Nuclear physics with heavy hadrons

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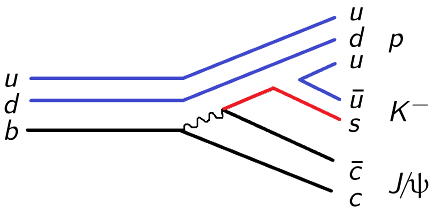
15 February 2017

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

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

LHCb amplitude analysis of the three-body decay $\Lambda_b \to J/\psi p K^-$.

[LHCb,PRL115,072001,2015]



In the pK^- channel they observe conventional Λ^* resonances.

They also look in the exotic $J/\psi p$ and $J/\psi K^-$ channels. . .

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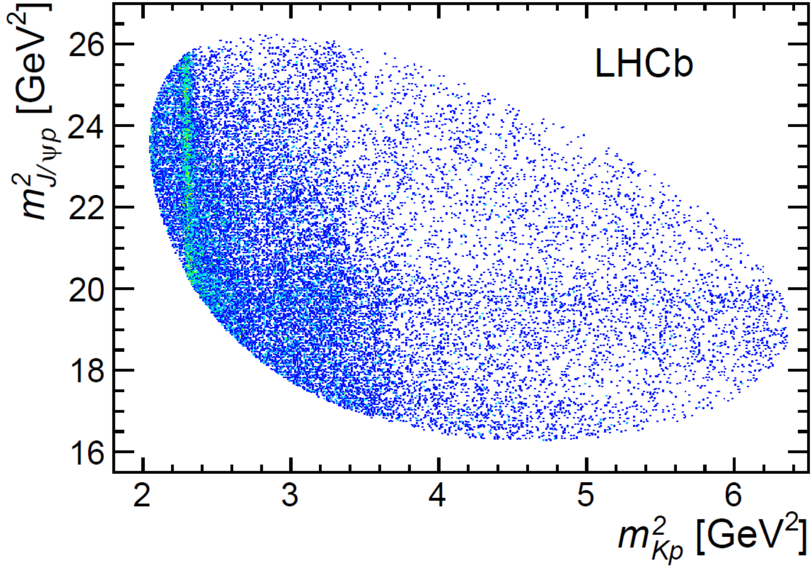

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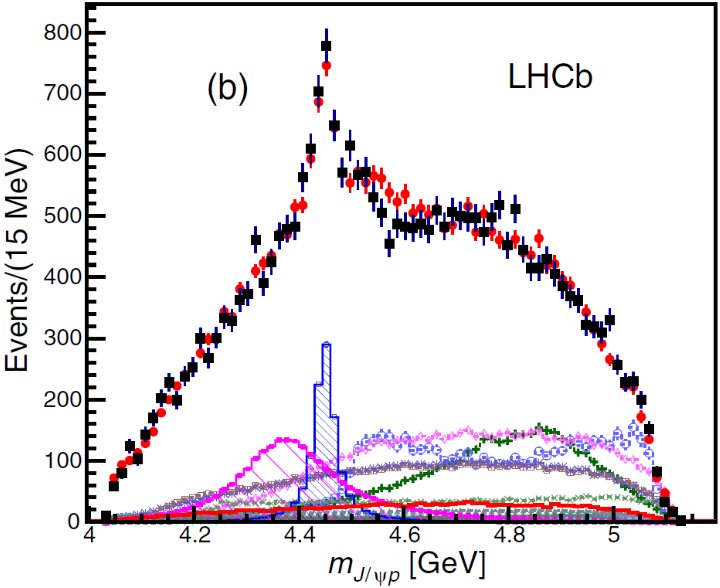
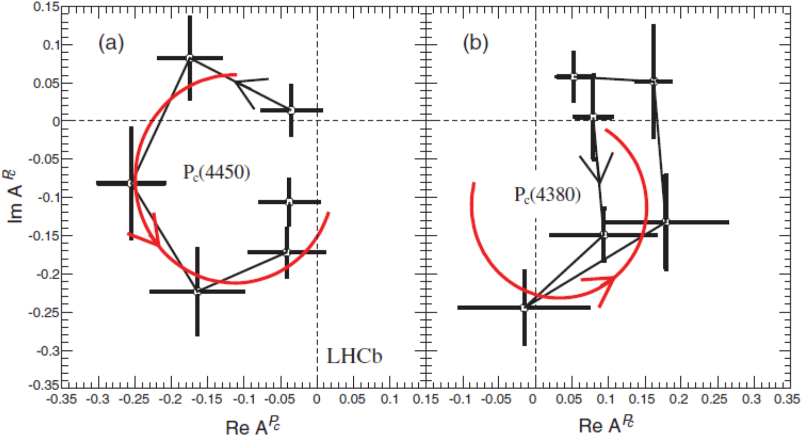


Two states with flavour of the proton, but "hidden charm": $uudc\bar{c}$.

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

Amplitudes:



The states subsequently confirmed in $\Lambda_b \to J/\psi p \pi^-$, and in a model-independent analysis.

$P_c(4380)$ 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	$3/2^+$	$5/2^-$
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$\Sigma_c^{*+}\bar{D}^0$	$(udc)(u\bar{c})$	4382.3 ± 2.4	
$\Sigma_c^+\bar{D}^{*0}$	$(udc)(u\bar{c})$		4459.9 ± 0.5
$\Lambda_c^+(1P)\bar{D}^0$	$(udc)(u\bar{c})$		4457.09 ± 0.35
$\chi_{c1}p$	$(udu)(c\bar{c})$		4448.93 ± 0.07

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The π exchange molecule model works well for this state.

