Molecular hadrons (particularly pentaquarks) from the EFT perspective

Manuel Pavon Valderrama

Beihang University

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With FZ Peng, MJ Yan, ZY Yang, M Sánchez

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FZ Peng,MJ Yan, M Sánchez, MPV; EPJC 81 (2021) 7, 666

MJ Yan, FZ Peng, M Sánchez, MPV; EPJC 82 (2022) 6, 574; PRD 107 (2023) 7, 074025

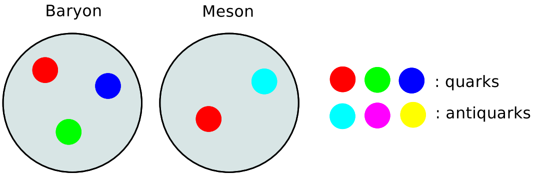
ZY Yang, FZ Peng, MJ Yan, M Sánchez, MPV; arXiv:2211.08211

FZ Peng,MJ Yan, M Sánchez, MPV; PLB 846 (2023) 138207

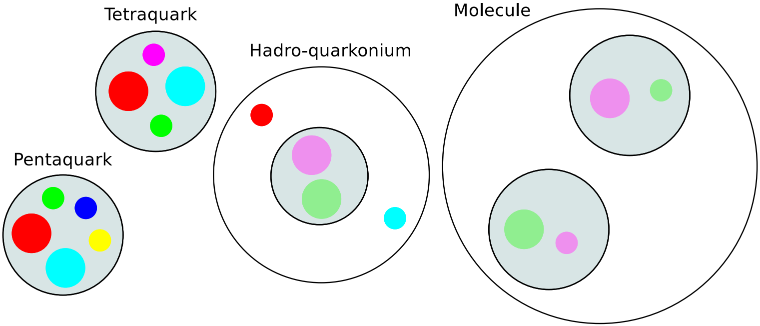
Exotic hadrons

Exotic hadrons

Standard hadrons come in two varieties

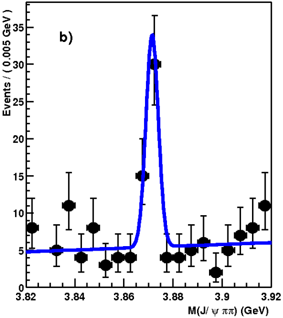


But there are more types of possible hadrons...



Exotic hadrons: the X(3872)

Exotic hadrons became extremely popular thanks to a discovery by the Belle collaboration in $B^{\pm} \to K^{\pm} J/\Psi\pi\pi$ (03):



Looks molecular, but no wide consensus about its nature yet!

Exotic hadrons: are you a fox or a hedgehog?

Phillip Tetlock: Expert political judgement, how good it is? (2005)
(hint: as good as dart-throwing chimps... except for the foxes)

- **Hedgehog**: knows one big idea (intellectual economy)
  Resistance to update priors Convergence Fav word: Moreover
- **Fox**: knows many little ideas (intellectual scavenger)
  Bayesian operators Zigzagging Fav word: However

They form a “thought ecosystem”.

Yet, hadron physics is also messy: better lean to the fox side.

Exotic hadrons: practicing your fox skills with the $X(3872)$

For $X(3872)$: contradictory/ambiguous information to be balanced

(i) Close to $D^*\bar{D}$ threshold: large coupling with it

Tornqvist hep-ph/0308277; Voloshin PLB 579, 316; Braaten, Kusunoki PRD 69, 074005

(ii) $X \to \psi(nS)\gamma$, $n = 1, 2$: $c\bar{c}$ core Guo et al. PLB 742 (2015) 394-398

(iii) $X \to J/\psi\, 2\pi$ and $X \to J/\psi\, 3\pi$ pattern easier to explain in molecular picture Gamermann, Oset PRD 80 (2009) 014003 ...but compact state can also have this branching ratio Swanson PLB 588 (2004) 189-195

(iv) $X(4014)$ by Belle (predicted mol partner, but poor statistics)

> Often forgotten fact:
> **the wave function is not an observable**

Though it seems to lean more to molecular than not...

But before dealing with the problem of molecularness:

EFT crash course in one slide

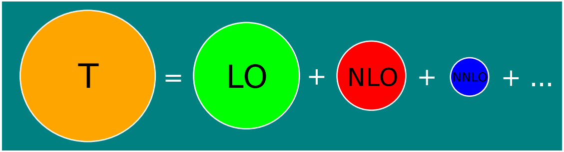
Effective field theories: the way of the fox (a crash course)

- Generic low energy descriptions of physical phenomena

$$\underbrace{\text{quarks \& gluons}}_{\text{high energy}} \iff \underbrace{\text{hadrons } (D^{(*)},\, \Sigma_c^{(*)},\, \pi)}_{\text{low energy (EFT)}}$$

  (equivalent by virtue of the renormalization group)

- Everything within EFT is an expansion:



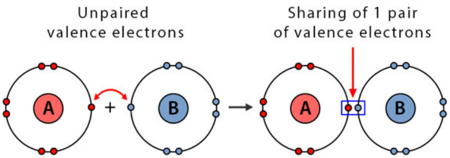
  Calculations are amenable to error estimations
  (that is, the expected size of the next blob)

- Hadronic molecules: scarcity of data, that is,
  usually leading order (LO) is enough in most cases

What is a molecule?

