Coupled channel dynamics for LHCb pentaquarks

Tim Burns

Swansea University

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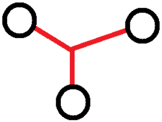
[T.B., Eur.Phys.J. A51, 152 (2015), 1509.02460]
[T.B. & E.Swanson, ongoing]

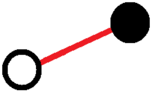
Conventional and exotic hadrons

Conventional and exotic hadrons

Baryons

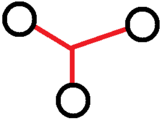


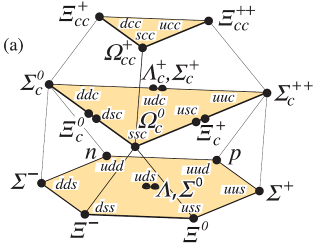
Mesons



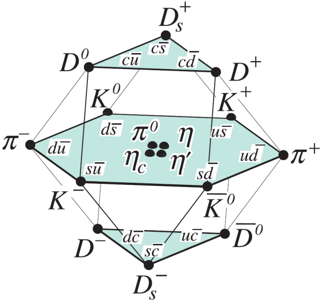
Conventional and exotic hadrons

Baryons



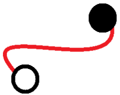


Mesons



Conventional and exotic hadrons

Hybrids



Conventional and exotic hadrons

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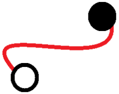
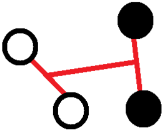
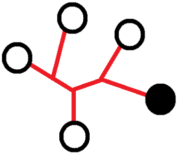


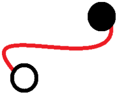
Compact multiquarks





Conventional and exotic hadrons

Hybrids



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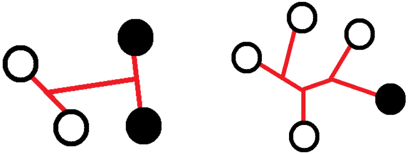
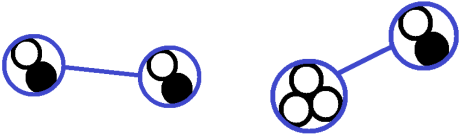
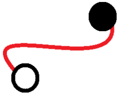


Hadronic molecules

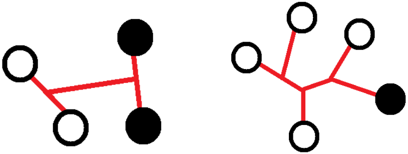


Conventional and exotic hadrons

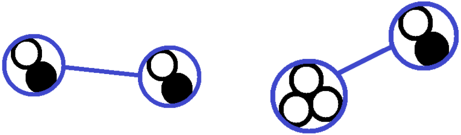
Hybrids



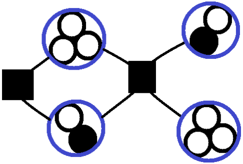
Compact multiquarks



Hadronic molecules

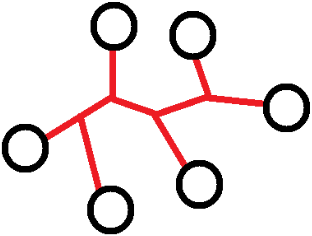


Threshold effect

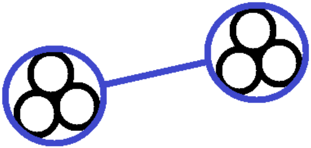


Deuteron

- 2.2 MeV below *pn* threshold
- $I = 0,\ J^P = 1^+$



vs.



- Relevant degrees of freedom are *p* and *n*
- Binding dominated by π exchange

Hadronic molecules

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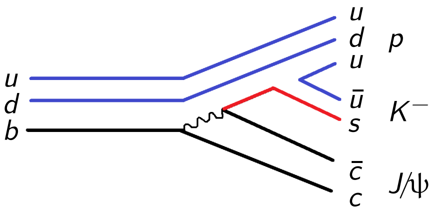
LHCb "pentaquarks"