Comparison of models

Comparison of models

d.o.f.	
Interactions	
colour	
masses	
wavefunction	
$I(J^P)$ spectrum	

Comparison of models

	Compact pentaquark
d.o.f.	quarks/diquarks
Interactions	binding via confinement + gluon-exch.
colour	$(qqq)_1(q\bar{q})_1 \oplus (qqq)_8(q\bar{q})_8$
masses	model-dependent
wavefunction	compact
$I(J^P)$ spectrum	vast

Comparison of models

	Compact pentaquark	Hadronic molecule
d.o.f.	quarks/diquarks	baryon+meson
Interactions	binding via confinement + gluon-exch.	$(udc)(u\bar{c})$ binding via π exchange
colour	$(qqq)_1(q\bar{q})_1 \oplus (qqq)_8(q\bar{q})_8$	$(qqq)_1(q\bar{q})_1$
masses	model-dependent	near thresholds
wavefunction	compact	extended
$I(J^P)$ spectrum	vast	restricted

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masses	model-dependent	near thresholds	near thresholds
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$I(J^P)$ spectrum	vast	restricted	restricted?
Exotic-ness	high!	medium	low

Hadronic molecule

Molecules

Molecular approaches:

- Yang, Sun, He, Liu, Zhu (2011)
- Wu, Molina, Oset, Zou, Xiao, Nieves, Uchino, Liang, Roca, Magas, Feijoo, Ramos, . . . (2010-2016)
- Karliner, Rosner (2015)
- He (2015)
- Shimizu, Suenaga, Harada (2016)
- Chen, Liu, Li, Zhu (2015)
- Yamaguchi, Santopinto (2016)
- Huang, Deng, Ping, Wang (2015)
- Yang, Ping (2015)
- Ortega, Entem, Fernandez (2016)
- . . .

Pion exchange: basics

Pion-exchange (or light-meson exchange) in a $uudc\bar{c}$ system implies open charm constituents:

$\Longrightarrow \quad (udc)(u\bar{c})$, not $(uud)(c\bar{c})$.

The $I(J^P)$ of constituents (assuming ground states) are

Λ_c :	$(ud)_0c$	$0(1/2^+)$	$\bar{D}$:	$u\bar{c}$	$1/2(0^-)$
Σ_c :	$(ud)_1c$	$1(1/2^+)$	$\bar{D}^*$:	$u\bar{c}$	$1/2(1^-)$
Σ_c^* :	$(ud)_1c$	$1(3/2^+)$			

This gives 17 combinations of constituents and total $I(J^P)$...
...but fewer if restricting to π exchange in elastic channels.

Pion exchange: basics

Position space potential due to a sum of quark-pion couplings, parameters fixed to NN potential.

$$V(\vec{r}) = \sum_{ij} \left[C(r)\vec{\sigma}_i \cdot \vec{\sigma}_j + T(r)S_{ij}(\hat{r}) \right] \vec{\tau}_i \cdot \vec{\tau}_j$$

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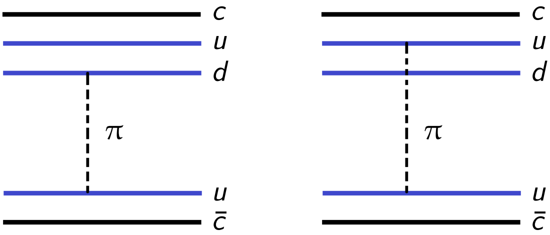

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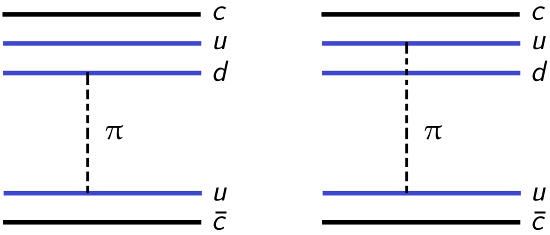

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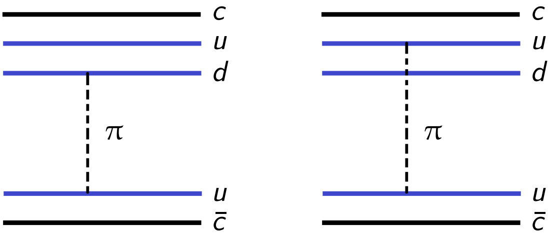

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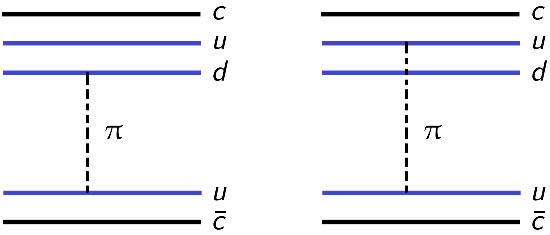

Coefficient of $C(r)$ is important. But:

- For NN both $0(1^+)$ and $1(0^+)$ have the same coefficient, but only $0(1^+)$ (the deuteron) is bound: role of tensor.
- For NN the coefficient is negative (attractive) due to Fermi stats: not true in general!

Pion exchange: central potential

Point-like constituents: $$C(r) = \frac{g^2 m^3}{12\pi f_\pi^2}\left(\frac{e^{-mr}}{mr} - \frac{4\pi}{m^3}\delta^3(\vec{r})\right)$$

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Extended hadrons:

- dipole form factor, cut-off Λ
- heavy-hadron molecules have smaller constituents, larger Λ

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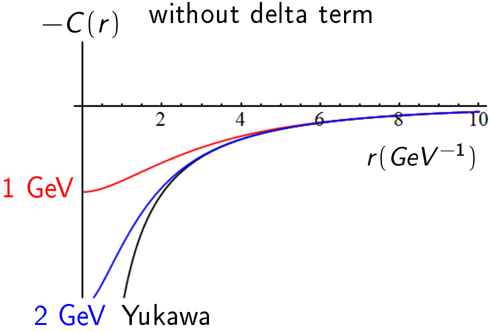