Exotic hadrons: what is a molecule?

Chemistry textbook molecules (a.k.a. actual molecules):



Hadronic molecules: definitely not two clearly separated heavy quarks sharing a pair (or a few pairs) of light-quarks

(Exception: Born-Oppenheimer approx. with exotics)

But the name is catchy! $\Rightarrow$ We adopted it ;)

Here: $|\text{molecule}\rangle = (1-\delta)|H_1 H_2\rangle + \delta|\text{other things}\rangle$, δ smallish

And... we obviate the evident lack of rigor with this, as usual.

(After all, we are physicists...)

Exotic hadrons: molecular or not? (the deuteron)

The deuteron D-wave probability (P_D): **not an observable!**

(a) Deuteron wave function:

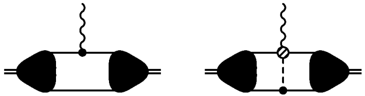
$$|d\rangle = \cos\theta_D |^3S_1\rangle + \sin\theta_D |^3D_1\rangle$$

(b) Deuteron magnetic moment: $\mu_{exp} = 0.86\,\mu_N$,
but $\mu(^3S_1) = 0.88\,\mu_N \Rightarrow \exists$ non S-wave component

(c) D-wave probability $P_D \sim (3-5)\%$, but with assumptions:

(c.1) No relativistic corrections included Gilman, Gross JPG 28, R37

(c.2) No two-body currents included D.R. Phillips, JPG 34, 365



$O(e)$ $\quad$ $O(eP^3)$

That is: within EFT P_D still makes sense at lower orders.

Exotic hadrons: molecular or not? (the $T_{cc}^+(3875)$)

The T_{cc}^+ decay width into $DD\pi$ and $DD\gamma$:

(a) T_{cc}^+ wave function:

$$|T_{cc}\rangle = \cos\theta_C |D^* D\rangle + \sin\theta_C |cc\bar{u}\bar{d}\rangle$$

(b) T_{cc}^+ width: $\Gamma_{\rm exp}^{(*)} = 48 \pm 2^{+0}_{-12}\,{\rm KeV}$, but if $\Gamma_{\rm th}^{\rm mol} > \Gamma_{\rm exp}$
$\Rightarrow \exists$ non molecular component (provided $\Gamma_{\rm th}^{\rm tetra} \ll \Gamma_{\rm th}^{\rm mol}$)

(c) Same caveats as in the deuteron (also $\exists$ T_{cc}'s D-wave)

What do we have? Well... (hint: molecularness can be determined)

$$\Gamma_{\rm th}^{\rm LO} = 49 \pm 3 \pm 16\,{\rm KeV} \quad , \quad \Gamma_{\rm th}^{\rm NLO} = 58^{+5}_{-3} \pm 5\,{\rm KeV}$$

And this is with $\Lambda \to \infty$ (otherwise $\Gamma_{\rm th}^{\rm LO} > \Gamma_{\rm exp}^{(*)}$ already.)

If T_{cc} not highly molecular $\Rightarrow$ no T_{cc}^* $(D^* D^*)$ partner

From arguments analogous to those in Cincioglu et al. EPJC76, 576

(*): not the actual T_{cc} experimental width, includes theoretical assumptions.

Exotic hadrons: molecular or not? (the $P^{\Lambda}_{\psi s}(4338)$)

The $P^{\Lambda}_{\psi s}(4338)$ slightly above threshold: not describable with your usual single channel, energy- and momentum-independent contact.

How molecular is it then? Use $X_{\rm mol} = \sqrt{\frac{1}{1+2|\frac{r_0}{a_0}|}}$ Matuschek et al. EPJA 57, 101

(a) Energy-dependent: $V_C = d_a + 2\, d_{2a}\, k^2 \Rightarrow X_{\rm mol} = 0.33$

(b) Momentum-dependent:

$$V_C = d_a + d_{2a}\,(p^2 + p'^2) \Rightarrow X_{\rm mol} = 0.95$$

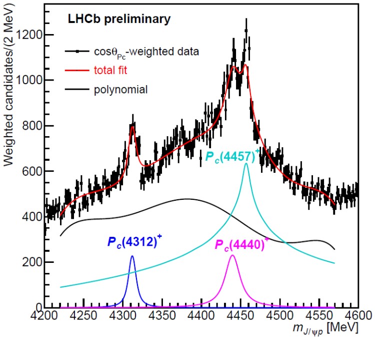
(c) Coupled-channel:

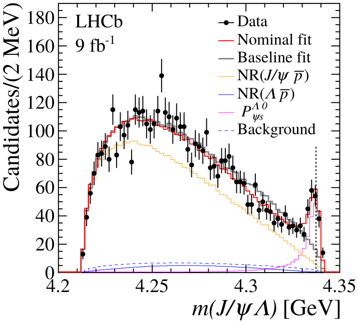
$$V_C = \begin{pmatrix} \frac{1}{2}(d_a + \tilde{d}_a) & \frac{1}{\sqrt{2}}(d_a - \tilde{d}_a) \\ \frac{1}{\sqrt{2}}(d_a - \tilde{d}_a) & d_a \end{pmatrix} \quad \Rightarrow \quad X_{\rm mol} = 0.77$$

