Pentaquarks with strangeness: the role of coupled channels and a new unitarization strategy

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E.E. Garcia-Gonzales, V.K. Magas, A. Ramos, e-Print: 2605.21205 [hep-ph]

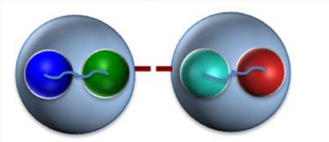
Exotic hadrons
(anything that goes beyond $q\bar{q}$ and qqq)

Sine the early 2000's an increasing amount of data in the charm (hidden charm) sector (collected at Belle, BaBar, LHCb and BESIII…) has provided clean evidence for many new **exotic** states which appear to be inconsistent with the predictions of the conventional quark model.

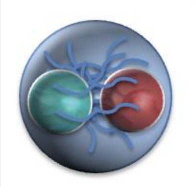
Mesons

compact tetraquark

Glueball



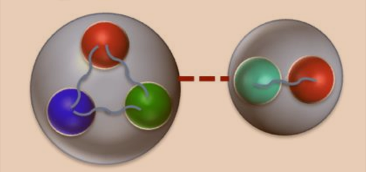
meson-meson molecule



hybrid

Baryons

compact pentaquark

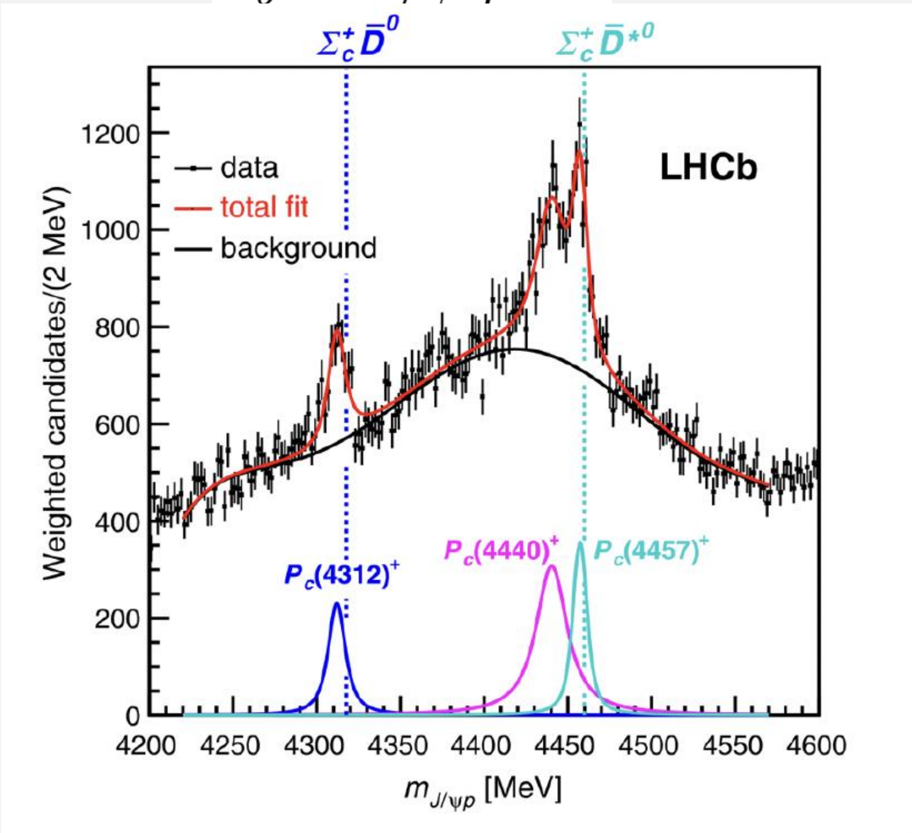


baryon-meson molecule

S=0 Pentaquarks

$P_{c\bar{c}}$ $(c\bar{c}qqq)$ $q = u, d$

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



$P_{c\bar{c}}(4380)^+$ LHCb, PRL 115, 072001 (2015)

$P_{c\bar{c}}(4312)^+, P_{c\bar{c}}(4440)^+, P_{c\bar{c}}(4457)^+$ LHCb, PRL 122, 222001 (2019)

$P_{c\bar{c}}(4337)^+$ LHCb, PRL 128, 062001 (2022)

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

$\bar{D}^0\Sigma_c^+$ threshold: 4318 MeV → $P_{c\bar{c}}(4312)$
$\bar{D}^{*0}\Sigma_c^+$ threshold: : 4460 MeV (J=1/2, 3/2) → $P_{c\bar{c}}(4440)$, $P_{c\bar{c}}(4457)$

