From the deuteron to $P_c(4450)$

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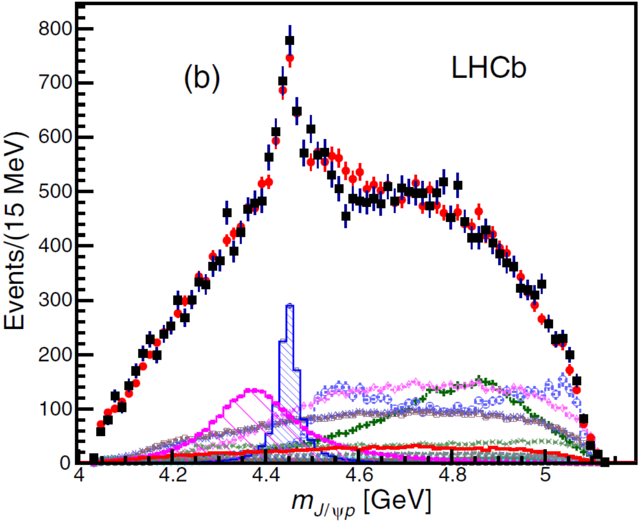
[T.B., Eur.Phys.J. A51, 152 (2015), 1509.02460]
[T.B. & E.Swanson (ongoing)]

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

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



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

$P_c(4380)$ 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	$5/2^+$	$3/2^-$

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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.

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

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 :	$(ud)_0 c$	$0(1/2^+)$	$\bar{D}$:	$u\bar{c}$	$1/2(0^-)$
Σ_c :	$(ud)_1 c$	$1(1/2^+)$	$\bar{D}^*$:	$u\bar{c}$	$1/2(1^-)$
Σ_c^* :	$(ud)_1 c$	$1(3/2^+)$			

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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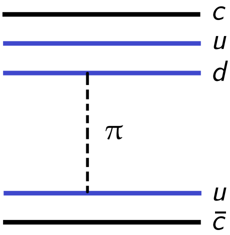

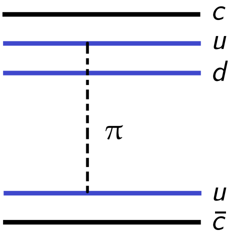

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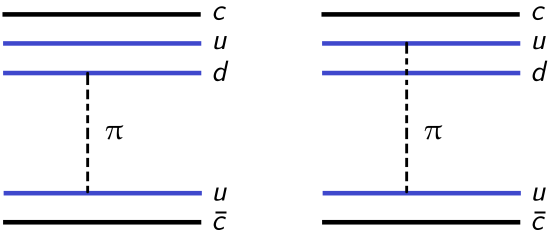

Coefficient of $C(r)$ is important.

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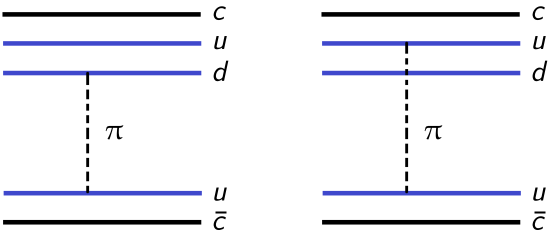

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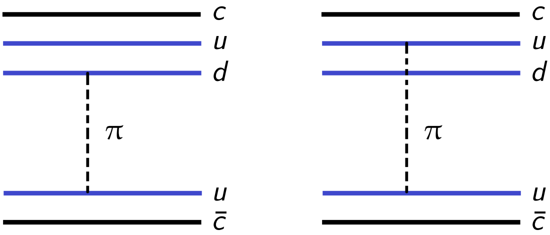

Coefficient of $C(r)$ is important. But:

- 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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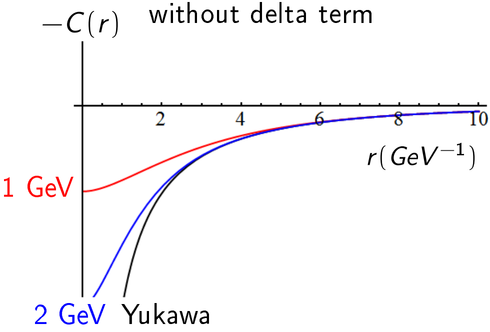