(a) and (b) on-shell equivalent, but different $X_{\rm mol}$ (that is, a counterexample) $\Rightarrow$ non-observability of the wave function

Pentaquarks

Pentaquarks: the discoveries of the LHCb





The most famous and the most recent, as found in the respective LHCb manuscripts

Pentaquarks: current candidates

The pre- and post-pandemic pentaquark candidates as molecules:

Candidate	Molecule	J^P
$P_{\psi}^{N}(4312)$	$\Sigma_c \bar{D}$	$\frac{1}{2}^-$
$P_{\psi}^{N}(4440)$	$\Sigma_c \bar{D}^*$	$\frac{1}{2}^-, \frac{3}{2}^-?$
$P_{\psi}^{N}(4457)$	$\Sigma_c \bar{D}^*, \Lambda_{c1} \bar{D}$	$\frac{3}{2}^-, \frac{1}{2}^-, \frac{1}{2}^+?$
$P_{\psi s}^{\Lambda}(4338)$	$\Xi_c \bar{D}$	$\frac{1}{2}^-$
$P_{\psi s}^{\Lambda}(4459)$	$\Xi_c \bar{D}^*$	$\frac{1}{2}^-, \frac{3}{2}^-?$

Caveat: they are nor necessarily molecules (or even states)

Also a $P_{\psi}^{N}(4337)$, but difficult to interpret as a molecule

MJ Yan, FZ Peng, M Sánchez, MPV, EPJC 82, 6, 574; Nakamura, Hosaka, Yamaguchi, PRD 104, 9, L091503

$P_{\psi s}^{\Lambda}(4338/4459)$ and their partners: a possible $P_{\psi s}(4255/4398)$?

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules

Two P^{Λ}_{ψ} ($c\bar{c}sqq$) molecular pentaquark candidates:

$$M_1 = 4338.2 \pm 0.7\,\mathrm{MeV}\,, \quad \Gamma_1 = 7.0 \pm 1.2\,\mathrm{MeV}\,,$$
$$M_2 = 4458.8 \pm 2.9^{+4.7}_{-1.1}\,\mathrm{MeV}\,, \quad \Gamma_2 = 17.3 \pm 6.5^{+8.0}_{-5.7}\,\mathrm{MeV}\,,$$

Most straightforward molecular explanations:

$$P^{\Lambda}_{\psi s1} \sim \bar{D}\Xi_c \quad , \quad P^{\Lambda}_{\psi s2} \sim \bar{D}^{*}\Xi_c$$

with binding energies $B_1 = -2.5$ (resonance), $B_2 = 18.8$.

$P_{\psi s}^{\Lambda}$ as meson-baryon molecules

What are the implications of HQSS for these two pentaquarks?

Molecule	J^P	Without HQSS	With HQSS
$\bar{D}\Xi_c$	$\frac{1}{2}^-$	$V = c_1$	$V = d_a$
$\bar{D}\Xi_c^*$	$\frac{1}{2}^-, \frac{3}{2}^-$	$V = c_2$	$V = d_a$

If we use the $P_{\psi s}^{\Lambda}(4459)$ as input, this will predict $B_1 = 16.9$ ($M_1 = 4319.4$) for the $P_{\psi s}^{\Lambda}(4338)$. But:

(i) Exp. error: $B_1 = 16.9^{+2.9}_{-4.7}$ ($M_1 = 4319.4^{+4.7}_{-2.9}$) (underestimation?)

(ii) EFT truncation error: $B = 16.9^{+9.3}_{-8.5}$ ($M_1 = 4319.4^{+8.5}_{-9.3}$)

(iii) HQSS error: $B_1 = 16.9^{+18.5}_{-13.3}$ ($M_1 = 4319.4^{+13.3}_{-18.5}$)

Together: $B_1 = 17^{+21}_{-16}$ ($M = 4319^{+16}_{-21}$)

vs $B_1 = -2.5 \pm 0.7$ ($M = 4338.2 \pm 0.7$)

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules

Yet, there are more factors in play:

(iv) Breit-Wigner param not ideal for near-threshold poles: the $P^{\Lambda}_{\psi s}(4338)$ might be below threshold (bound/virtual)

Albaladejo, Guo, Hidalgo-Duque, Nieves PLB755 (2016) 337-342; JPAC Coll. PRL 123 (2019) 9, 092001

(v) Nearby $\bar{D}\Xi_c^*$ CC dynamics for the $P^{\Lambda}_{\psi s}(4459)$ (if $J^P = \frac{3}{2}^-$):

$$V(\bar{D}^*\Xi_c - \bar{D}\Xi_c^*) = \begin{pmatrix} d_a & e_a \\ e_a & c_a \end{pmatrix}$$

This further reduces B_1 by a few MeV.

