

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

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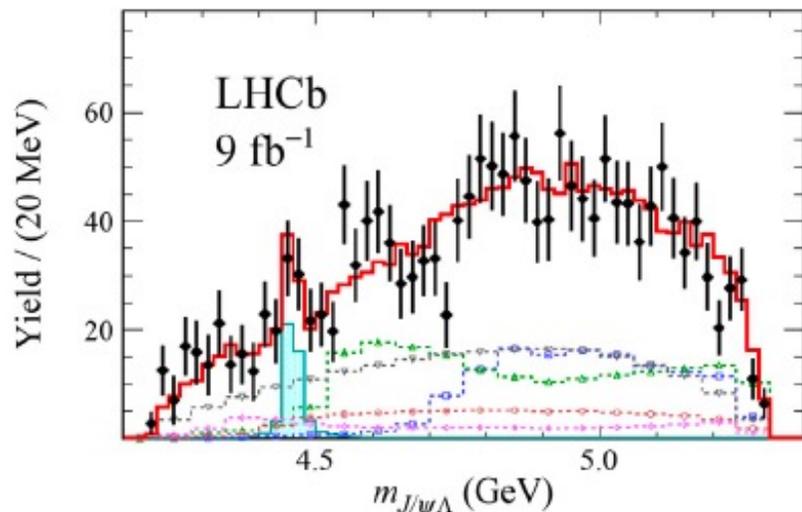
School of Physics and Electronics, Central South University, Changsha

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School of Physics Sciences, University of Chinese Academy of Sciences

Introduction: Historical Background

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



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

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

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

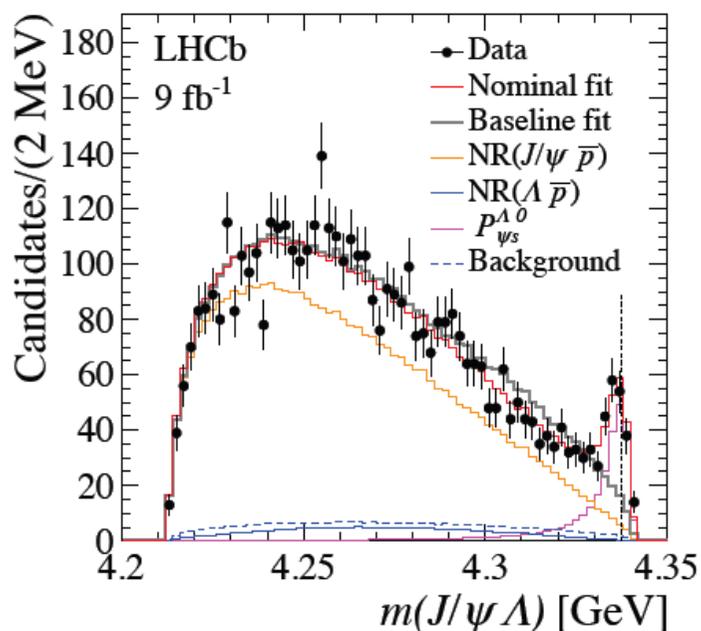
W.-Y. Liu, W. Hao, G.-Y. Wang, Y.-Y. Wang, E. Wang, D.-M. Li, Phys. Rev. D 103 (2021) 034019

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



$$M = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

$$\Gamma = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

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

R. Aaij, et al., LHCb, arXiv:2210.10346 [hep-ex], 2022

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Introduction: Historical Background

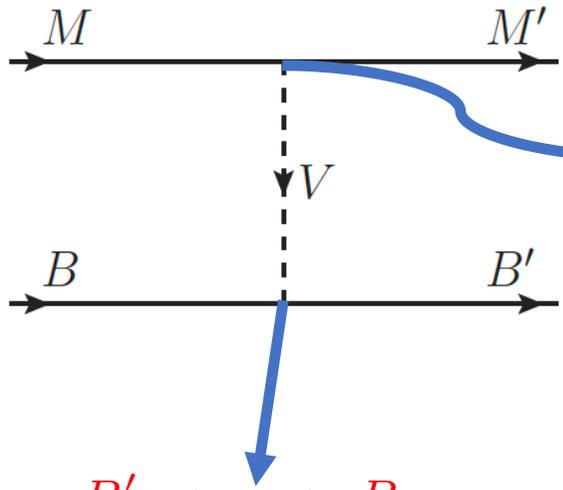
After the measurements of both P_{CS} there was an avalanche of theoretical studies addressing the problem from different approaches and providing interpretations ...

