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

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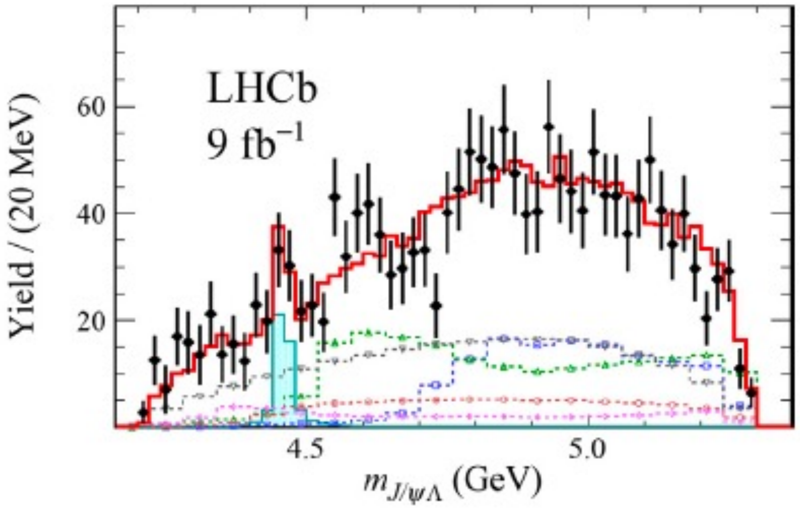
Introduction: Historical Background

Observation of a $J/\psi\Lambda$ structure in the $\Xi_b^- \to K^- J/\psi\Lambda$



$$M = 4458.8 \pm 2.9^{+4.7}_{-1.1}\,\mathrm{MeV}$$

$$\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}\,\mathrm{MeV}$$

R. Aaij, et al., LHCb, Sci. Bull. 66 (2021) 1278

Such kind of states were already predicted, with qualitative agreement with the experiment in

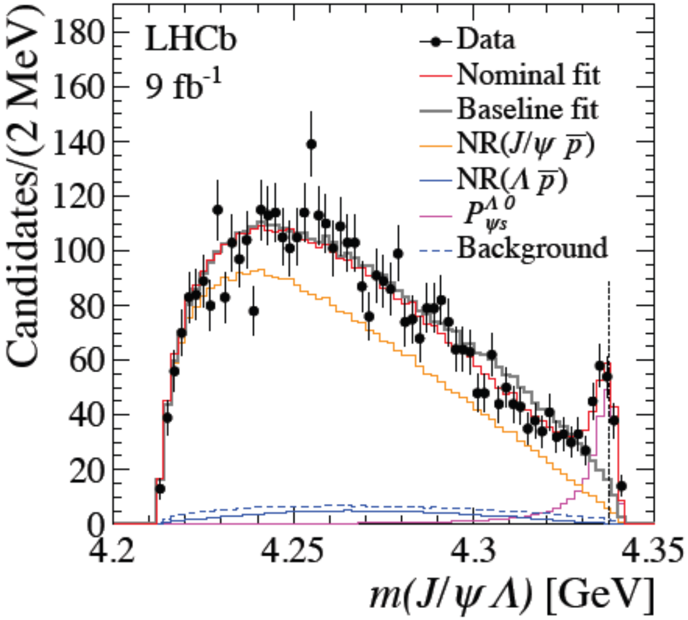
J.-J. Wu, R. Molina, E. Oset, B.S. Zou, Phys. Rev. Lett. 105 (2010) 232001, Phys. Rev. C 84 (2011) 015202

This experimental breakthrough sparked lot of activity in the theoretical community

H.-X. Chen, W. Chen, X. Liu, X.-H. Liu, Eur. Phys. J. C 81 (2021) 409
Z.-G. Wang, Int. J. Mod. Phys. A 36 (2021) 2150071
K. Azizi, Y. Sarac, H. Sundu, Phys. Rev. D 103 (2021) 094033
U. Özdem, Eur. Phys. J. C 81 (2021) 277
F.-Z. Peng, M.-J. Yan, M. Sánchez Sánchez, M.P. Valderrama, Eur. Phys. J. C 81 (2021) 666
R. Chen, Phys. Rev. D 103 (2021) 054007
R. Chen, Eur. Phys. J. C 81 (2021) 122
M.-Z. Liu, Y.-W. Pan, L.-S. Geng, Phys. Rev. D 103 (2021) 034003
J.-T. Zhu, L.-Q. Song, J. He, Phys. Rev. D 103 (2021) 074007
W.-Y. Liu, W. Hao, G.-Y. Wang, Y.-Y. Wang, E. Wang, D.-M. Li, Phys. Rev. D 103 (2021) 034019
F.-L. Wang, X. Liu, Phys. Lett. B 835 (2022) 137583
U. Özdem, Phys. Lett. B 836 (2023) 137635