(vi) The $P^{\Lambda}_{\psi s}(4459)$ might be two peaks / plus poorer statistics

check the LHCb paper on the $P^{\Lambda}_{\psi s}(4459)$

(vii) The $P^{\Lambda}_{\psi s}(4338)$ might be the $P^{\Sigma^0}_{\psi s}(4338)$

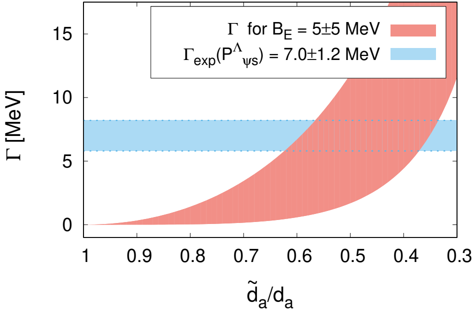
From our previous prediction in EPJC 82 (2022) 6, 574

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules: EFT description

We will consider contact EFT with $\bar{D}_s^{(*)}\Lambda_c$-$\bar{D}^{(*)}\Xi_c$ dynamics

$$V_C(P^{\Lambda}_{\psi s}) = \begin{pmatrix} \frac{1}{2}(d_a + \tilde{d}_a) & \frac{1}{\sqrt{2}}(d_a - \tilde{d}_a) \\ \frac{1}{\sqrt{2}}(d_a - \tilde{d}_a) & d_a \end{pmatrix} ,$$

Creates a width for $P^{\Lambda}_{\psi s}$ proportional to $(d_a - \tilde{d}_a)^2$



$(d_a - \tilde{d}_a)^2$ too large: excessive width.

$M, \Gamma \rightarrow d_a, \tilde{d}_a$ (determines spectrum)

$P_{\psi s}^{\Lambda}$ as meson-baryon molecules: predictions

Predictions for the spectrum (from mass and width):
Set B_1: $P_{cs}(4338)$ as input; Set B_2: $P_{cs}(4459)$ as input

System	Potential	Set B_1	Set B_2	Type
$\bar{D}\Lambda_c$	$\tilde{d}_a$	$(4111.3)^V$	$(4153.7)^V$	P_{ψ}^{N}
$\bar{D}^*\Lambda_c$	$\tilde{d}_a$	$(4256.7)^V$	4295.0	P_{ψ}^{N}
$\bar{D}_s\Lambda_c$	$\begin{pmatrix} \frac{1}{2}(d_a+\tilde{d}_a) & \frac{1}{\sqrt{2}}(d_a-\tilde{d}_a) \\ \frac{1}{\sqrt{2}}(d_a-\tilde{d}_a) & d_a \end{pmatrix}$	4254.8	4230.5	$P_{\psi s}^{\Lambda}$
$\bar{D}\Xi_c$		Input	4316.7	$P_{\psi s}^{\Lambda}$
$\bar{D}_s^*\Lambda_c$	$\begin{pmatrix} \frac{1}{2}(d_a+\tilde{d}_a) & \frac{1}{\sqrt{2}}(d_a-\tilde{d}_a) \\ \frac{1}{\sqrt{2}}(d_a-\tilde{d}_a) & d_a \end{pmatrix}$	4398.4	4375.2	$P_{\psi s}^{\Lambda}$
$\bar{D}^*\Xi_c$		4479.2	Input	$P_{\psi s}^{\Lambda}$
$\bar{D}\Xi_c$	$\tilde{d}_a$	$(4297.4)^V$	4336.3	$P_{\psi s}^{\Sigma}$
$\bar{D}^*\Xi_c$	$\tilde{d}_a$	$(4442.7)^V$	4477.5	$P_{\psi s}^{\Sigma}$
$\bar{D}_s\Xi_c$	$\tilde{d}_a$	$(4401.4)^V$	4437.3	$P_{\psi ss}^{\Xi}$
$\bar{D}_s^*\Xi_c$	$\tilde{d}_a$	$(4548.3)^V$	4580.9	$P_{\psi ss}^{\Xi}$

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules

We consistently predict a $P^{\Lambda}_{\psi s}(4255/4398)$ ($\bar{D}_s \Lambda_c$ / $\bar{D}^*_s \Lambda_c$).
But how solid is this? No clear consensus:

(i) LHCb manuscript: constraints on fit fractions
- (i.a) $P^{\Lambda}_{\psi s}(4338)$, $f = 0.125 \pm 0.007 \pm 0.019$
- (i.b) $P^{\Lambda}_{\psi s}(4255)$, $f < 0.087$ at 90% C.L.

Fit fraction of X in $A \to BCD$ ($X = P^{\Lambda}_{\psi s}$, $A = \Lambda_b$, $B = J/\psi$, $C = \Lambda$, $D = \bar{p}$)

$$f(X|BC) = \frac{\Gamma(A \to XD \to BCD)}{\Gamma(A \to BCD)} \approx \frac{\mathcal{B}(A \to XD)\,\mathcal{B}(X \to BC)}{\mathcal{B}(A \to BCD)}$$

Problem: $\mathcal{B}(P^{\Lambda}_{\psi s}(4255) \to J/\Psi\Lambda) > \mathcal{B}(P^{\Lambda}_{\psi s}(4338) \to J/\Psi\Lambda)$
Solutions: production of $P^{\Lambda}_{\psi s}(4255)$ smaller (likely from couplings), $P^{\Lambda}_{\psi s}(4255)$ virtual, $P^{\Lambda}_{\psi s}(4338)$ virtual
Reminder: fit fractions also problematic for P^{N}_{ψ} pentaquarks (P^{Δ}_{ψ}?)

