MESON 2023

17th International Workshop on Meson Physics

Kraków, Poland, June 22nd-27th, 2023

Volodymyr Magas

Double strangeness molecular-type pentaquarks from coupled channel dynamics

Collaborators: ***Arnau Marsé-Valera, Angels Ramos*** *(Barcelona)*

Universitat de Barcelona

Phys. Rev. Lett. ***130*** *(2023) 9*

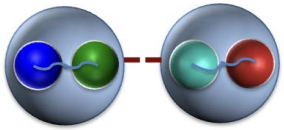
ICCUB

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

Mesons

compact tetraquark

Glueball

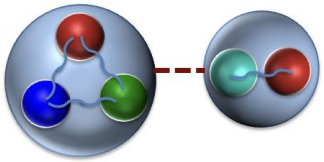


meson-meson molecule

hybrid

Baryons

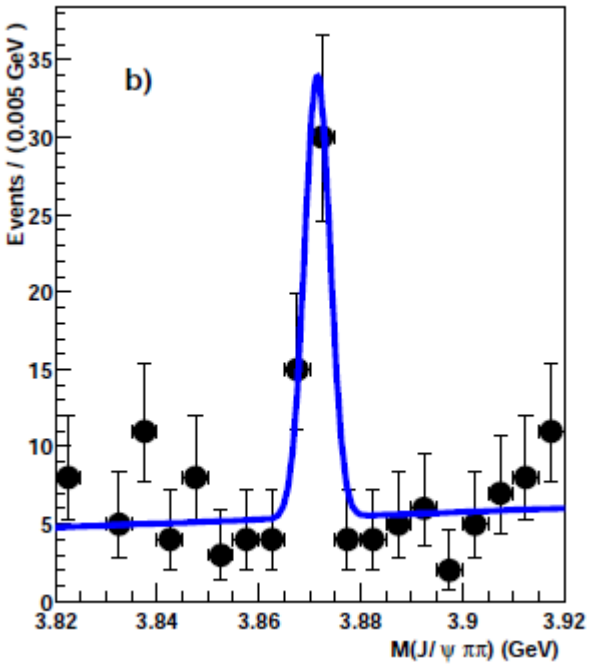
compact pentaquark



baryon-meson molecule

Exotic hadrons

The story started in 2003 with discovery of X(3872)



[Belle collaboration],
Phys.Rev.Lett. 91 (2003) 262001

The first exotic meson !

$$M_X = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}$$

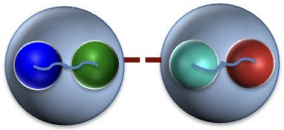
Exotic (non-standard) quarkonium states

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

Mesons

compact tetraquark

Glueball

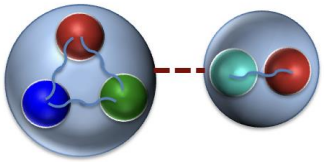


meson-meson molecule

hybrid

Baryons

compact pentaquark



baryon-meson molecule

Since the beginning of 2000s, an increasing amount of data in the (hidden/open) charm sector (collected at Belle, BaBar, LHCb and BESIII…), has provided **evidences** for many new **exotic** states, which appear to be inconsistent with the conventional quark model

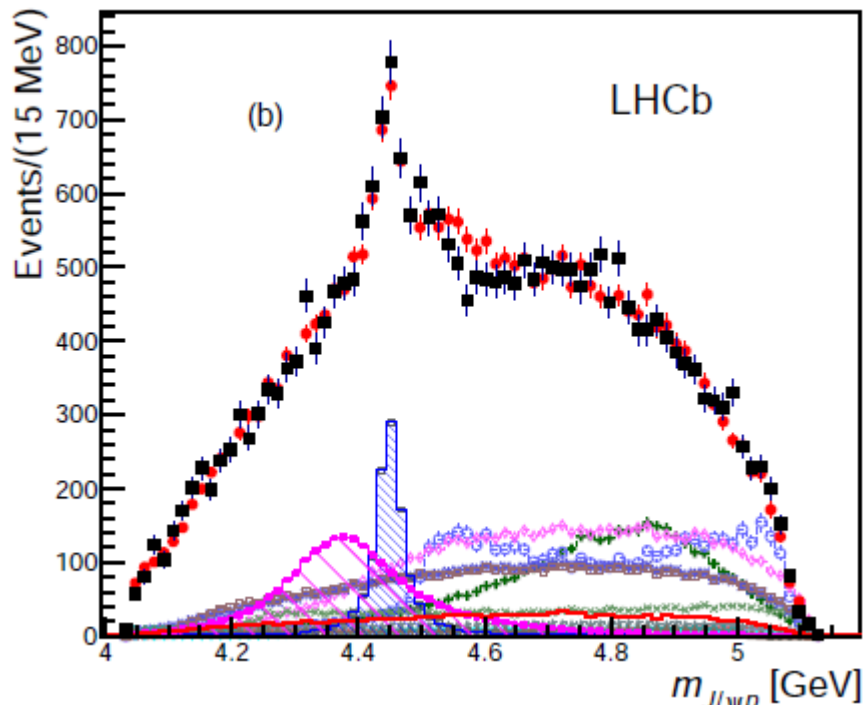
Exotic baryons

P_c or P_ψ^N **S=0** $(c\bar{c}qqq)$, $q = u, d$

$$\Lambda_b \to J/\Psi\, p\, K^-$$

LHCb Coll., **Phys.Rev.Lett. 115 (2015) 072001**

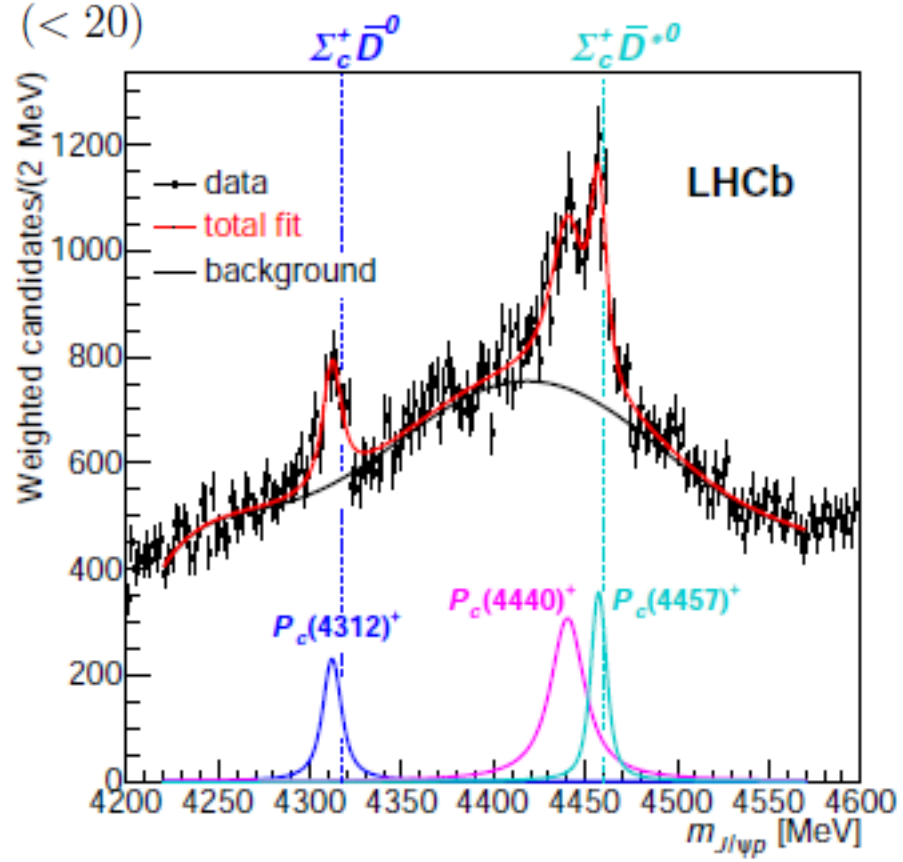
Resonance	M_R [MeV]	Γ_R [MeV]
$P_c(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$P_c(4450)$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$