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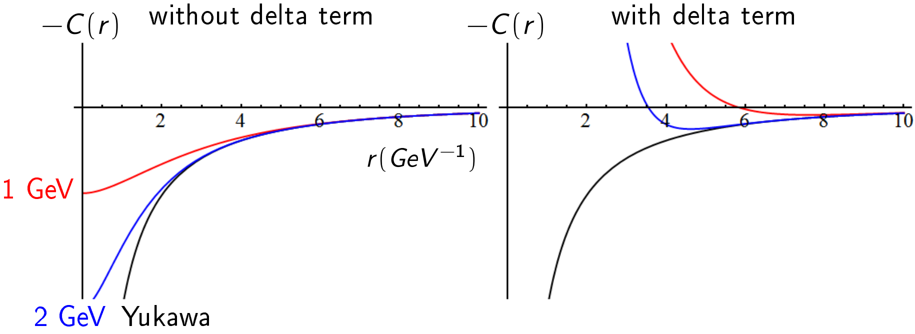

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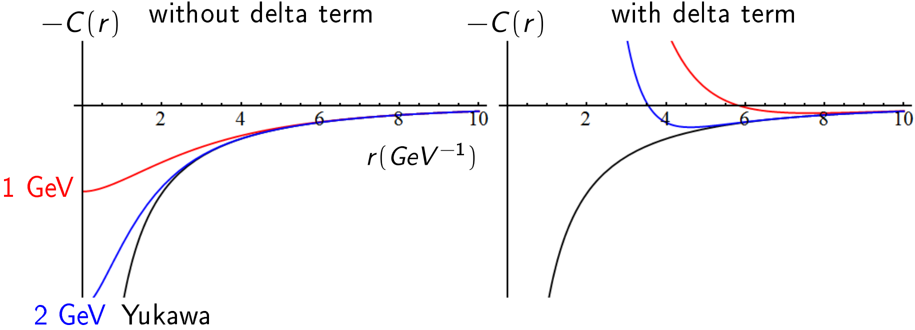

Ambiguities: choice of potential, value of Λ.

Pion exchange: central and tensor

The full potential

$$V(\vec{r}) = \sum_{ij} \left(C(r) \vec{\sigma}_i \cdot \vec{\sigma}_j + T(r) S_{ij}(\hat{r}) \right) \vec{\tau}_i \cdot \vec{\tau}_j$$

is a matrix problem, with tensor mixing S- and D-waves.

E.g. for the the $P_c(4450)$ candidate state $\Sigma_c \bar{D}^*$ $1/2(3/2^-)$:

$$\begin{array}{cccc} & |^4S_{3/2}\rangle & |^2D_{3/2}\rangle & |^4D_{3/2}\rangle \\ \langle^4S_{3/2}| & -\frac{8}{3}C & -\frac{8}{3}T & -\frac{16}{3}T \\ \langle^2D_{3/2}| & -\frac{8}{3}T & +\frac{16}{3}C & +\frac{8}{3}T \\ \langle^4D_{3/2}| & -\frac{16}{3}T & +\frac{8}{3}T & -\frac{8}{3}C \end{array}$$

As with the deuteron, including the tensor facilitates binding, and binding energies depend (strongly) on the form factor cutoff.

Spectrum of molecules

Pion-exchange: spectrum of states

Summary of channels by $I(J^P)$. The same number of states arises in "compact pentaquark" scenarios.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		✓	✓
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	✓	✓
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						✓
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	✓	✓
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						✓

Pion-exchange: spectrum of states

But there is no coupling $\Lambda_c \to \Lambda_c \pi$ due to isospin: $0 \nrightarrow 0 \times 1$

[Karliner & Rosner (2015)]

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		✓	✓
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	✓	✓
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						✓
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	✓	✓
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Pion-exchange: spectrum of states

The binding is driven by the coeff. $\langle \sum_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j \rangle$ of $C(r)$.

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$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

Pion-exchange: spectrum of states

$I = 3/2$ potentials suppressed by $-1/2$.
Attractive potentials have negative coefficient.

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$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		$-8/3$	$-10/3$
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

Pion-exchange: spectrum of states

Two states remain, one of which matches $P_c(4450)$.
The properties of the other state discussed later.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		$+16/3$	$+20/3$
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	$-8/3$	$+8/3$
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						-4
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		$-8/3$	$-10/3$
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

Pion-exchange: spectrum of states

But binding requires both central and tensor potential. Consider minimum cut-off Λ to bind a given channel.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		$+16/3$	$+20/3$
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	$-8/3$	$+8/3$
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						-4
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		$-8/3$	$-10/3$
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

Pion-exchange: spectrum of states

Potential without the delta term.
(Deuteron binding requires $\Lambda = 0.8$ GeV.)

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		$+16/3$	$+20/3$
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	$-8/3$	$+8/3$
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						-4
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		$-8/3$	$-10/3$
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

Pion-exchange: spectrum of states

Potential without the delta term.
(Deuteron binding requires $\Lambda = 0.8$ GeV.)

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>2.0	1.6
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.1	1.4
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						0.9
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	1.9
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	2.0	2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						>2.0

Pion-exchange: spectrum of states

The two most easily bound states are same as before, and require modest increase in Λ compared to deuteron.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>2.0	1.6
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.1	1.4
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						0.9
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	1.9
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	2.0	2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						>2.0

Pion-exchange: spectrum of states

For $1.1 \leqslant \Lambda < 1.4$ GeV these are the only states, and if $\Lambda > 1.4$ GeV the $P_c(4450)$ is too deeply bound.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>2.0	1.6
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.1	1.4
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						0.9
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	1.9
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	2.0	2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						>2.0

Pion-exchange: spectrum of states

This eliminates all $I = 3/2$ states, and both $1/2(1/2^-)$ states.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>2.0	1.6
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.1	1.4
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						0.9
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	1.9
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	2.0	2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						>2.0

Pion-exchange: spectrum of states

This eliminates all $I = 3/2$ states, and both $1/2(1/2^-)$ states.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>2.0	1.6
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.1	1.4
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						0.9
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	1.9
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	2.0	2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						>2.0

Pion-exchange: spectrum of states

Potential with the delta term (restricting to correct sign potentials).
(Deuteron binding requires $\Lambda = 1.0$ GeV.)

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>2.0	1.6
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.1	1.4
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						0.9
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	1.9
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	2.0	2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						>2.0

Pion-exchange: spectrum of states

Potential with the delta term (restricting to correct sign potentials).
(Deuteron binding requires $\Lambda = 1.0$ GeV.)