Sakai, Jing, Guo, PRD 100 (2019) 7, 074007; Burns, Swanson, EPJA 58 (2022) 4, 68; FZ Peng, MJ Yan, M Sánchez, MPV arXiv: 2211.09154

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules

We consistently predict a $P^{\Lambda}_{\psi s}(4255)$.
But how solid is this? No clear consensus (cont'd):

(ii) Analyses of the $J/\psi\Lambda$ spectrum:

- (ii.a) Burns & Swanson: $P^{\Lambda}_{\psi s}(4338)$ triangle singularity, no trace of a $P^{\Lambda}_{\psi s}(4255)$
  Fit w/ condition $\tilde{d}_a > 0$: can't reproduce narrow $P^{\Lambda}_{\psi s}$ by design (results in $d_a - \tilde{d}_a$ too large for narrow state)
- (ii.b) Nakamura & Wu: $P^{\Lambda}_{\psi s}(4255)$ virtual
  Possible from small changes in our couplings

Both are possible solutions.

Or it might require better data ($P^{\Lambda}_{\psi s}(4255)$ ultra narrow).

And do not forget the Breit-Wigner issue!

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules: mini-summary

To summarize:

- $P^{\Lambda}_{\psi s}(4338)$ and $P^{\Lambda}_{\psi s}(4459)$ are probably compatible with each other in the molecular picture with HQSS
- If either of them are molecular, we predict a $P^{\Lambda}_{\psi s}(4255)$

However, these conclusions have a low degree of confidence.

Better data are required.

$P_\psi^N(4457)$ or $P_\psi^\Delta(4457)$?

P_ψ^N molecular interpretation

Three $c\bar{c}$ molecular pentaquark candidates:

$$
\begin{aligned}
m_{P_{c1}} &= 4311.9 \pm 0.7^{+6.8}_{-0.6}, \quad \Gamma_{P_{c1}} = 9.8 \pm 2.7^{+3.7}_{-4.5}, \\
m_{P_{c2}} &= 4440.3 \pm 1.3^{+4.1}_{-4.7}, \quad \Gamma_{P_{c2}} = 20.6 \pm 4.9^{+8.7}_{-10.1}, \\
m_{P_{c3}} &= 4457.3 \pm 0.6^{+4.1}_{-1.7}, \quad \Gamma_{P_{c3}} = 6.4 \pm 2.0^{+5.7}_{-1.9},
\end{aligned}
$$

Most likely molecular explanations:

$$P_{c1} \sim \bar{D}\Sigma_c \quad P_{c2}, P_{c3} \sim \bar{D}^*\Sigma_c \quad \text{with isospin } I = 1/2!$$

with binding energies $B_1 = 8.9$, $B_2 = 21.8$ and $B_3 = 4.8\,\mathrm{MeV}$.

Add HQSS $\Rightarrow$ prediction of seven P_ψ^N molecular pentaquarks

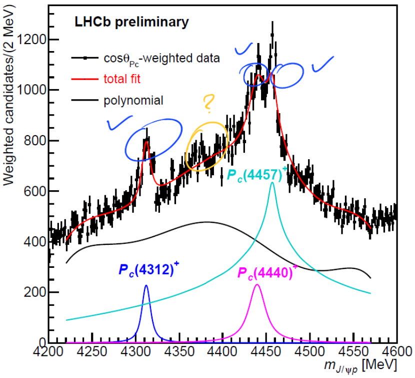
Reminder: HQSS for P_ψ molecular pentaquarks

What are the implications of HQSS for the pentaquark family?

Molecule	J^P	Without HQSS	With HQSS
$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	C_1	C_a
$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	C_2	C_a
$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	C_3	$C_a - \frac{4}{3}\,C_b$
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	C_4	$C_a + \frac{2}{3}\,C_b$
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	C_5	$C_a - \frac{5}{3}C_b$
$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	C_6	$C_a - \frac{2}{3}C_b$
$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	C_7	$C_a + C_b$

Liu, Peng, Sanchez, Valderrama (19)

P_{ψ}^{N} as molecules: where are the seven pentaquarks?



At most four are observed (instead of six).