More detailed reanalysis of the pentaquark states in $\Lambda_b \to J/\psi\ K^-\ p$ decays

LHCb Coll., **Phys.Rev.Lett. 122 (2019) 222001**

State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)



More detailed reanalysis of the pentaquark states in $\Lambda_b \to J/\psi\ K^-\ p$ decays

LHCb Coll., **Phys.Rev.Lett. 122 (2019) 222001**

State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)

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 ($c\bar{c}uud$)

More detailed reanalysis of the pentaquark states in $\Lambda_b \to J/\psi\ K^-\ p$ decays

LHCb Coll., **Phys.Rev.Lett. 122 (2019) 222001**

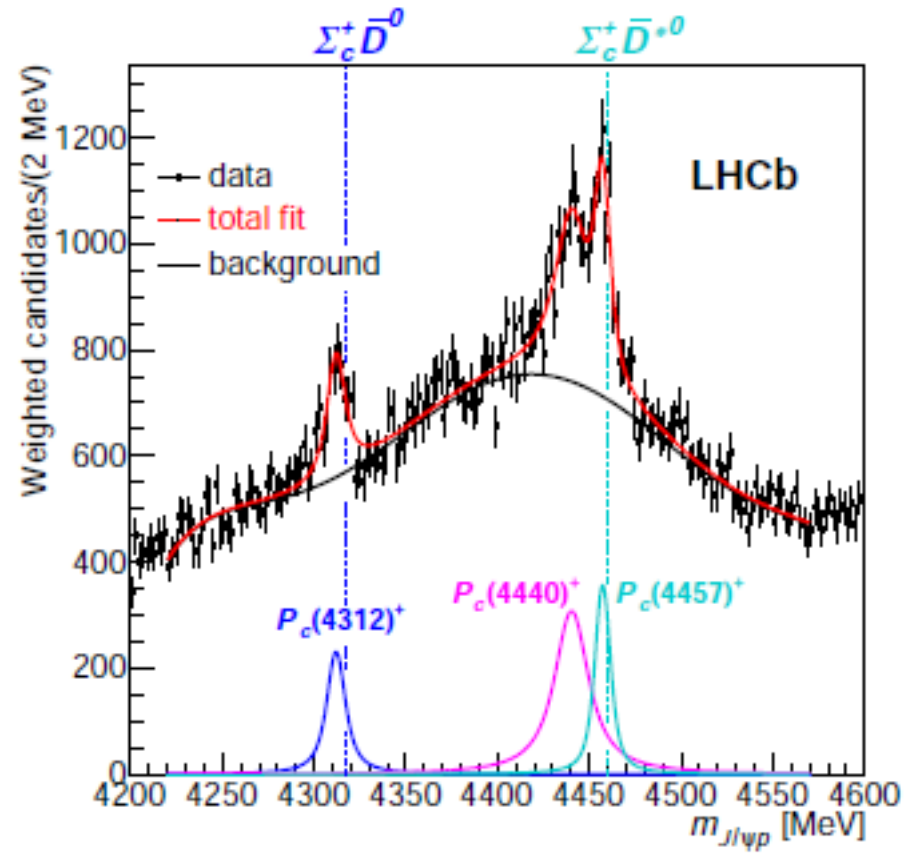
State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	

These states find a natural explanation as baryon-meson molecules:

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

$\overline{D}^{*0}\Sigma_c^+$ threshold: : 4460 MeV → **P_c(4440), P_c(4457)**

and were already predicted in 2010!



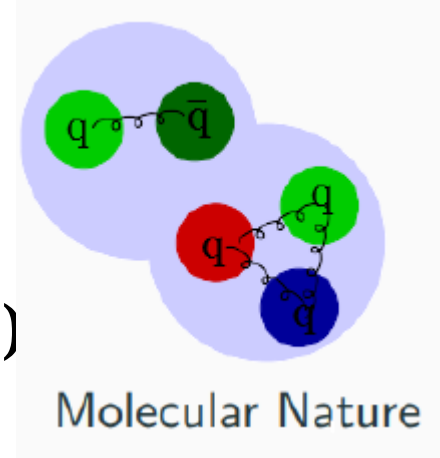
Exotic baryons

P_c or P_Ψ^N **S=0** $(c\bar{c}qqq)$, $q = u, d$

Molecular models

- Wu, Molina, Oset, Zou,
  PRL 105, 232001 (2010); PRC 84, 015202 (2011)

- Yang, Sun, He, Liu, Zhu**, Chin. Phys. C 36, 6 (2012)**
- Xiao, Nieves, Oset, **PRD 88, 056012 (2013)**
- Karliner, Rosner, **PRL 115, 122001 (2015)**

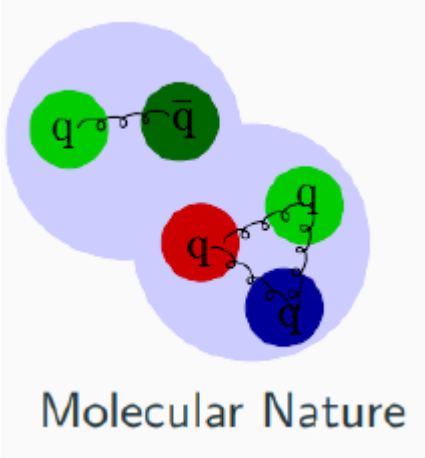


Exotic baryons

P_c or P_Ψ^N **S=0** $(c\bar{c}qqq)$, $q = u, d$

Molecular models

- Wu, Molina, Oset, Zou,
  PRL 105, 232001 (2010); PRC 84, 015202 (2011)



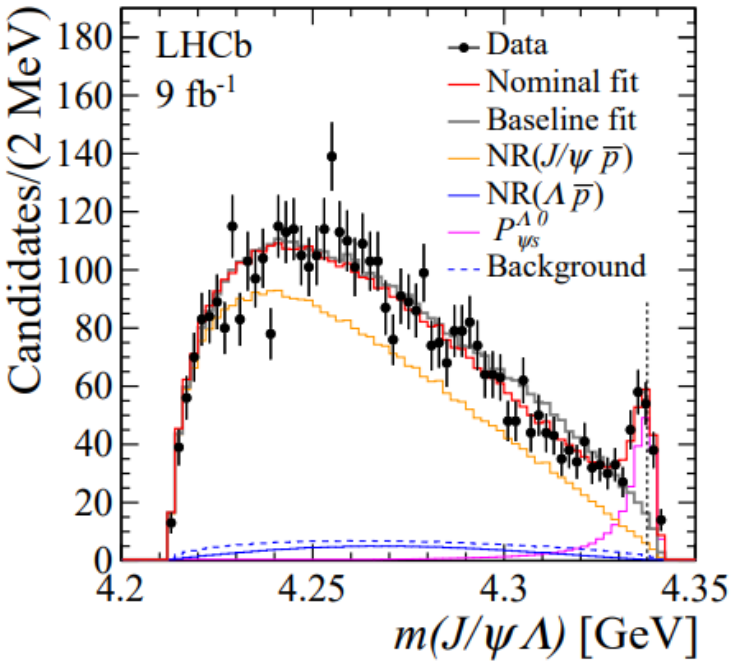
This work also predicted **S=-1** states at
4209 MeV $(\bar{D}\Xi_c)$, 4394 MeV $(\bar{D}\Xi_c')$
4368 MeV $(\bar{D}^*\Xi_c)$, 4544 MeV $(\bar{D}^*\Xi_c')$