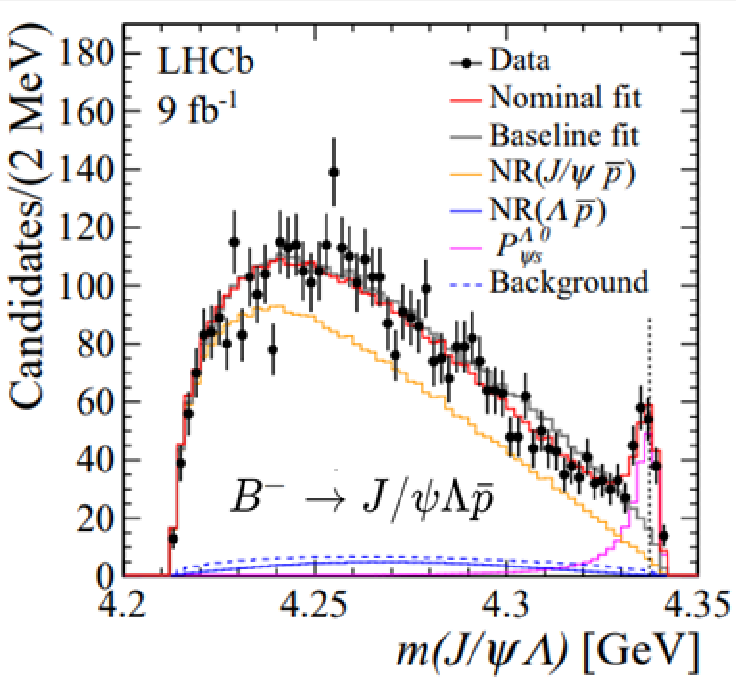
and were already predicted as meson-baryon molecules in 2010!

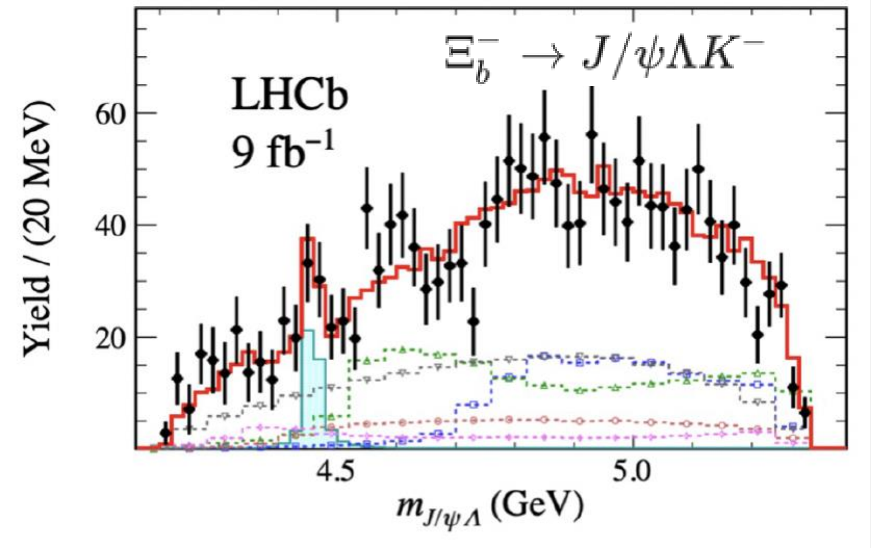
J.J .Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010);
Phys. Rev. C 84, 015202 (2011).

This work also predicted **S=-1** states

S=-1 Pentaquarks

$P_{c\bar{c}s}$ $(c\bar{c}qqs)$ $q = u, d$





$P_{c\bar{c}s}(4338)^0$ LHCb, PRL. 131, 031901 (2023)

$P_{c\bar{c}s}(4459)^0$ LHCb, Sci. Bull. 66, 1278 (2021)

Belle, Belle II, PRL 135 , 041901 (2025)

Since the pioneering work of Wu, Molina, Oset, Zou in 2010, many works (using a similar theoretical model) have predicted S=0 and S=-1 hidden charm pentaquarks.

