Exotic hadrons (or not) at LHCb

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[T.B., Eur.Phys.J. A51, 152 (2015), 1509.02460]
[T.B. & E.Swanson, Phys.Lett.B. ..., 1603.04366]

Conventional & exotic hadrons

Conventional hadrons in the constituent quark model

Mesons $q\bar{q}$ and baryons qqq are classified according to

- J^P (or J^{PC} for neutral-flavoured mesons).
- I for those with u, d quarks.

Strong interactions conserve $J^{P(C)}$ and I.

Non-relativistic decomposition $\vec{J} = \vec{S} + \vec{L}$ where

- S is the coupling of intrinsic quark spins (0 or 1 for mesons, 1/2 or 3/2 for baryons)
- L is the orbital angular momentum (each unit of L flips parity)

Masses (and relations among masses) are consistent with potential models “inspired by” QCD (one-gluon exchange, flux tube model).

Beyond this simple picture

Gluonic degrees of freedom

- Hybrid mesons with excited flux tubes, exotic J^{PC}
- decay selection rules [T.B., PRD74, 034003 (2006)]

The coupling $Q\bar{Q} \to (Q\bar{q})(q\bar{Q})$ and "unquenched" quark models

- model-independent coupling parametrised by angular momentum coefficients [T.B., PRD90,034009(2014)]
- coupling causes mass shifts and spin-dependent splittings, so why does the conventional (quenched) quark model work? [T.B., 1411.2485]

This talk:

- "molecular" states (hadronic constituents)
- cusps/threshold effects (hadronic constituents)
- compact multiquarks (quark or diquark constituents)

Molecules

Hadrons interact (eg exchanging pions or quarks), and attractive interactions can give bound states (c.f. the deuteron). Weak binding implies

- masses are tied to thresholds
- expect S-wave only
- extended wavefunctions of colour singlet hadrons

Dominant interactions are π exchange, which restricts possibilities:

- conservation of $\mathrm{I}(\mathrm{J}^{\mathrm{P}})$ at π vertex limits constituents.
- not all channels are attractive. E.g. for NN the $\mathrm{I}(\mathrm{J}^{\mathrm{P}})$ combinations $0(0^+)$, $0(1^+)$, $1(0^+)$, $1(1^+)$ are possible, but only $0(1^+)$ is bound.

Molecules

Heavy hadronic molecules were predicted years ago.

[Tornqvist Z.Phys.C61,525(1994)]

Since π has $\mathrm{I}(\mathrm{J}^{\mathrm{P}}) = 1(0^-)$,

- both constituents must have isospin, since $0 \not\to 1 \times 0$
- no molecules with only 0^- constituents, since $0^- \not\to 0^- \times 0^-$

This rules out molecules of $\mathrm{D}_s^{(*)}\bar{\mathrm{D}}^{(*)}$, $\mathrm{D}_s^{(*)}\bar{\mathrm{D}}_s^{(*)}$, and $\mathrm{D}\bar{\mathrm{D}}$.

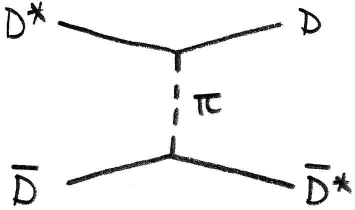
For $\mathrm{D}^*\bar{\mathrm{D}} \oplus \mathrm{D}\bar{\mathrm{D}}^*$ there are four $\mathrm{I}(\mathrm{J}^{\mathrm{P}})$ channels...

$0(1^{++})$

$0(1^{+-})$

$1(1^{++})$

$1(1^{+-})$



...but one is uniquely attractive

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$0(1^{+-})$
$1(1^{++})$
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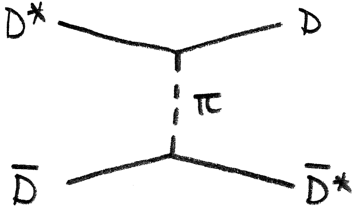
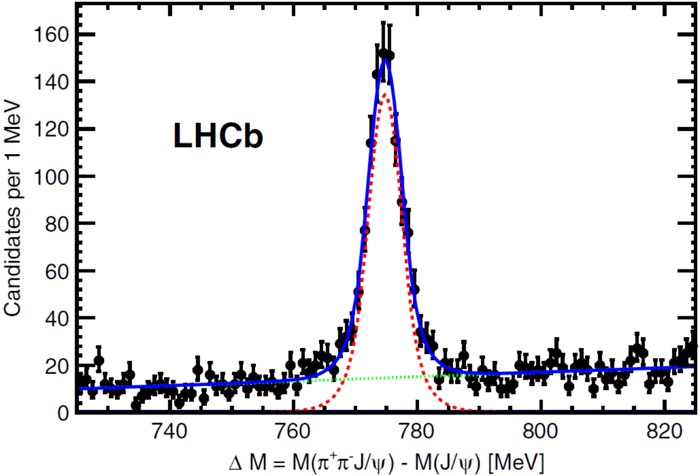


...but one is uniquely attractive

Molecules: X(3872)



[LHCb,PRD92,011102(2015)]

$$Mass = 3871.69 \pm 0.17\ MeV$$

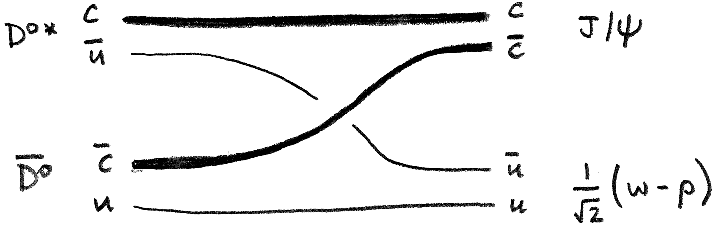
$$\mathrm{D^{0*}\bar{D}^0\ threshold} = 3871.81 \pm 0.13\ MeV$$

Molecules: X(3872)

The charged channel is also nearby

$$
\begin{aligned}
\mathit{Mass} &= 3871.69 \pm 0.17\ \mathit{MeV} \\
\mathrm{D}^{0*}\bar{\mathrm{D}}^{0}\ \text{threshold} &= 3871.81 \pm 0.13\ \mathit{MeV} \\
\mathrm{D}^{+*}\bar{\mathrm{D}}^{-}\ \text{threshold} &= 3879.88 \pm 0.14\ \mathit{MeV}
\end{aligned}
$$

but due to the mass gap the wavefunction is dominated by the neutral pair, so the state has mixed isospin.



Coupling via quark exchange to nearby $J/\psi\rho$ and $J/\psi\omega$ thresholds gives additional attraction [Swanson PLB288, 189 (2004)]

Compact multiquarks

Tetraquarks $qq\bar{q}\bar{q}$ or pentaquarks $qqqq\bar{q}$ with quark (or diquark) constituents, non-trivial spatial and colour wavefunctions. S-wave mass formula:

$$H = \sum_k m_k + \sum_{ij} \alpha_{ij} \vec{S}_i \cdot \vec{S}_j$$

For $qq\bar{q}\bar{q}$:

- Full model: bases $\begin{pmatrix} |(q\bar{q})_1(q\bar{q})_1\rangle \\ |(q\bar{q})_8(q\bar{q})_8\rangle \end{pmatrix}$ or $\begin{pmatrix} |(qq)_{\bar{3}}(\bar{q}\bar{q})_3\rangle \\ |(qq)_6(\bar{q}\bar{q})_{\bar{6}}\rangle \end{pmatrix}$.
- "Diquark" models: truncated basis $|(qq)_{\bar{3}}(\bar{q}\bar{q})_3\rangle$.