Exotic baryons

P_{cs} or $P^{\Lambda}_{\psi s}$ **S=-1** $(c\bar{c}qqs)$, $q = u, d$

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

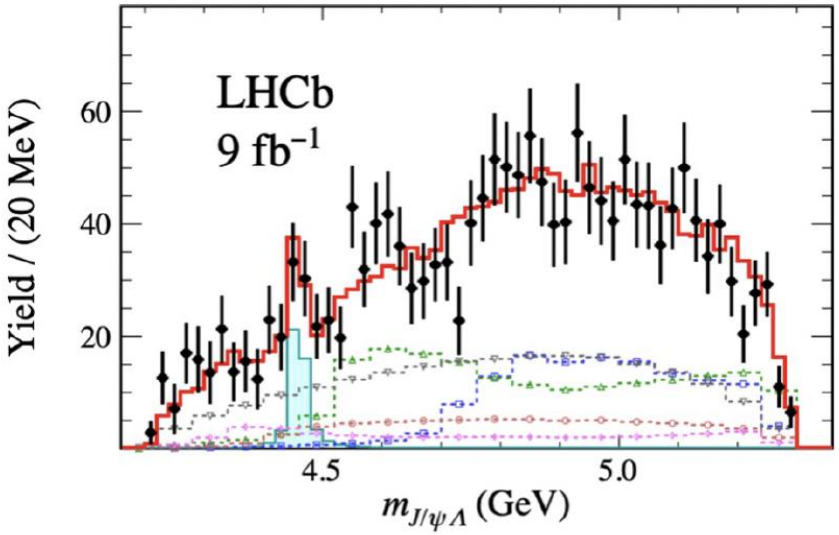
LHCb, arXiv:2210.10346 (Oct 2022)



$P_{cs}(4338)$

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

LHCb, Sci. Bull. 66 (2021) 1278



$P_{cs}(4459)$

Exotic baryons

P_{css} or $P^{\Xi}_{\psi ss}$ **S=-2** $(c\bar{c}qss)$, $q = u, d$

S=-2 pentaquarks?

Exotic baryons

P_{css} or $P^{\Xi}_{\psi ss}$ **S=-2** $(c\bar{c}qss)$, $q = u, d$

S=-2 pentaquarks?

Our theoretical study predicts molecular-type states

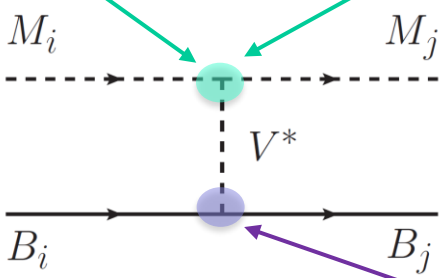
Marsé-Valera, Ramos, Magas, Phys. Rev. Lett. ***130*** (2023) 9

Unitarized t-channel vector-meson exchange interaction

Effective Chiral Lagrangian

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

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



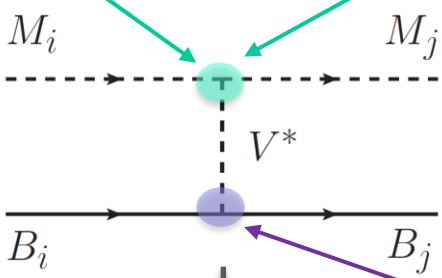
$$\mathcal{L}_{VBB} = \frac{g}{2} \sum_{i,j,k,l=1}^{4} \bar{B}_{ijk}\gamma^\mu \left(V^k_{\mu,l} B^{ijl} + 2V^j_{\mu,l} B^{ilk}\right)$$

Unitarized t-channel vector-meson exchange interaction

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

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

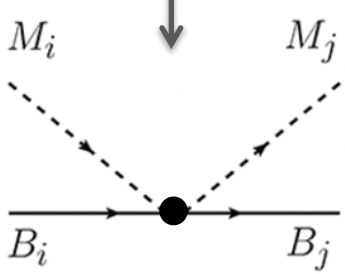
Effective Chiral Lagrangian



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

S-wave

$t \ll m^2_{V^*}$



Interaction kernel

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

The only model parameter is **pion decay constant, $f = af_\pi$**

Unitarization via coupled channels

Interaction kernel V_{ij}

Scattering amplitud T_{ij}

Bethe-Salpeter equation

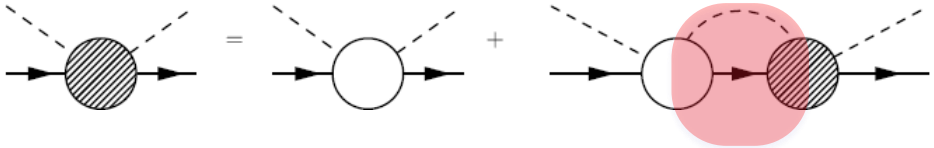
On shell factorization

$$T_{ij} = V_{ij} + V_{il} G_l T_{lj} \quad \Rightarrow \quad \boxed{T = (1 - VG)^{-1} V}$$

System of the algebraic equations

Unitarization via coupled channels

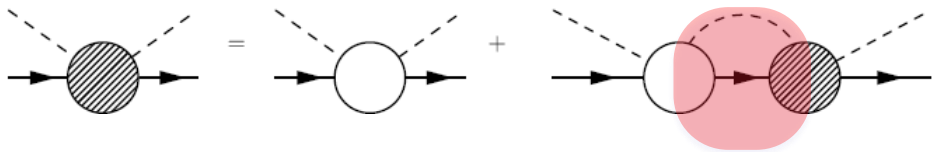
$$T_{ij} = V_{ij} + V_{il} G_l T_{lj}$$



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

Unitarization via coupled channels

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



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

dim reg.

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

cut-off

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

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

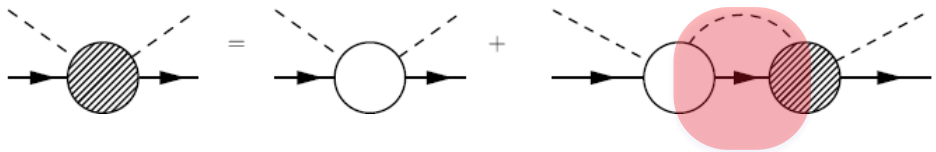
$$a_l(\mu) = \frac{16\pi^2}{2M_l}\left(G_l^{\mathrm{cut}}(\Lambda) - G_l^{\mathrm{DR}}(\mu, a_l = 0)\right)$$

$a_l(\mu) \simeq -2$ → "natural size" (μ=630 MeV)

[Oller and Meissner, PL B500 (2001) 263]

Unitarization via coupled channels

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



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

dim reg.