Recent reviews:

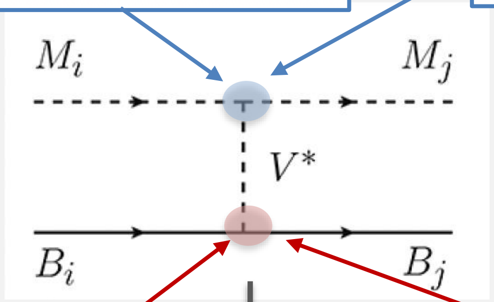
A. Esposito, A. Pilloni, A. D. Polosa, Phys. Rep. 668, 1 (2017).
H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, Rep. Prog. Phys. 80, 076201 (2017).
L. Meng, B. Wang, G.-J. Wang, and S.-L. Zhu, Phys. Rep. 1019, 1 (2023).
H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, and S.-L. Zhu, Rep. Prog. Phys. 86, 026201 (2023).
H. Huang, C. Deng, X. Liu, Y. Tan, and J. Ping, Symmetry 15, 1298 (2023).
H. Garcilazo and A. Valcarce, Symmetry 17, 1324 (2025).

Unitarized t-channel vector-meson exchange (TVME) interaction

Interaction kernel:

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

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



Local hidden gauge approach based on SU(4) flavour symmetry

LHGA-SU(4)

B: $J^P = 1/2^-$

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

Local hidden gauge approach employing the wave-function method

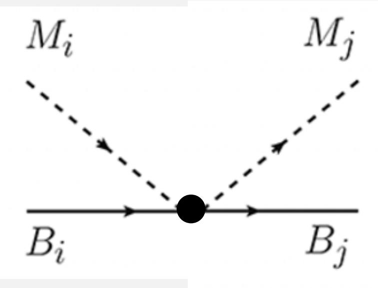
LHGA-WF

B: $J^P = 1/2^-$ *B**: $J^P = 3/2^-$

$$\underbrace{g\,\langle\phi_j\chi_j|}_{B_i}\,\underbrace{(q\bar{q})}_{V^*}\,\underbrace{|\phi_i\chi_i\rangle}_{B_j}$$

c-quark: spectator

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

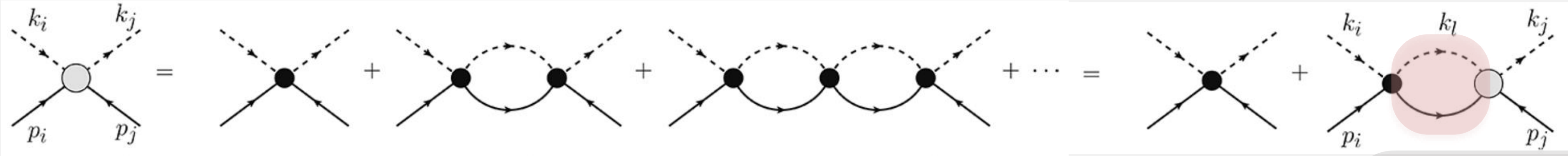


$$\rightarrow \quad V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

s-wave

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

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



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

$\rightarrow$

$$T = (1 - VG)^{-1} V$$

Poles: $\det(1 - VG) = 0$

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

dim reg.

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

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

cut-off

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

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

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

S=-2 Pentaquarks ?

$P_{c\bar{c}ss}$ $(c\bar{c}qss)$ $q = u, d$

Experimentally not observed (yet…)

CMS, Eur. Phys. J. C 84, 1062 (2024) $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$

LHCb, Eur. Phys. J. C 85, 812 (2025) $\Xi_b^0 \to J/\psi\, \Xi^- \pi^+$

Theoretically, within the **TVME model**:

- ✓ The early work of **Wu et al (2010)** didn't find S=-2 pentaquarks
- ✓ TVME model was revisited in **Marsé-Valera, Magas, Ramos, PRL 130, 091903 (2023)**
  → $P_{c\bar{c}ss}$ found!
- ✓ Confirmed in **Roca, Song, Oset, PRD 109, 094005 (2024)**

Why was the state missed?

1) The state emerges fom a delicate **coupled-channel mechanism**
2) The employed **unitarization scheme** may have obscured its identification

1) Coupled-channel mechanism in the $S=-2, I=\frac{1}{2}$ sector

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

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

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

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

repulsion

$\bar{D}_s\Xi_c'$ and $\bar{D}\Omega_c$.
strongly coupled!
→ induces attraction

$$\begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix} + \begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix}\begin{pmatrix} G_1 & 0 \\ 0 & G_2 \end{pmatrix}\begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}$$

$$T_{11} = \frac{V_{11}+V_{12}G_2(1-V_{22}G_2)^{-1}V_{21}}{1-(V_{11}+V_{12}G_2(1-V_{22}G_2)^{-1}V_{21})G_1} \rightarrow T_{11} = \frac{V_{11}^{\text{eff}}}{1-V_{11}^{\text{eff}}G_1}$$