[Maiani et al.,PRD71,014028(2005)]

Generically:

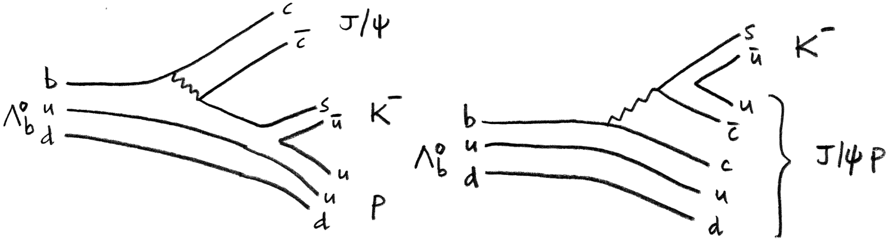
- There is a proliferation of states
- Masses are not tied to thresholds.

$P_c(4380)$ and $P_c(4450)$

[T.B., Eur.Phys.J. A51, 152 (2015), 1509.02460]

$P_c(4380)$ and $P_c(4450)$

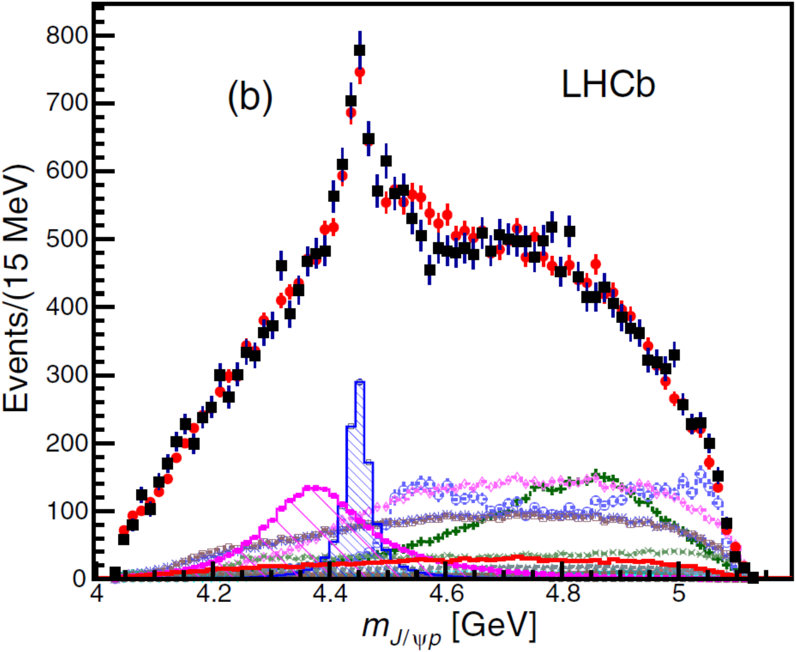
LHCb amplitude analysis of the three-body decay $\Lambda_b \to J/\psi p K^-$, studying the pK^- and exotic $J/\psi p$ mass spectra.



A state in $J/\psi p$ is a "pentaquark" with flavour $uudc\bar{c}$.

[LHCb,PRL115,072001,2015]

$P_c(4380)$ and $P_c(4450)$



$P_c(4380)$ and $P_c(4450)$

	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width	$205 \pm 18 \pm 86$	$35 \pm 5 \pm 19$
Assignment 1	$3/2^-$	$5/2^+$
Assignment 2	$3/2^+$	$5/2^-$
Assignment 3	$5/2^+$	$3/2^-$

The $J/\psi p$ combination has $I = 1/2$ and (in S-wave) $1/2^-$ or $3/2^-$.

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$\Sigma_c^{*+}\bar{D}^0$	$(udc)(u\bar{c})$	4382.3 ± 2.4	

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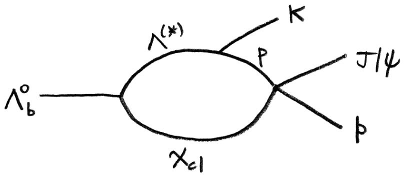
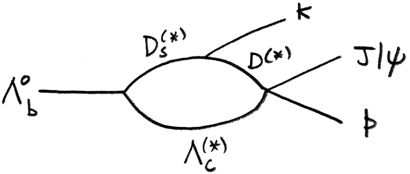
$\Sigma_c^+\bar{D}^{*0}$	$(udc)(u\bar{c})$		4459.9 ± 0.5
$\Lambda_c^{*+}\bar{D}^0$	$(udc)(u\bar{c})$		4457.09 ± 0.35
$\chi_{c1}p$	$(udu)(c\bar{c})$		4448.93 ± 0.07

The $J/\psi p$ combination has $I = 1/2$ and (in S-wave) $1/2^-$ or $3/2^-$.

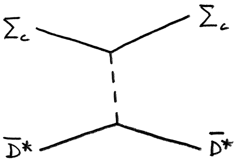
$P_c(4380)$ and $P_c(4450)$: some possibilities

Cusps:
[Guo et al.]
[Liu et al.]
[Mikhasenko]





Molecules
[Karliner & Rosner]
[Yang et al.]
[He]



Compact pentaquarks [Maiani et al.,Lebed]

$P_c(4380)$ and $P_c(4450)$: partner states

$\chi_{c1}p$ scenario:

- neutral $\chi_{c1}n$ partner heavier by ≈ 1.29 MeV
- $1/2^-$, $3/2^-$ and $5/2^-$ partners (P-wave is required)

$\Lambda_c^{+*}\bar{D}^0$ scenario:

- neutral $\Lambda_c^{+*}D^-$ partner heavier by ≈ 4.77 MeV
- other J^P partners

$\Sigma_c^{(*)}\bar{D}^{(*)}$ scenario:

- neutral $I = 1/2$ partner
- possible $I = 3/2$ partners including doubly-charged, decaying into $J/\psi\Delta$
- possible J^P partners

Compact pentaquark scenario:

- many partners with different flavours and J^P

$P_c(4450)$ as a $\Sigma_c \bar{D}^*$ molecule

No π exchange for $\chi_{c1} p$ (isospin), $\Lambda_c^* \bar{D}$ (isospin) or $\Sigma_c^{(*)} \bar{D}$ (J^P).

The remaining π exchange potentials have relative weights:

$\Sigma_c \bar{D}^*$		$\Sigma_c^* \bar{D}^*$	
$1/2(1/2^-)$	$+8$	$1/2(1/2^-)$	$+10$
$1/2(3/2^-)$	-4	$1/2(3/2^-)$	$+4$
		$1/2(5/2^-)$	-6
$3/2(1/2^-)$	-4	$3/2(1/2^-)$	-5
$3/2(3/2^-)$	$+2$	$3/2(3/2^-)$	-2
		$3/2(5/2^-)$	$+3$

5 out of 10 channels are repulsive.

