Phenomenology of $P_c(4380)^+$, $P_c(4450)^+$ and related states

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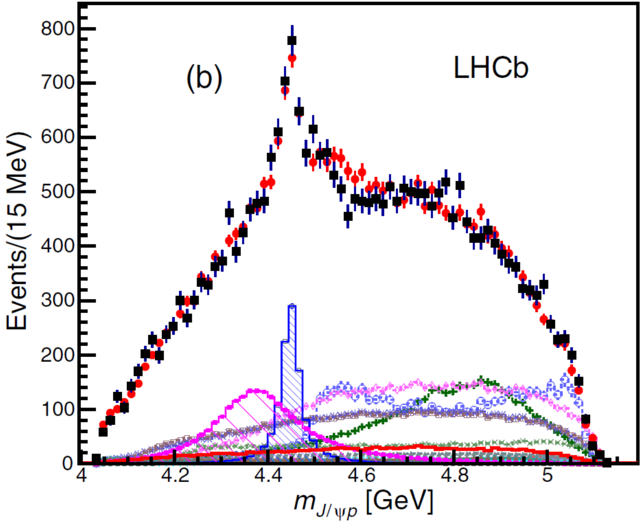
[T.B., Eur.Phys.J. A51, 152 (2015), 1509.02460]
[T.B. & E.Swanson (ongoing)]

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

$J/\psi p$ states in $\Lambda_b \to J/\psi p K^-$ and $\Lambda_b \to J/\psi p \pi^-$.



$uudc\bar{c}$ = exotic flavour

[LHCb(2015,2016);A.Alvares Jnr talk]

$P_c(4380)$ 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		$5/2^+$	$3/2^-$
Assignment 4		$5/2^-$	$3/2^+$
$\Sigma_c^{*+} \bar{D}^0$	$(udc)(u\bar{c})$	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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Molecules

Molecular approaches:

- Wu, Molina, Oset, Zou, Xiao, Nieves, Uchino, Liang, Roca, Magas, Feijoo, Ramos, . . . (2010-2016)
- Yang, Sun, He, Liu, Zhu (2011)
- 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

Pion exchange: basics

Hadronic molecules due to light meson exchange:

- constituents have flavour: $(udc)(u\bar{c})$ but not $(uud)(c\bar{c})$
- π exchange dominance: restrictions due to $I(J^P)$
- expect loosely bound (dominantly) S-wave states

Position space potential, parameters fixed to NN:

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

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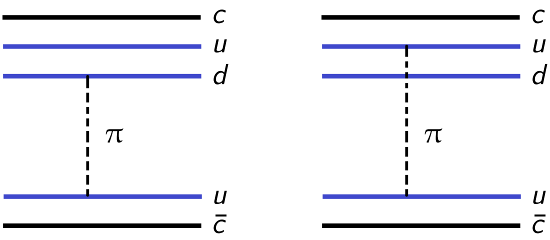

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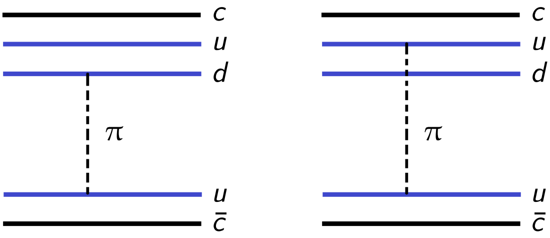

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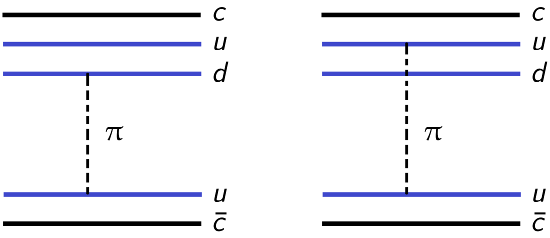

Note: for NN, $\langle \sum_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j \rangle < 0$ due to Fermi stats.