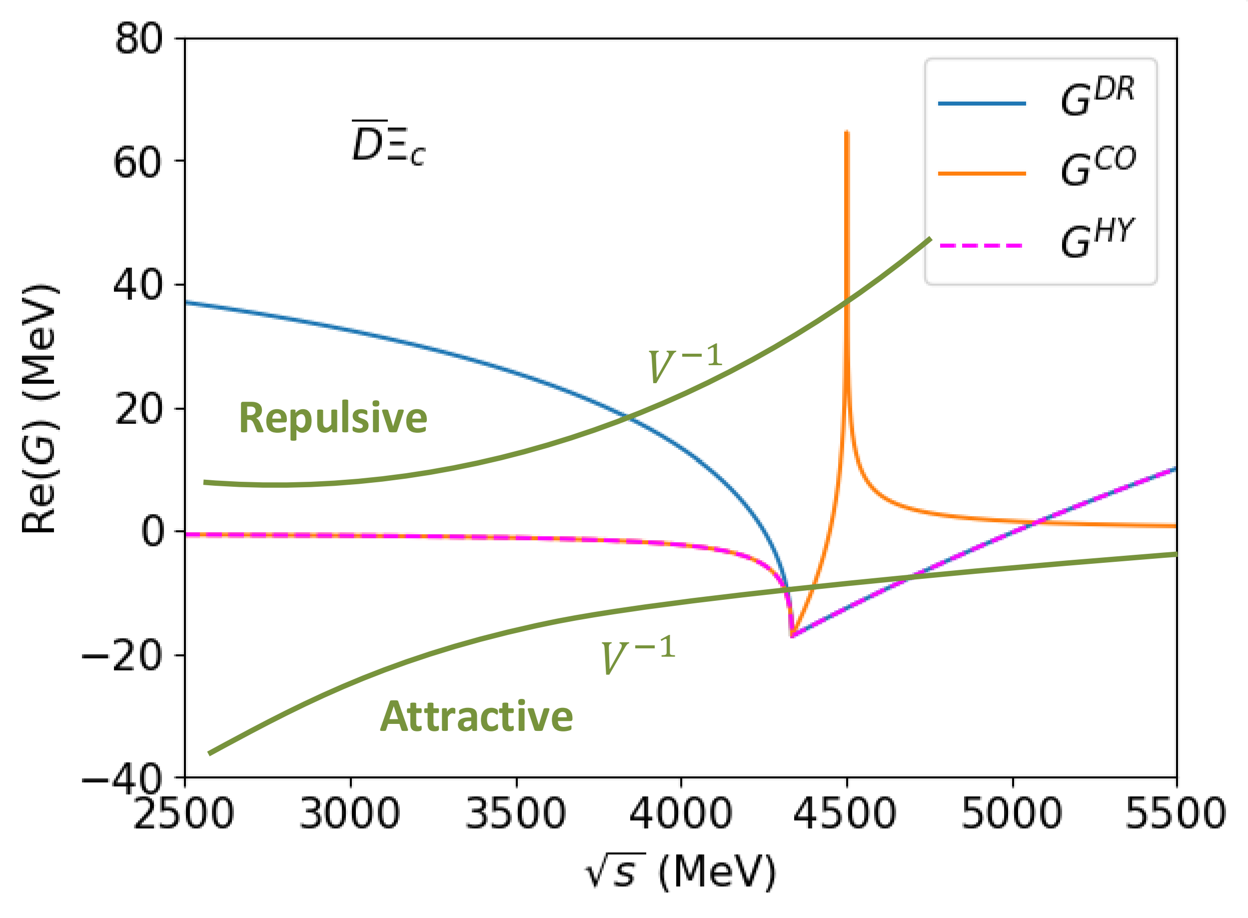
$$\boxed{V_{11}^{\text{eff}} = V_{11}+V_{12}G_2(1-V_{22}G_2)^{-1}V_{21}}$$

→ A molecular pentaquark with S=-2, $P_{c\bar{c}ss}$, appears around 4500 MeV

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 $\bar{D}\Omega_c$ channels

Marsé-Valera, Magas, Ramos, PRL 130, 091903 (2023)
Roca, Song, Oset, PRD 109, 094005 (2024)

2) The unitarization scheme may have obscured its identification in earlier works



$$T = (1 - VG)^{-1}V$$

Poles: $\det(1 - VG) = 0$

Uncoupled approach: $\mathrm{Re}(G_i) \sim V_{ii}^{-1}$

→ Fake (unphysical) poles might be generated in both DR and CO schemes!