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$3/2(1/2^-)$	-4	$3/2(1/2^-)$	-5
$3/2(3/2^-)$	$+2$	$3/2(3/2^-)$	-2
		$3/2(5/2^-)$	$+3$

For $J/\psi p$ only $I = 1/2$ is possible...

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... and $5/2^-$ is D-wave.

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The remaining channel is one of the possibilities at LHCb.

$P_c(4450)$ as a $\Sigma_c \bar{D}^*$ molecule

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		$3/2(5/2^-)$	$+3$

If $P_c(4450)$ is $1/2(3/2^-)$, it has a degenerate $3/2(1/2^-)$ partner.

Isospin violation in the $\Sigma_c^{(*)}\bar{D}^{(*)}$ scenario

The $uudc\bar{c}$ combination is $\begin{cases} (udc)(u\bar{c}) = \Sigma_c^{(*)+}\bar{D}^{(*)0} \\ (uuc)(d\bar{c}) = \Sigma_c^{(*)++}D^{(*)-} \end{cases}$

Isospin-conserving interactions would produce $|I, I_3\rangle$ eigenstates,

$$\begin{pmatrix} |\frac{1}{2},\frac{1}{2}\rangle \\ |\frac{3}{2},\frac{1}{2}\rangle \end{pmatrix} = \begin{pmatrix} -\sqrt{\frac{1}{3}} & \sqrt{\frac{2}{3}} \\ \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} \end{pmatrix} \begin{pmatrix} |\Sigma_c^+\bar{D}^0\rangle \\ |\Sigma_c^{++}D^-\rangle \end{pmatrix}$$

but isospin is broken by the threshold masses:

$$\begin{aligned} P_c(4380) &= 4380 \pm 8 \pm 29 & P_c(4450) &= 4449 \pm 1.7 \pm 2.5 \\ \Sigma_c^{*+}\bar{D}^0 &= 4382.3 \pm 2.4 & \Sigma_c^{+}\bar{D}^{*0} &= 4459.9 \pm 0.5 \\ \Sigma_c^{*++}D^- &= 4387.5 \pm 0.7 & \Sigma_c^{++}D^{*-} &= 4464.24 \pm 0.23 \end{aligned}$$

The $\Sigma_c^{(*)+}\bar{D}^{(*)0}$ components are enhanced and the physical states are admixtures of $|\frac{1}{2},\frac{1}{2}\rangle$ and $|\frac{3}{2},\frac{1}{2}\rangle$.

Isospin violation in the $\Sigma_c^{(*)}\bar{D}^{(*)}$ scenario

Decays by quark-rearrangement are related.

In the $\Sigma_c^{(*)}\bar{D}^{(*)}$ scenario with mixing angle

$$|P_c\rangle = \cos\phi|\tfrac{1}{2},\tfrac{1}{2}\rangle + \sin\phi|\tfrac{3}{2},\tfrac{1}{2}\rangle$$

and assuming the most natural assignment:

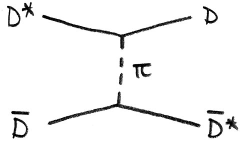
$$J/\psi N : J/\psi\Delta : \eta_c\Delta = 2\cos^2\phi : 5\sin^2\phi : 3\sin^2\phi \qquad [P_c(4380)]$$
$$J/\psi N : J/\psi\Delta : \eta_c\Delta = \cos^2\phi : 10\sin^2\phi : 6\sin^2\phi \qquad [P_c(4450)]$$

The Δ^+ modes could be inferred from the ratio of $p\pi^0$ to $n\pi^+$.

There are further relations and selection rules for other scenarios.

$P_c(4450)$: parallels with $X(3872)$

$X(3872)$

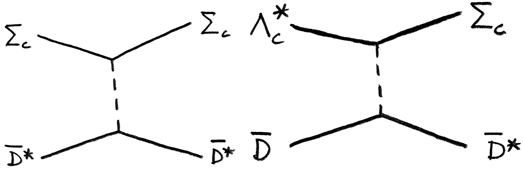


$\bar{D}^{*0} - \bar{D}^0 = 142.1$

Nearby $J/\psi\rho$ & $J/\psi\omega$

Isospin violation

$P_c(4450)$



$\Lambda_c^{*+} - \Sigma_c^+ = 139.4$

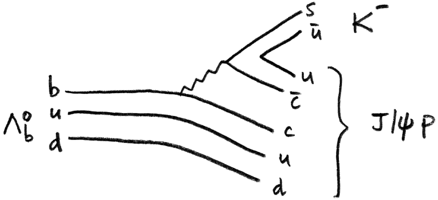
Nearby $\chi_{c1}p$

Isospin violation?

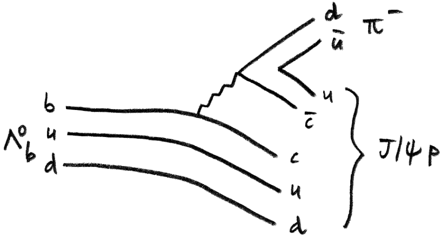
Enhanced binding (S-wave vertex)?

P_c states in the Cabibbo-suppressed mode

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



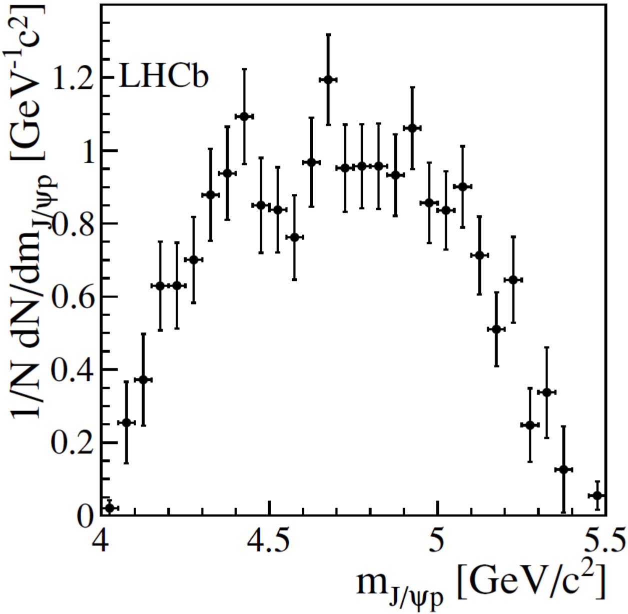
$\Lambda_b \to J/\psi p \pi^-$



Before P_c discovery LHCb had previously observed $\Lambda_b \to J/\psi p \pi^-$, and reported no sign of a $J/\psi p$ structure.

