Pion exchange for $P_c(4450)^+$ and related states

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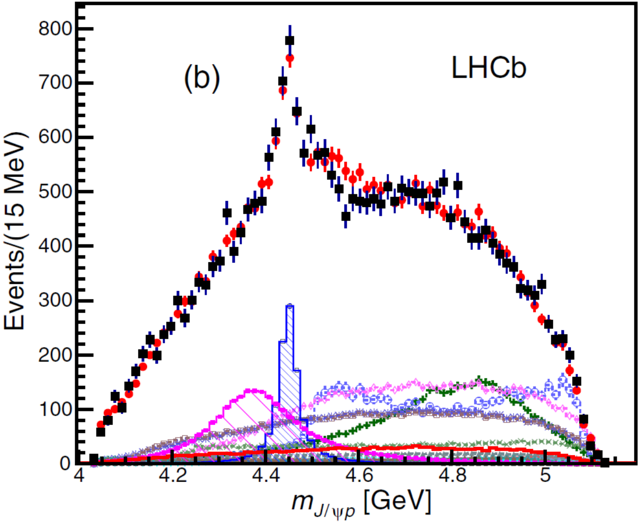
[T.B., Eur.Phys.J. A51, 152 (2015), 1509.02460]
[T.B. & E.Swanson (ongoing)]

$P_c(4380)$ 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);S.Neubert 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

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

Potential between hadrons due to quark-pion vertices, with parameters fit to the deuteron:

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

For $uudc\bar{c}$, each constituent must have:

- light quarks: $(udc)(u\bar{c})$ but not $(uud)(c\bar{c})$
- non-zero isospin: Σ_c, Σ_c^*, but not Λ_c.
- non-zero spin: $\bar{D}^*$ but not $\bar{D}$.

This leaves

- $\Sigma_c \bar{D}^*$ [$P_c(4450)$]
- $\Sigma_c^* \bar{D}^*$

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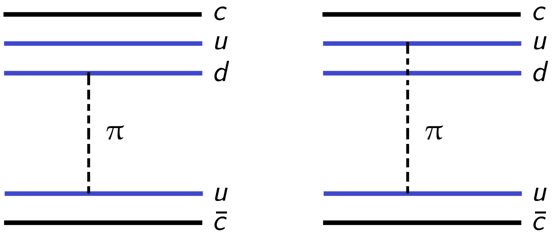

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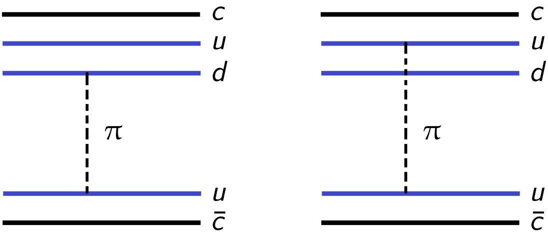
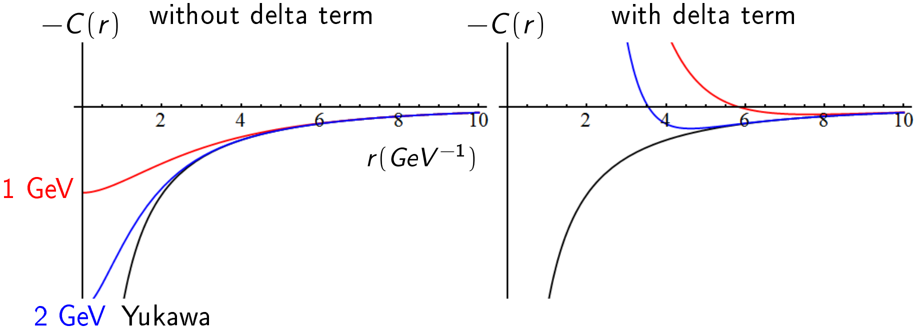


Pion exchange: central potential

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

The potential is "attractive" if $\langle \sum_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j < 0 \rangle$, and for NN this is guaranteed by Pauli stats.



