Molecular $P_{\psi s}^{\Lambda}$ Pentaquarks: EFT & Phenomenological Considerations

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Contents

- Exotic hadrons, including hadronic molecules
- Pentaquarks
  - Molecular interpretation
  - Relation between the $P^{\Lambda}_{\psi s}(4338)$ and $P^{\Lambda}_{\psi s}(4459)$ or, easier to pronounce: $P_{cs}(4338)$ and $P_{cs}(4459)$
  - EFT predictions & loose ends
  - Phenomenology
- Summary and Conclusions

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

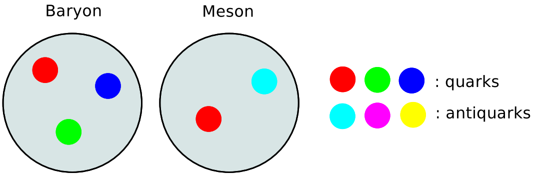
MJ Yan, FZ Peng, M Sánchez, MPV; EPJC 82 (2022) 6, 574

MJ Yan, FZ Peng, M Sánchez, MPV; arXiv:2207.11144

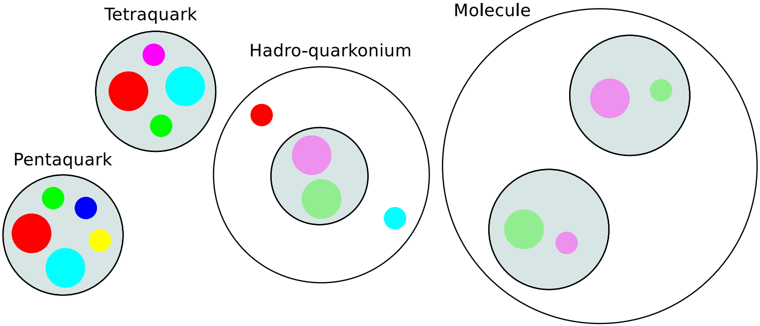
Exotic hadrons

Exotic hadrons

Standard hadrons come in two varieties

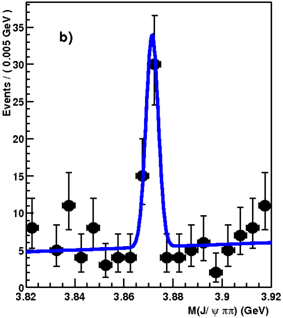


But there are more types of possible hadrons...



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: foxes and hedgehogs

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

- **Hedgehog**: knows one big idea (intellectual economy)
- **Fox**: knows many little ideas (intellectual scavenger)

Exotic hadrons

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

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

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

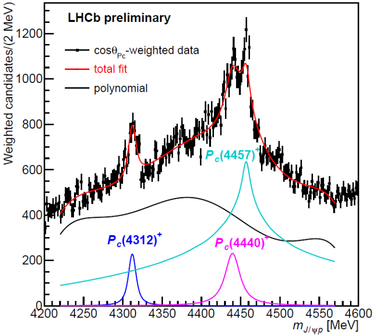
(iii) $X \to J/\psi\, 2\pi$ and $X \to J/\psi\, 3\pi$ pattern easier to explain in molecular picture Gamermann, Oset PRD 80 (2009) 014003
...but compact state can also have this branching ratio

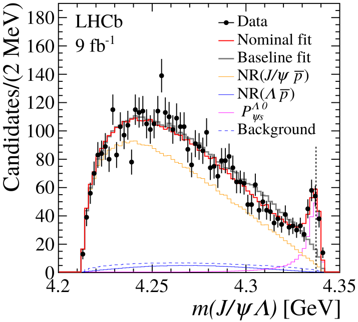
Swanson PLB 588 (2004) 189-195

Often forgotten fact:
the wave function is not an observable

Pentaquarks

Pentaquarks: the discoveries of the LHCb





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

Pentaquarks: a new era (again)

This is the dawn of a new era...

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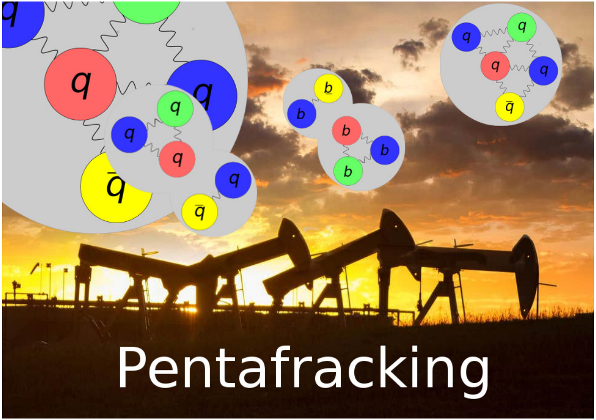
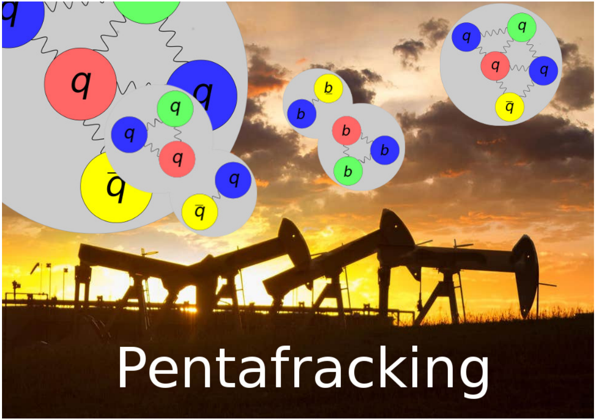


The ~~shale gas~~ shallow bound state revolution &
the second pentaquark party in 20 years!

