $P^{\Xi}_{\psi ss}$)

Unitarized t-channel vector-meson exchange interaction

Interaction kernel:

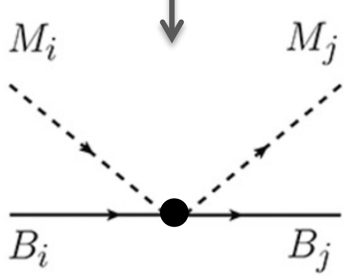
$$\mathcal{L}_{VPP} = -ig\langle[\phi, \partial_\mu \phi]V^\mu\rangle$$

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



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

$t \ll m_{V^*}^2$



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

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

$$S = -2, I = \frac{1}{2}$$

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

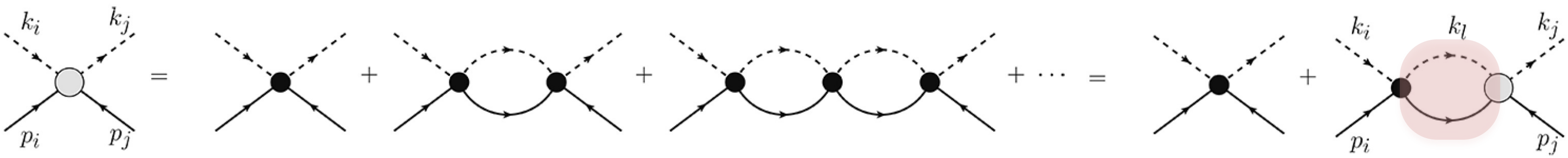
		$\pi\Xi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$	$\eta'\Xi$	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
light sector	$\pi\Xi(1456)$	2	$\frac{3}{2}$	$\frac{1}{2}$	0	0	0	0	0	$\sqrt{\frac{3}{2}}\kappa_c$
	$\bar{K}\Lambda(1611)$		0	0	$-\frac{3}{2}$	0	0	$-\frac{1}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
	$\bar{K}\Sigma(1689)$			2	$\frac{3}{2}$	0	0	$\frac{3}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
	$\eta\Xi(1866)$				0	0	0	κ_c	$\frac{1}{\sqrt{3}}\kappa_c$	$\frac{1}{\sqrt{6}}\kappa_c$
	$\eta'\Xi(2276)$					0	0	$\frac{1}{\sqrt{8}}\kappa_c$	$-\frac{1}{\sqrt{6}}\kappa_c$	$\frac{1}{\sqrt{3}}\kappa_c$
heavy sector	$\eta_c\Xi(4302)$						0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
	$\bar{D}_s\Xi_c(4437)$							$-1+\kappa_{cc}$	0	0
	$\bar{D}_s\Xi'_c(4545)$								$-1+\kappa_{cc}$	$-\sqrt{2}$
	$\bar{D}\Omega_c(4565)$									κ_{cc}

$$\kappa_c = \frac{m_\rho^2}{m_{D^*}^2} \sim \frac{1}{4}$$

$$\kappa_{cc} = \frac{m_\rho^2}{m_{J/\psi}^2} \sim \frac{1}{9}$$

Light and heavy sectors are practically "decoupled"

Unitarization: *Bethe-Salpeter equation with on-shell factorization*



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

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

dim reg.

cut-off

$$\begin{aligned} G_l^{\mathrm{DR}} = \frac{1}{16\pi^2} \Big\{ & a_l(\mu) + \ln \frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln \frac{m_l^2}{M_l^2} + \\ & + \frac{q_l}{\sqrt{s}} \Big[\ln \left(s + (m_l^2 - M_l^2) + 2q_l\sqrt{s} \right) \\ & \quad + \ln \left(s - (m_l^2 - M_l^2) + 2q_l\sqrt{s} \right) \\ & \quad - \ln \left(-s - (m_l^2 - M_l^2) + 2q_l\sqrt{s} \right) \\ & \quad - \ln \left(-s + (m_l^2 - M_l^2) + 2q_l\sqrt{s} \right) \Big] \Big\} \end{aligned}$$

$$a_l(\mu) \sim -2 \qquad (\mu = 1\ \mathrm{GeV})$$

$$G_l^{\mathrm{cut}} = 2M_l \int^{\Lambda} \frac{q^2\,\mathrm{d}q}{4\pi^2} \frac{(\omega_l + E_l)}{\omega_l\, E_l} \frac{1}{s - (\omega_l + E_l)^2 + \mathrm{i}\epsilon}$$

$$\Lambda = 600 - 1000\ \mathrm{MeV}$$

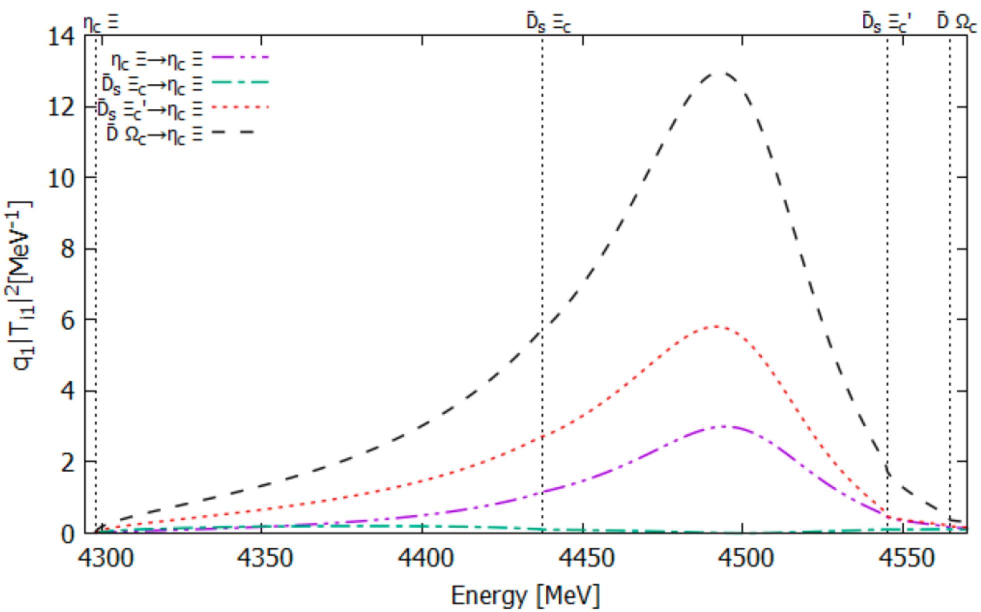
$$a_l(\mu) = \frac{16\pi^2}{2M_l} \left(G_l^{\mathrm{cut}}(\Lambda) - G_l^{\mathrm{DR}}(\mu, a_l = 0) \right)$$