[See also Close & Thomas PRD78,034007(2008)]

Pion exchange: central potential

The coefficients $\langle \sum_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j \rangle$ of $C(r)$ are:

$\Sigma_c \bar{D}^*$		$\Sigma_c^* \bar{D}^*$	
$1/2(1/2^-)$	$+16/3$	$1/2(1/2^-)$	$+20/3$
$1/2(3/2^-)$	$-8/3$	$1/2(3/2^-)$	$+8/3$
		$1/2(5/2^-)$	-4
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$3/2(3/2^-)$	$+4/3$	$3/2(3/2^-)$	$-4/3$
		$3/2(5/2^-)$	$+2$

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Two attractive channels in $I = 1/2$:

- $\Sigma_c \bar{D}^*$ $1/2(3/2^-)$: matches $P_c(4450)$
- $\Sigma_c^* \bar{D}^*$ $1/2(5/2^-)$: $\rightarrow J/\psi p$ in D-wave with spin violation

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Several attractive $I = 3/2$ states.

Pion exchange: central potential

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Several attractive $I = 3/2$ states.
But...the central potential alone is too weak to bind!

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: central and tensor

Dipole cut-offs Λ (GeV) required to achieve binding:

			$P_c(4450)$		
	NN	$\Sigma_c^*\bar{D}^*$	$\Sigma_c\bar{D}^*$	other	other
	$0(1^-)$	$\frac{1}{2}(\frac{5}{2}^-)$	$\frac{1}{2}(\frac{3}{2}^-)$	$\frac{1}{2}(J^-)$	$\frac{3}{2}(J^-)$
No delta	0.8	0.9	1.1	$\geqslant 1.4$	$\geqslant 1.7$
Delta	1.0	1.2	1.4		

For both extremes (with or without the δ term):

- $\Sigma_c^{(*)}\bar{D}^*$ binding with modest increase in Λ cf. deuteron
- $I = 1/2$ binding c.f. central potential, but not $I = 3/2$
- over large range of Λ there are (only) two bound states: the $P_c(4450)$ candidate, plus (more deeply bound) $\Sigma_c^*\bar{D}^*$ $\frac{1}{2}(\frac{5}{2}^-)$.
- Λ is constrained: if additional states bind, $P_c(4450)$ is too bound, and the additional states cannot be "explained away".

N.B.: an attractive delta function core spoils the pattern.

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

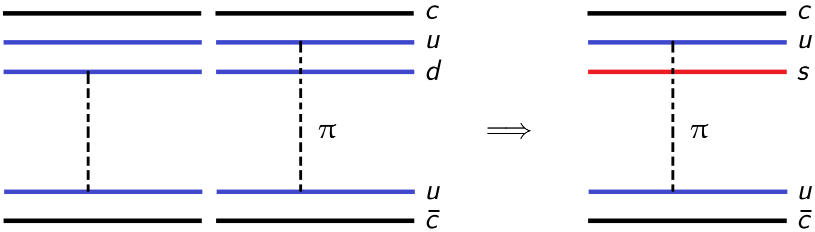
$\Xi_c^* \bar{D}^*$ molecules

The Ξ_c family also couple to pions.

$$\Lambda_c = ((ud)_0 c)_{1/2} \quad \Longrightarrow \quad \Xi_c = ((us)_0 c)_{1/2}$$
$$\Sigma_c = ((ud)_1 c)_{1/2} \quad \Longrightarrow \quad \Xi_c' = ((us)_1 c)_{1/2}$$
$$\Sigma_c^* = ((ud)_1 c)_{3/2} \quad \Longrightarrow \quad \Xi_c^* = ((us)_1 c)_{3/2}$$

and so potentially form molecules

$$\Sigma_c \bar{D}^* \quad \Longrightarrow \quad \Xi_c' \bar{D}^*$$
$$\Sigma_c^* \bar{D}^* \quad \Longrightarrow \quad \Xi_c^* \bar{D}^*$$



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

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

Thus anticipate some $I = 0$ but no $I = 1$ states:

$$\Sigma_c^* \bar{D}^* \ 1/2(5/2^-) \quad \Longrightarrow \quad \Xi_c^* \bar{D}^* \ 0(5/2^-)$$

$$\Sigma_c \bar{D}^* \ 1/2(3/2^-) \quad \Longrightarrow \quad \Xi_c' \bar{D}^* \ 0(3/2^-)$$