Note: the $J = 5/2\ \bar{D}^*\Sigma_c$ only decays into $J/\psi p$ in P-wave, thus less visible than the other six

$P(4457)$ as P_ψ^Δ: "production fractions" and isospin (I)

But there is also a problem with this ratio:

(Sakai, Jing, Guo, PRD 100 (2019) 7, 074007; Burns, Swanson, EPJA 58 (2022) 4, 68, PRD 106 (2022) 5, 054029)

$$\textit{Production fractions:} \quad \mathcal{F}(P_c) = \frac{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)\,\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to K^- J/\psi p)}$$

Experimentally:

- $\mathcal{F}_i = 0.30^{+0.35}_{-0.11}$, $1.11^{+0.40}_{-0.34}$, $0.53^{+0.22}_{-0.21}$ for $P_c(4312/4440/4457)$
- Or, in relative terms: $\mathcal{F}_i/\mathcal{F}_1\Big|_{\text{exp}} = 1 : 3.7^{+2.5}_{-2.3} : (1.8 \pm 1.2)$

and we would like to now how well this compares with theory...

$P(4457)$ as P_ψ^Δ: "production fractions" and isospin (II)

Experiment: $\mathcal{F}_i/\mathcal{F}_1\Big|_{\rm exp} = 1 : 3.7^{+2.5}_{-2.3} : (1.8 \pm 1.2)$

Let's assume the following:

$$|P_c(4457)^+\rangle = \cos\theta_I\,|\bar{D}^{*0}\Sigma_c^+\rangle + \sin\theta_I\,|D^{*-}\Sigma_c^{++}\rangle$$

(a) If $P_c(4457)$ is a $P_\psi^N(4457)$, i.e. $I = 1/2$ or $\theta_I = -54.7^\circ$
then $\mathcal{F}_i/\mathcal{F}_1\Big|_{\rm th} = 1 : (0.86^{+1.10}_{-0.53})\,\mathcal{R}_2 : (18^{+16}_{-13})\,\mathcal{R}_3$
with $\mathcal{R}_i$ the ratios of $\mathcal{B}(\Lambda_b^0 \to K^- P_{ci}^+)$.

(b) If $P_c(4457)$ is a $P_\psi^\Delta(4457)$, i.e. $I = 3/2$ or $\theta_I = 35.3^\circ$
then $\mathcal{F}_i/\mathcal{F}_1\Big|_{\rm th} = 1 : (0.86^{+1.10}_{-0.53})\,\mathcal{R}_2 : (0.054^{+0.049}_{-0.042})\,\mathcal{R}_3$

(c) If $P_c(4457)$ is mostly a $P_\psi^\Delta(4457)$, i.e. $\theta_I = 20.1^\circ$
then $\mathcal{F}_i/\mathcal{F}_1\Big|_{\rm th} = 1 : (0.86^{+1.10}_{-0.53})\,\mathcal{R}_2 : (1.5^{+1.4}_{-1.1})\,\mathcal{R}_3$

If $\mathcal{R}_2$, $\mathcal{R}_3 = \mathcal{O}(1)$, then option (c) is the preferred one.

$P(4457)$ as P_{ψ}^{Δ}: "production fractions" and isospin (III)

Now we predict 6 states that are $I = 1/2$ (-ish):

Molecule (J^P)	M ($I = 1/2$)	M ($I = 3/2$)
$\bar{D}\Sigma_c$ ($\frac{1}{2}^-$)	Input	-
$\bar{D}\Sigma_c^*$ ($\frac{3}{2}^-$)	$4376.2^{+5.7}_{-11.2}$	-
$\bar{D}^{*0}\Sigma_c^+$-$D^{*-}\Sigma_c^{++}$ ($\frac{1}{2}^-$)	$4464.4^{+2.1}_{-6.7} - (0.0^{+4.2}_{-0.0})\,i$	Input
$\bar{D}^*\Sigma_c$ ($\frac{3}{2}^-$)	Input	-
$\bar{D}^{*0}\Sigma_c^{*+}$-$D^{*-}\Sigma_c^{*++}$ ($\frac{1}{2}^-$)	$4531.3^{+9.7}_{-2.6} - (2.7^{+10.2}_{-2.7})\,i$	4514^{+10}_{-39}
$\bar{D}^{*0}\Sigma_c^{*+}$-$D^{*-}\Sigma_c^{*++}$ ($\frac{3}{2}^-$)	$4523.8^{+0.5}_{-7.7}$	$4530.3^{+7.0}_{-4.6} - (1.9^{+10.2}_{-1.9})\,i$
$\bar{D}^*\Sigma_c^*$ ($\frac{5}{2}^-$)	4498^{+10}_{-17}	-

Four of them easily observable in $J/\psi p$, a fifth one ($\bar{D}^{*0}\Sigma_c^{*+}$-$D^{*-}\Sigma_c^{*++}$ ($J^P = \frac{3}{2}^-$)) contingent on isospin angle

$\Rightarrow$ **In general, more compatible with exp. "fit fractions"**

Also: the $P_{\psi}^{\Delta^-}$'s can decay into $\Lambda_c^+\pi^-D^-$: relation with the 2.35σ structure in the previous talk (G. Robertson)?

$P(4457)$ as P_ψ^Δ: mini-summary

Problem with the *production fractions* (or "fit fractions"):

- If $P_c(4457)$ is N-like, we should clearly see six peaks
- If $P_c(4457)$ is Δ-like, we should see four to five peaks

But, again, the degree of confidence is low:

- The two missing peaks could appear once we have more data
- There might be reasons why the production rates are very different for the missing pentaquarks

More data of the $J/\psi p$ spectrum will be needed.