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

$a_l(\mu) \simeq -2$ → "natural size" (μ=630 MeV)

[Oller and Meissner, PL B500 (2001) 263]

cut-off

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

$\Lambda = 600 - 1000$ MeV

We employ the cut-off method with Λ=800 MeV

S=-2 sector

Interaction kernel

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

	$\pi\Xi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$	$\eta'\Xi$	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
$\pi\Xi(1456)$	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	$\frac{1}{\sqrt{8}}\kappa_c$	$-\frac{1}{\sqrt{6}}\kappa_c$	$\frac{1}{\sqrt{3}}\kappa_c$
$\eta_c\Xi(4302)$						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}

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

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

S=-2 sector

Interaction kernel

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

		$\pi\Xi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$	$\eta'\Xi$	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
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}

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

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

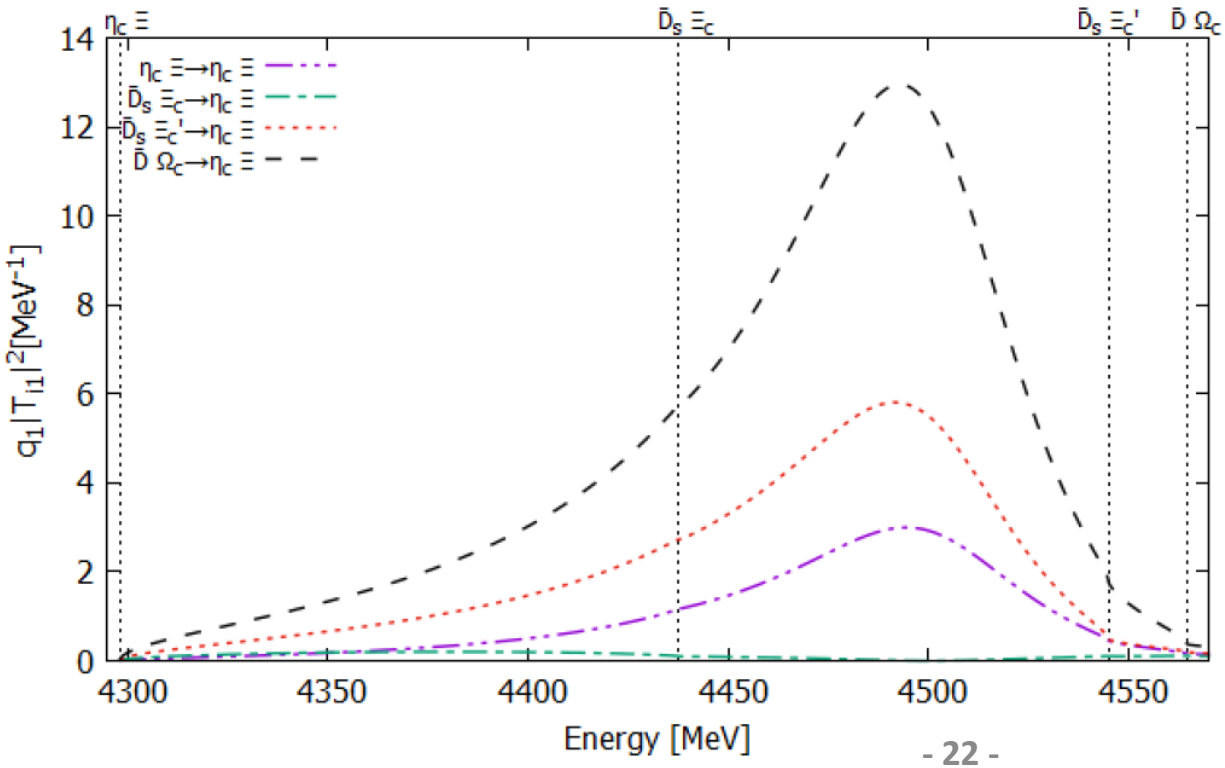
Light and heavy sectors are practically "decoupled"

Results: heavy PB sector

$P^{\Xi}_{\Psi_{ss}}(4493)$ $\quad M_R = 4493.35$ MeV $\quad \Gamma_R = 73.67$ MeV

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

	Threshold Energy (MeV)	g_i	$\lvert g_i \rvert$	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



$\eta_c \Xi$ spectrum:

$q_{\eta_c} \mid T_{i \to \eta_c \Xi} \mid^2$

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

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

$S=0, I=1/2$

	$\eta_c N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$
$\eta_c N$	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

1 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
$\bar{D}\Xi'_c$				$1+\kappa_{cc}$

→ 2 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

???

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

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

$S=0, I=1/2$

	$\eta_c N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$
$\eta_c N$	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

1 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
$\bar{D}\Xi'_c$				$1+\kappa_{cc}$