Pion exchange: central potential

For 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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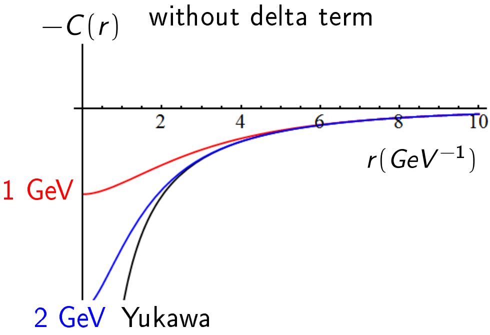

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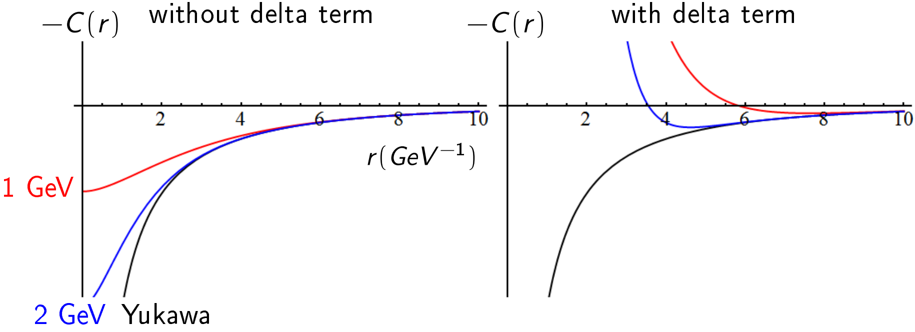

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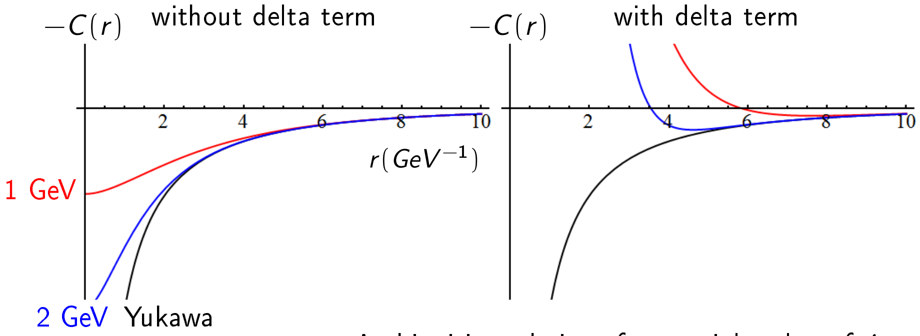

Ambiguities: choice of potential, value of Λ.

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.

Pion-exchange: spectrum of states

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

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

Pion-exchange: spectrum of states

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

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

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$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	✓	✓
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						✓
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		✓	✓
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	✓	✓
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						✓

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And there is no $D \to D\pi$ coupling due to J^P: $0^- \nrightarrow 0^- \times 0^-$

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

Pion-exchange: spectrum of states

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

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
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$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	$-8/3$	$+8/3$
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						-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

And attractive potentials have negative coefficient.

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Pion-exchange: spectrum of states

Experiment has looked in $J/\psi p$, which is $I = 1/2$.

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Pion-exchange: spectrum of states

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

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
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$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

Pion-exchange: spectrum of states

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

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		$+16/3$	$+20/3$
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Pion-exchange: spectrum of states

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

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
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$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>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 cf. deuteron.

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>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.

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>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.

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>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.

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>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.)

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		>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.)

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

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

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

So regardless short-distance potential, the same two channels are strongly preferred. Prediction: $1/2(5/2^-)$ $\Sigma_c^* \bar{D}^*$ state.

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

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

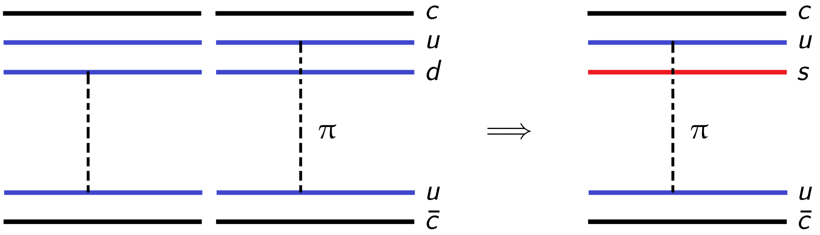
$\Xi_c^* \bar{D}^*$ molecules

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

Spins and constituents differ from local hidden-gauge approach

[Wu,Molina,Oset,Zhu(2010,2011);Feijoo,Magas,Ramos,Oset(2015)

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

Isospin and decays

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

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

Mass gap is significant on the scale of the binding energies,

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

so the P_c states have mixed isospin,

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

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

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

Isospin and decays: 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.