(we employ the cut-off method with Λ~800 MeV)

Results: heavy PB sector

$J^\pi = \frac{1}{2}^-$

$0^- \oplus 1/2^+$ PB interaction in the $(I,S)=(1/2,-2)$ sector				
$P^{\Xi}_{\Psi ss}(4493)$		$M_R = 4493.35$ MeV	$\Gamma_R = 73.67$ MeV	
	Threshold Energy (MeV)	g_i	$\|g_i\|$	χ_i
$\eta_c \Xi$	4298	$-1.60 + i0.34$	1.63	0.220
$\bar{D}_s \Xi_c$	4437	$-0.17 + i0.27$	0.32	0.019
$\bar{D}_s \Xi_c'$	4545	$-2.41 + i0.58$	2.48	0.398
$\bar{D} \Omega_c$	4564	$3.59 - i0.77$	3.67	0.711



We find a $P^{\Xi}_{\psi ss}$ state around **4500 MeV** and width of 70 MeV, coupling strongly to $\bar{D}_s \Xi_c'$ and $\bar{D}\Omega_c$

J.A. Marsé-Valera, V.K. Magas, A. Ramos, *Phys. Rev. Lett.* 130 (2023) 9

Was a meson-baryon molecule expected in this $\left(S=-2, I=\frac{1}{2}\right)$ sector?

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

$S=0, I=1/2$

	$\eta_c N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$
$\eta_c N$	0	$-\sqrt{\frac{3}{2}}\kappa_c$	$\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}\Lambda_c$		$-1+\kappa_{cc}$	0
$\bar{D}\Sigma_c$			$1+\kappa_{cc}$

repulsion

attraction

one state ←

$S=-1, I=0$

	$\eta_c\Lambda$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
$\eta_c\Lambda$	0	κ_c	$-\frac{1}{\sqrt{2}}\kappa_c$	$-\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}_s\Lambda_c$		κ_{cc}	$\sqrt{2}$	0
$\bar{D}\Xi_c$			$1+\kappa_{cc}$	0
$\bar{D}\Xi_c'$				$1+\kappa_{cc}$

→ two states

$$\kappa_c = \frac{m_\rho^2}{m_{D^*}^2} \sim \frac{1}{4}$$

$$\kappa_{cc} = \frac{m_\rho^2}{m_{J/\psi}^2} \sim \frac{1}{9}$$

$S=-2, I=1/2$

	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi_c'$	$\bar{D}\Omega_c$
$\eta_c\Xi$	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c$		$-1+\kappa_{cc}$	0	0
$\bar{D}_s\Xi_c'$			$-1+\kappa_{cc}$	$-\sqrt{2}$
$\bar{D}\Omega_c$				κ_{cc}

→ no state expected

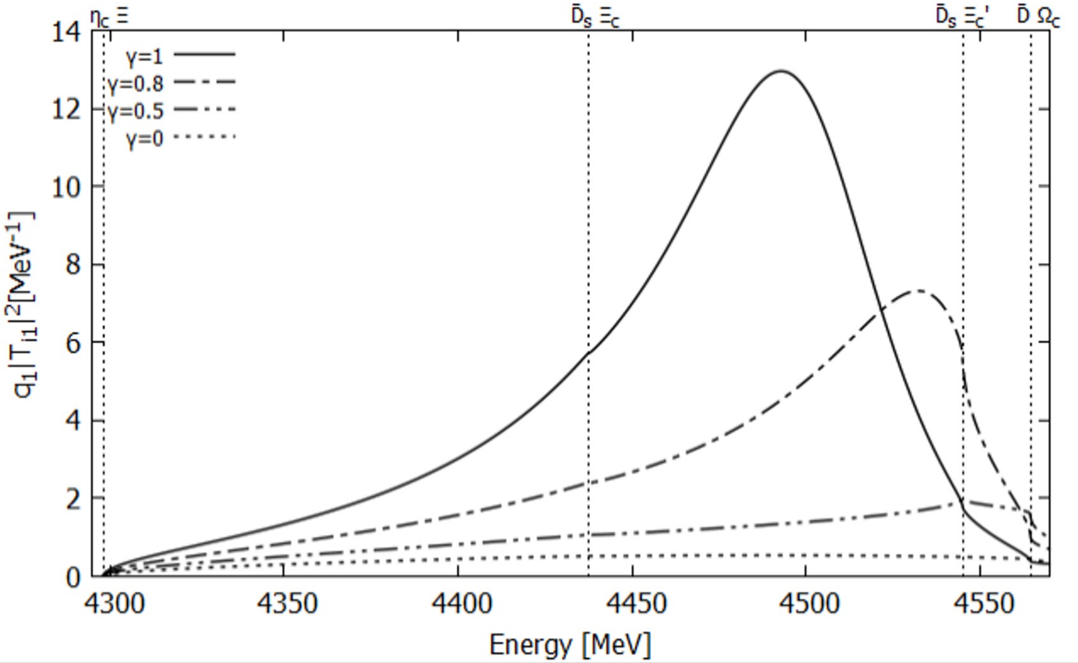
but…

strong coupled channel effect!