2015: $P_c(4380)$ and $P_c(4450)$

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

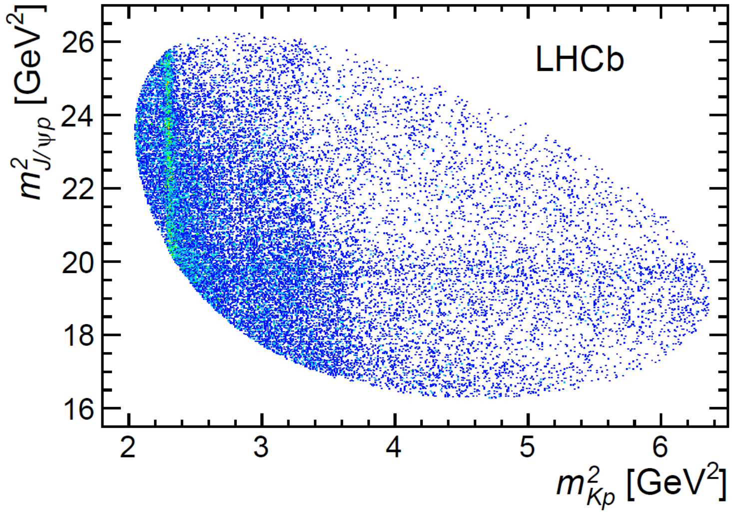
[LHCb,PRL115,072001,2015]



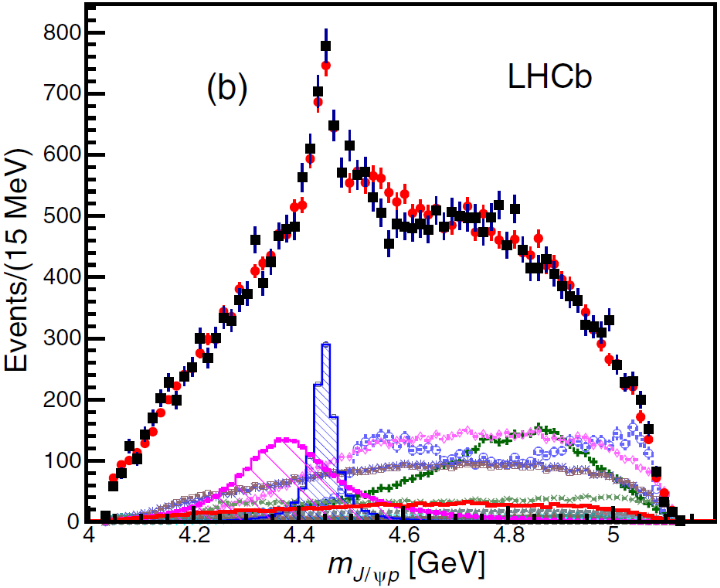
Two $J/\psi p$ states, the flavour of the proton with hidden charm ($uudc\bar{c}$).

2015: $P_c(4380)$ and $P_c(4450)$

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

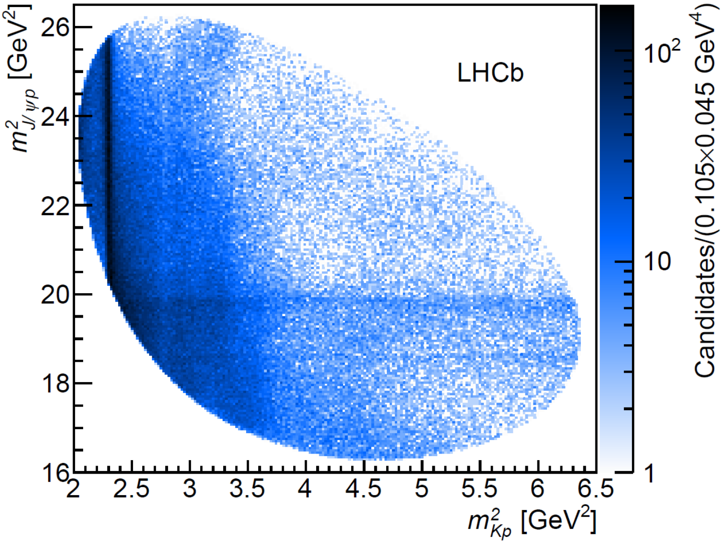


2015: $P_c(4380)$ and $P_c(4450)$

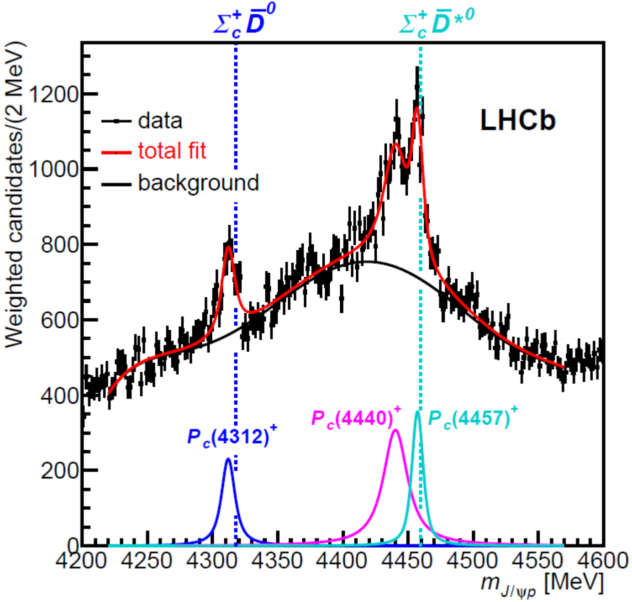


Two states with flavour of the proton, but "hidden charm": $uudc\bar{c}$.