	NN $0(1^-)$	$\Sigma_c^* \bar{D}^*$ $\frac{1}{2}(\frac{5}{2}^-)$	$P_c(4450)$ $\Sigma_c \bar{D}^*$ $\frac{1}{2}(\frac{3}{2}^-)$	$\Xi_c^* \bar{D}^*$ $0(\frac{5}{2}^-)$	$\Xi_c' \bar{D}^*$ $0(\frac{3}{2}^-)$	other $\frac{1}{2}(J^-)$	other $\frac{3}{2}(J^-)$
Delta	0.8	0.9	1.1	1.2	1.4	1.4	1.7
No delta	1.0	1.2	1.4	1.5	1.8		

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

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

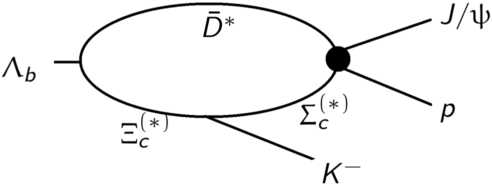
Local-hidden gauge: $\Xi_c \bar{D}^*$ $0(3/2^-)$, $\Xi_c' \bar{D}^*$ $0(3/2^-)$

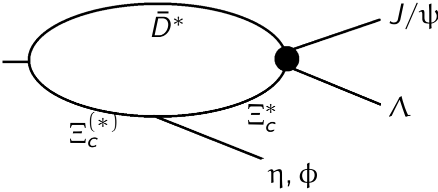
[Wu,Molina,Oset,Zhu(2010,2011);Feijoo,Magas,Ramos,Oset(2015)

[see talk V.Magas]

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

- weakly bound, with mass $\approx$ 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 $P_c(4450)$

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,

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

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:

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

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

Isospin mixing: other states

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

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

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

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

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

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

Eigenstate of mixed isopsin:
$|P\rangle = \cos\phi|0, 0\rangle + \sin\phi|1, 0\rangle$

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

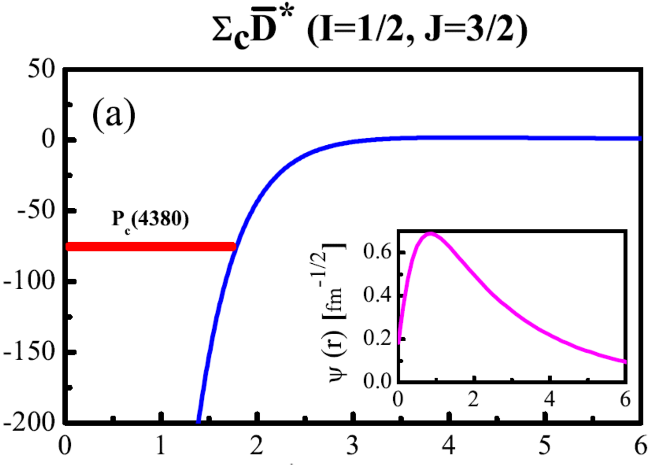
Conclusions

- 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.
- A corresponding $\Xi^* \bar{D}^*$ molecule is also bound, and is produced via similar diagrams to the P_c states.
- 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)]

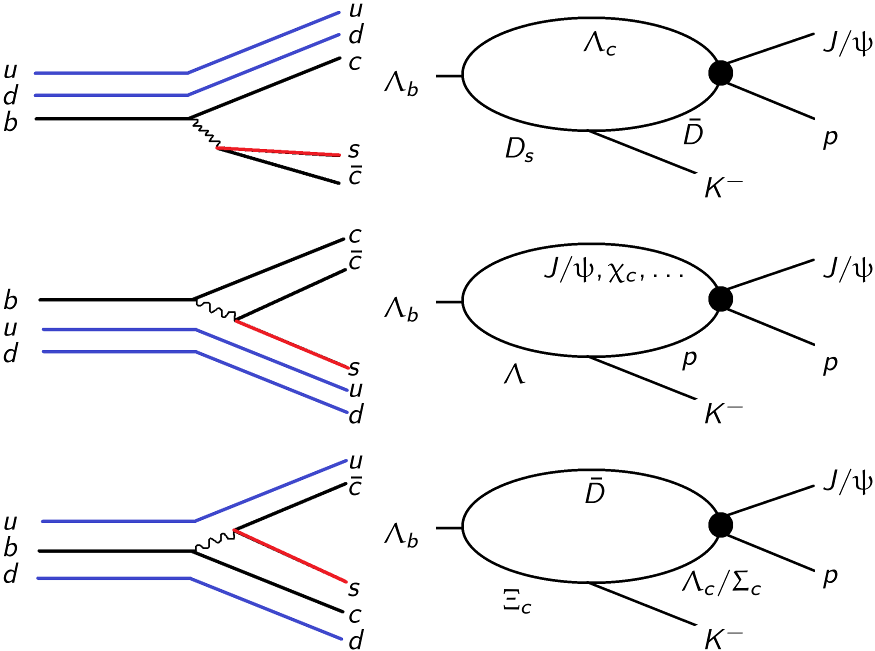
But should it be trusted?