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.4	-
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						1.2
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						-

Pion-exchange: spectrum of states

Over a very large range of Λ only two states are bound, and for $\Lambda \geqslant 1.8$ GeV the $P_c(4450)$ is too deeply bound.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.4	-
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						1.2
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						-

Pion-exchange: spectrum of states

Over a very large range of Λ only two states are bound, and for $\Lambda \geqslant 1.8$ GeV the $P_c(4450)$ is too deeply bound.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.4	-
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						1.2
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						-

Pion-exchange: spectrum of states

Allowing states bound in the attractive delta function core spoils this pattern: deeply bound states, wrong quantum numbers.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.4	-
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						1.2
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						-

Pion-exchange: spectrum of states

Regardless of short-distance potential, same two channels are preferred. Predict $1/2(5/2^-)$ $\Sigma_c^*\bar{D}^*$ state (suppressed decay!)

$I(J^P)$	$\Lambda_c\bar{D}$	$\Lambda_c\bar{D}^*$	$\Sigma_c\bar{D}$	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}^*$	$\Sigma_c^*\bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.4	-
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						1.2
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						-

Pion-exchange: spectrum of states

The model is falsifiable: it only works if $P_c(4450)$ is $1/2(3/2^-)$.

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	1.4	-
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						1.2
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						-

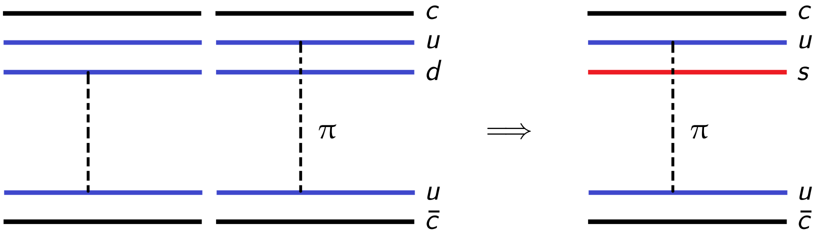
$\Xi_c^* \bar{D}^*$ molecules

$\Xi_c^* \bar{D}^*$ molecules

$$\Lambda_c = ((ud)_0 c)_{1/2} \quad \Longrightarrow \quad \Xi_c = ((us)_0 c)_{1/2}$$

$$\Sigma_c = ((ud)_1 c)_{1/2} \quad \Longrightarrow \quad \Xi_c' = ((us)_1 c)_{1/2}$$

$$\Sigma_c^* = ((ud)_1 c)_{3/2} \quad \Longrightarrow \quad \Xi_c^* = ((us)_1 c)_{3/2}$$



The potential matrices (central + tensor) are directly related:

$\Sigma_c^{(*)} \bar{D}^*$ $I = 1/2$	$\Xi_c^{(\prime,*)} \bar{D}^*$ $I = 0$	$\Sigma_c^{(*)} \bar{D}^*$ $I = 3/2$	$\Xi_c^{(\prime,*)} \bar{D}^*$ $I = 1$
$+4$	$+3$	-2	-1

$\Xi_c^* \bar{D}^*$ molecules: spectrum of states

The same pattern emerges. Results shown for the potential with delta function term.

	$\Xi_c \bar{D}$	$\Xi_c \bar{D}^*$	$\Xi_c' \bar{D}$	$\Xi_c^* \bar{D}$	$\Xi_c' \bar{D}^*$	$\Xi_c^* \bar{D}^*$
$0\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$0\left(\frac{3}{2}^-\right)$		✓		✓	1.8	-
$0\left(\frac{5}{2}^-\right)$						1.5
$1\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$1\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$1\left(\frac{5}{2}^-\right)$						-

$\Xi_c^* \bar{D}^*$ molecules: spectrum of states

$0(5/2^-)$ $\Xi_c^* \bar{D}^*$: predict loosely bound state.
$0(3/2^-)$ $\Xi_c' \bar{D}^*$: analogue of $P_c(4450)$, may or may not bind.

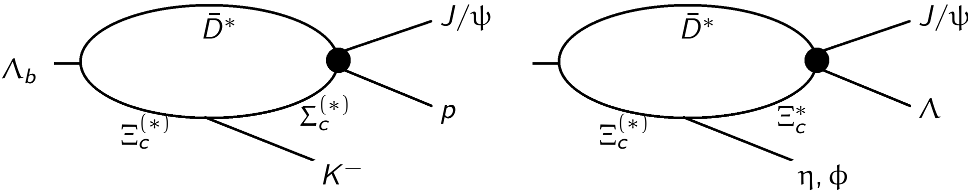
	$\Xi_c \bar{D}$	$\Xi_c \bar{D}^*$	$\Xi_c' \bar{D}$	$\Xi_c^* \bar{D}$	$\Xi_c' \bar{D}^*$	$\Xi_c^* \bar{D}^*$
$0\left(\frac{1}{2}^-\right)$	✓	✓	✓		-	-
$0\left(\frac{3}{2}^-\right)$		✓		✓	1.8	-
$0\left(\frac{5}{2}^-\right)$						1.5
$1\left(\frac{1}{2}^-\right)$			✓		>2.0	>2.0
$1\left(\frac{3}{2}^-\right)$				✓	-	>2.0
$1\left(\frac{5}{2}^-\right)$						-

$\Xi_c^* \bar{D}^*$ molecules

Pion-exchange: $\Xi_c^* \bar{D}^*$ $0(5/2^-)$
Local-hidden gauge: $\Xi_c \bar{D}^*$ $0(3/2^-)$, $\Xi_c' \bar{D}^*$ $0(3/2^-)$
[Wu,Molina,Oset,Zhu(2010,2011);Feijoo,Magas,Ramos,Oset(2015)

The $\Xi_c^* \bar{D}^*$ $0(5/2^-)$ state is

- weakly bound, with mass ≈ 4652 MeV
- narrow, decaying into $J/\psi\Lambda$
- produced in $\Lambda_b^0 \to J/\psi\Lambda\eta$, $\Lambda_b^0 \to J/\psi\Lambda\phi$
- produced via similar diagrams to $P_c(4450)$



Isospin mixing

Isospin mixing: $P_c(4380)$ and $P_c(4450)$

$uudc\bar{c}$ comes in two charge combinations $\begin{cases} (udc)(u\bar{c}) = \Sigma_c^+ \bar{D}^0 \\ (uuc)(d\bar{c}) = \Sigma_c^{++} D^- \end{cases}$

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 only if the masses $\Sigma_c^+ = \Sigma_c^{++}$ and $\bar{D}^0 = D^-$.