We propose a **Hybrid Loop (HY)** scheme:

$$\mathrm{Re}(G_k^{\mathrm{HY}}) = \begin{cases} \mathrm{Re}(G_k^{\mathrm{cut}}) & if \quad \sqrt{s} < M_k + m_k \\ \mathrm{Re}(G^{\mathrm{DR}}) & if \quad \sqrt{s} \geq M_k + m_k \end{cases}$$

$$\mathrm{Im}(G_k^{\mathrm{HY}}) = \mathrm{Im}(G_k^{\mathrm{DR}})$$

$S = 0$

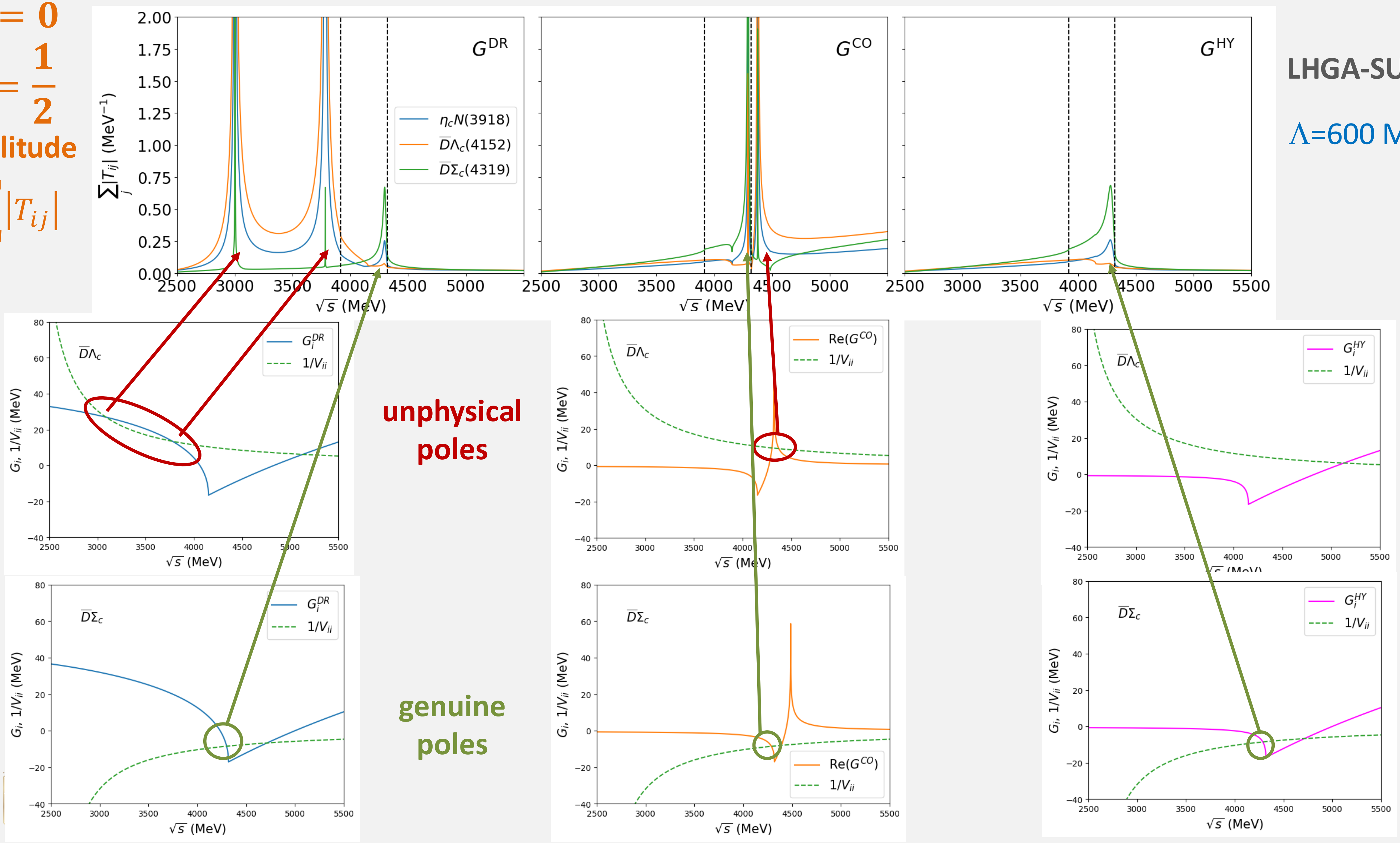
$I = \frac{1}{2}$

amplitude

$\sum_j |T_{ij}|$

LHGA-SU(4)