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:

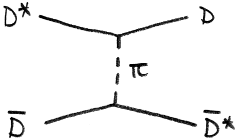
- neutral $I = 1/2$ partner
- possible $I = 3/2$ partners including doubly-charged, decaying into $J/\psi\Delta$
- possible J^P partners

Compact pentaquark scenario:

- many partners with different flavours and J^P

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

$X(3872)$

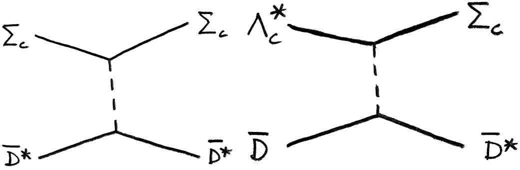


$\bar{D}^{*0} - \bar{D}^0 = 142.1$

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

Isospin violation

$P_c(4450)$



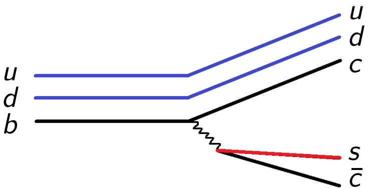
$\Lambda_c^{*+} - \Sigma_c^+ = 139.4$

Nearby $\chi_{c1} p$

Isospin violation?

Enhanced binding (S-wave vertex)?

Cusps and triangle diagrams



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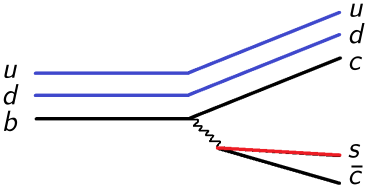

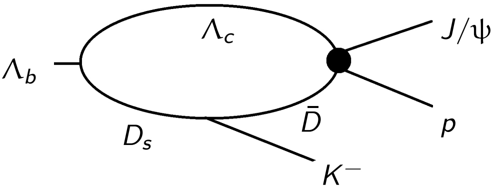

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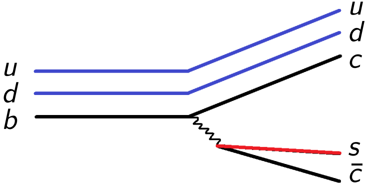