Otherwise, isospin is not a good quantum number.

Isospin mixing: $P_c(4380)$ and $P_c(4450)$

$$\Sigma_c^{*+}\bar{D}^0 = 4382.3 \pm 2.4 \qquad \Sigma_c^{+}\bar{D}^{*0} = 4459.9 \pm 0.5$$
$$\Sigma_c^{*++}D^- = 4387.5 \pm 0.7 \qquad \Sigma_c^{++}D^{*-} = 4464.24 \pm 0.23$$

Isospin mixing: $P_c(4380)$ and $P_c(4450)$

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

Isospin mixing: $P_c(4380)$ and $P_c(4450)$

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

The P_c states have mixed isospin:

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

Isospin mixing: $P_c(4380)$ and $P_c(4450)$

$$P_c(4380) = 4380 \pm 8 \pm 29 \qquad P_c(4450) = 4449 \pm 1.7 \pm 2.5$$
$$\Sigma_c^{*+}\bar{D}^0 = 4382.3 \pm 2.4 \qquad \Sigma_c^{+}\bar{D}^{*0} = 4459.9 \pm 0.5$$
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The P_c states have mixed isospin:

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

They should decay also into $J/\psi\Delta^+$ and $\eta_c\Delta^+$, with weights:

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

Isospin mixing: predicted $5/2^-$ states

$\Sigma_c^* \bar{D}^*$ $1/2(5/2^-)$

$$\Sigma_c^{*+} \bar{D}^{*0} = 4524.4 \pm 2.4$$
$$\Sigma_c^{*++} D^{*-} = 4528.2 \pm 0.7$$

Mixed isopsin:
$|P\rangle = \cos\phi|\frac{1}{2}, \frac{1}{2}\rangle + \sin\phi|\frac{3}{2}, \frac{1}{2}\rangle$

Decays:
$\rightarrow J/\psi p$: D-wave, spin flip
Reason for absence at LHCb?

$\rightarrow J/\psi \Delta$: S-wave, spin cons.
$\Longrightarrow$ $I = 3/2$ decay enhanced.

Isospin mixing: predicted $5/2^-$ states

$\Sigma_c^* \bar{D}^*\ 1/2(5/2^-)$

$$\Sigma_c^{*+} \bar{D}^{*0} = 4524.4 \pm 2.4$$
$$\Sigma_c^{*++} D^{*-} = 4528.2 \pm 0.7$$

Mixed isopsin:
$|P\rangle = \cos\phi|\frac{1}{2},\frac{1}{2}\rangle + \sin\phi|\frac{3}{2},\frac{1}{2}\rangle$

Decays:
$\to J/\psi p$: D-wave, spin flip
Reason for absence at LHCb?

$\to J/\psi \Delta$: S-wave, spin cons.
$\implies I = 3/2$ decay enhanced.

$\Xi_c^* \bar{D}^*\ 0(5/2^-)$

$$\Xi_c^{*0} \bar{D}^{*0} = 4652.9 \pm 0.6$$
$$\Xi_c^{*+} D^{*-} = 4656.2 \pm 0.7$$

Mixed isopsin:
$|P\rangle = \cos\phi|0,0\rangle + \sin\phi|1,0\rangle$

Decays:
$\to J/\psi \Lambda$: D-wave, spin flip
e.g. $\Lambda_b^0 \to J/\psi \Lambda \eta, J/\psi \Lambda \phi$

$\to J/\psi \Sigma^*$: S-wave, spin cons.
$\implies I = 1$ decay enhanced.

Conclusions

- Pion exchange (normalised to the deuteron) binds a $\Sigma_c \bar{D}^*$ molecule, consistent with $P_c(4450)$.
- The model is falsifiable, and only works if $P_c(4450)$ is $1/2(3/2^-)$.
- Only one $\Sigma_c^* \bar{D}^*$ partner is expected, and its absence (so far) has a possible explanation.
- Results apply within a significant (and constrained) parameter range, and independently of short-distance potential.
- A corresponding $\Xi_c^* \bar{D}^*$ molecule is also bound, and could be seen in Λ_b^0 decays.
- Small isospin admixtures in all states could be observed due to enhanced decays.

Backup slides

Compact pentaquark

Compact pentaquark

In the simplest (S-wave) scenario, 17 $uudc\bar{c}$ states are required, with no obvious restricting principle.

	1	2	3	4	5	6	7	8	9	10
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓			✓	✓		✓		
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓				✓	✓	✓		
$\frac{1}{2}\left(\frac{5}{2}^-\right)$								✓		
$\frac{3}{2}\left(\frac{1}{2}^-\right)$				✓					✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$			✓	✓						✓
$\frac{3}{2}\left(\frac{5}{2}^-\right)$				✓						

Compact pentaquark

Masses are very model-dependent, and all $I(J^P)$ are allowed, so any experimental observation can be accommodated...

	1	2	3	4	5	6	7	8	9	10
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓			✓	✓		✓		
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓				✓	✓	✓		
$\frac{1}{2}\left(\frac{5}{2}^-\right)$								✓		
$\frac{3}{2}\left(\frac{1}{2}^-\right)$				✓					✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$			✓	✓						✓
$\frac{3}{2}\left(\frac{5}{2}^-\right)$				✓						

Compact pentaquark

…put another way: the model cannot be falsified.