→ induces attraction

Coupled-channel effect

$$C_{34} = -\sqrt{2} \quad \rightarrow \quad C'_{34} = \gamma\, C_{34}$$



The resonance is not generated in the coupling coefficient is reduced by 30%.

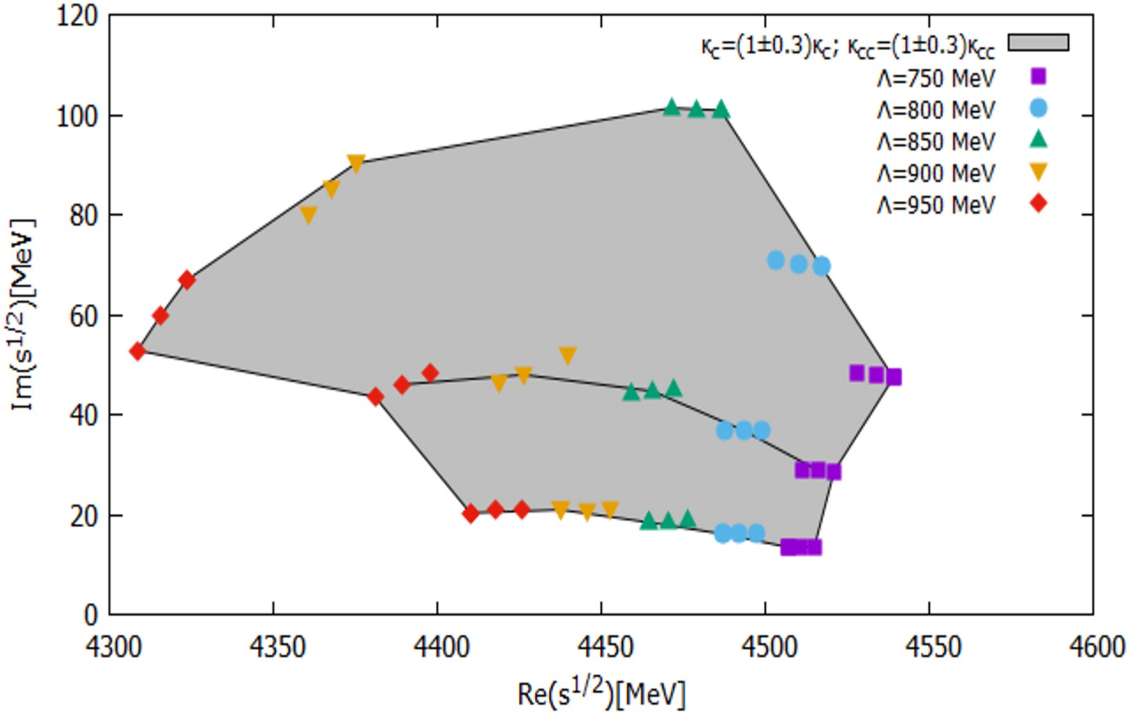
This state is generated in a very specific and unique mechanism:

→ via an attraction induced by a strong coupling between the $D_s\Xi_c'$ and $D\Omega_c$ channels

Parameter dependence: cut-off Λ, SU(4) breaking

$$\Lambda = 750 - 950 \text{ MeV} \qquad \kappa_c = \frac{m_{D^*}^2}{m_\rho^2} \sim \frac{1}{4} \pm 30\% \qquad \kappa_{cc} = \frac{m_{J/\psi}^2}{m_\rho^2} \sim \frac{1}{9} \pm 30\%$$

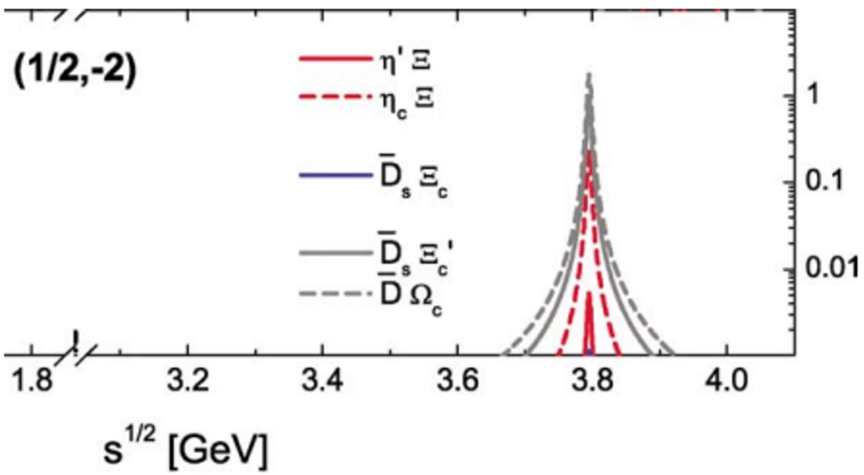
	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
$\eta_c\Xi$	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c$		$-1+\kappa_{cc}$	0	0
$\bar{D}_s\Xi'_c$			$-1+\kappa_{cc}$	$-\sqrt{2}$
$\bar{D}\Omega_c$				κ_{cc}



Even changing the parameters of the model,
the prediction of this resonance is robust

Comparison with other works
(unitarized vector-meson exchange)

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



→ a state around 3800 MeV is found

Very different regularization approach!