[LHCb, JHEP07(2014)103]

P_c states in the Cabibbo-suppressed mode



X(5568)

[T.B. & E.Swanson, Phys.Lett.B. ..., 1603.04366]

X(5568): discovery at DØ

In $p\bar{p}$ collisions DØ discovers $B_s\pi^+$ state,

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ MeV$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ MeV$$

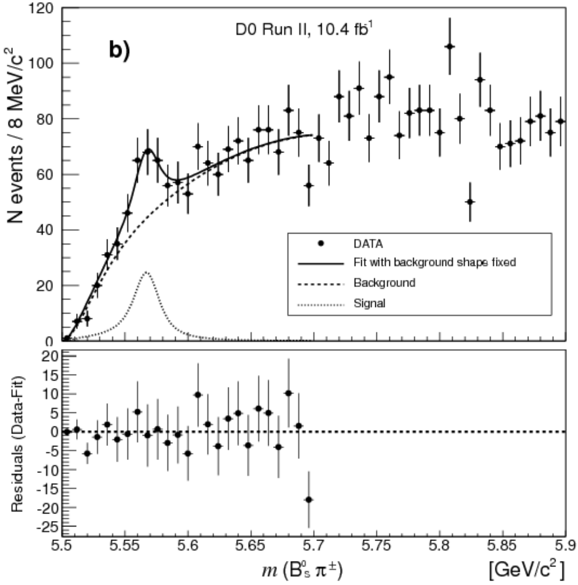
With $B_s = s\bar{b}(0^-)$ and $\pi^+ = u\bar{d}(0^-)$,

- Quark content $su\bar{b}\bar{d}$, with no "hidden" flavour
- $I = 1$
- $J^P = 0^+$ (or $1^-, 2^+, \ldots$)

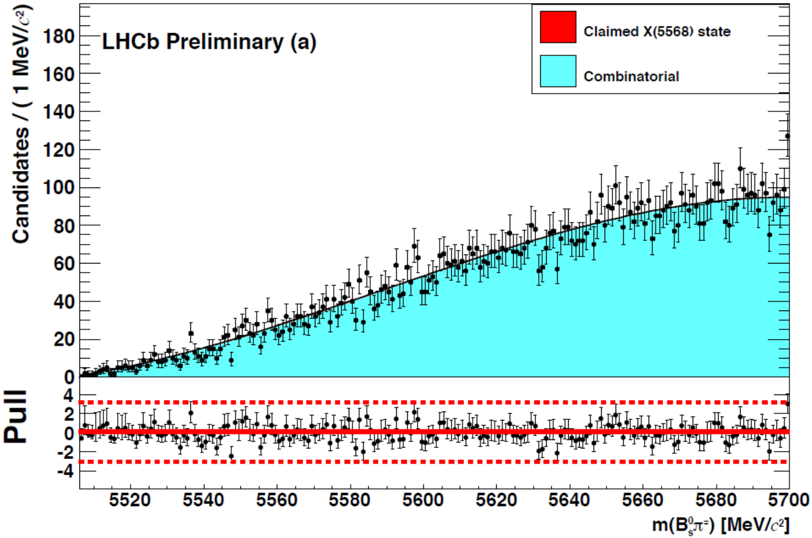
(Another possibility is $B_s^*\pi^+$ with a hidden $B_s^* \to B_s\gamma$).

[1602.07588]

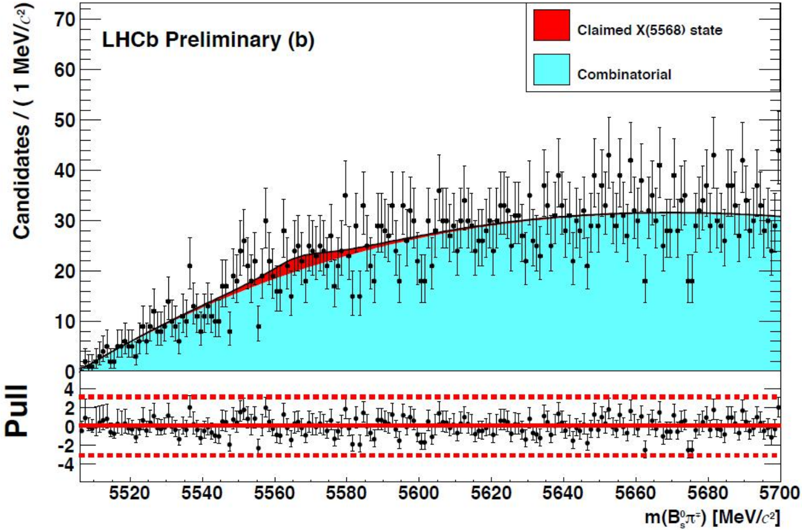
X(5568): discovery at DØ



X(5568): non-observation at LHCb ($p_T > 5$ GeV)



X(5568): non-observation at LHCb ($p_T > 10$ GeV)



DØ fraction of B_s from $X(5568) \to B_s\pi$ around 9%; at LHCb the upper limit is around 10× smaller. [LHCb-CONF-2016-004]

X(5568): the possibilities

The $su\bar{b}\bar{d}$ thresholds $(s\bar{b})(u\bar{d})$ and $(u\bar{b})(s\bar{d})$ are

$$
\begin{aligned}
B_s\pi &= 5507\ MeV \\
B_s^*\pi &= 5554\ MeV \\
B\bar{K} &= 5774\ MeV
\end{aligned}
$$

We looked at weak coupling scenarios

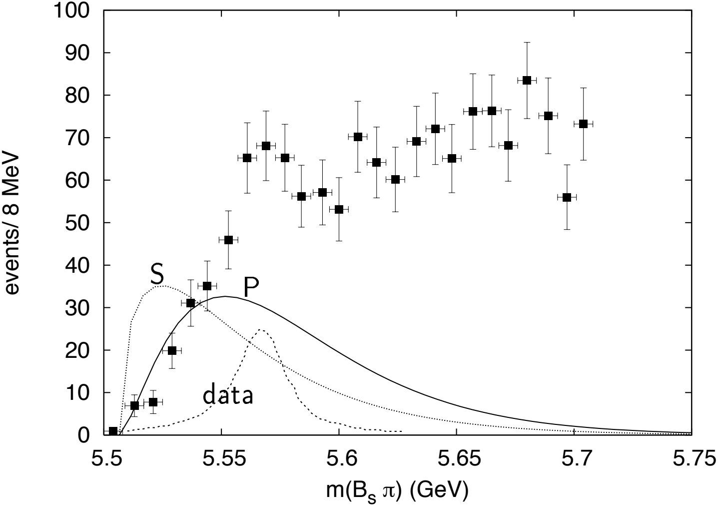
- threshold enhancement (opening of $B_s\pi$)
- cusp (due to $B_s^*\pi \to B_s\pi$)
- hadronic molecule ($B_s\pi - B\bar{K}$)

and the strong coupling scenario

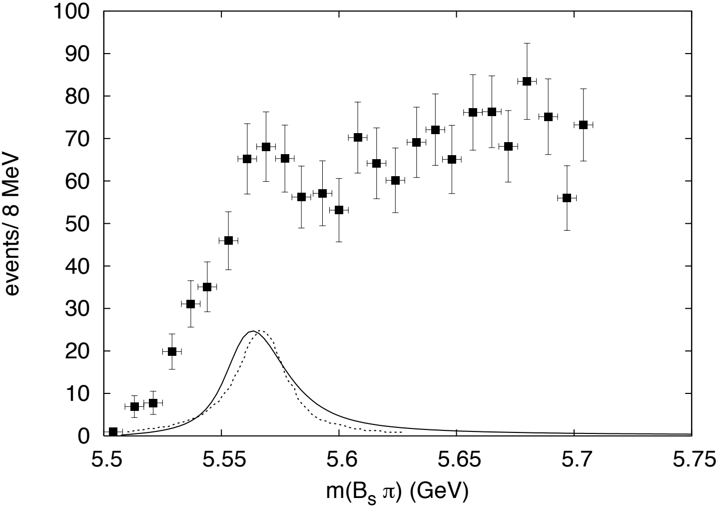
- "compact" tetraquark $su\bar{b}\bar{d}$

Nothing works.