Isospin and decays: 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.
$\implies I = 3/2$ 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:
$\rightarrow J/\psi \Lambda$: D-wave, spin flip
e.g. $\Lambda_b^0 \rightarrow J/\psi \Lambda \eta, J/\psi \Lambda \phi$

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

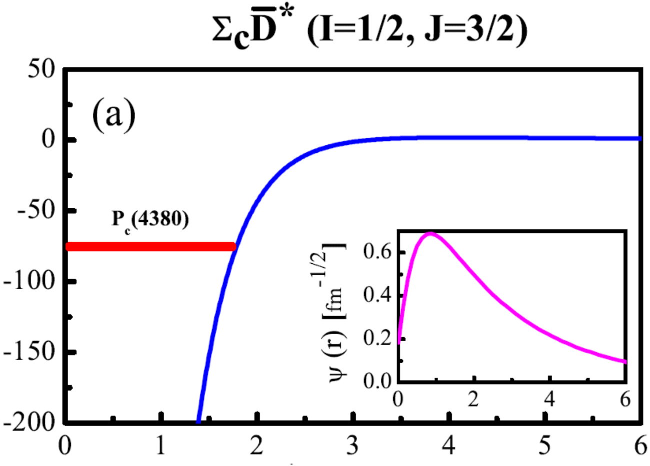
Conclusions

- Pion exchange (normalised to the deuteron) binds a $\Sigma_c \bar{D}^*$ molecule, consistent with $P_c(4450)$.
- Within a significant (and constrained) parameter range, and independently of the poorly-known short-distance potential, only one $\Sigma_c^* \bar{D}^*$ partner is expected, and its absence (so far) has a possible explanation.
- 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

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)]

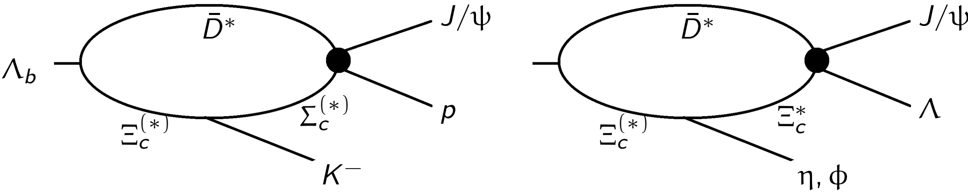
But should it be trusted?

$\Xi_c^* \bar{D}^*$ 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 $P_c(4450)$

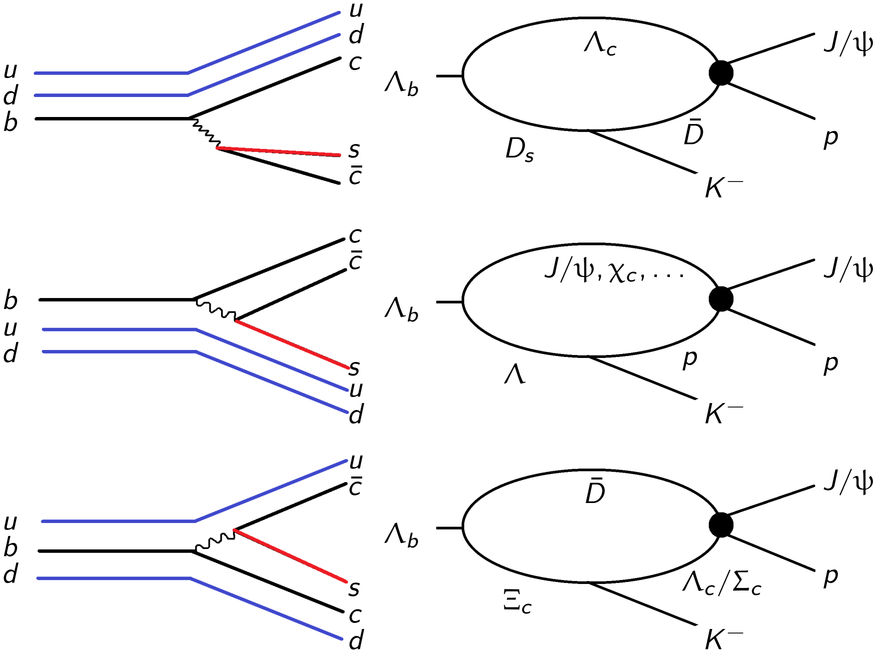


Cusps and triangle singularities

Models:

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

Cusps and triangle singularities



$P_c(4380)$ 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:

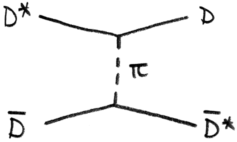
- neutral $I = 1/2$ partner
- possible $I = 3/2$ partners including doubly-charged, decaying into $J/\psi\Delta$
- possible J^P partners

Compact pentaquark scenario:

- many partners with different flavours and J^P

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

$X(3872)$

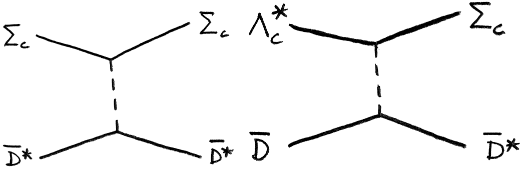


$\bar{D}^{*0} - \bar{D}^0 = 142.1$

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

Isospin violation

$P_c(4450)$



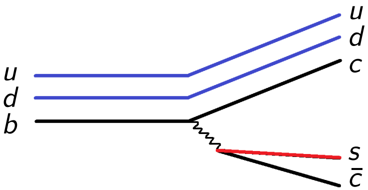
$\Lambda_c^{*+} - \Sigma_c^+ = 139.4$

Nearby $\chi_{c1} p$

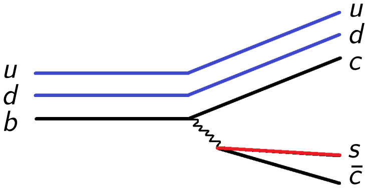
Isospin violation?

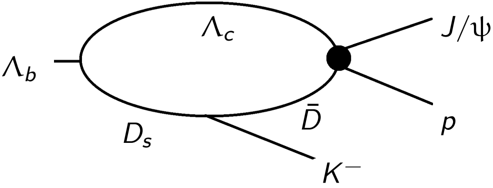
Enhanced binding (S-wave vertex)?