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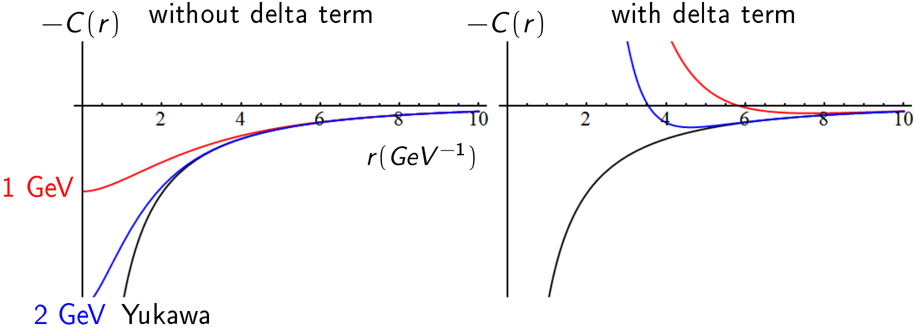

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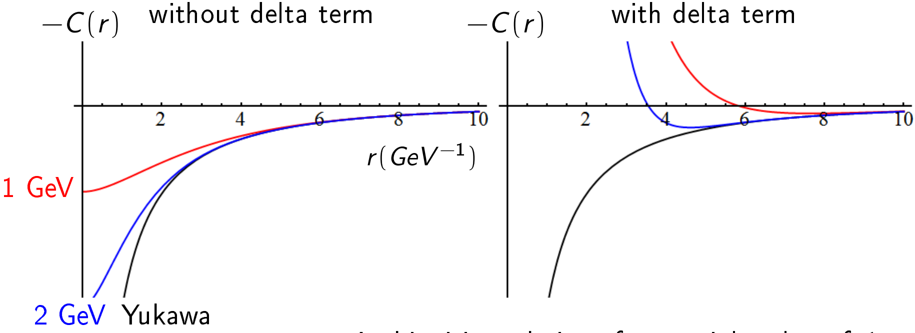

Ambiguities: choice of potential, value of Λ.

Pion-exchange: 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)]

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

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

$I = 3/2$ potentials suppressed by $-1/2$.

Attractive potentials have negative coefficient.

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

Pion-exchange: spectrum of states

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

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
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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

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

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

Pion-exchange: spectrum of states

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

$I(J^P)$	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
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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 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

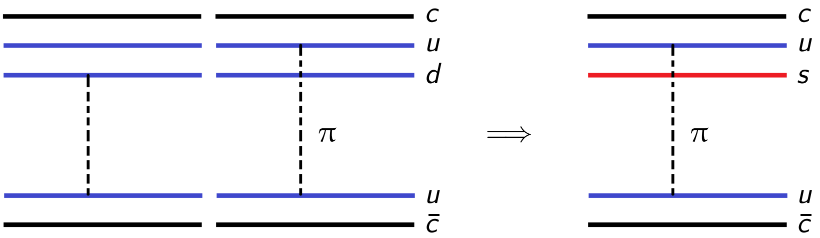
The model is falsifiable: it only works if $P_c(4450)$ is $1/2(3/2^-)$.

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

Preview of other results

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

Predict loosely bound $0(5/2^-)$ $\Xi_c^* \bar{D}^*$ state, observable in $\Lambda_b \to J/\psi \Lambda \eta$.

Isospin mixing

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

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:

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

Similar situation for the other predicted states.

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

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

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

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

	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

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

	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

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

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

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

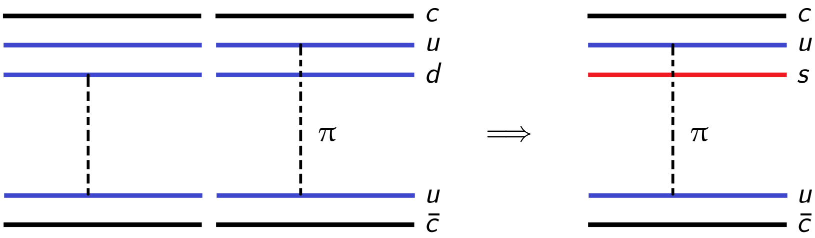
	Compact pentaquark	Hadronic molecule	Threshold effect
d.o.f.	quarks/diquarks	baryon+meson	baryon+meson
Interactions	binding via confinement + gluon-exch.	$(udc)(u\bar{c})$ binding via π exchange	$(udc)(u\bar{c})$ $\to (udd)(c\bar{c})$ scattering
colour	$(qqq)_1(q\bar{q})_1 \oplus (qqq)_8(q\bar{q})_8$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

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

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.
$\Longrightarrow$ $I = 3/2$ decay enhanced.

Isospin and decays: predicted $5/2^-$ states

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$$\Sigma_c^{*+} \bar{D}^{*0} = 4524.4 \pm 2.4$$
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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.
$\Longrightarrow$ $I = 3/2$ decay enhanced.