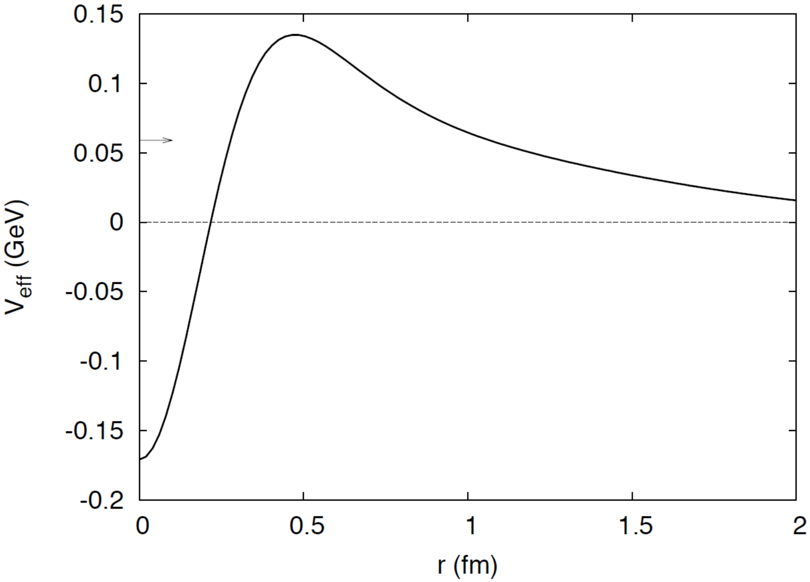
X(5568) as a $B_s\pi$ threshold enhancement



X(5568) as a $B_s^*\pi \to B_s\pi$ cusp



X(5568) as a $B_s\pi - B\bar{K}$ molecule



Shape of V_{eff} is right, but there is no resonance.

X(5568) as a tetraquark: mass

Very quickly several authors claimed to explain X(5568) as an $su\bar{b}\bar{d}$ tetraquark using constituent quark models.

But its mass is too low:

- Compare to sub baryons $\Xi_b = 5794 MeV$, $\Xi_b^* = 5945 MeV$.
- It is around $B_s^{(*)}\pi$ threshold, but π is anomalously light in the constituent quark picture.
- Estimating the sums of constituent quark masses:

$$
\begin{aligned}
(u\bar{b})(s\bar{d}): \quad & \frac{1}{4}\left(3B^* + B + 3K^* + K\right) = 6107 MeV \\
(s\bar{b})(u\bar{d}): \quad & \frac{1}{4}\left(3B_s^* + B_s + 3\rho + \pi\right) = 6019 MeV
\end{aligned}
$$

So how did they get the mass right?

$X(5568)$ as a tetraquark: neutral partners

Whereas for the cusp there is one neutral partner, for the tetraquark there are two.
If isospin is good, the partners of $|I, I_3\rangle = |1, +1\rangle = |su\bar{b}\bar{d}\rangle$ are

$$\begin{pmatrix} |1,0\rangle \\ |0,0\rangle \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} |su\bar{b}\bar{u}\rangle \\ |sd\bar{b}\bar{d}\rangle \end{pmatrix}$$

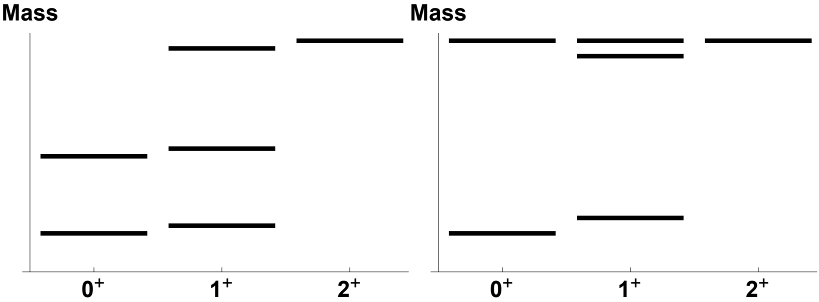
- $|1,0\rangle$ peak in $B_s\pi^0$, degenerate with $X(5568)$ (c.f. cusp, lower)
- $|0,0\rangle$ state has no open channels! ($B_s\eta$, $B\bar{K}$ are much higher)

For mixed isospin,

- masses split either side of $X(5568)$
- both decay into $B_s\pi^0$ via $|1,0\rangle$ component
- two $B_s\pi^0$ peaks, either side of $X(5568)$, and narrower

$X(5568)$ as a tetraquark: other partners

Discovery of partners can discriminate models:



Pair interactions among $su\bar{b}\bar{d}$ (dominated by $su\bar{d}$ spin)

Only su and $\bar{b}\bar{d}$ interactions

In both models the lightest states are a $0^+/1^+$ doublet, so if $X(5568)$ is one of these, it must have a nearly degenerate partner.

X(5568) as a tetraquark: other partners

The proliferation of partner states in tetraquark models cannot be "explained away".

If $X(5568) \to B_s\pi$ is the lightest $I(J^P) = 1(0^+)$ state,

- Doublet partner $1(1^+) \to B_s^*\pi$ with less phase space. Narrow.
- Doublet $0(0^+)$ and $0(1^+)$ have no strong decays. Narrow.
- Higher $0(0^+)$, $0(1^+)$ and $0(2^+)$ likely below $B^{(*)}\bar{K}^{(*)}$. Narrow.
- $1(2^+) \to B_s^{(*)}\pi$ in D-wave and HQ spin violation. Narrow.

... and in more general models there are twice as many states.

Conclusions

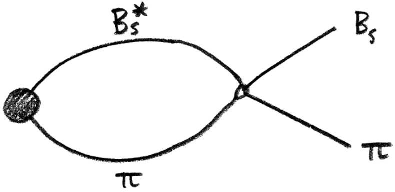
- Meson-baryon degrees of freedom seem to be relevant for the $\mathrm{P_c}$ states, and their roles can be inferred from missing partners and strong decays.
- The $\mathrm{P_c}(4450)$ emerges naturally as a $\Sigma_c \bar{D}^*$ state due to π exchange, which also implies a degenerate partner.
- There are other intriguing parallels between $\mathrm{P_c}(4450)$ and $\mathrm{X}(3872)$, including the signature of isospin violation.
- Models cannot easily accommodate $X(5568)$, and it very likely does not exist.
- Models based on interacting hadronic constituents are better constrained and do not suffer the proliferation of partners expected for compact multiquarks.