→ 2 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}

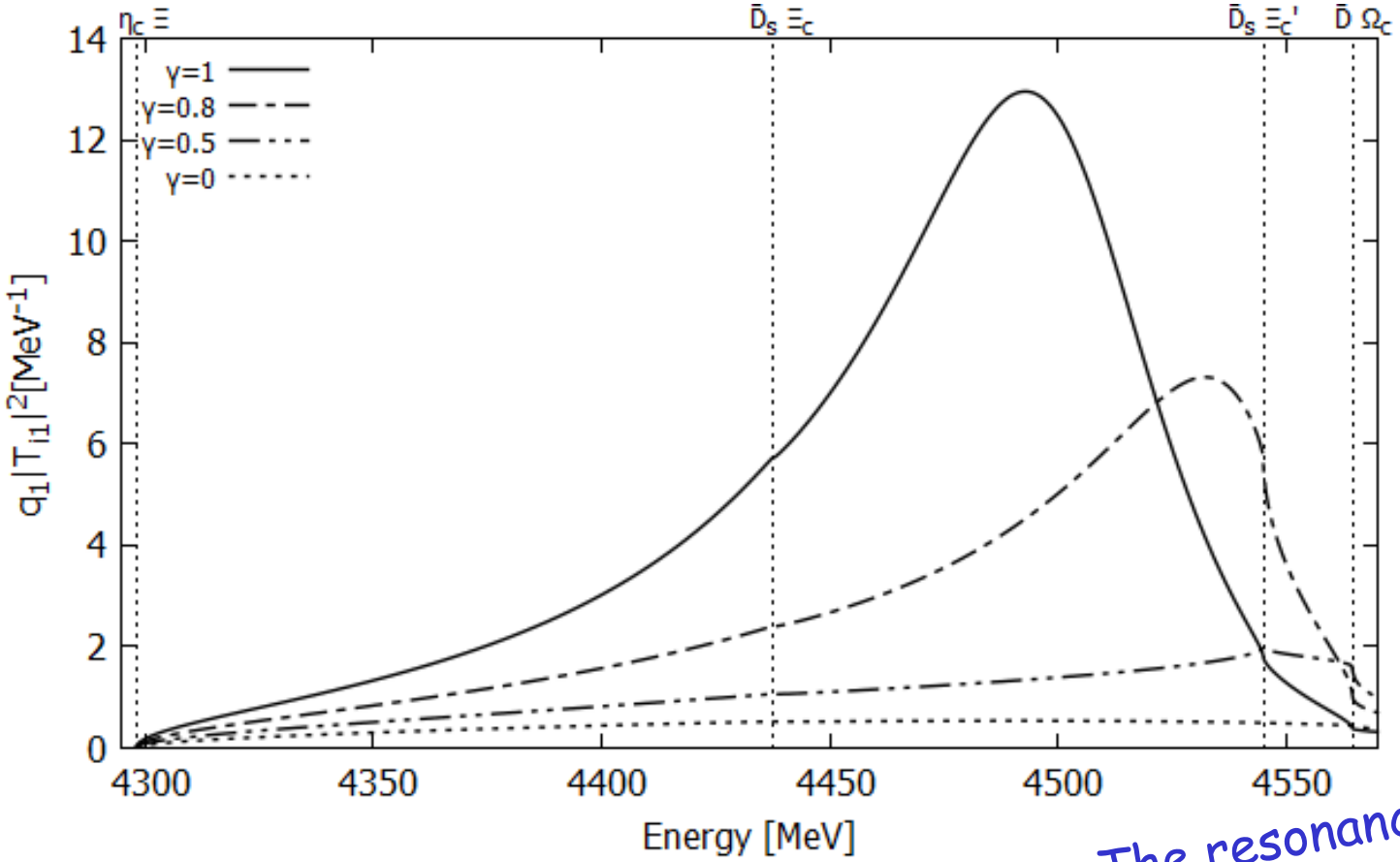
→ no state expected

but…

strong coupled channel effect!
→ induces attraction

Coupled-channel effect

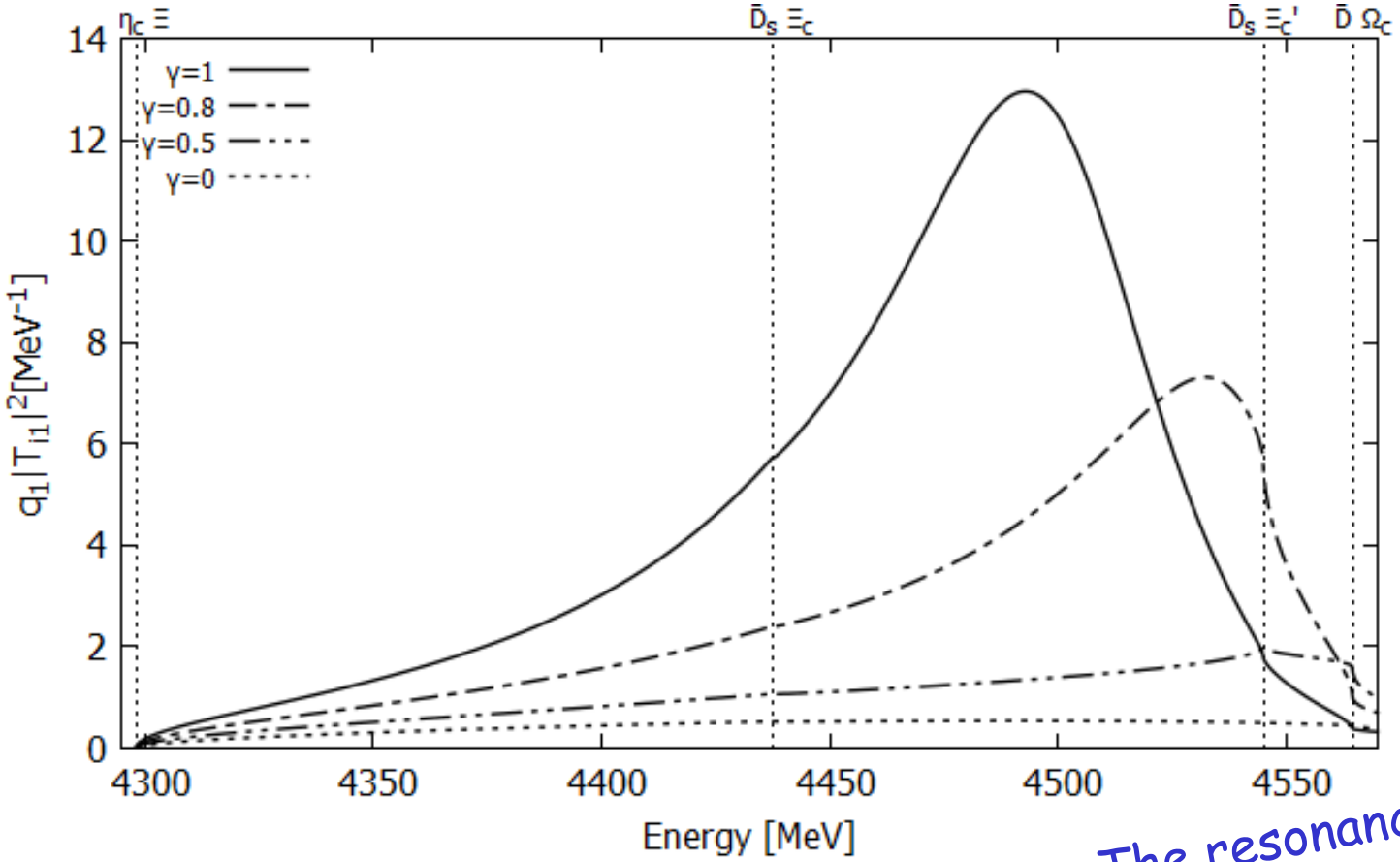
$$C_{34} = -\sqrt{2} \quad \rightarrow \quad C'_{34} = \gamma\, C_{34}$$



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

Coupled-channel effect

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



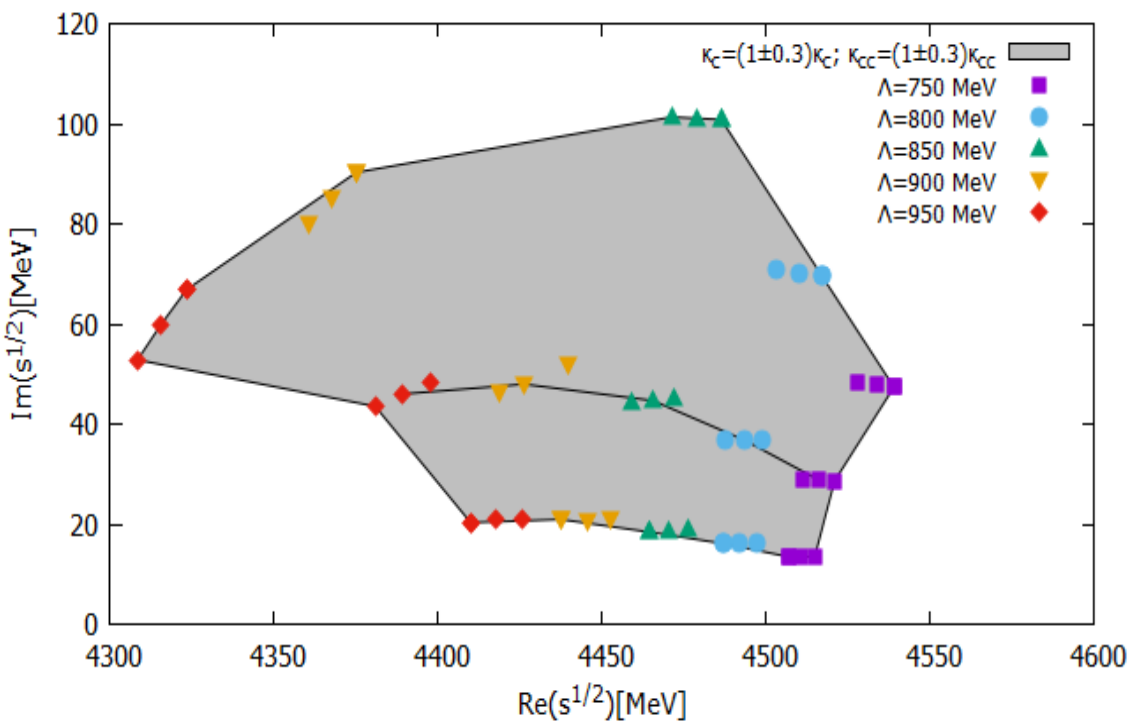
The resonance is not generated if the coupling coefficient is reduced by 30%

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

→ via an attraction induced by a strong coupling between the $\overline{D_s}\Xi'_c$ and $\overline{D}\Omega_c$ channels