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

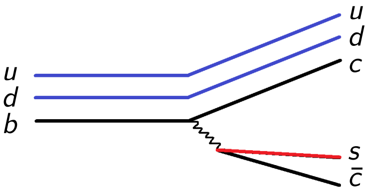
$$\Xi_c^{*0} \bar{D}^{*0} = 4652.9 \pm 0.6$$
$$\Xi_c^{*+} D^{*-} = 4656.2 \pm 0.7$$

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

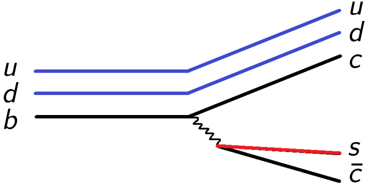
Decays:
$\to J/\psi\Lambda$: D-wave, spin flip
e.g. $\Lambda_b^0 \to J/\psi\Lambda\eta, J/\psi\Lambda\phi$

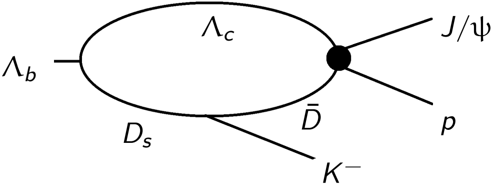
$\to J/\psi\Sigma^*$: S-wave, spin cons.
$\Longrightarrow$ $I = 1$ decay enhanced.