Backup slides

	P_c^*				P_c	
	$\chi_{c1}p$	$\Sigma_c\bar{D}^*$	$\Lambda_c^*\bar{D}$	$J/\psi N^*$	$\Sigma_c^*\bar{D}$	$J/\psi N^*$
$J/\psi N$	✓	✓	✓	✓	✓	✓
$\eta_c N$	×	×	✓	×	×	×
$J/\psi\Delta$	×	✓	×	×	✓	×
$\eta_c\Delta$	×	✓	×	×	✓	×
$\Lambda_c\bar{D}$	✓	[×]	[✓]	×	[×]	×
$\Lambda_c\bar{D}^*$	✓	✓	[✓]	✓	✓	✓
$\Sigma_c\bar{D}$	✓	[×]	✓	×	[×]	×
$\Sigma_c^*\bar{D}$	✓	✓	[×]	✓		
$J/\psi N\pi$	×	✓	×	✓	✓	✓
$\Lambda_c\bar{D}\pi$	×	×	×	×	✓	×
$\Lambda_c\bar{D}^*\pi$	×	✓	×	×		
$\Sigma_c^+\bar{D}^0\pi^0$	×	✓	✓	×		

X(5568) as a cusp

Since X(5568) is near $B_s^*\pi$ threshold (5554 MeV), could it be a cusp due to $B_s^*\pi \to B_s\pi$ rescattering?
Consider generic process (invariant mass $\sqrt{s}$) producing $B_s^*\pi$ loop.



Non-relativistic model with contact interactions:

$$\Pi(s) = \int \frac{d^3q}{(2\pi)^3} \frac{q^{2L} e^{-2q^2/\beta^2}}{\sqrt{s} - M_{B_s^*} - M_\pi - q^2/(2\mu) + i\epsilon}$$

and require $L = 1$.

X(5568) as a cusp

Problems:

- Requires $\beta = 50$ MeV, an order of magnitude too small.
- P-wave scattering is typically weak.
- Low energy hadron scattering entails flavour exchange, but no such diagram is possible.

Consequences:

- X(5568) is a 1^- state.
- A peak in $B_s^*\pi^+ \to B_s\pi^+$ implies a peak in $B_s^*\pi^0 \to B_s\pi^0$, so X(5568) has a neutral partner around 5 MeV lighter.
- Analogous state(s) at 5909 MeV due to $B_s^*\bar{K} \to B_s\bar{K}$.

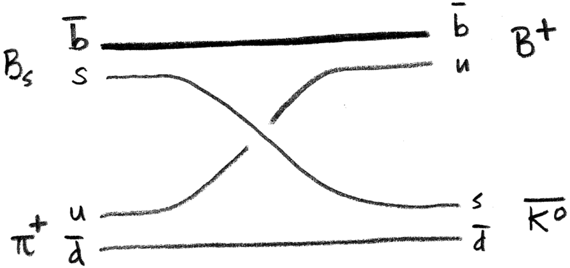
X(5568) as a hadronic molecule

The thresholds are all wrong. . .

$$B_s\pi = 5507 \text{ MeV}, \qquad B_s^*\pi = 5554 \text{ MeV}, \qquad B\bar{K} = 5774 \text{ MeV}$$

. . . and there is no π exchange.

An alternative: a coupled-channel $B_s\pi - B\bar{K}$ system?



- Quark-level interactions and quark exchange
- No elastic scattering
- $T(B_s\pi \to B\bar{K})$ gives $V(B_s\pi \to B\bar{K})$

Conventional hadrons in the constituent quark model

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$
$1\,^3D_2$	2^{--}		$K_2(1820)$		
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$
$1\,^3G_5$	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$		
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$

Conventional hadrons in the constituent quark model

$n\,^{2s+1}\ell_J$	J^{PC}	I = 0 $c\bar{c}$	I = 0 $b\bar{b}$	I = $\frac{1}{2}$ $c\bar{u}$, $c\bar{d}$; $\bar{c}u$, $\bar{c}d$	I = 0 $c\bar{s}$; $\bar{c}s$	I = $\frac{1}{2}$ $b\bar{u}$, $b\bar{d}$; $\bar{b}u$, $\bar{b}d$	I = 0 $b\bar{s}$; $\bar{b}s$	I = 0 $b\bar{c}$; $\bar{b}c$
$1\,^1S_0$	0^{-+}	$\eta_c(1S)$	$\eta_b(1S)$	D	$D_s^{\pm}$	B	B_s^0	$B_c^{\pm}$
$1\,^3S_1$	1^{--}	$J/\psi(1S)$	$\Upsilon(1S)$	D^*	$D_s^{*\pm}$	B^*	B_s^*	
$1\,^1P_1$	1^{+-}	$h_c(1P)$	$h_b(1P)$	$D_1(2420)$	$D_{s1}(2536)^{\pm}$	$B_1(5721)$	$B_{s1}(5830)^0$	
$1\,^3P_0$	0^{++}	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$			
$1\,^3P_1$	1^{++}	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$			
$1\,^3P_2$	2^{++}	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$D_2^*(2460)$	$D_{s2}^*(2573)^{\pm}$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$	
$1\,^3D_1$	1^{--}	$\psi(3770)$			$D_{s1}^*(2860)^{\pm\ddagger}$			
$1\,^3D_3$	3^{--}				$D_{s3}^*(2860)^{\pm}$			
$2\,^1S_0$	0^{-+}	$\eta_c(2S)$	$\eta_b(2S)$	$D(2550)$				
$2\,^3S_1$	1^{--}	$\psi(2S)$	$\Upsilon(2S)$		$D_{s1}^*(2700)^{\pm\ddagger}$			
$2\,^1P_1$	1^{+-}		$h_b(2P)$					
$2\,^3P_{0,1,2}$	$0^{++}, 1^{++}, 2^{++}$	$\chi_{c0,2}(2P)$	$\chi_{b0,1,2}(2P)$					
$3\,^3P_{0,1,2}$	$0^{++}, 1^{++}, 2^{++}$		$\chi_b(3P)$					

Chromomagnetism

A common potential for mesons and baryons

$$H = \sum_i \left(m_i + \frac{p_i^2}{2m_i} \right) + \sum_{ij} \left(V(r_{ij}) - \frac{C}{m_i m_j} \delta^3(\vec{r}_{ij}) \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{S}_i \cdot \vec{S}_j \right) + \ldots$$

[De Rujula, Georgi and Glashow PRD12, 147 (1975)]

$$\begin{aligned} q\bar{q}: \qquad & 3 \times \bar{3} = 1 + 8 \\ qqq: \qquad & 3 \times 3 \times 3 = 3 \times (\bar{3} + 6) \\ & = 3 \times \bar{3} + 3 \times 6 \\ & = 1 + 8 + \ldots \end{aligned}$$