Pentaquarks: a new era (again)

This is the dawn of a new era...



The ~~shale gas~~ shallow bound state revolution &
the second pentaquark party in 20 years!

But **never forget** the **massive hangover** after **the first party**

Pentaquarks: don't worry

Pentaquarks: don't worry

Unlike **regular fracking**, **pentafracking** is still legal in Europe ;)

Pentaquarks: current candidates

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

Candidate	Molecule	$I^G(J^{PC})$ / 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 (2022) 6, 574; Nakamura, Hosaka, Yamaguchi, PRD 104 (2021) 9

$P^{\Lambda}_{\psi s}$ 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 likely molecular explanations:

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

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: $B_1 = 16.9^{+2.9}_{-4.7}$ ($M_1 = 4319.4^{+4.7}_{-2.9}$)

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

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

Yet, there are more factors in play:

(iv) Breit-Wigner param not ideal for near-threshold poles: the $P_{\psi s}^{\Lambda}(4338)$ 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 $P_{\psi s}^{\Lambda}(4459)$ (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 $P_{\psi s}^{\Lambda}(4459)$ might be two peaks

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

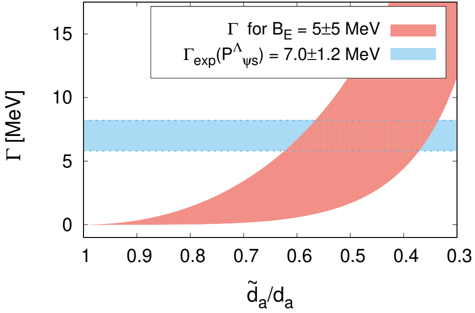
(vii) The $P_{\psi s}^{\Lambda}(4338)$ might be the $P_{\psi s}^{\Sigma}(4338)$

$P^{\Lambda}_{\psi s}$ 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)

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

Predictions for the spectrum (from mass and width):

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

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

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

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

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

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

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

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

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

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

- (ii.a) Burns & Swanson: $P_{\psi s}^{\Lambda}(4338)$ triangle singularity, no trace of a $P_{\psi s}^{\Lambda}(4255)$
  d_a coupling still attractive
- (ii.b) Nakamura & Wu: $P_{\psi s}^{\Lambda}(4255)$ virtual
  Possible from small changes in our couplings

Both are possible solutions.

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

And do not forget the Breit-Wigner issue!

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

What about phenomenological models?

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

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

System	$I(J^P)$	$R_{\rm mol}$	$B_{\rm mol}$	$M_{\rm mol}$	Candidate	$M_{\rm candidate}$
$\Lambda_c \bar{D}$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.69	$(0.1)^V$	4153.4		
$\Lambda_c \bar{D}^*$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.72	$(0.0)^V$	4295.0		
$\Lambda_c \bar{D}_s$	0 $(\frac{1}{2}^-)$	0.86	2.4	4252.4		
$\Lambda_c \bar{D}_s^*$	0 $(\frac{1}{2}^-)$	0.89	3.4	4395.2		
$\Xi_c \bar{D}$	0 $(\frac{1}{2}^-)$	1.00	8.9	4327.4	$P^{\Lambda}_{\psi s}(4338)$	4338.2
$\Xi_c \bar{D}^*$	0 $(\frac{1}{2}^-)$	1.04	11.0	4466.7	$P^{\Lambda}_{\psi s}(4459)$	4458.9
$\Xi_c \bar{D}$	1 $(\frac{1}{2}^-)$	0.72	$(0.0)^V$	4336.3		
$\Xi_c \bar{D}^*$	1 $(\frac{1}{2}^-)$	0.74	0.1	4477.6		
$\Xi_c \bar{D}_s$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.82	1.2	4436.3		
$\Xi_c \bar{D}_s^*$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.85	2.0	4579.2		

Conclusions (list)

- $P^{\Lambda}_{\psi s}(4338)$, $P^{\Lambda}_{\psi s}(4449)$ are **easy to explain and relate** as baryon-meson **molecular candidates**
- But nature of $P^{\Lambda}_{\psi s}(4338)$ obviously still under debate:
  it was discovered four months ago...
  meson-baryon state, triangle singularity, compact pentaquark?
- Predictions of a few partners, most notably $P^{\Lambda}_{\psi s}(4255)$
  - Not found in experiment, but there are constraints
  - Found in one analysis of $J/\psi\Lambda$ (Nakamura & Wu)
  - Not found in other analysis of $J/\psi\Lambda$ (Burns & Swanson)
  - If it exists & is molecular: should be really narrow!
  - Phenomenological model also predicts it.

The End

Thanks For Your Attention!