	1	2	3	4	5	6	7	8	9	10
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓			✓	✓		✓		
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓				✓	✓	✓		
$\frac{1}{2}\left(\frac{5}{2}^-\right)$								✓		
$\frac{3}{2}\left(\frac{1}{2}^-\right)$				✓					✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$			✓	✓						✓
$\frac{3}{2}\left(\frac{5}{2}^-\right)$				✓						

Compact pentaquark

In P-wave many, many additional states is required...

	1	2	3	4	5	6	7	8	9	10
$\frac{1}{2}\left(\frac{1}{2}^{-}\right)$	✓	✓			✓	✓		✓		
$\frac{1}{2}\left(\frac{3}{2}^{-}\right)$		✓				✓	✓	✓		
$\frac{1}{2}\left(\frac{5}{2}^{-}\right)$								✓		
$\frac{3}{2}\left(\frac{1}{2}^{-}\right)$				✓					✓	✓
$\frac{3}{2}\left(\frac{3}{2}^{-}\right)$			✓	✓						✓
$\frac{3}{2}\left(\frac{5}{2}^{-}\right)$				✓						

Compact pentaquark

...and there are $uds c\bar{c}$, $uss c\bar{c}$, $sss c\bar{c}$ states, etc.

	1	2	3	4	5	6	7	8	9	10
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓			✓	✓		✓		
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓				✓	✓	✓		
$\frac{1}{2}\left(\frac{5}{2}^-\right)$								✓		
$\frac{3}{2}\left(\frac{1}{2}^-\right)$				✓					✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$			✓	✓						✓
$\frac{3}{2}\left(\frac{5}{2}^-\right)$				✓						

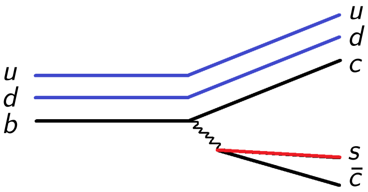
Cusps and triangle diagrams

Cusps and triangle diagrams

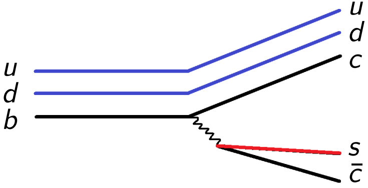
Models:

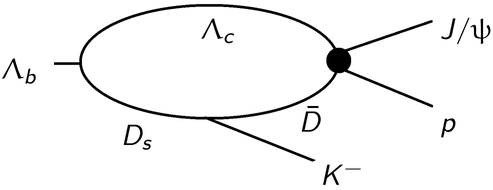
- Guo, Meißner, Wang, Yang [PRD92,07152(2015)]
- Mikhasenko [1507.06552]
- Liu, Wang, Zhao [PLB757,231(2015)]