(it amounts to $\Lambda_{cut} \sim 2800$ MeV)

J. J. Wu, R. Molina, E. Oset and B. S. Zou,
Phys. Rev. C 84 (2011) 015202

	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
$\eta_c\Xi$	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c$		$-1+\cancel{\kappa_{cc}}$	0	0
$\bar{D}_s\Xi'_c$			$-1+\cancel{\kappa_{cc}}$	$-\sqrt{2}$
$\bar{D}\Omega_c$				$\cancel{\kappa_{cc}}$

$$\kappa_{cc} = \frac{m^2_{J/\psi}}{m^2_\rho} \sim \frac{1}{9} \to 0$$

Dimensional regularization scheme

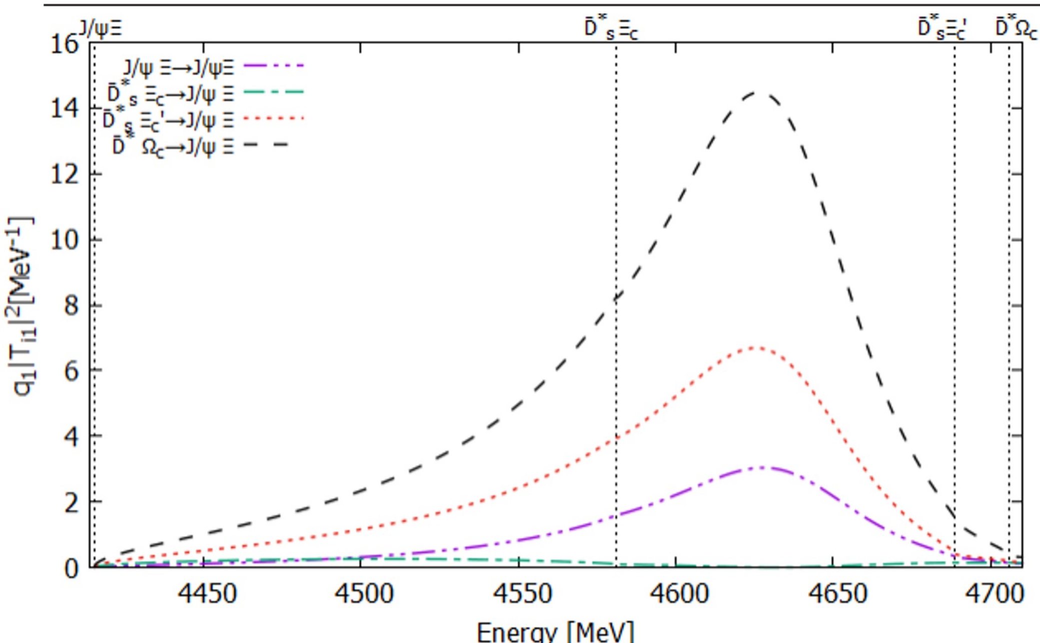
→ generates a *fake* pole at a lower energy, “hiding” the real signature

Results: heavy VB sector

$$J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$$

$1^- \oplus 1/2^+$ VB interaction in the $(I,S)=(1/2,-2)$ sector				
$P^{\Xi}_{\Psi ss}(4633)$		$M_R = 4633.38$ MeV	$\Gamma_R = 79.58$ MeV	
	Threshold Energy (MeV)	g	$\lvert g_i \rvert$	χ_i
$J/\psi\Xi$	4415	$-1.62 + i0.38$	1.66	0.252
$\bar{D}_s^*\Xi_c$	4581	$-0.143 + i0.32$	0.34	0.022
$\bar{D}_s^*\Xi_c'$	4689	$-2.49 + i0.67$	2.58	0.406
$\bar{D}^*\Omega_c$	4706	$3.67 + i0.89$	3.78	0.740

We find a $P^{\Xi}_{\psi ss}$ state around **4630 MeV** and width of 80 MeV, coupling strongly to $\bar{D}_s^*\Xi_c'$ and $\bar{D}^*\Omega_c$



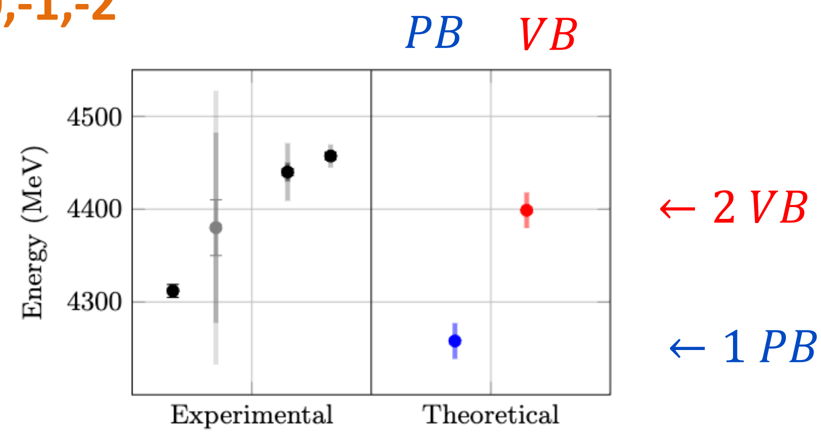
It could be seen as a peak in the invariant mass spectrum of $J/\psi\,\Xi$ pairs produced in the decays: $\Xi_b \to J/\psi\,\Xi\,\phi$ or $\Omega_b \to J/\psi\,\Xi\,\bar{K}$

The t-channel vector-exchange formalism predicts pentaquarks with strangeness S=0,-1,-2