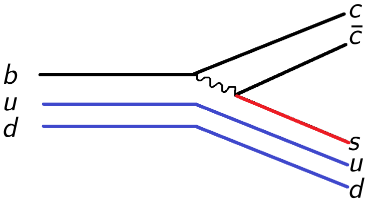

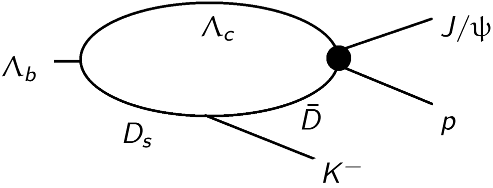

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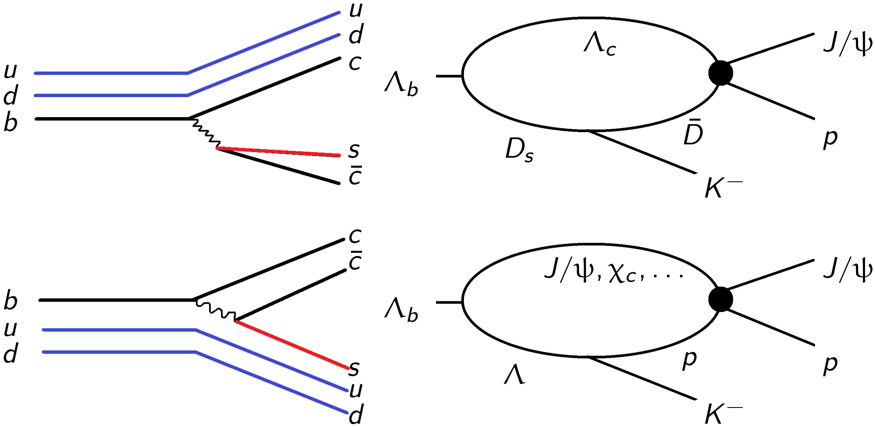
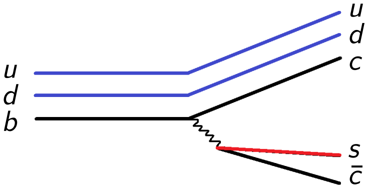
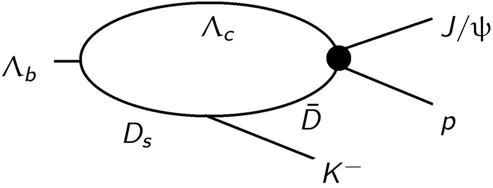
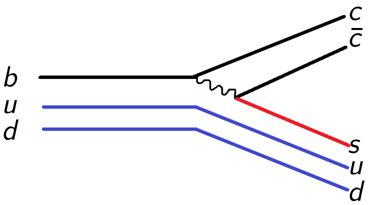
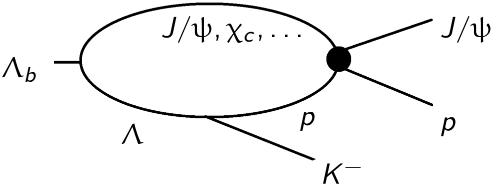