Conclusions (list)

- How molecular is a state? Fundamentally, this is not observable, but:
  - Molecularness might make sense within a certain set of assumptions (e.g. lowest orders within a given EFT), but not always! (T_{cc} vs $P^{\Lambda}_{\psi s}(4338)$)
- Regarding the Λ-like pentaquarks:
  - $P^{\Lambda}_{\psi s}(4338)$, $P^{\Lambda}_{\psi s}(4449)$ are **easy to explain and relate** as baryon-meson **molecular candidates**
  - But nature of $P^{\Lambda}_{\psi s}(4338)$ still under debate
  - Predictions of a few partners, most notably $P^{\Lambda}_{\psi s}(4255)$
- Regarding the N- (or Δ-) like pentaquarks:
  - Three to four clear peaks in $J/\psi p$
  - Problem with the informal fit fractions for $P_c(4457)$
  - Both problems could be resolved by assuming $P_c(4457)$ to be a Δ-like (instead of N-like) pentaquark

Thanks For Your Attention!

Extra Slides

Isospin breaking: $P_{\psi s}^{\Lambda}$ or $P_{\psi s}^{\Sigma^0}$?

$P_{cs}(4338)$ close to $D^- \Xi_c^+$ and $\bar{D}^0 \Xi_c^0$ $\Rightarrow$ Isospin breaking

Potential in the $\bar{D}^0 \Xi_c^0$ and $D^- \Xi_c^+$ basis:

$$V_C(\bar{D}^0 \Xi_c^0 - D^- \Xi_c^+) = \begin{pmatrix} \frac{1}{2}(d_a + \tilde{d}_a) & -\frac{1}{2}(d_a - \tilde{d}_a) \\ -\frac{1}{2}(d_a - \tilde{d}_a) & \frac{1}{2}(d_a + \tilde{d}_a) \end{pmatrix},$$

Notice the dependence in $(d_a - \tilde{d}_a)$!

Ratio of the decay widths for a $P_{\psi s}$:

$$\frac{\Gamma(P_{\psi s} \to J/\psi \Lambda)}{\Gamma(P_{\psi s} \to J/\psi \Sigma^0)} = \frac{1}{3} \frac{p_\Lambda}{p_\Sigma} \left| \frac{\Psi_c(0) - \Psi_n(0)}{\Psi_c(0) + \Psi_n(0)} \right|^2,$$

For $P_{\psi s} = P_{\psi s}^{\Sigma^0}$ from $(0.5 - 5.0)\%$ $\Rightarrow$ small
(i.e. we probably observed a $P_{\psi s}^{\Lambda}$)

Isospin breaking: $P_{\psi s}^{\Lambda}$ or $P_{\psi s}^{\Sigma^0}$? Wigner symmetry scenario

But if $d_a \approx \tilde{d}_a \Rightarrow$ decoupling of $\bar{D}^0 \Xi_c^0$ and $D^- \Xi_c^+$ d.o.f.

$$V_C(\bar{D}^0\Xi_c^0 - D^-\Xi_c^+) = \begin{pmatrix} \frac{1}{2}(d_a + \tilde{d}_a) & -\frac{1}{2}(d_a - \tilde{d}_a) \\ -\frac{1}{2}(d_a - \tilde{d}_a) & \frac{1}{2}(d_a + \tilde{d}_a) \end{pmatrix} \approx \begin{pmatrix} d_a & 0 \\ 0 & d_a \end{pmatrix}$$

Reminiscent of Wigner SU(4) symmetry in NN!

Ratio of the decay widths for a $P_{\psi s}$ is now:

$$\frac{\Gamma(P_{\psi s} \to J/\psi \Lambda)}{\Gamma(P_{\psi s} \to J/\psi \Sigma^0)} = \frac{1}{3}\,\frac{p_\Lambda}{p_\Sigma} \left| \frac{\Psi_c(0) - \Psi_n(0)}{\Psi_c(0) + \Psi_n(0)} \right|^2 \approx \frac{1}{3}\,\frac{p_\Lambda}{p_\Sigma} = 0.53$$

If close to this scenario $\Rightarrow$ $P_{cs}(4338)$ might be either $P_{\psi s}^{\Lambda}$ or $P_{\psi s}^{\Sigma^0}$!

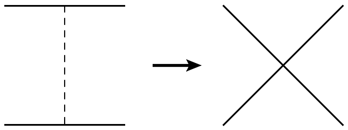
$P_{\psi s}^{\Lambda}$ as meson-baryon molecules: phenomenology

What about phenomenological models? Our model:

(i) Saturation model w/ scalar and vector meson exchanges.