Λ=600 MeV



Comparison with other theoretical studies

LHGA-SU(4) model

Pseudoscalar-Baryon (PB) states: J^P=1/2$^-$
Vector-Baryon (VB) states: J^P=1/2$^-$and 3/2$^-$

	Our model			Other works			
$(S,\, I)$	M [MeV]	Γ [MeV]	J^P	M [MeV]	Γ [MeV]	J^P	References
$(0,\, 1/2)$	4283 4422	21 30	$1/2^-$ $1/2^-, 3/2^-$	4265 4415	23 19	$1/2^-$ $1/2^-, 3/2^-$	Wu, Molina, Oset & Zou, PRC (2011)
$(-1,\, 0)$	4189 4328 4405 4544	0.3 0.3 31 31	$1/2^-$ $1/2^-, 3/2^-$ $1/2^-$ $1/2^-, 3/2^-$	4210 4368 4398 4547	6 6 16 13	$1/2^-$ $1/2^-, 3/2^-$ $1/2^-$ $1/2^-, 3/2^-$	Wu, Molina, Oset & Zou, PRC (2011)
$(-1,\, 1)$	4386 4527	27 28	$1/2^-$ $1/2^-, 3/2^-$	?			
$(-2,\, 1/2)$	4515 4654	33 30	$1/2^-$ $1/2^-, 3/2^-$	4493 4633	74 80	$1/2^-$ $1/2^-, 3/2^-$	Marsé-Valera, Magas & Ramos, PRL (2023)

→ Consistent results with the reported states in the literature.

→ New predictions in the $S=-1, I=1$ sector.

Consistency also with the wave-function approach: LHGA-WF

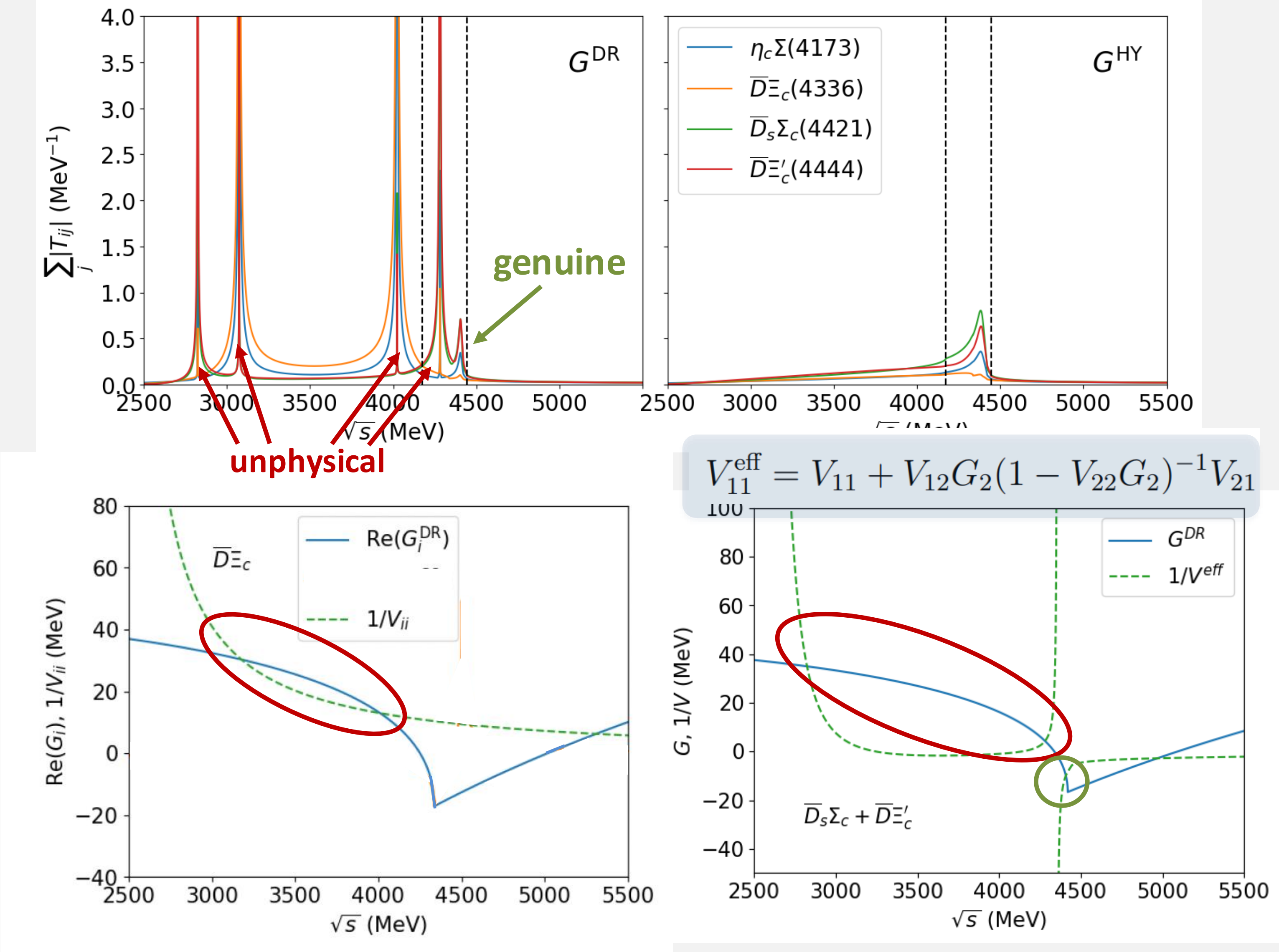
PB states: J^P=1/2$^-$ VB states: J^P=1/2$^-$, 3/2$^-$ PB* states: J^P=3/2$^-$ VB* states: J^P=1/2$^-$, 3/2$^-$, 5/2$^-$