$S=0$

P_{ψ}^{N}

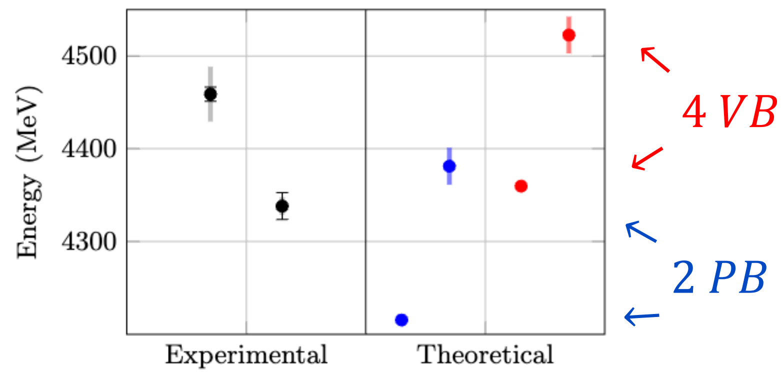
	$\eta_c N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$
$\eta_c N$	0	$-\sqrt{\frac{3}{2}}\kappa_c$	$\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}\Lambda_c$		$-1+\kappa_{cc}$	0
$\bar{D}\Sigma_c$			$1+\kappa_{cc}$



$S=-1$

$P_{\psi s}^{\Lambda}$

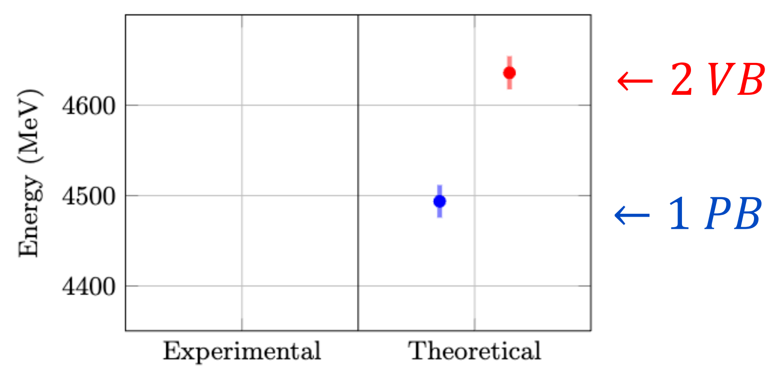
	$\eta_c \Lambda$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
$\eta_c \Lambda$	0	κ_c	$-\frac{1}{\sqrt{2}}\kappa_c$	$-\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}_s\Lambda_c$		κ_{cc}	$\sqrt{2}$	0
$\bar{D}\Xi_c$			$1+\kappa_{cc}$	0
$\bar{D}\Xi_c'$				$1+\kappa_{cc}$

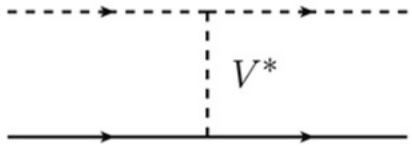


$S=-2$

$P_{\psi ss}^{\Xi}$

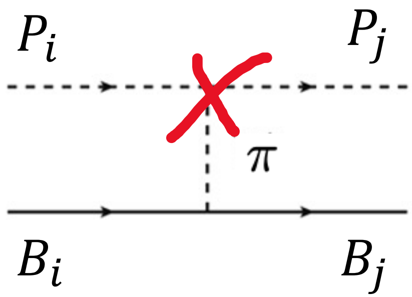
	$\eta_c \Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi_c'$	$\bar{D}\Omega_c$
$\eta_c \Xi$	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c$		$-1+\kappa_{cc}$	0	0
$\bar{D}_s\Xi_c'$			$-1+\kappa_{cc}$	$-\sqrt{2}$
$\bar{D}\Omega_c$				κ_{cc}





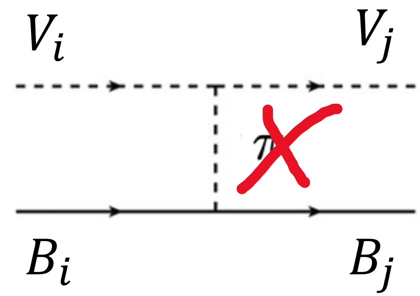
The t-channel vector-exchange formalism predicts pentaquarks with S=-2: $P^{\Xi}_{\psi ss}$

Long range open-pion-exchange (alternative molecular picture) is forbidden!



Channels:

$\eta_c\Xi \quad \bar{D}_s\Xi_c \quad \bar{D}_s\Xi'_c \quad \bar{D}\Omega_c$



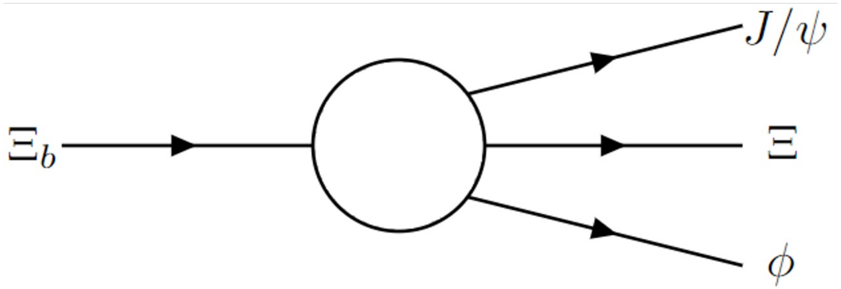
Channels:

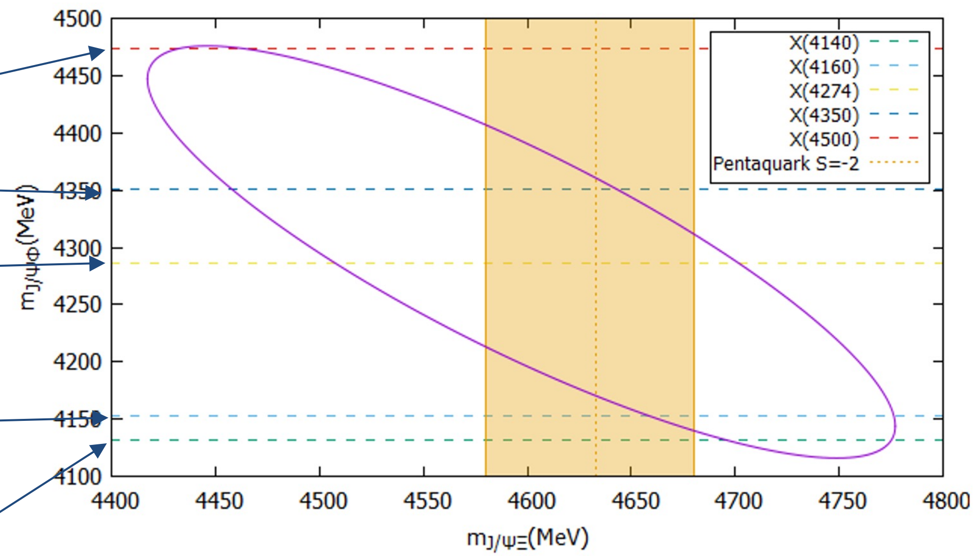
$J/\psi\,\Xi \quad \bar{D}^*_s\Xi_c \quad \bar{D}^*_s\Xi'_c \quad \bar{D}^*\Omega_c$

These transitions cannot proceed via OPE because they involve either an isoscalar meson or baryon

→ If $P^{\Xi}_{\psi ss}$ are discovered, this would strengthen the validity of unitary t-channel vector-exchange models for meson-baryon molecules

The decay $\Xi_b \to J/\psi\, \phi\, \Xi$





X(4500)

X(4350)

X(4270)

- seen at Belle, 2008
- 2^{++} $D_s^* \overline{D}_s^*$ molecule
  Molina, Oset, 2009
- not seen at LHCb, 2017

? X(4160)

X(4140)

narrow? CDF, 2009
wide? LHCb, 2017

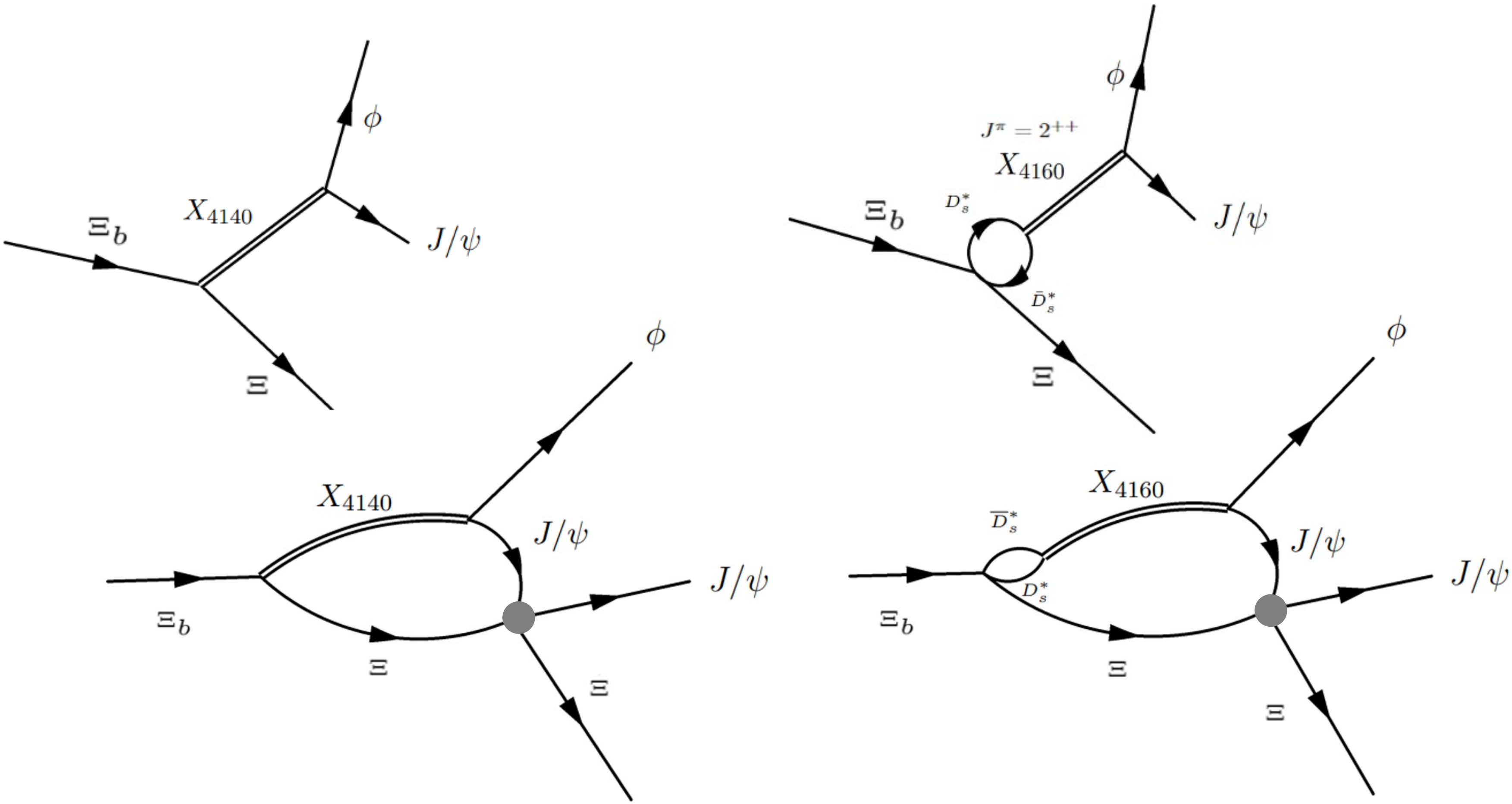
$\Xi_b \to J/\psi\, \phi\, \Xi$

(Similar to the proces $\Lambda_b \to J/\psi\ \phi\ \Lambda$)