Introduction: Historical Background

Observation of a $J/\psi\Lambda$ structure in the $B^- \to \bar{p}\, J/\psi\Lambda$



R. Aaij, et al., LHCb, arXiv:2210 .10346 [hep -ex], 2022

$$M = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$$

$$\Gamma = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$$

In between both P_{cs} measurements, predictions were made within a HQSS scheme:

C.W. Xiao, J. Nieves, E. Oset, Phys. Lett. B 799 (2019) 135051

Findings obtained were in rough qualitative agreement with the experimental states

Introduction: Historical Background

After the measurements of both P_{cs} there was an avalanche of theoretical studies addressing the problem from different approaches and providing interpretations …

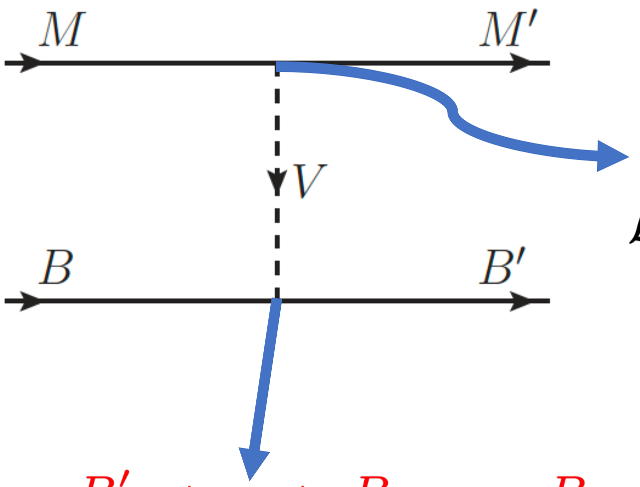
- QCD sum rule method used to find a $\bar{D}\Xi_c$molecular structure for $P_{cs}(4338)$ and a $\bar{D}^*\ \Xi_c$ one for the $P_{cs}(4459)$
  X.-W. Wang, Z.-G. Wang, Chin. Phys. C 47 (2023) 013109
- Boson exchange models have been used to find a $\bar{D}\Xi_c$ molecule associated to $P_{cs}(4338)$ and 2 $\bar{D}^*\ \Xi_c$ structures $(\frac{1}{2}^-, \frac{3}{2}^-)$ related to $P_{cs}(4459)$
  L. Meng, B. Wang, S.-L. Zhu, Phys.Rev.D 107 (2023) 1, 014005
- $P_{cs}(4338)$ suggested as an effect of a TS
  T.J. Burns, E.S. Swanson, Phys.Lett.B 838 (2023) 137715
- In the CQM framework, this work look at meso-baryon molecular structures and found that $P_{cs}(4338)$ is mostly a $\bar{D}\Xi_c$ molecule with sizable $\bar{D}_s^{(*)}\Lambda_c$ component
  P.G. Ortega, D.R. Entem, F. Fernandez, Phys.Lett.B 838 (2023) 137747
- There are many other approaches…(compact pentaquark states, more on molecular picture…)

A. Esposito, A. Pilloni, A.D. Polosa, Phys. Rep. 668 (2017) 1, J.-T. Zhu, S.-Y. Kong, J. He, Phys.Rev.D 107 (2023) 3, 034029; S.X. Nakamura, J.J. Wu, arXiv:2208 .11995 [hep -ph], 2022;   K. Chen, Z.-Y. Lin, S.-L. Zhu, Phys.Rev.D 106 (2022) 11, 116017; *Z.-Y. Yang, F.-Z. Peng, M.-J. Yan, M. Sánchez Sánchez, M. Pavon Valderrama, arXiv:2211.08211 [hep -ph], 2022;* R.F. Lebed, R.E. Mitchell, E.S. Swanson, Prog. Part. Nucl. Phys. 93 (2017) 143 …

Formalism

C.W. Xiao, J. Nieves, E. Oset, Phys. Lett. B 799 (2019) 135051

Local Hidden gauge approach + HQSS scheme:



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

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

$$\langle \phi^{B'}_{flavor} \chi^{B'}_{spin} | g q \bar{q} | \phi^{B}_{flavor} \chi^{B}_{spin} \rangle$$