Cusps and triangle diagrams

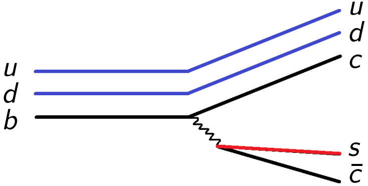


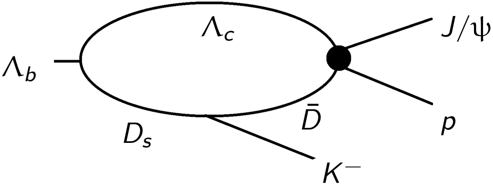
Cusps and triangle diagrams

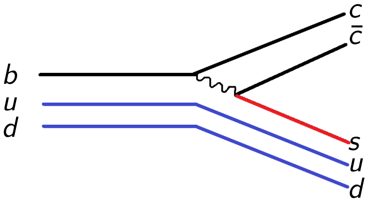




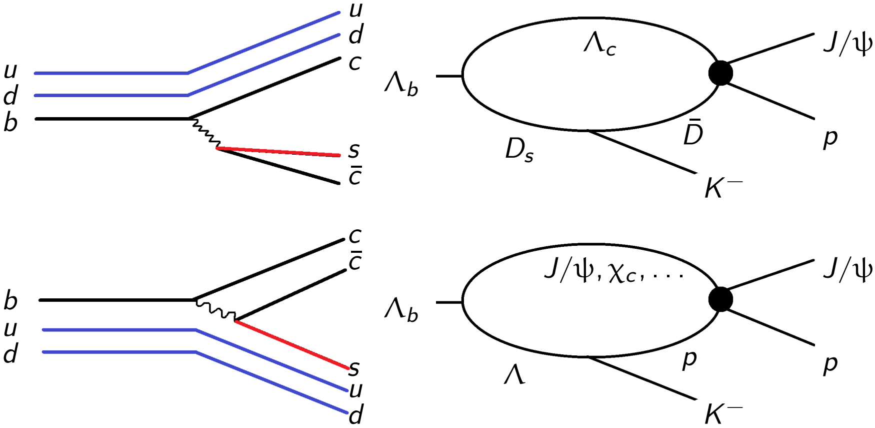
Cusps and triangle diagrams



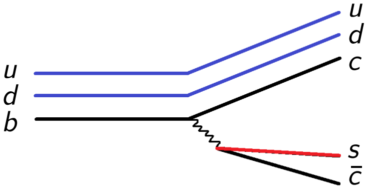


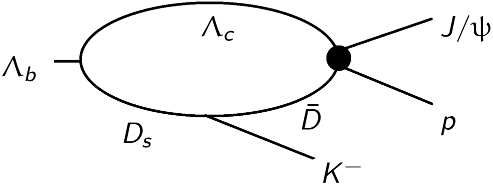


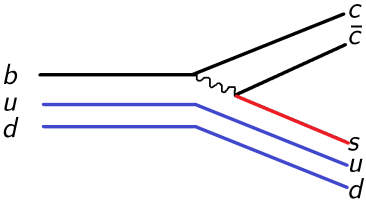
Cusps and triangle diagrams

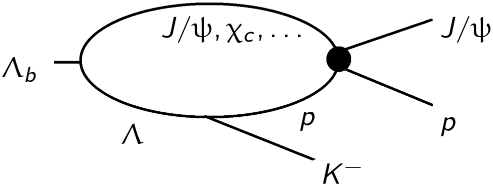


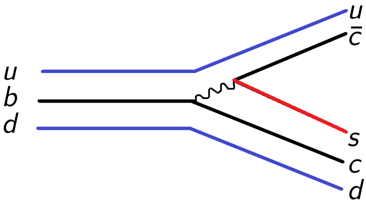
Cusps and triangle diagrams



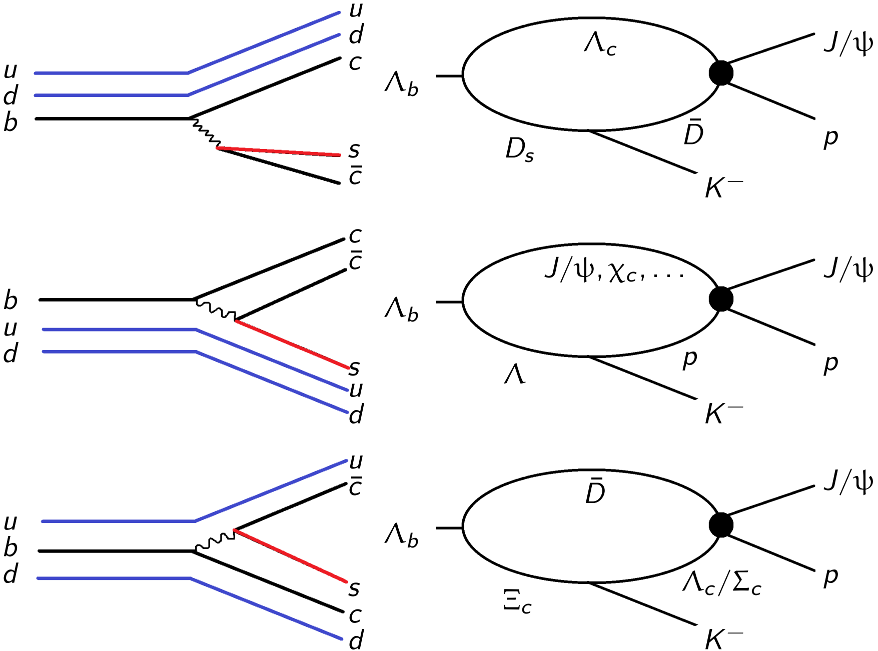






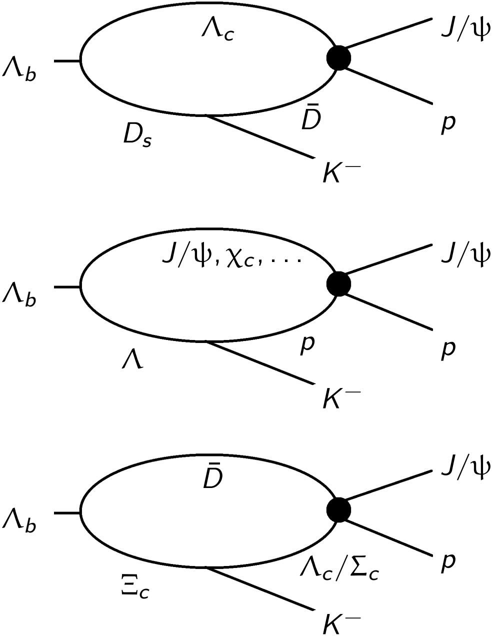


Cusps and triangle diagrams



Cusps and triangle diagrams

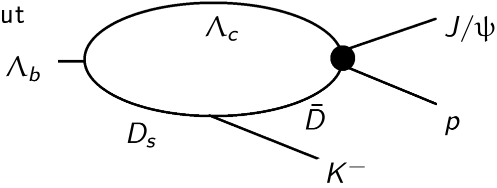
Enhancements expected at
$\Lambda_c \bar{D} = 1/2^-$
$\Lambda_c \bar{D}^* = 1/2^-, 3/2^-$
not seen at LHCb

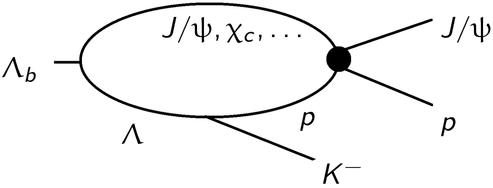


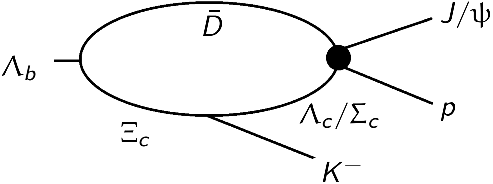
Cusps and triangle diagrams

$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but

- S-wave $= 1/2^+$
- P-wave $= 1/2^-, 3/2^-$
- why no $\Lambda_c^* \bar{D}^*$ states?







Cusps and triangle diagrams

$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but
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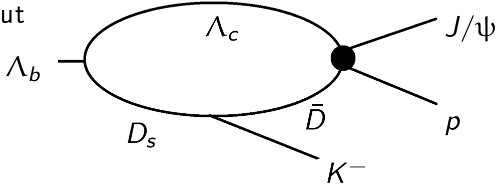
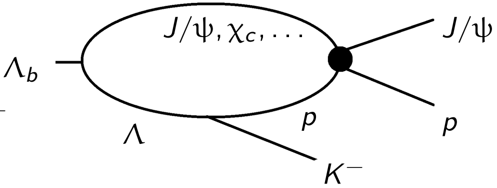
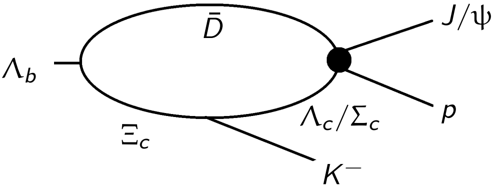