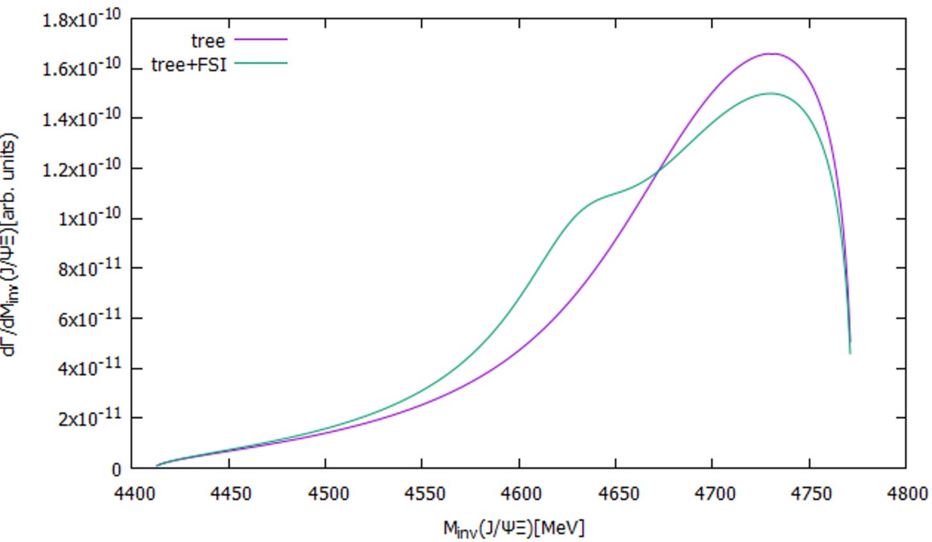
Magas, Ramos, Somasundaram, Phys.Rev.D 102 (2020) 054027

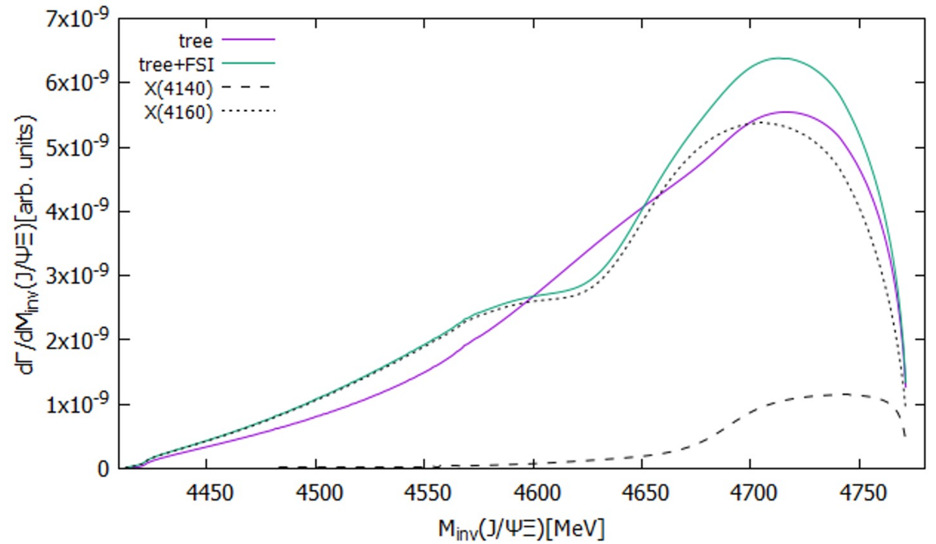
(inspired on $B^+ \to J/\psi\ \phi\ K^+$)

Wang, Xie, Geng, Oset, Phys.Rev.D 97 (2018) 014017



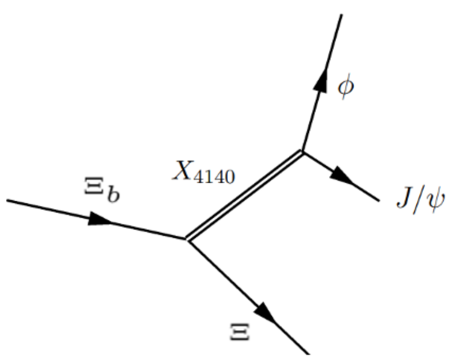
$J/\psi\ \Xi$ invariant mass distribution