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

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



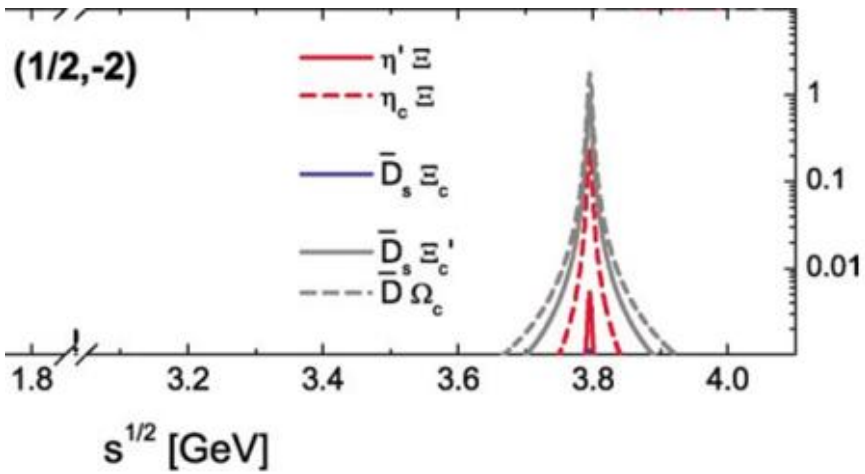
	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi_c'$	$\bar{D}\Omega_c$
$\eta_c\Xi$	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c$		$-1+\kappa_{cc}$	0	0
$\bar{D}_s\Xi_c'$			$-1+\kappa_{cc}$	$-\sqrt{2}$
$\bar{D}\Omega_c$				κ_{cc}

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

Comparison with other works based on similar models

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

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



➡ a state around 3800 MeV is found

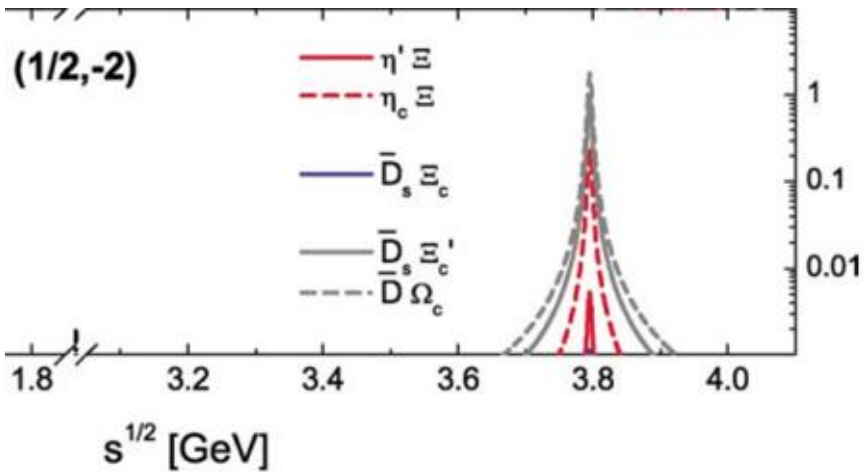
Very different regularization approach for the loop function

(for us it would effectively correspond to $\Lambda_{cut} \sim 2800$ MeV)

Comparison with other works based on similar models

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

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



➡ a state around 3800 MeV is found

Very different regularization approach for the loop function

(for us it would effectively correspond 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
$\bar{D}_s\Xi_c'$			$-1+\cancel{\kappa_{cc}}$	$-\sqrt{2}$
$\bar{D}\Omega_c$				$\cancel{\kappa_{cc}}$

Very similar model

$$\kappa_{cc} = \frac{m_{J/\psi}^2}{m_\rho^2} \sim \frac{1}{9} \rightarrow 0$$

➡ no states were found

Dimensional regularization scheme

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

Results: heavy VB sector

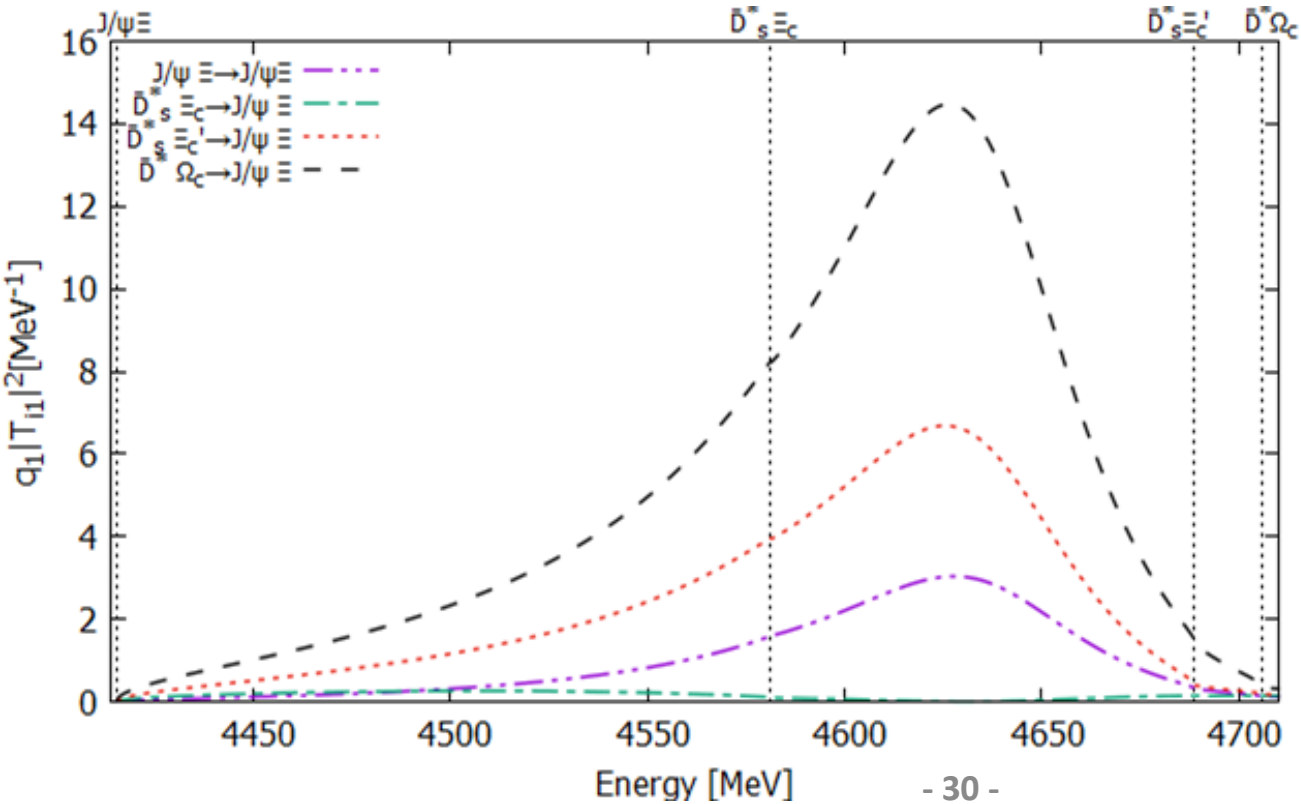
$P^{\Xi}_{\Psi ss}(4633)$

$M_R = 4633.38$ MeV $\quad \Gamma_R = 79.58$ 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

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

$1^- \oplus 1/2^+$ VB interaction



$J/\Psi\Xi$ spectrum:

$q_{J/\Psi} \mid T_{i\to J/\Psi\Xi} \mid^2$

Results: heavy VB sector

$P^{\Xi}_{\psi ss}(4633)$ $\qquad$ $J^P = \frac{1}{2}^-, \ \frac{3}{2}^-$

It could be seen in the invariant mass spectrum of $J/\psi\, \Xi$ pairs produced in the decays:

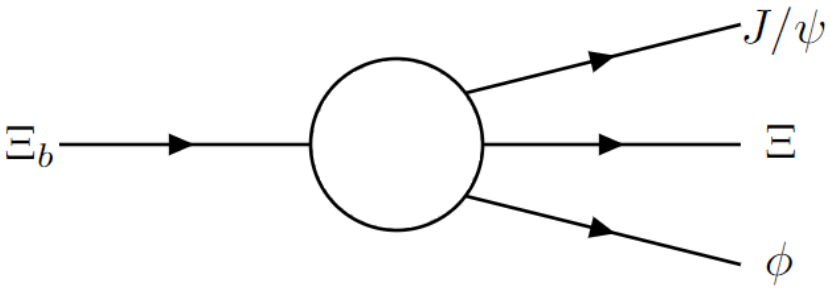
$\Xi_b \to J/\psi\, \Xi\, \phi$ or $\Omega_b \to J/\psi\, \Xi\, \bar{K}$