Interaction Kernel

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

Symmetric spin-flavor wave function $\phi_{flavor} \cdot \chi_{spin}$

Formalism

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

$PB(\frac{1}{2}^+)$: Pseudoscalar meson-baryon of $J^P = \frac{1}{2}^+$,
$\eta_c\Lambda(4099.6), \bar{D}_s\Lambda_c(4259.8), \bar{D}\Xi_c(4336.3), \bar{D}\Xi'_c(4445.7);$

$PB(\frac{3}{2}^+)$: Pseudoscalar meson-baryon of $J^P = \frac{3}{2}^+$,
$\bar{D}\Xi^*_c(4512.9);$

$VB(\frac{1}{2}^+)$: Vector meson-baryon of $J^P = \frac{1}{2}^+$,
$J/\psi\Lambda(4212.6), \bar{D}^*_s\Lambda_c(4398.7), \bar{D}^*\Xi_c(4477.6), \bar{D}^*\Xi'_c(4587.0);$

$VB(\frac{3}{2}^+)$: Vector meson-baryon of $J^P = \frac{3}{2}^+$,
$\bar{D}^*\Xi^*_c(4654.2);$

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

$$\lambda = 0.25$$

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

$$C_{\bar{D}\Xi^*_c\to\bar{D}\Xi^*_c} = C_{\bar{D}^*\Xi^*_c\to\bar{D}^*\Xi^*_c} = -1$$

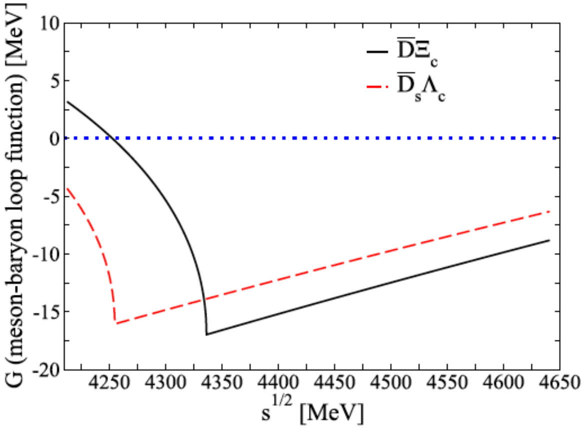
Formalism

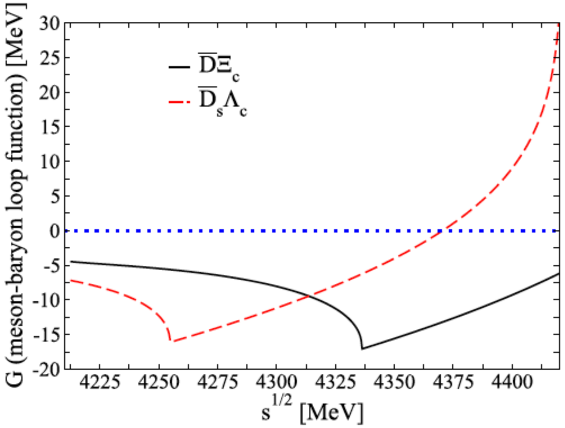
Bethe-Salpeter equation $T = [1 - VG]^{-1} V$

Meson-Baryon Loop function

$q_{\max} = 600\,MeV$

$$G_l = \int_{|\mathbf{q}|<q_{max}} \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega_l(\mathbf{q})} \frac{M_l}{E_l(\mathbf{q})} \cdot \frac{1}{\sqrt{s} - \omega_l(\mathbf{q}) - E_l(\mathbf{q}) + i\epsilon}$$