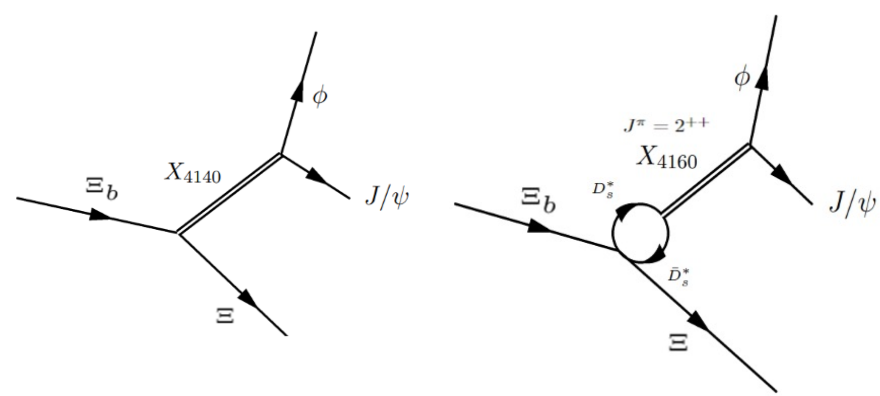




Production via a *wide* X(4140)

Production via a *narrow* X(4140) + X(4160)



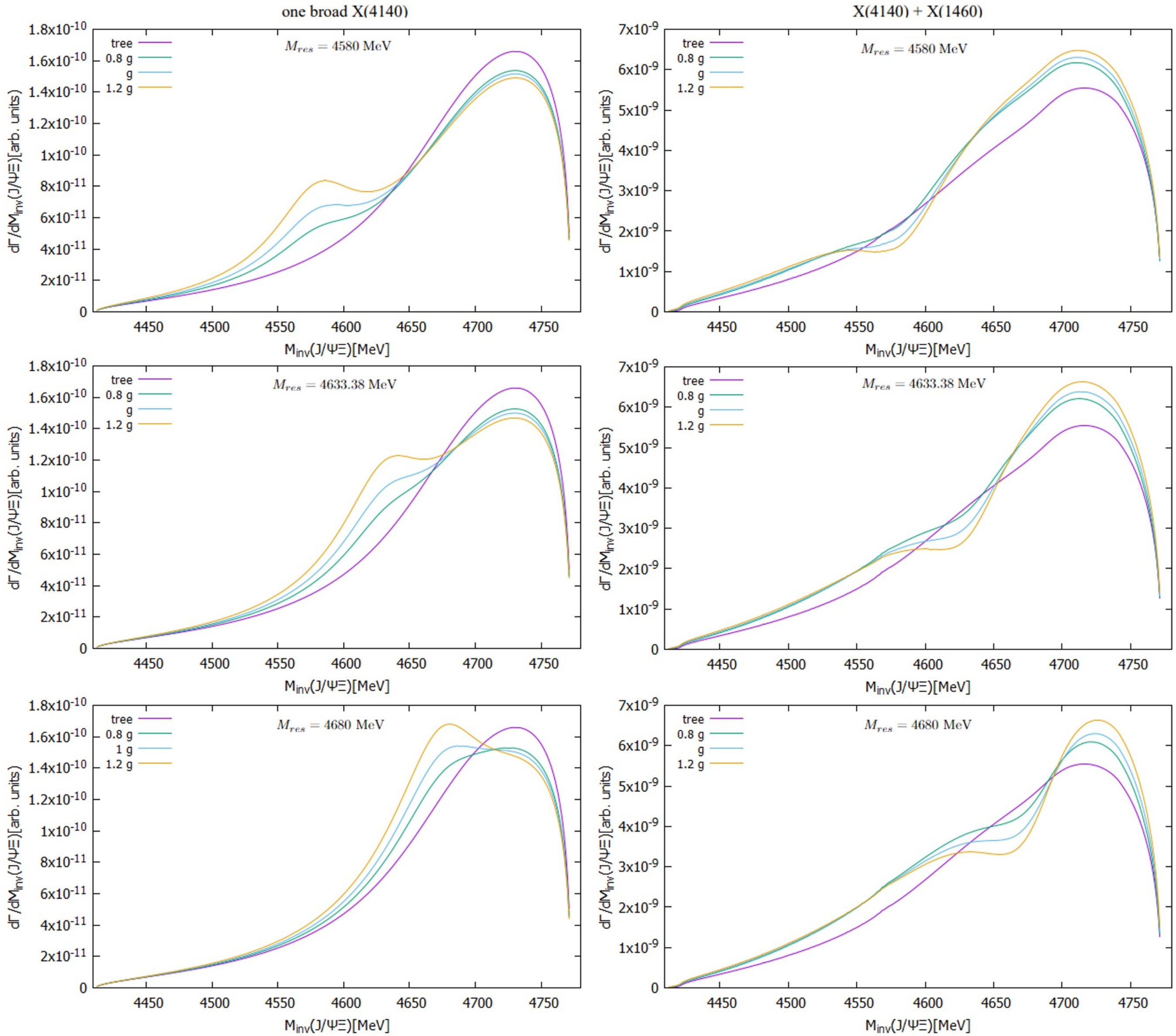


Sensitivity to M and to coupling $g(P^{\Xi}_{\psi ss} \to J/\psi\ \Xi)$

M=4580 MeV

M=4633 MeV

M=4680 MeV



Summary

Stimulated by the recent discoveries by the LHCb of hidden-charm pentaquark states with strangeness S=0 and S =−1, we have revisited the vector-meson exchange interaction models to **study the possible existence of pentaquarks with strangeness S=−2**

Employing realistic regularization parameters, **we predict S=-2 pentaquarks of molecular nature around 4500 and 4600 MeV**

These $P_{\psi ss}^{\Xi}$ states are generated in a very specific and unique way:
→ via an **attraction induced** by a **strong coupling between** the two heaviest MB **channels**

The **absence in this sector of a long-range OPE** mechanism makes the search of $P_{\psi ss}^{\Xi}$ especially interesting
→ if found, their interpretation as **molecules** would require a change of paradigm, since they **could be only bound through heavier-meson exchange** mechanisms.

Thank you for your attention