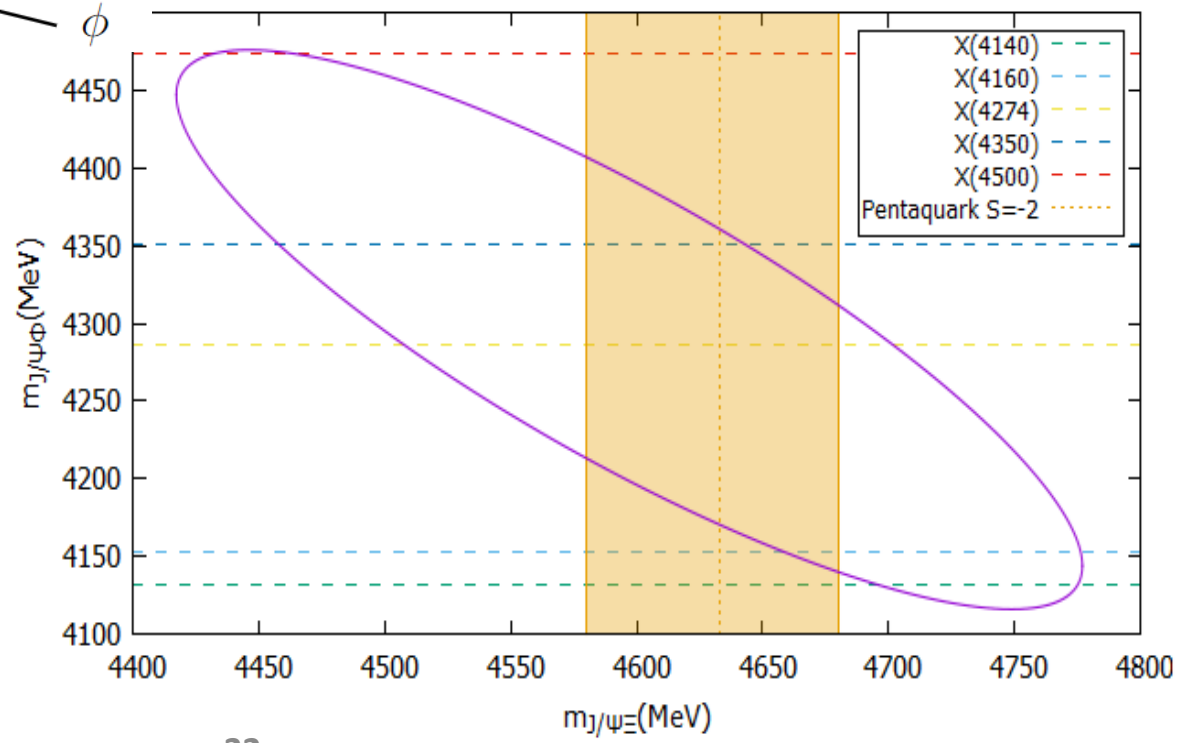
Results: heavy VB sector

$P^{\Xi}_{\psi ss}(4633)$

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

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

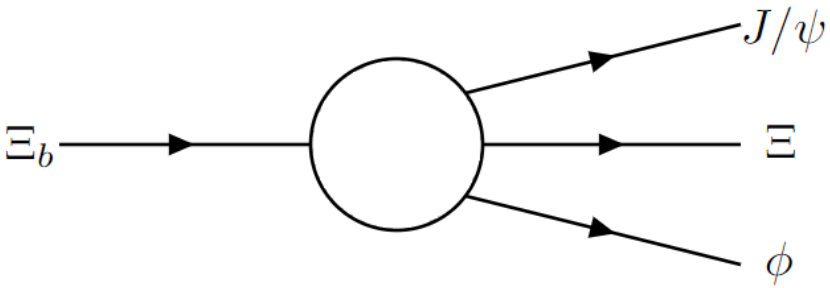




Results: heavy VB sector

$P^{\Xi}_{\psi ss}(4633)$ $\qquad$ $J^P = \frac{1}{2}^-, \ \frac{3}{2}^-$

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



Marsé-Valera, Magas, Ramos ***under preparation***

We simulate this decay similarly to the process $\Lambda_b \to J/\psi \ \phi \ \Lambda$

Magas, Ramos, Somasundaram, PRD 102 (2020) 0540270

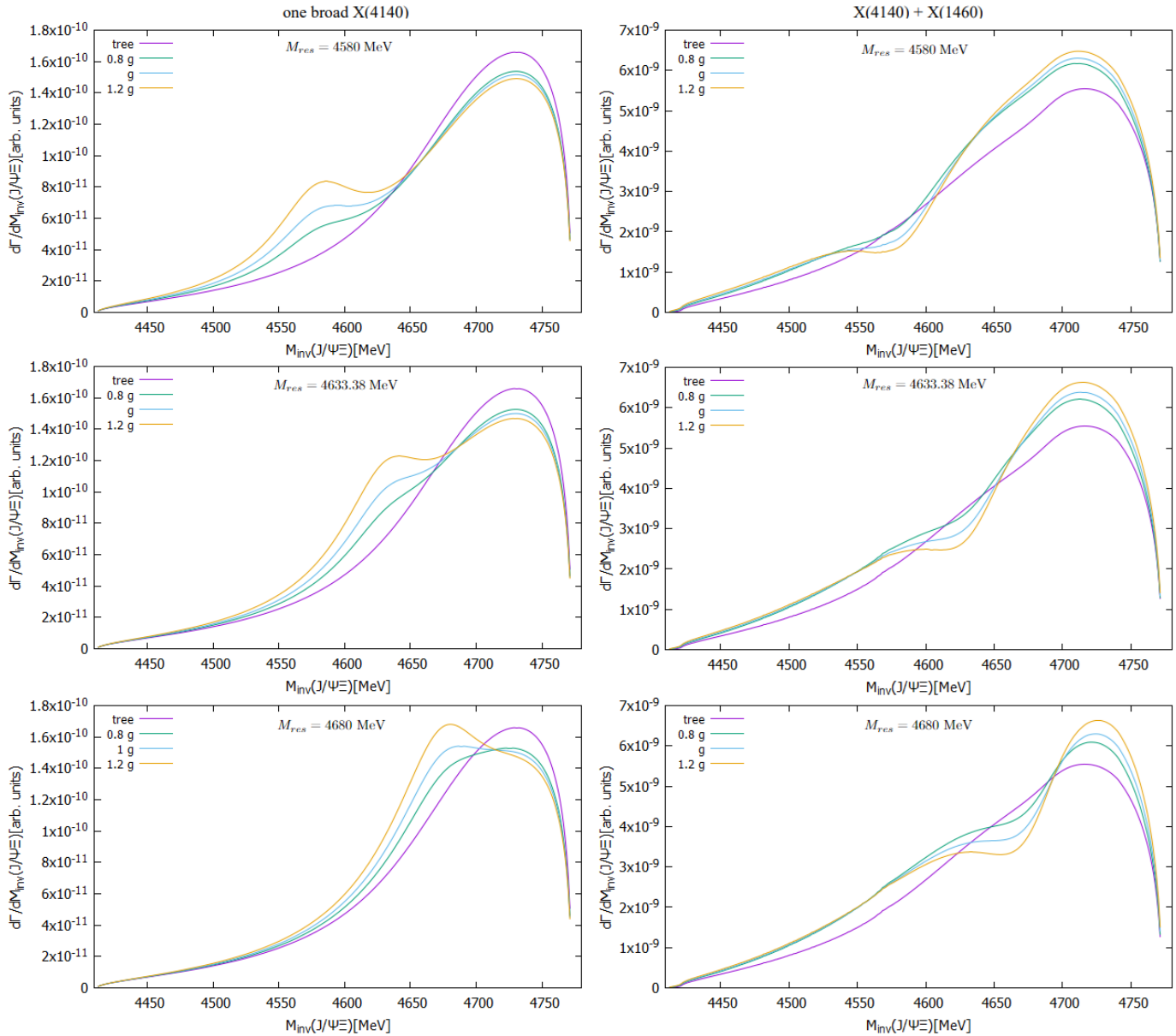
(inspired by Wang, Xie, Geng, Oset, PRD 97 (2018) 014017)