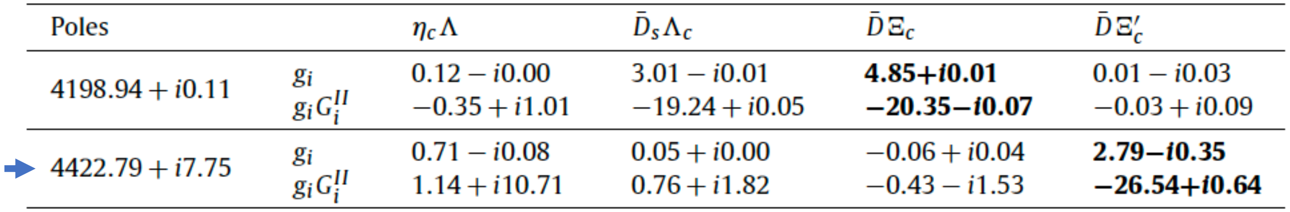

Dimensional regularization


Cut off regularization

Results: pole content

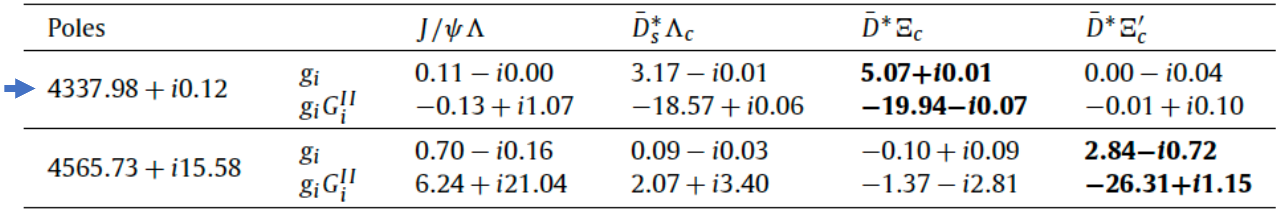
Phys.Lett.B 839 (2023) 137760

$PB(1/2^+)$ sector with $J^P = \frac{1}{2}^-$



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

$VB(1/2^+)$ 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 $g_iG_i^{II}$	$0.11 - i0.00$ $-0.13 + i1.07$	$3.17 - i0.01$ $-18.57 + i0.06$	$\mathbf{5.07+i0.01}$ $\mathbf{-19.94-i0.07}$	$0.00 - i0.04$ $-0.01 + i0.10$
$4565.73 + i15.58$	g_i $g_iG_i^{II}$	$0.70 - i0.16$ $6.24 + i21.04$	$0.09 - i0.03$ $2.07 + i3.40$	$-0.10 + i0.09$ $-1.37 - i2.81$	$\mathbf{2.84-i0.72}$ $\mathbf{-26.31+i1.15}$

$PB(3/2^+)$ sector

$$\bar{D}\Xi_c^*:\ 4488.52\ \mathrm{MeV},\ g = 2.81,\ gG^{II} = -26.47,\quad J^P = \frac{3}{2}^-;$$

$$\bar{D}^*\Xi_c^*:\ 4627.48\ \mathrm{MeV},\ g = 2.96,\ gG^{II} = -25.93,\quad J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-.$$

$VB(3/2^+)$ sector

One would expect an equivalent picture to the one provided by the P_c pentaquarks…

$$P_c : \bar{D}\Sigma_c, \bar{D}\Lambda_c \text{ and } \bar{D}^*\Sigma_c, \bar{D}^*\Lambda_c$$

~~$P_{cs} : \bar{D}\Xi_c, \bar{D}_s\Lambda_c$ and $\bar{D}^*\Sigma_c, \bar{D}_s^*\Lambda_c$~~

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Results: pole content, $P_{cs}(4459)$ candidate

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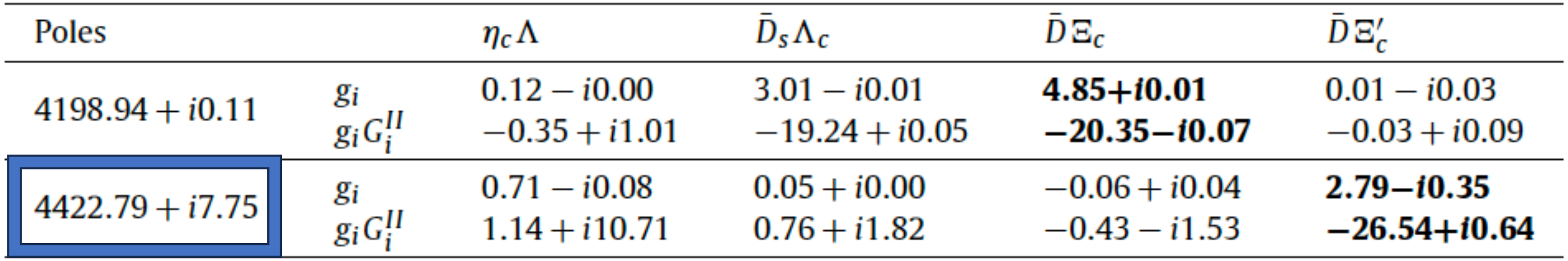
$PB(1/2^+)$ sector with $J^P = \frac{1}{2}^-$



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

This state is almost a $\bar{D}\Xi_c'$ bound state, despite it has small coupling to $\eta_c\Lambda$