- 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:



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

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

Interaction Kernel

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

$$\langle \phi_{flavor}^{B'} \chi_{spin}^{B'} | gq\bar{q} | \phi_{flavor}^B \chi_{spin}^B \rangle$$

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

$$C_{\bar{D} \Xi_c^* \rightarrow \bar{D} \Xi_c^*} = C_{\bar{D}^* \Xi_c^* \rightarrow \bar{D}^* \Xi_c^*} = -1$$

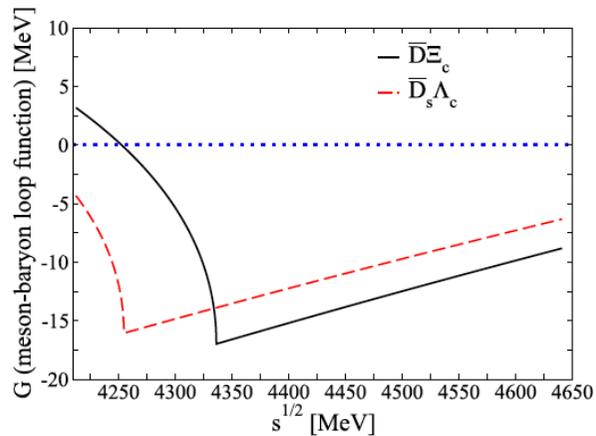
Formalism

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

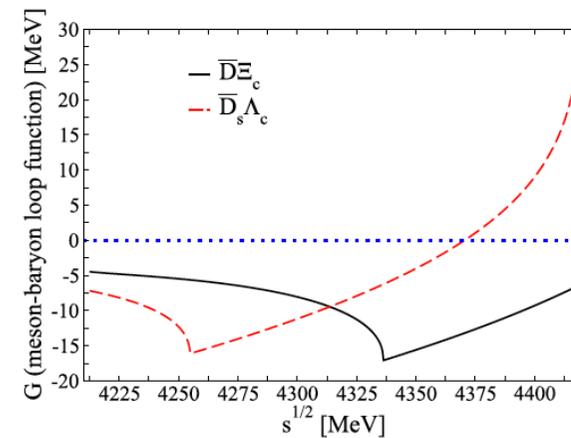
Meson-Baryon Loop function $q_{\max} = 600 \text{ MeV}$

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

Dimensional regularization



Cut off regularization



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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 $g_i G_i^{II}$	0.12 - i0.00 -0.35 + i1.01	3.01 - i0.01 -19.24 + i0.05	4.85+i0.01 -20.35-i0.07	0.01 - i0.03 -0.03 + i0.09
→ 4422.79 + i7.75	g_i $g_i G_i^{II}$	0.71 - i0.08 1.14 + i10.71	0.05 + i0.00 0.76 + i1.82	-0.06 + i0.04 -0.43 - i1.53	2.79-i0.35 -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 $g_i G_i^{II}$	0.11 - i0.00 -0.13 + i1.07	3.17 - i0.01 -18.57 + i0.06	5.07+i0.01 -19.94-i0.07	0.00 - i0.04 -0.01 + i0.10
4565.73 + i15.58	g_i $g_i G_i^{II}$	0.70 - i0.16 6.24 + i21.04	0.09 - i0.03 2.07 + i3.40	-0.10 + i0.09 -1.37 - i2.81	2.84-i0.72 -26.31+i1.15

$PB(3/2^+)$ sector

$\bar{D} \Xi_c^*$: 4488.52 MeV, $g = 2.81$, $gG^{II} = -26.47$,

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

$\bar{D}^* \Xi_c^*$: 4627.48 MeV, $g = 2.96$, $gG^{II} = -25.93$,

$$J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^- .$$

$VB(3/2^+)$ sector

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

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

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

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

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	0.12 - i0.00	3.01 - i0.01	4.85+i0.01	0.01 - i0.03
	$g_i G_i^{II}$	-0.35 + i1.01	-19.24 + i0.05	-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	2.79-i0.35
	$g_i G_i^{II}$	1.14 + i10.71	0.76 + i1.82	-0.43 - i1.53	-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

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

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

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

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$VB(1/2^+)$ 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	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

$$M = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

Width is almost 2 orders of magnitude smaller

$$\Gamma = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

- 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

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

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

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: $\mathbf{PB}(\frac{1^+}{2})$, $\mathbf{PB}(\frac{3^+}{2})$, $\mathbf{VB}(\frac{1^+}{2})$, $\mathbf{VB}(\frac{3^+}{2})$.

- Counting all spin possibilities, we find 10 states
- We find a natural interpretation of

$\mathbf{P}_{cs}(4338)$ as a molecular state coupling mostly to \bar{D}^*E_c

$\mathbf{P}_{cs}(4459)$ as a $\bar{D}E'_c$ molecule

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

Thank you for your attention!