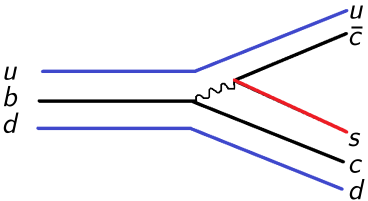
Cusps and triangle diagrams



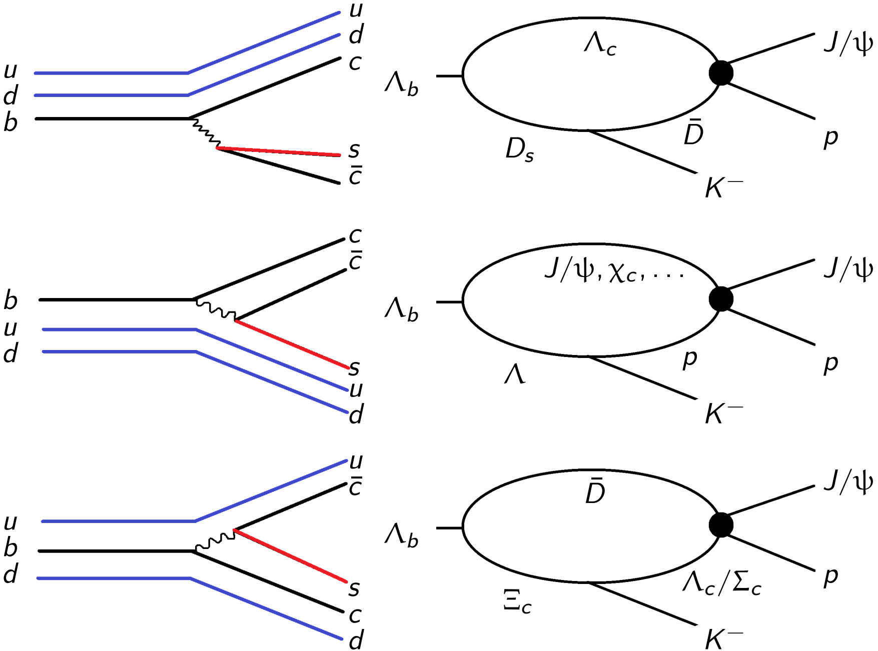






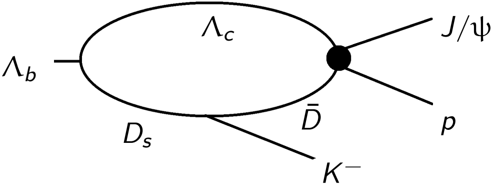


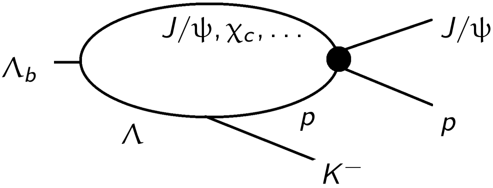
Cusps and triangle diagrams

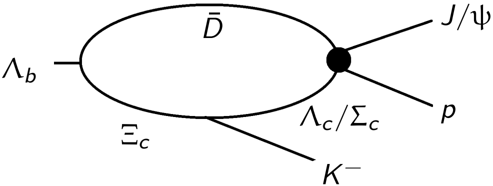


Cusps and triangle diagrams

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



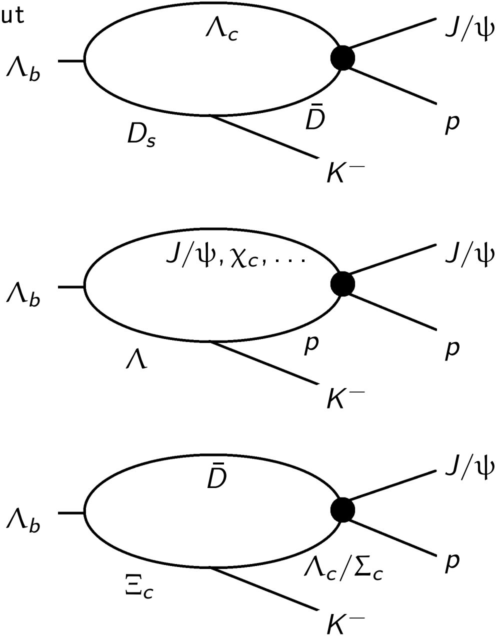




Cusps and triangle diagrams

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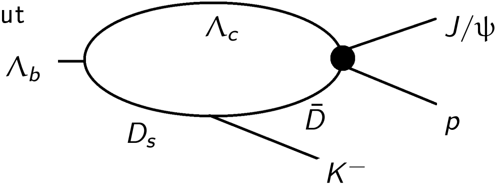
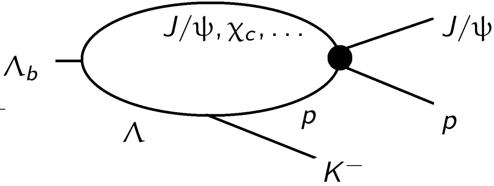
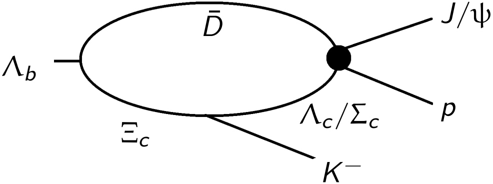


$\chi_{c1} p = P_c(4450)$ mass, but

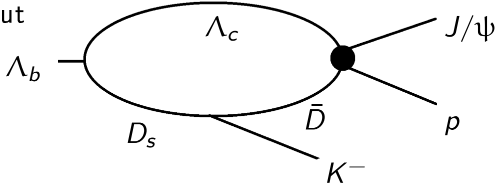
- doubly suppressed
- S-wave $= 1/2^+, 3/2^+$
- P-wave $= 1/2^-, 3/2^-, 5/2^-$



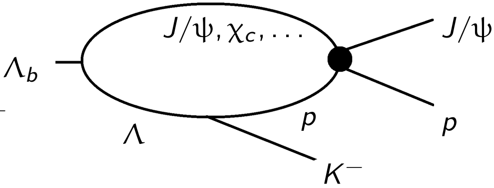


Cusps and triangle diagrams

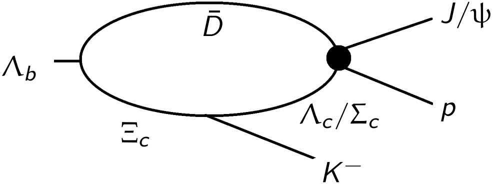
$\Lambda_c^* \bar{D} \approx P_c(4450)$ mass, but
- S-wave $= 1/2^+$
- P-wave $= 1/2^-, 3/2^-$
- why no $\Lambda_c^* \bar{D}^*$ states?