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

M=4580 MeV

M=4633 MeV

M=4680 MeV



Marsé-Valera, Magas, Ramos ***under preparation***

Conclusions

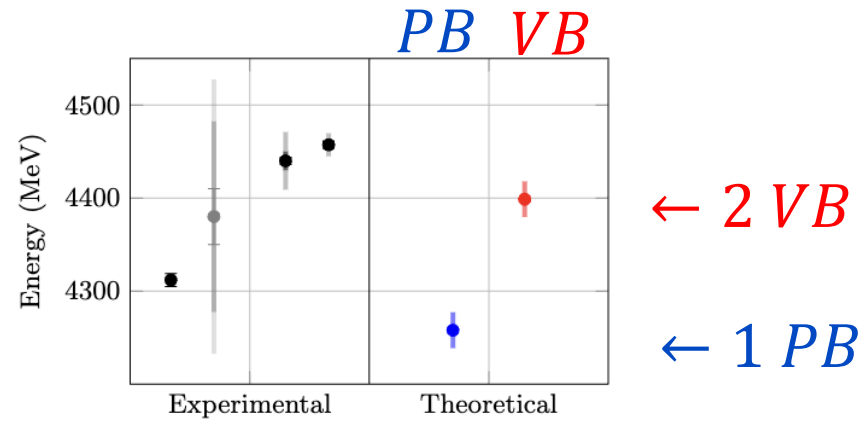
- Chital Perturbation theory with unitarization in the coupled channels predicts pentaquarks with strangeness S=0,-1,-2

Chital Perturbation theory with unitarization in the coupled channels predicts pentaquarks with strangeness S=0,-1,-2

$S = 0$

P_{ψ}^{N}

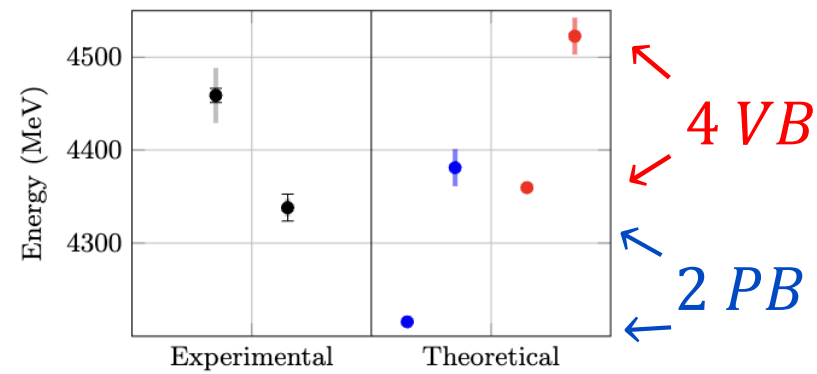
	$\eta_c N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$
$\eta_c N$	0	$-\sqrt{\frac{3}{2}}\kappa_c$	$\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}\Lambda_c$		$-1+\kappa_{cc}$	0
$\bar{D}\Sigma_c$			$1+\kappa_{cc}$



$S = -1$

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

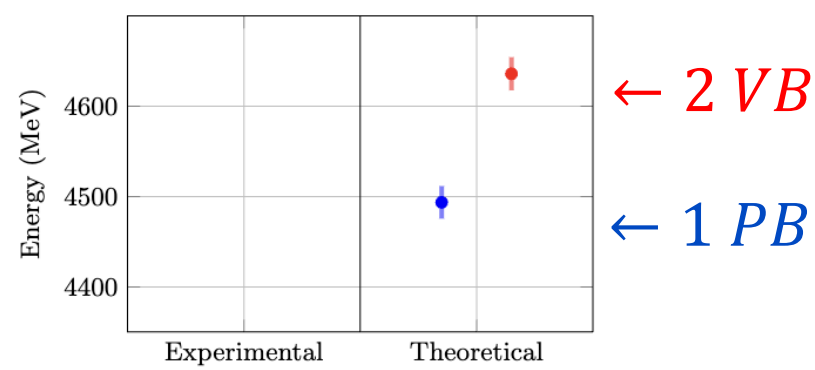
	$\eta_c\Lambda$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$
$\eta_c\Lambda$	0	κ_c	$-\frac{1}{\sqrt{2}}\kappa_c$	$-\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}_s\Lambda_c$		κ_{cc}	$\sqrt{2}$	0
$\bar{D}\Xi_c$			$1+\kappa_{cc}$	0
$\bar{D}\Xi'_c$				$1+\kappa_{cc}$



$S = -2$

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

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



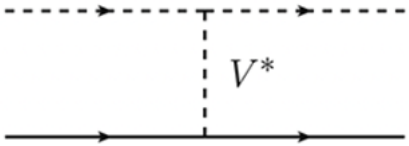
Conclusions

- Chital Perturbation theory with unitarization in the coupled channels predicts pentaquarks with strangeness S=0,-1,-2

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

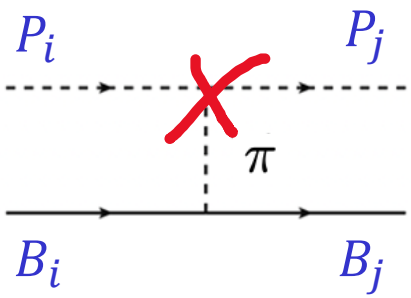
- These $P_{\psi ss}^{\Xi}$ states are generated in a very specific and unique way, via a strong nondiagonal attraction between the two heaviest channels

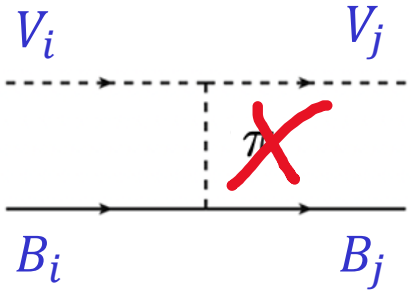
- In S=-2 sector the long range one-pion-exchange mechanism is absent!



The t-channel vector-exchange formalism predicts molecular type pentaquarks with S=-2

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 one-pion-exchange, because they involve either an isoscalar meson or baryon

Conclusions

- Chital Perturbation theory with unitarization in the coupled channels predicts pentaquarks with strangeness S=0,-1,-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 a strong nondiagonal attraction between the two heaviest channels

- In S=-2 sector the long range one-pion-exchange mechanism is absent! Thus, if $P_{\psi ss}^{\Xi}$ states are discovered

→ Their interpretation as **molecules** would require a change of paradigm, since they could be only bound through **heavier-meson exchange** mechanisms

→ More strength to reliability of **unitary t-channel vector-exchange models**

- Theoretical study of $\Xi_b \to J/\psi\, \phi\, \Xi$ decay is in progress now…