Mass 5σ below the experimental value
Width is compatible with the measured one

$$M = 4458.8 \pm 2.9^{+4.7}_{-1.1}\,\mathrm{MeV}$$

$$\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}\,\mathrm{MeV}$$

Results: pole content, $P_{cs}(4338)$ candidate

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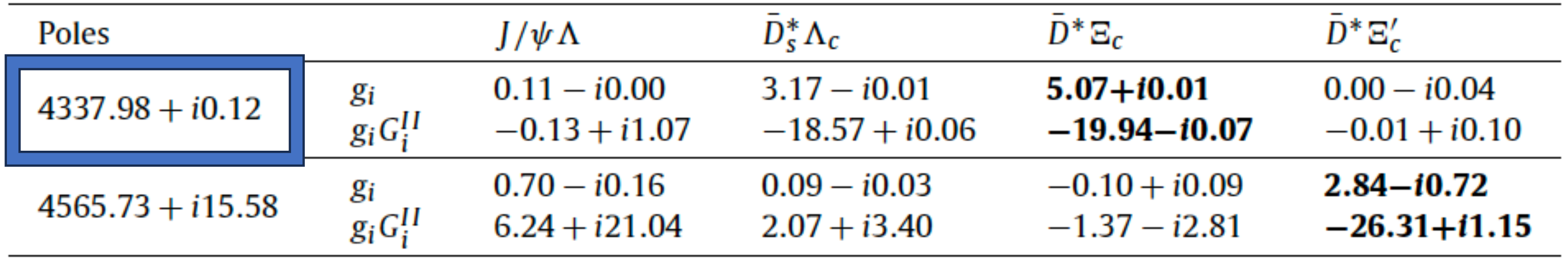
V$B(1/2^+)$ sector with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$



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

This state is almost a $\bar{D}^*\Xi_c$ bound state, despite it has non-negligible coupling to $\bar{D}_s^*\Lambda_c$

Mass in very good agreement with the experimental value

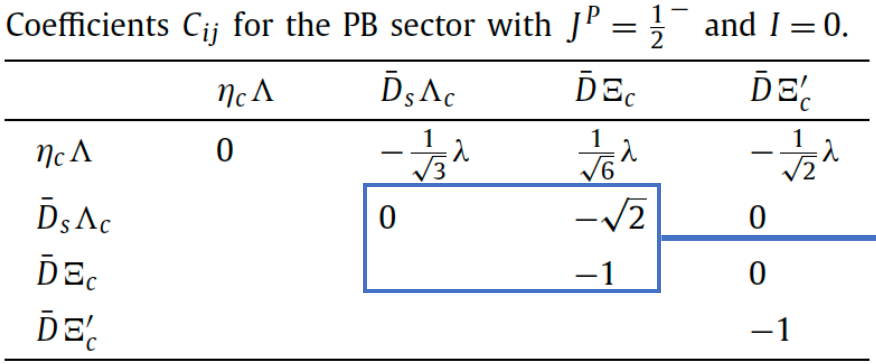
$$M = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$$

$$\Gamma = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$$

Width is almost 2 orders of magnitude smaller

- Small coupling to $J/\psi\Lambda$ (only open channel)
- It could be the effect of having 2 degenerate states there
- The effects of the experimental resolution

Effects of the strong transition between $\bar{D}\Xi_c$ and $\bar{D}_s\Lambda_c$ or $\bar{D}^*\Xi_c$ and $\bar{D}_s^*\Lambda_c$



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

$$\begin{array}{cc} \begin{array}{cc} \bar{D}\Xi_c & \bar{D}_s\Lambda_c \end{array} & \\ \begin{pmatrix} V_{11} & V_{12} \\ V_{12} & 0 \end{pmatrix} & \begin{array}{c} \bar{D}\Xi_c \\ \bar{D}_s\Lambda_c \end{array} \end{array}$$

$$T = [1 - VG]^{-1}V \longrightarrow T_{11} = \frac{V_{11} + V_{12}^2 G_2}{1 - (V_{11} + V_{12}^2 G_2)G_1}$$

Strong overbinding! $V_{eff} = V_{11} + V_{12}^2 G_2 < 0$

CONCLUSIONS

We have studied the meson-baryon dynamics with $\bar{c}csqq$ quark content in coupled channels within a LHG + HQSS based model.

Several blocks have been considered: **PB($\frac{1}{2}^+$), PB($\frac{3}{2}^+$), VB($\frac{1}{2}^+$), VB($\frac{3}{2}^+$).**

- **Counting all spin possibilities, we find 10 states**

- **We find a natural interpretation of**

  $\mathrm{P_{cs}}(4338)$ as a molecular state coupling mostly to $\bar{D}^*\Xi_c$

  $\mathrm{P_{cs}}(4459)$ as a $\bar{D}\Xi_c'$ molecule

Hopefully, future measurements would shed some light on the other structures obtained from the present model.

Thank you for your attention!