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

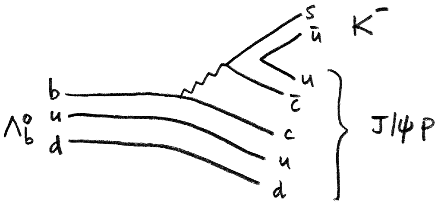


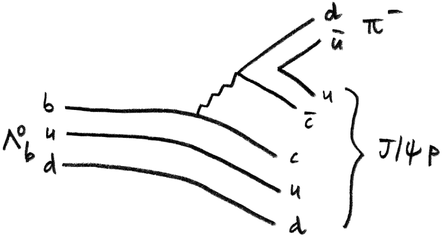
$\Sigma_c^* \bar{D} \approx P_c(4380)$ mass, and
$\Sigma_c \bar{D}^* \approx P_c(4450)$ mass, but
- doubly suppressed
- what restricts J^P?
- why not $\Sigma_c \bar{D}, \Sigma_c^* \bar{D}^*$?



P_c states in the Cabibbo-suppressed mode

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

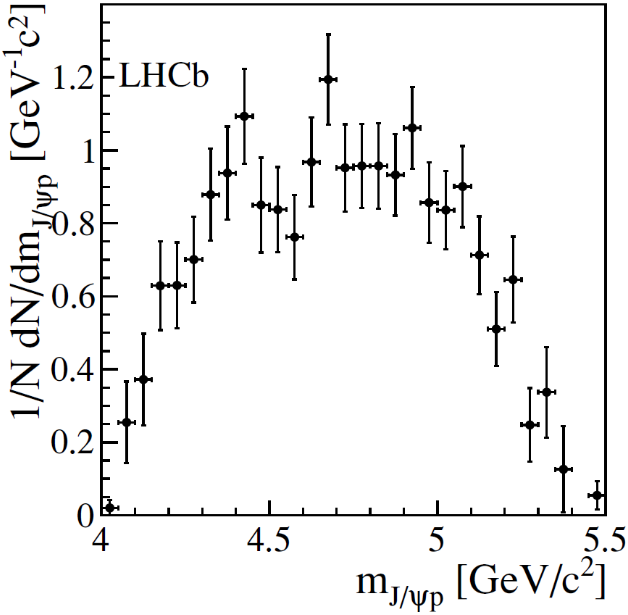




Before P_c discovery LHCb had previously observed $\Lambda_b \to J/\psi p \pi^-$, and reported no sign of a $J/\psi p$ structure.

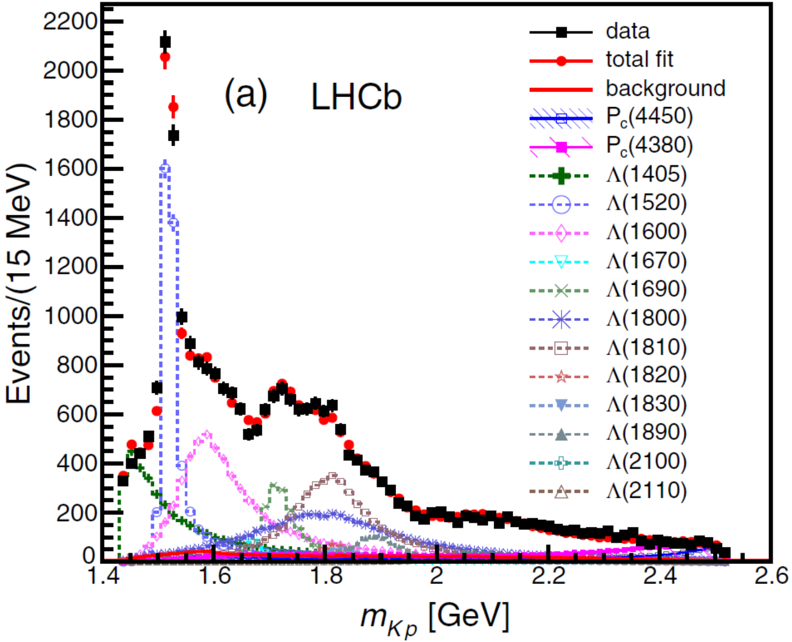
[LHCb, JHEP07(2014)103]