Cusps and triangle diagrams

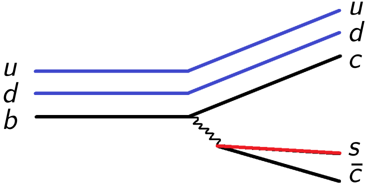


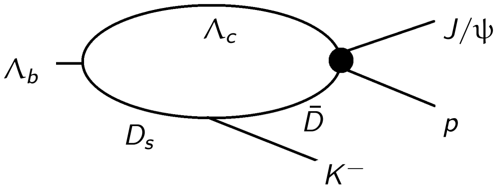
Cusps and triangle diagrams

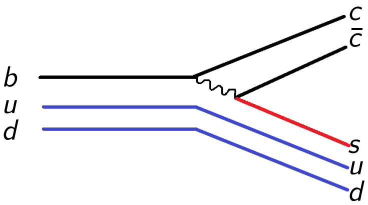




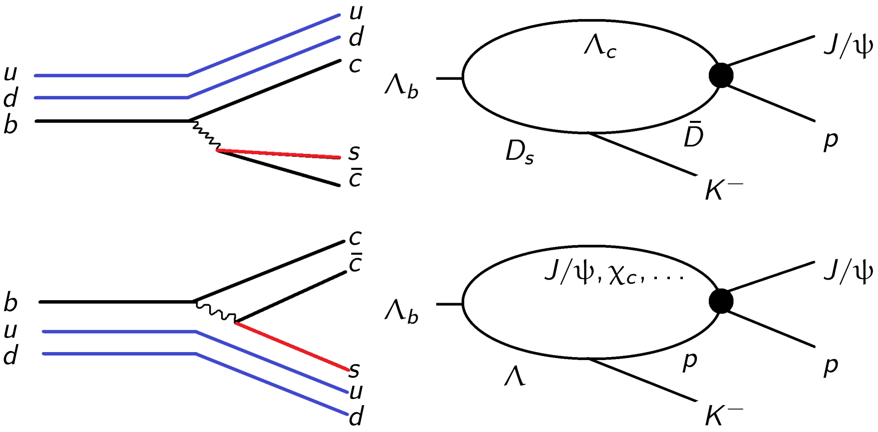
Cusps and triangle diagrams



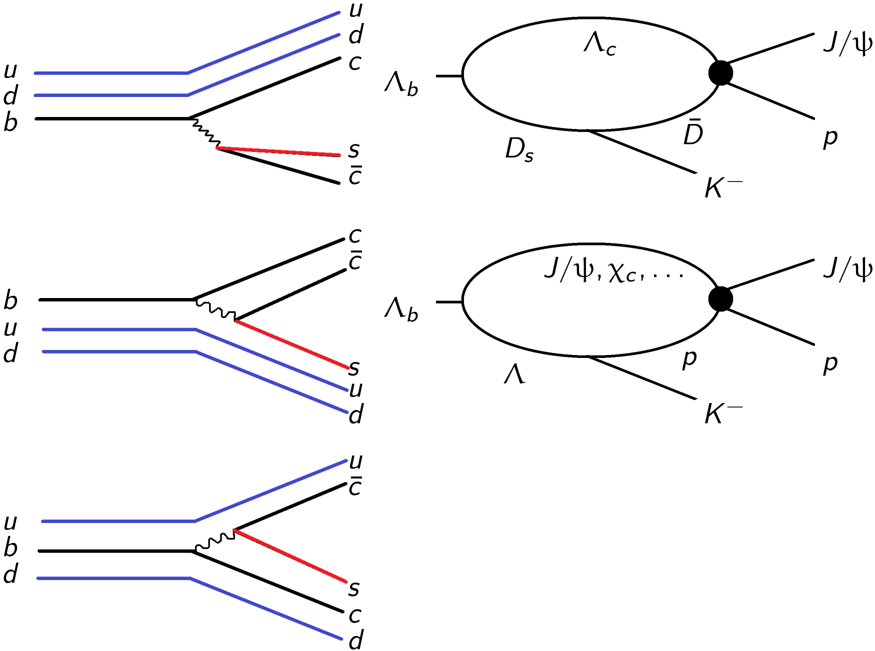




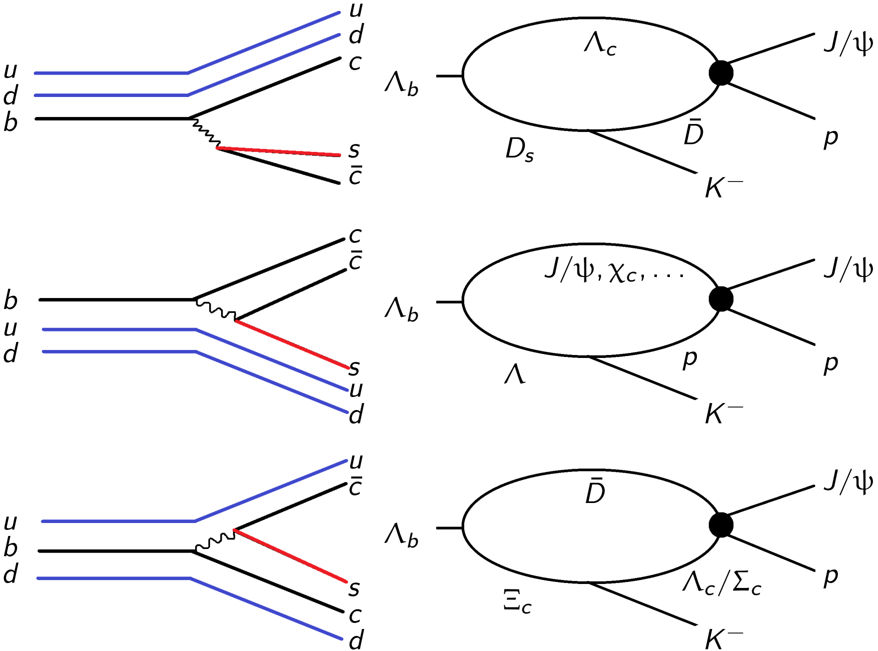
Cusps and triangle diagrams



Cusps and triangle diagrams

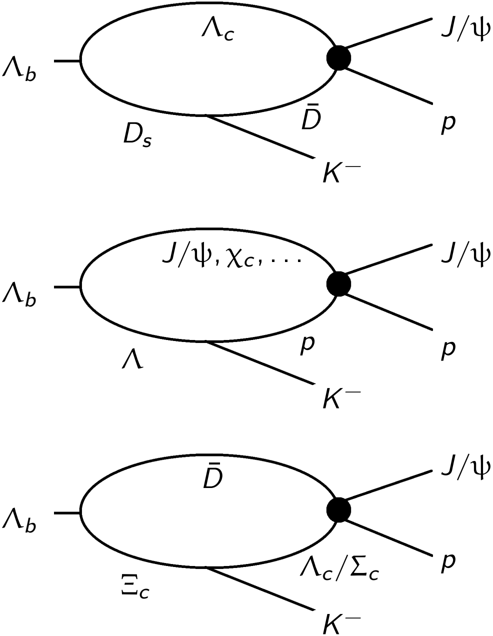


Cusps and triangle diagrams



Cusps and triangle diagrams

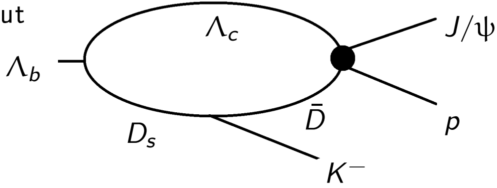
Enhancements expected at
$\Lambda_c \bar{D} = 1/2^-$
$\Lambda_c \bar{D}^* = 1/2^-, 3/2^-$
not seen at LHCb

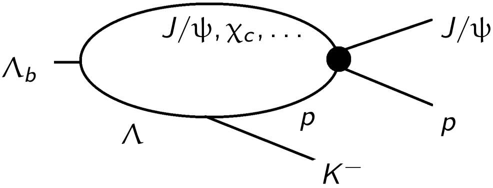


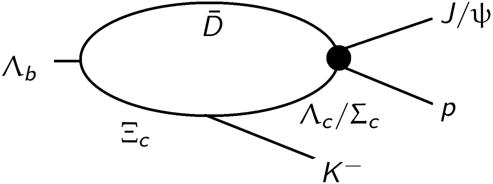
Cusps and triangle diagrams