	LHGA-SU(4)			LHGA-WF			Other works			
(S, I)	M	Γ	J^P	M	Γ	J^P	M	Γ	J^P	Ref.
(0, 1/2)	4283	21	$1/2^-$	4286	9	$1/2^-$	4265	23	$1/2^-$	[36]
	4422	30	$1/2^-, 3/2^-$	4425	10	$1/2^-, 3/2^-$	4415	19	$1/2^-, 3/2^-$	
				4353	0	$3/2^-$	4306	15	$1/2^-$	
				4492	0	$1/2^-, 3/2^-, 5/2^-$	4453	23	$1/2^-$	
							4452	3	$3/2^-$	
							4374	14	$3/2^-$	[50]
							4520	22	$1/2^-$	
							4519	14	$3/2^-$	
							4519	0	$5/2^-$	
(−1, 0)	4189	0.3	$1/2^-$	4189	0	$1/2^-$	4210	6	$1/2^-$	
	4328	0.3	$1/2^-, 3/2^-$	4328	0	$1/2^-, 3/2^-$	4368	6	$1/2^-, 3/2^-$	[36]
	4405	31	$1/2^-$	4409	10	$1/2^-$	4398	16	$1/2^-$	
	4544	31	$1/2^-, 3/2^-$	4548	10	$1/2^-, 3/2^-$	4547	13	$1/2^-, 3/2^-$	
				4480	0	$3/2^-$	4277	15	$1/2^-$	
				4619	0	$1/2^-, 3/2^-, 5/2^-$	4430	16	$1/2^-$	
							4430	15	$3/2^-$	
							4437	2	$1/2^-$	
							4581	5	$1/2^-$	
							4581	1	$3/2^-$	[51]
							4507	2	$3/2^-$	
							4651	5	$1/2^-$	
							4651	3	$3/2^-$	
							4651	0	$5/2^-$	
							4199	0.2	$1/2^-$	
							4338	0.2	$1/2^-, 3/2^-$	
							4423	15	$1/2^-$	
							4566	31	$1/2^-, 3/2^-$	[52]
							4489	0	$3/2^-$	
							4627	0	$1/2^-, 3/2^-, 5/2^-$	

	LHGA-SU(4)			LHGA-WF			Other works			
(S, I)	M	Γ	J^P	M	Γ	J^P	M	Γ	J^P	Ref.
(−1, 1)	4386	27	$1/2^-$	4392	8	$1/2^-$	?			
	4527	28	$1/2^-, 3/2^-$	4533	9	$1/2^-, 3/2^-$				
				4461	0	$3/2^-$				
				4602	0	$1/2^-, 3/2^-, 5/2^-$				
(−2, 1/2)	4515	33	$1/2^-$	4521	9	$1/2^-$	4493	74	$1/2^-$	[39]
	4654	30	$1/2^-, 3/2^-$	4661	10	$1/2^-, 3/2^-$	4633	80	$1/2^-, 3/2^-$	
				4607	0	$3/2^-$	4535	9	$1/2^-$	
				4747	0	$1/2^-, 3/2^-, 5/2^-$	4675	10	$1/2^-, 3/2^-$	[40]
							4602	0	$3/2^-$	
							4743	0	$1/2^-, 3/2^-, 5/2^-$	