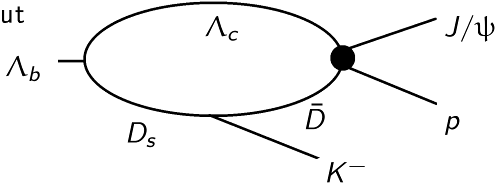
$\chi_{c1} p = P_c(4450)$ mass, but
- doubly suppressed
- S-wave $= 1/2^+, 3/2^+$
- P-wave $= 1/2^-, 3/2^-, 5/2^-$



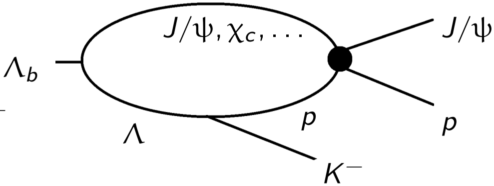


Cusps and triangle diagrams

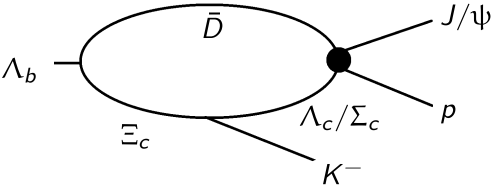
$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but
- S-wave $= 1/2^+$
- P-wave $= 1/2^-, 3/2^-$
- why no $\Lambda_c^* \bar{D}^*$ states?



$\chi_{c1} p = P_c(4450)$ mass, but
- doubly suppressed
- S-wave $= 1/2^+, 3/2^+$
- P-wave $= 1/2^-, 3/2^-, 5/2^-$

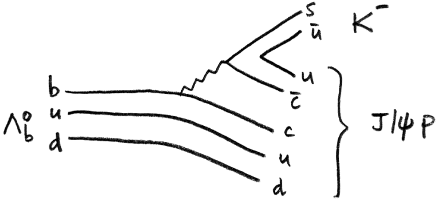


$\Sigma_c^* \bar{D} \approx P_c(4380)$ mass, and
$\Sigma_c \bar{D}^* \approx P_c(4450)$ mass, but
- doubly suppressed
- what restricts J^P?
- why not $\Sigma_c \bar{D}, \Sigma_c^* \bar{D}^*$?

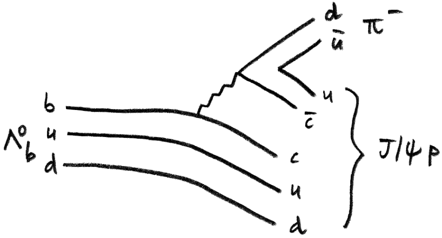


P_c states in the Cabibbo-suppressed mode

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



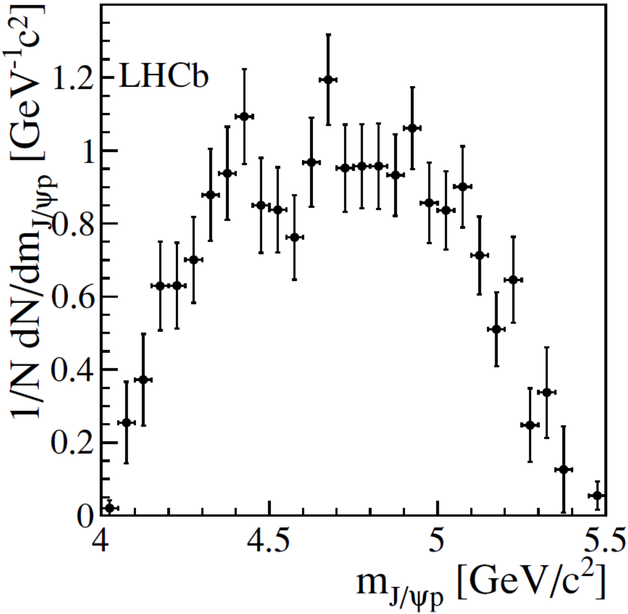
$\Lambda_b \to J/\psi p \pi^-$



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.

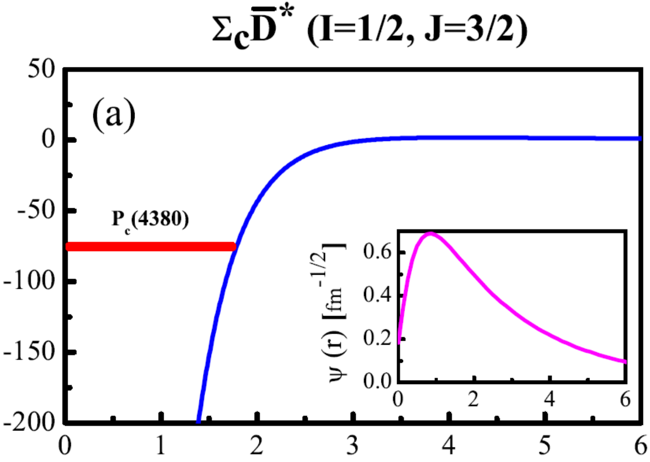
[LHCb, JHEP07(2014)103]

P_c states in the Cabibbo-suppressed mode



Pion exchange: central potential

For channels with $\langle \sum_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j > 0 \rangle$, the central potential with delta term has a deeply attractive core.



[Chen,Liu,Li&Zhu,PRL115,132002(2015)]

But should it be trusted?

$P_c(4380)$ 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:

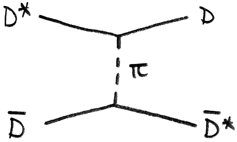
- neutral $I = 1/2$ partner
- possible $I = 3/2$ partners including doubly-charged, decaying into $J/\psi\Delta$
- possible J^P partners

Compact pentaquark scenario:

- many partners with different flavours and J^P

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

$X(3872)$

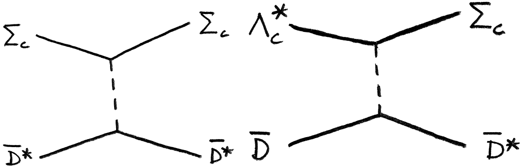


$\bar{D}^{*0} - \bar{D}^0 = 142.1$

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