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

- S-wave $= 1/2^+$
- P-wave $= 1/2^-, 3/2^-$
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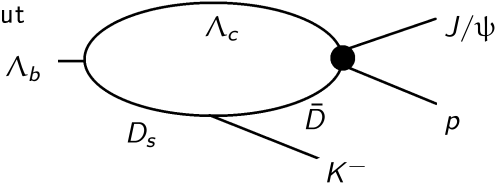
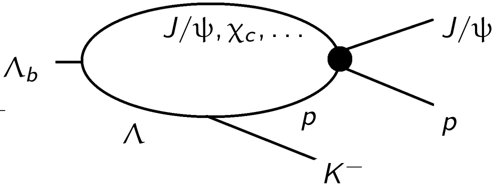
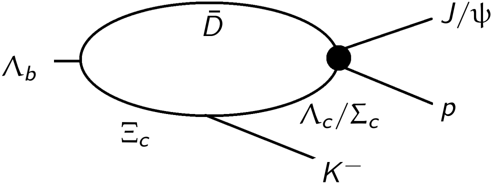


$\chi_{c1} p = P_c(4450)$ mass, but

- doubly suppressed
- S-wave $= 1/2^+, 3/2^+$
- P-wave $= 1/2^-, 3/2^-, 5/2^-$

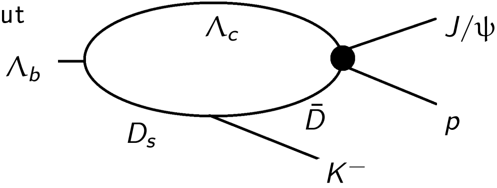




Cusps and triangle diagrams

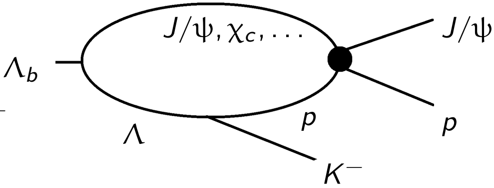
$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but

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



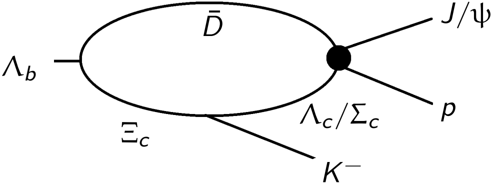
$\chi_{c1} p = P_c(4450)$ mass, but

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

Amplitudes for P_c states