Cusps and triangle diagrams

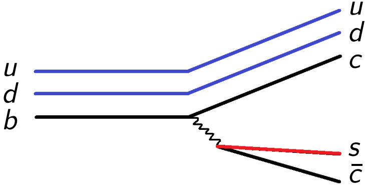


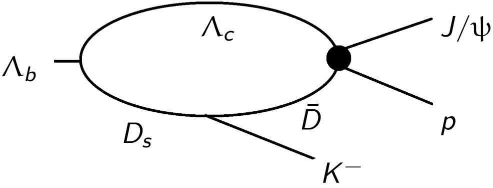
Cusps and triangle diagrams

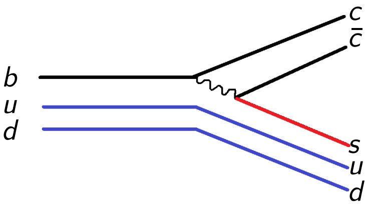




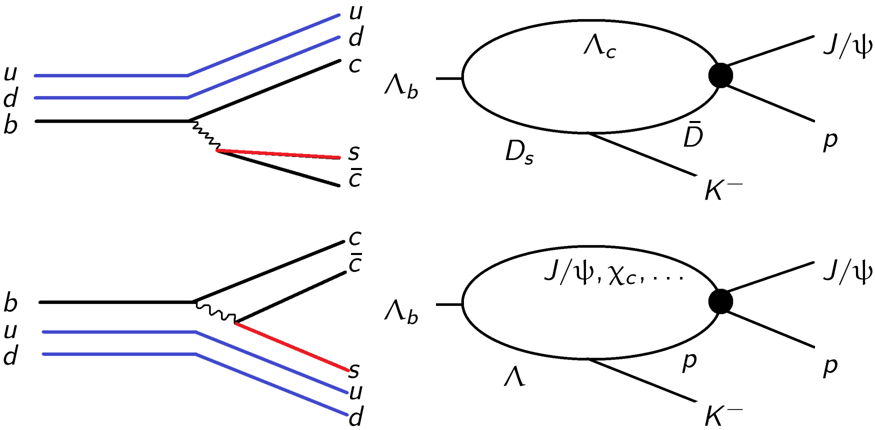
Cusps and triangle diagrams



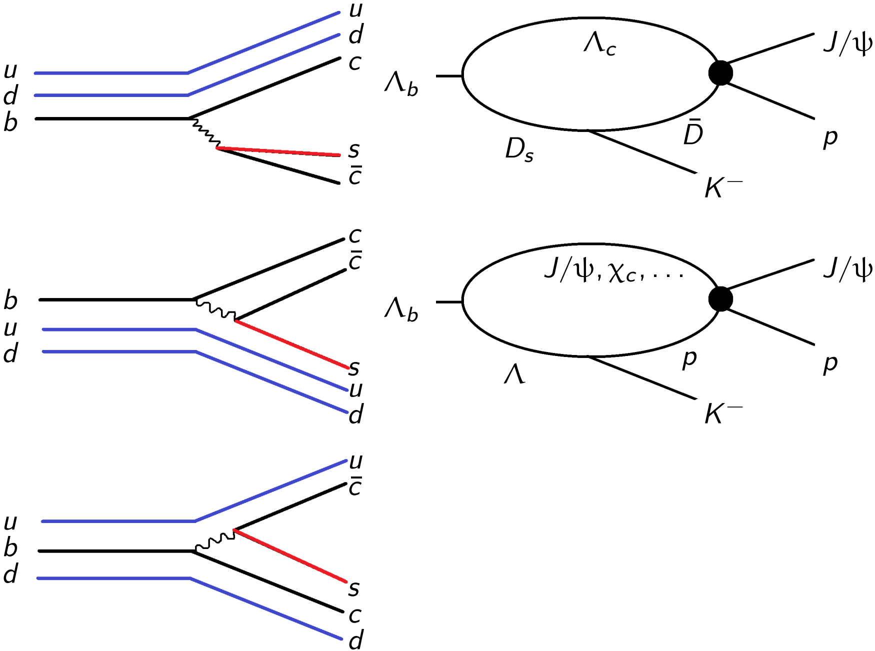




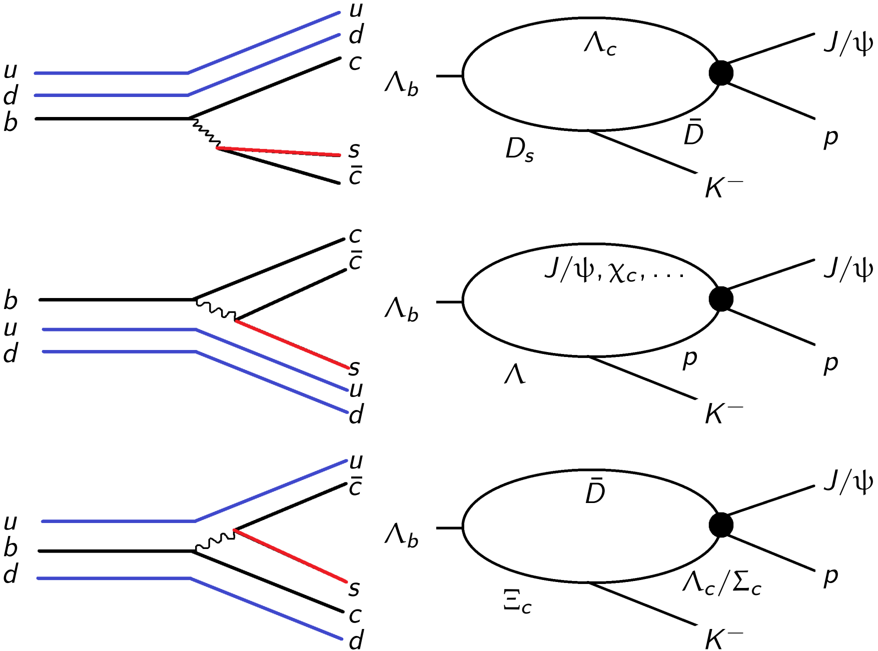
Cusps and triangle diagrams



Cusps and triangle diagrams

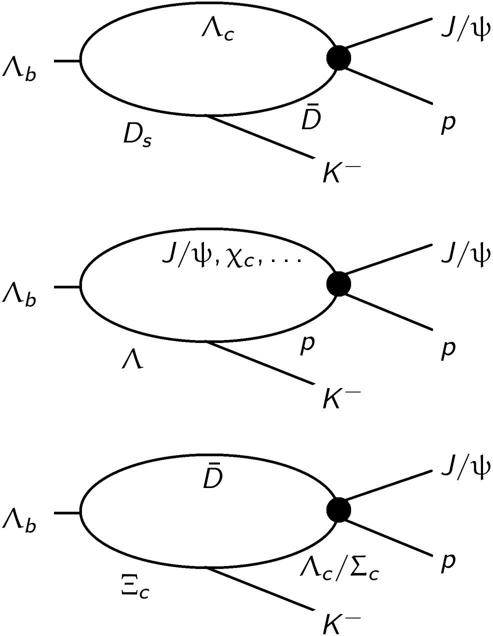


Cusps and triangle diagrams



Cusps and triangle diagrams

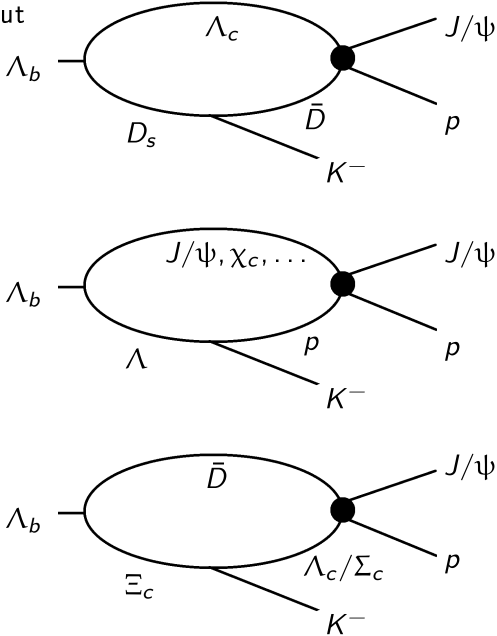
Enhancements expected at
$\Lambda_c \bar{D} = 1/2^-$
$\Lambda_c \bar{D}^* = 1/2^-, 3/2^-$
not seen at LHCb



Cusps and triangle diagrams

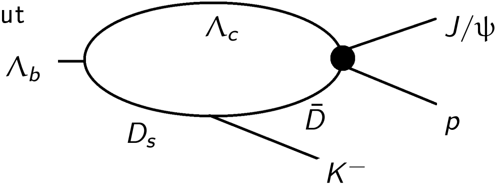
$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but

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

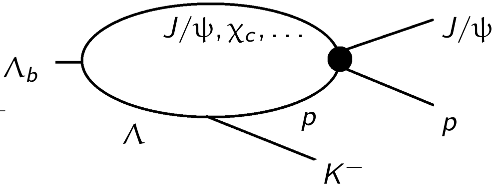