P_c states in the Cabibbo-suppressed mode

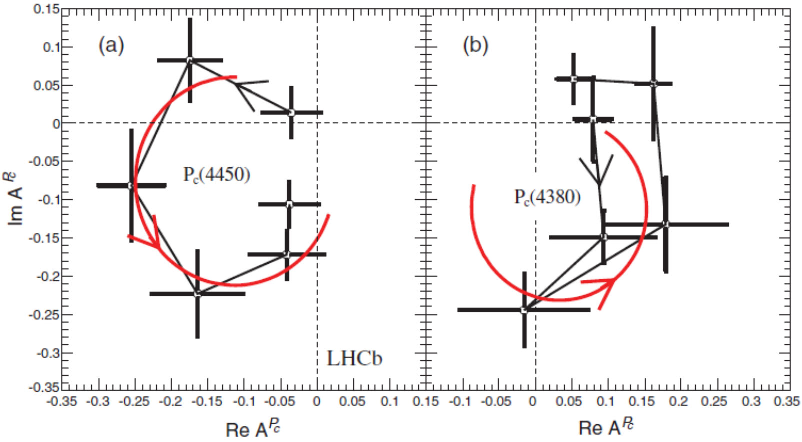


	P_c^*				P_c	
	$\chi_{c1} p$	$\Sigma_c \bar{D}^*$	$\Lambda_c^* \bar{D}$	$J/\psi N^*$	$\Sigma_c^* \bar{D}$	$J/\psi N^*$
$J/\psi N$	✓	✓	✓	✓	✓	✓
$\eta_c N$	×	×	✓	×	×	×
$J/\psi \Delta$	×	✓	×	×	✓	×
$\eta_c \Delta$	×	✓	×	×	✓	×
$\Lambda_c \bar{D}$	✓	[×]	[✓]	×	[×]	×
$\Lambda_c \bar{D}^*$	✓	✓	[✓]	✓	✓	✓
$\Sigma_c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

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



Amplitudes for P_c states

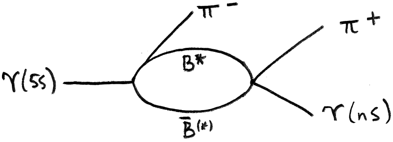


Cusps and triangle singularities

These effects are also connected to thresholds.

Belle study of decays

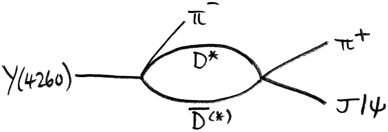
$$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$$
$$\Upsilon(5S) \to h_b(nS)\pi^+\pi^-$$



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

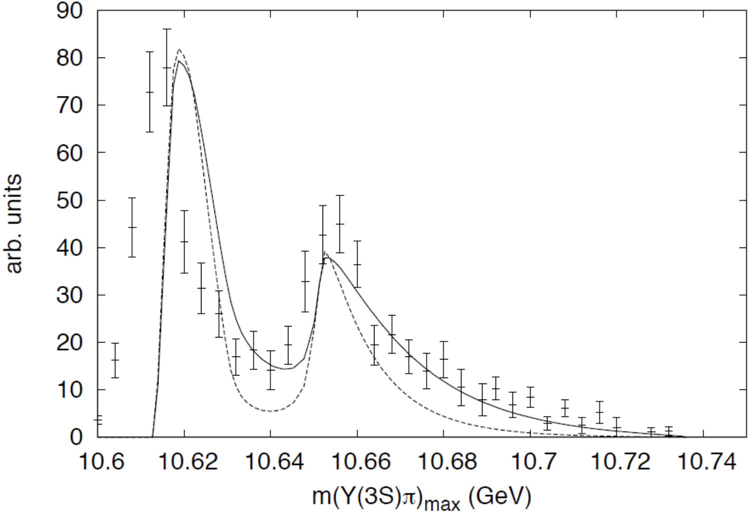
$$Y(4260) \to J/\psi\pi^+\pi^-$$



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)]

$P_c(4380)$ 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.

[LHCb,PRL115,072001,2015]