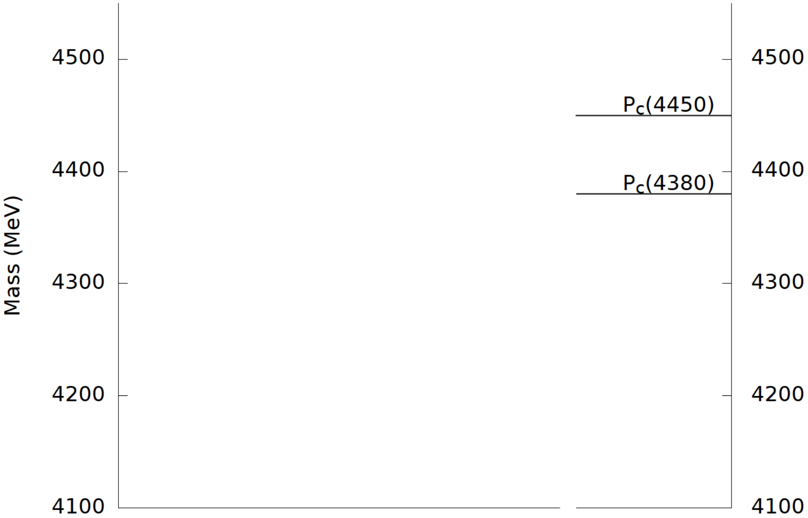
2019: $P_c(4312)$, $P_c(4440)$, $P_c(4457)$



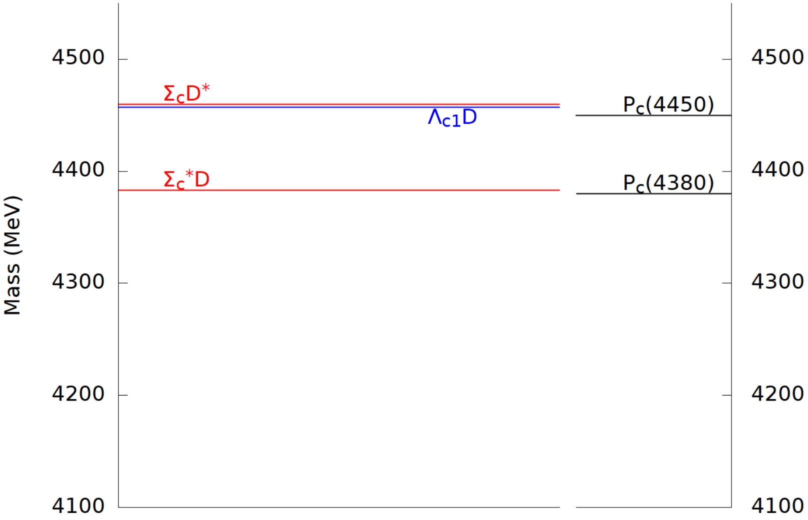
2019: $P_c(4312)$, $P_c(4440)$, $P_c(4457)$