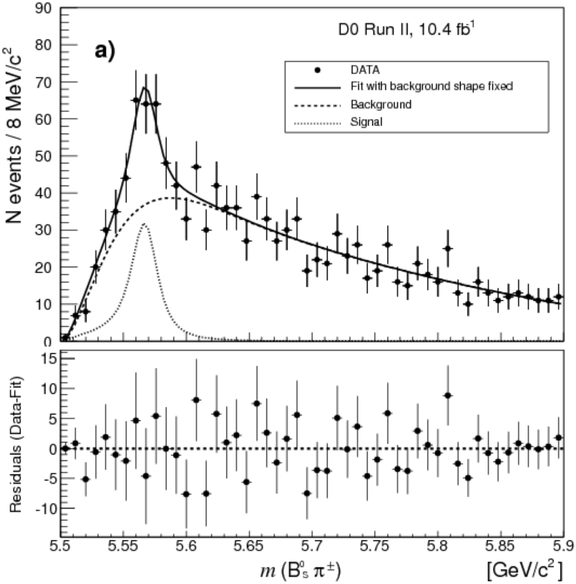
Any qq pair in a baryon is in colour $\bar{3}$, and

$$\langle \vec{\lambda}_q \cdot \vec{\lambda}_{\bar{q}} \rangle_1 = 2 \langle \vec{\lambda}_q \cdot \vec{\lambda}_q \rangle_{\bar{3}}$$

It works.

X(5568): discovery at DØ

Data after applying a "cone cut":



X(5568) as a tetraquark: mass

Several authors found masses (almost) in agreement with experiment. How?

- Liu *et al.* [1603.011310] take s, u, $\bar{d}$ from crude fit to $D_{sJ}(2632)$, and $\bar{b}$ from...? The masses fail badly for conventionals e.g. 5390 MeV for sub baryons (cf. $\Xi_b = 5794$ MeV, $\Xi_b^* = 5945$ MeV)
- Wang and Zhu [1602.08806] get the diquark masses from $a_0(980)$ as an S-wave $(us)(\bar{u}\bar{s})$ and $\Upsilon(10890)$ as a P-wave (!) $(bd)(\bar{b}\bar{d})$.
- Stancu [1603.03322] fits hyperfine term to the $\rho - \pi$ mass difference.

X(5568) as a tetraquark: other partners

For each flavour and colour, the $qq\bar{q}\bar{q}$ configuration in S-wave has

- two scalars (0^+)
- three axials (1^+)
- one tensor (2^+)

Splittings are controlled by the hyperfine term in

$$H = \sum_k m_k + \sum_{ij} \alpha_{ij} \vec{S}_i \cdot \vec{S}_j$$

For simplicity consider truncated diquark model, with interactions

- between all pair-wise constituents (Type I)
- only within diquarks (Type II)

X(5568) as a tetraquark: other partners (Type I)

Hyperfine terms involving heavy quarks Q vanish as $m_Q \to \infty$. In the heavy quark limit the $su\bar{b}\bar{d}$ splittings are determined by the $su\bar{d}$ spins, leading to three degenerate doublets.
[Liu et al.,1603.01131]

su	$su\bar{d}$	$su\bar{b}\bar{d}$
0	1/2	$0^+, 1^+$
1	1/2	$0^+, 1^+$
1	3/2	$1^+, 2^+$

After a simple calculation,

$$
\begin{aligned}
M_{0^+} &= M_{1^+} = M - 3\kappa_{qq}/2 \\
M'_{0^+} &= M'_{1^+} = M + \kappa_{qq}/2 - 2\kappa_{q\bar{q}} \\
M''_{1^+} &= M_{2^+} = M + \kappa_{qq}/2 + \kappa_{q\bar{q}}
\end{aligned}
$$

so definitely a $\begin{pmatrix} 0^+/1^+ \\ 1^+/2^+ \end{pmatrix}$ doublet is $\begin{pmatrix} \text{heaviest} \\ \text{lightest} \end{pmatrix}$.

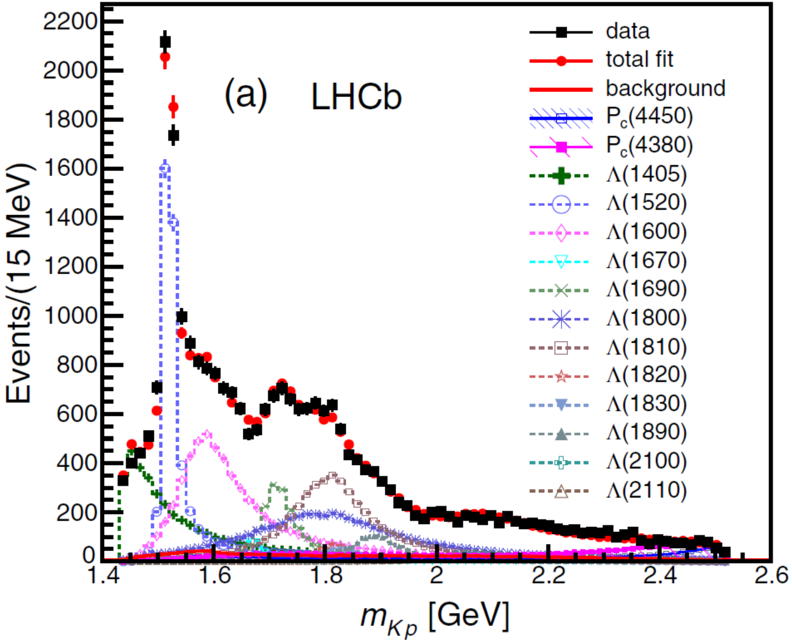
X(5568) as a tetraquark: other partners (Type II)

The Type II model treat diquarks genuinely as degrees of freedom. . . but is not well-motivated theoretically.
The pattern is

$$
\begin{aligned}
(su)_0(\bar{b}\bar{d})_0 : &\qquad M_{0^+} = M \\
(su)_0(\bar{b}\bar{d})_1 : &\qquad M_{1^+} = M + \delta \\
(su)_1(\bar{b}\bar{d})_0 : &\qquad M'_{1^+} = M + \Delta \\
(su)_1(\bar{b}\bar{d})_1 : &\qquad M'_{0^+} = M''_{1^+} = M_{2^+} = M + \delta + \Delta
\end{aligned}
$$

Note that $\Delta = (su)_1 - (su)_0 >> \delta = (\bar{b}\bar{d})_1 - (\bar{b}\bar{d})_0$.

$P_c(4380)$ and $P_c(4450)$



Compact multiquarks

Tetraquarks $qq\bar{q}\bar{q}$ or pentaquarks $qqqq\bar{q}$ with quark (or diquark) constituents, non-trivial spatial and colour wavefunctions. Start with a simple model for

$$H = \sum_k m_k + \sum_{ij} \alpha_{ij} \vec{S}_i \cdot \vec{S}_j$$

with coefficients α_{ij} weighted by colour factors.