(ii) Calibrate model to reproduce $P_{\psi}^{N}(4312)$

First piece, saturation:



The σ, ρ, ω contributions collapse into a contact

Reason: $\sqrt{2\mu B} \ll m_\rho, m_\omega, m_\sigma \Rightarrow$ can't resolve interaction details

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules: phenomenology

Saturation, how we do it:

(a) Scalar meson: the usual way

$$V_S = -\frac{g^2}{m_S^2 + \vec{q}^{\,2}} \Rightarrow C_S \propto -\frac{g^2}{m_S^2}$$

(b) Vector meson (isospin and G-parity factors implicit)

(b.1) Electric part: $C_V^{E0} \propto \frac{g_V^2}{m_V^2}$ (the usual way)

(b.2) Magnetic part (spin-spin implicit): we remove the Dirac-delta

$$V_V^{M1} = -\frac{f_V^2}{6M^2}\frac{\vec{q}^{\,2}}{m_V^2 + \vec{q}^{\,2}} = -\frac{f_V^2}{6M^2}\left[1 - \frac{m_V^2}{m_V^2 + \vec{q}^{\,2}}\right] \Rightarrow C_V^{M1} \propto \frac{f_V^2}{6M^2}$$

Reason: the Dirac-delta gives saturation at a shorter distance scale (hadron size instead of vector meson range)

$P_{\psi s}^{\Lambda}$ as meson-baryon molecules: phenomenology

Saturation, a few comments:

(i) Why a σ?: vector meson alone not always qualitatively correct
Example: the two-nucleon system

$$C_V^{E0}({}^1S_0) \propto +10\,\frac{g_v^2}{m_V^2} \quad , \quad C_V^{E0}({}^3S_1) \propto +6\,\frac{g_v^2}{m_V^2} \quad ,$$

ρ and ω imply both repulsive, but not what we observe in NN
Reminder: $\exists$ suspected molecular state in NN (the deuteron)

(ii) Combining mesons with different range: RG equation

$$\frac{d}{d\Lambda}\langle\Psi|V_C|\Psi\rangle = 0 \Rightarrow C^{\rm sat}(\Lambda \sim m_V) \propto (\frac{m_V}{m_S})^{\alpha}\, C_S(m_S) + C_V(m_V)$$

(iii) Regularize, determine proportionality constant from a given molecular candidate and then predict spectrum

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules: phenomenology

Results: $P^{N}_{\psi}(4312)$ as input, $\Lambda = 1\,\mathrm{GeV}$, Gaussian regulator

System	$I(J^P)$	B_{mol}	M_{mol}	Candidate	$M_{\mathrm{candidate}}$
$\Lambda_c\bar{D}$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	$(0.1)^V$	$(4153.4)^V$	-	-
$\Lambda_c\bar{D}^*$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	$(0.0)^V$	$(4295.0)^V$	-	-
$\Lambda_c\bar{D}_s$	0 $(\frac{1}{2}^-)$	2.4	4252.4	-	-
$\Lambda_c\bar{D}_s^*$	0 $(\frac{1}{2}^-)$	3.4	4395.2	-	-
$\Xi_c\bar{D}$	0 $(\frac{1}{2}^-)$	8.9	4327.4	$P^{\Lambda}_{\psi s}(4338)$	4338.2
$\Xi_c\bar{D}^*$	0 $(\frac{1}{2}^-)$	11.0	4466.7	$P^{\Lambda}_{\psi s}(4459)$	4458.9
$\Xi_c\bar{D}$	1 $(\frac{1}{2}^-)$	$(0.0)^V$	$(4336.3)^V$	-	-
$\Xi_c\bar{D}^*$	1 $(\frac{1}{2}^-)$	0.1	4477.6	-	-
$\Xi_c\bar{D}_s$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	1.2	4436.3	-	-
$\Xi_c\bar{D}_s^*$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	2.0	4579.2	-	-

$P^{\Lambda}_{\psi s}$ as meson-baryon molecules: EFT vs phenomenology

Comparison of RG-saturation with EFTs B_1 and B_2
Set B_1: $P_{cs}(4338)$ as input; Set B_2: $P_{cs}(4459)$ as input

System	RG-Saturation	Set B_1	Set B_2	Type
$\bar{D}\Lambda_c$	$(4153.4)^V$	$(4111.3)^V$	$(4153.7)^V$	P^N_{ψ}
$\bar{D}^*\Lambda_c$	$(4295.0)^V$	$(4256.7)^V$	4295.0	P^N_{ψ}
$\bar{D}_s\Lambda_c$	4252.4	4254.8	4230.5	$P^{\Lambda}_{\psi s}$
$\bar{D}_s^*\Lambda_c$	4395.2	4398.4	4375.2	$P^{\Lambda}_{\psi s}$
$\bar{D}\Xi_c$	4327.4	Input	4316.7	$P^{\Lambda}_{\psi s}$
$\bar{D}^*\Xi_c$	4466.7	4479.2	Input	$P^{\Lambda}_{\psi s}$
$\bar{D}\Xi_c$	$(4336.3)^V$	$(4297.4)^V$	4336.3	$P^{\Sigma}_{\psi s}$
$\bar{D}^*\Xi_c$	4477.6	$(4442.7)^V$	4477.5	$P^{\Sigma}_{\psi s}$
$\bar{D}_s\Xi_c$	4436.3	$(4401.4)^V$	4437.3	$P^{\Xi}_{\psi ss}$
$\bar{D}_s^*\Xi_c$	4579.2	$(4548.3)^V$	4580.9	$P^{\Xi}_{\psi ss}$