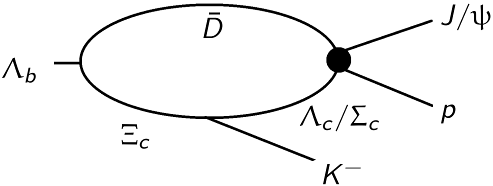
Cusps and triangle diagrams

$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but
- S-wave $= 1/2^+$
- P-wave $= 1/2^-, 3/2^-$
- 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 $= 1/2^-, 3/2^-, 5/2^-$

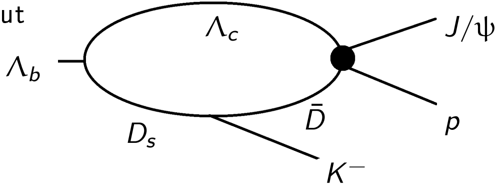




Cusps and triangle diagrams

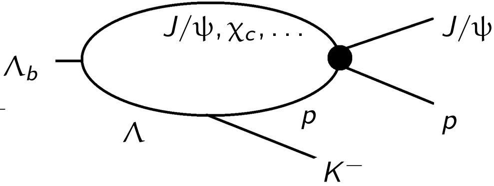
$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but

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



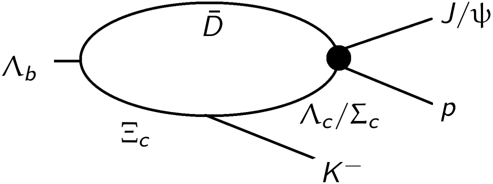
$\chi_{c1} p = P_c(4450)$ mass, but

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



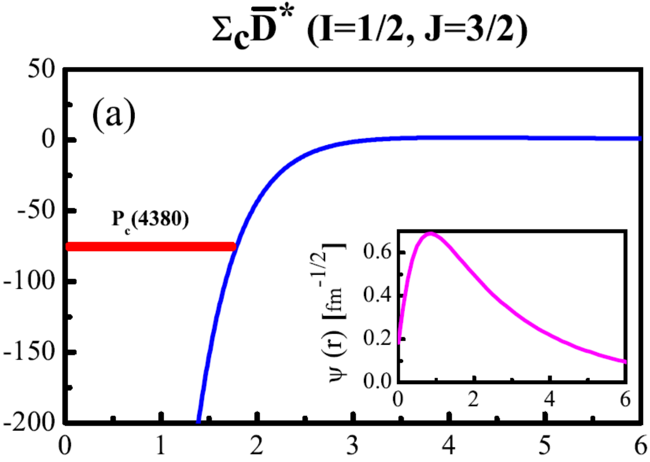
$\Sigma_c^* \bar{D} \approx P_c(4380)$ mass, and
$\Sigma_c \bar{D}^* \approx P_c(4450)$ mass, but

- doubly suppressed
- what restricts J^P?
- why not $\Sigma_c \bar{D}, \Sigma_c^* \bar{D}^*$?



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?