[De Rujula, Georgi and Glashow PRD12, 147 (1975)]

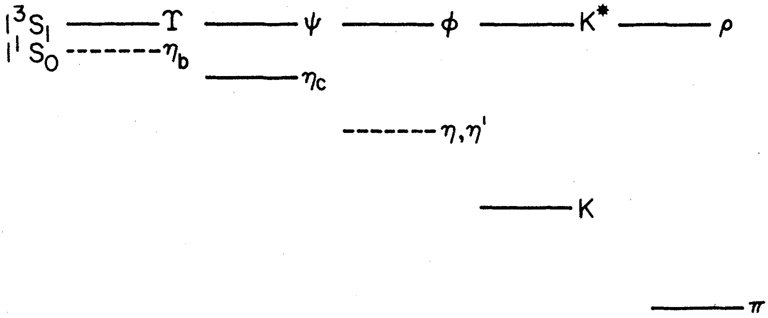
$$q\bar{q}: \; 3 \times \bar{3} = 1 + 8 \qquad qqq: \; 3 \times 3 \times 3 = 3 \times (\bar{3} + 6)$$
$$= 3 \times \bar{3} + 3 \times 6$$
$$= 1 + 8 + \ldots$$

Any qq pair in a baryon is in $\bar{3}$, and $(\alpha_{q\bar{q}})_1 = 2(\alpha_{qq})_{\bar{3}}$. It works. Inverting systems of equations for different mesons and baryons, e.g.

$$m_q + m_{\bar{q}} = \frac{1}{4}\left(3M_{^3S_1} + M_{^1S_0}\right)$$

gives independent extractions of m_q and $m_{\bar{q}}$, remarkably consistent.

Compact multiquarks



[Godfrey & Isgur PRD32, 189 (1985)]

Compact multiquarks

For multiquarks the colour wavefunctions are more intricate, e.g.

$q\bar{q}q\bar{q}$:

$$\begin{aligned} &3\times\bar{3}\times 3\times\bar{3}\\ &=(1+8)\times(1+8)\\ &=1\times 1+8\times 8+\ldots\\ &=1+(1+8+8+10+\overline{10}+27)+\ldots \end{aligned}$$

$qq\bar{q}\bar{q}$:

$$\begin{aligned} &3\times 3\times\bar{3}\times\bar{3}\\ &=(\bar{3}+6)\times(3+\bar{6})\\ &=\bar{3}\times 3+6\times\bar{6}+\ldots\\ &=(1+8)+(1+8+27)+\ldots \end{aligned}$$

Use either basis $\begin{pmatrix} |(q\bar{q})_1(q\bar{q})_1\rangle \\ |(q\bar{q})_8(q\bar{q})_8\rangle \end{pmatrix}$ or $\begin{pmatrix} |(qq)_{\bar{3}}(\bar{q}\bar{q})_3\rangle \\ |(qq)_6(\bar{q}\bar{q})_{\bar{6}}\rangle \end{pmatrix}$.

In "diquark" models the Fock space is truncated to $|(qq)_{\bar{3}}(\bar{q}\bar{q})_3\rangle$, and the massive constituents are $(qq)_{\bar{3}}$ and $(\bar{q}\bar{q})_3$ diquarks.

[Maiani et al.,PRD71,014028(2005)]

Compact multiquarks

Masses are not tied to thresholds.

States can decay via their 1×1 component.

There is a proliferation of states, because

- Fock space is (in general) twice as large
- No restrictions due to J^P
- No restrictions due to flavour
- No restriction to S-wave

X(5568) as a threshold enhancement

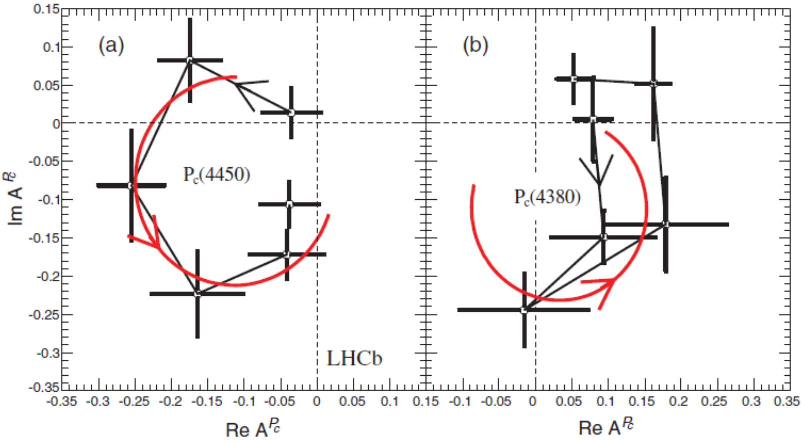
Near threshold the rate for $B_s\pi$ in partial wave L grows as

$$\sigma(s) \sim \left(\sqrt{s} - M_{B_s} - M_\pi\right)^{L+1/2}$$

and at higher s is attenuated by hadronic overlaps.

Competing effects produce a peak; can it explain $X(5568)$?

Amplitudes for P_c states

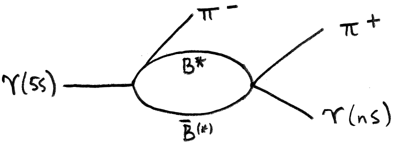


Cusps and triangle singularities

These effects are also connected to thresholds.

Belle study of decays

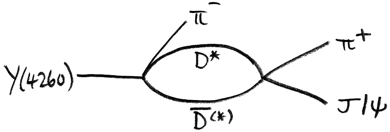
$$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$$
$$\Upsilon(5S) \to h_b(nS)\pi^+\pi^-$$



discovers charged Z_b states in $\Upsilon(nS)\pi^\pm$ and $h_b(nS)\pi^\pm$, just above $B^*\bar{B}$ and $B^*\bar{B}^*$ thresholds.

BESIII study of decays

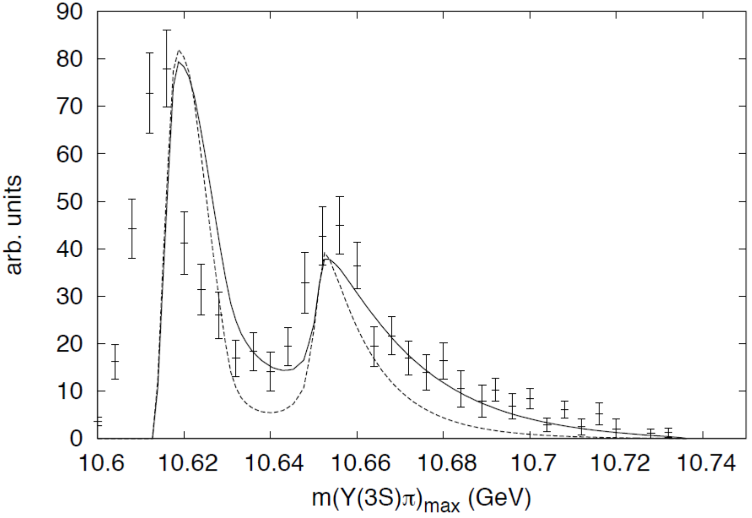
$$Y(4260) \to J/\psi\pi^+\pi^-$$



discovers charged Z_c states in $J/\psi\pi^\pm$, just above $D^*\bar{D}$ and $D^*\bar{D}^*$ thresholds.

Cusps and triangle singularities

An example for the Z_b states:



[Swanson PRD91,034009(2015)]