[36] Wu et al, PRCC 84, 015202 (2011)
[50] Xiao,Nieves,Oset, PRD 100, 014021 (2019)
[51] Xiao,Nieves,Oset, PLB 799, 135051 (2019)
[52] Feijoo et al, PLB 839, 137760 (2023)
[39] Marsé-Valera, Magas, Ramos, PRL 130, 091903 (2023)
[40] Roca, Song, Oset, PRD 109, 094005 (2024)

$S = -1,\ I = 1$ amplitude



$$V_{11}^{\mathrm{eff}} = V_{11} + V_{12}G_2(1 - V_{22}G_2)^{-1}V_{21}$$

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

repulsive

In the DR scheme, the unphysical artifacts obscure the identification of the genuine states.

The HY scheme proposed here simplifies the shape of the scattering amplitude by only preserving the physical poles.

Comparison with experimental data

	LHGA-SU(4)			LHGA-WF			EXP				
(S, I)	M	Γ	J^P	M	Γ	J^P	State	M	Γ	J^P	Ref.
$(0, 1/2)$	4283	21	$1/2^-$	4286	9	$1/2^-$	~~$P_{c\bar{c}}(4380)^+$~~	~~4380 ± 30~~	~~210 ± 90~~	-	[29]
	4422	30	$1/2^-, 3/2^-$	4425	10	$1/2^-, 3/2^-$	$P_{c\bar{c}}(4312)^+$	$4312^{+7}_{-0.9}$	10 ± 5	-	[30]
							$P_{c\bar{c}}(4440)^+$	4440.3^{+4}_{-5}	$20.6 \pm 4.9^{+8.7}_{-10.1}$	-	[30]
				4353	0	$3/2^-$	$P_{c\bar{c}}(4457)^+$	$4457.3^{+4}_{-1.8}$	$6.4 \pm 2^{+5.7}_{-1.9}$	-	[30]
				4492	0	$1/2^-, 3/2^-, 5/2^-$	$P_{c\bar{c}}(4337)^+$	4337^{+7+2}_{-4-2}	29^{+26+14}_{-12-14}	-	[34]
$(-1, 0)$	4189	0.3	$1/2^-$	4189	0	$1/2^-$	$P_{c\bar{c}s}(4338)^0$	4338.2 ± 0.8	7.0 ± 1.8	$1/2^-$	[32]
	4328	0.3	$1/2^-, 3/2^-$	4328	0	$1/2^-, 3/2^-$	$P_{c\bar{c}s}(4459)^0$	$4458.8^{+6}_{-3.1}$	$17.3 \pm 6.5^{+8}_{-5.7}$	-	[31]
	4405	31	$1/2^-$	4409	10	$1/2^-$	$P_{c\bar{c}s}(4459)^0$	$4471.7 \pm 4.8 \pm 0.6$	$22 \pm 13 \pm 3$	-	[33]
	4544	31	$1/2^-, 3/2^-$	4548	10	$1/2^-, 3/2^-$					
				4480	0	$3/2^-$					
				4619	0	$1/2^-, 3/2^-, 5/2^-$					

LHCb

Belle, Belle II

- ✓ 6 out of 7 of the observed exotic pentaquarks can be associated to a molecular state.
- ✓ The $P_{c\bar{c}}(4380)^+$ cannot be associated to any of our predicted states due to its large width.
- ✓ Fine tuning of the parameters is necessary.

Conclusions

- ✓ We introduce a hybrid loop function, G^{HY}, which avoids the generation of unphysical artifacts in the scattering amplide, hence enabling a **cleaner extraction** of the **genuine molecular states**.
- ✓ The states are **in agreement** with those predicted **with the G^{DR} and G^{CO} schemes** and are also consistent **with the states reported in other theoretical works**.
- ✓ The new hybrid scheme reveals **new pentaquark candidates with $S = -1$, $I = 1$**, which were likely obscured by unphysical artifacts in the traditional schemes
- ✓ It is found that **6** out of the **7** experimentally observed pentaquarks could correspond to a **meson-baryon molecule** reported here, but further parameter tuning is necessary .

E.E. Garcia-Gonzales, V.K. Magas, A. Ramos, e-Print: 2605.21205 [hep-ph]

Thank you!