Nearby thresholds



Nearby thresholds



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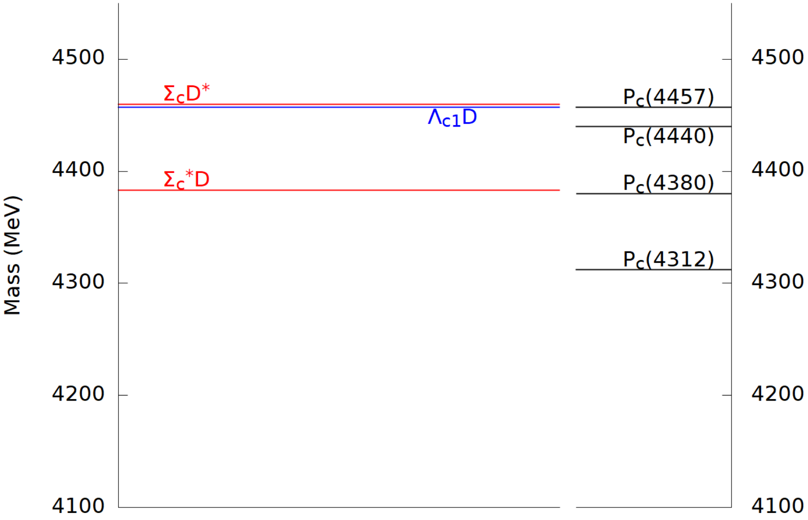
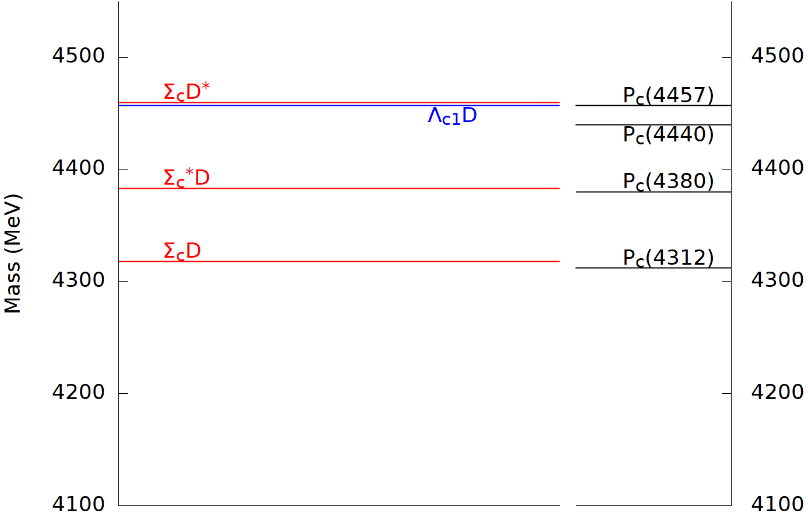
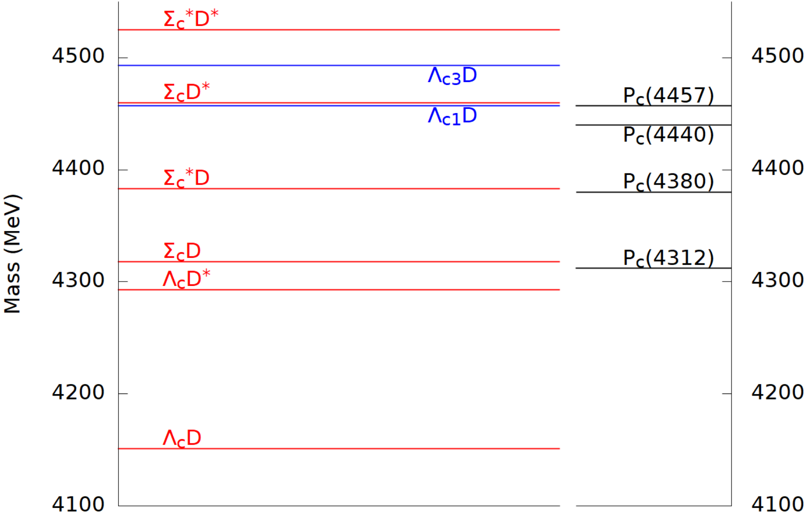


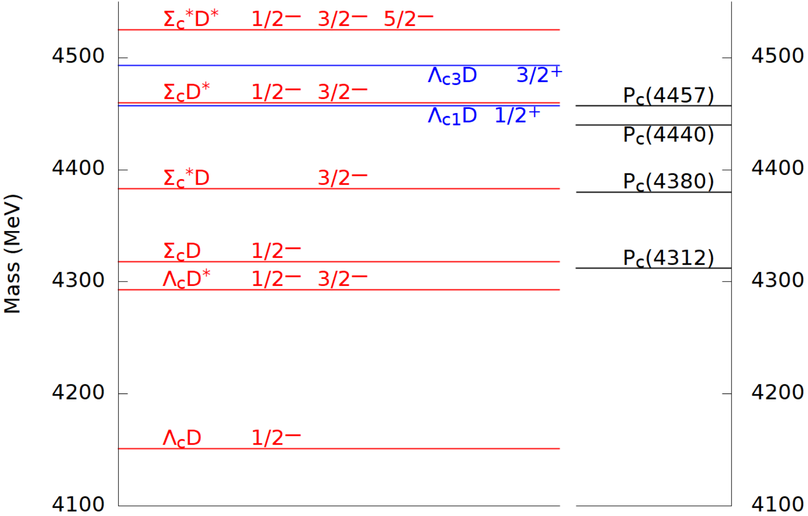
Nearby thresholds



Nearby thresholds



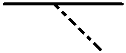
Nearby thresholds



Binding in hadronic molecules

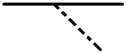
Heavy quark and chiral symmetry c.f. quark model

$N \to N\pi$



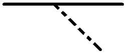
$g_{NN\pi}\ \vec{\sigma} \cdot \vec{q}\ \vec{\tau} \cdot \vec{\pi}$

$\Sigma_c \to \Sigma_c\pi$



$g_{\Sigma_c\Sigma_c\pi}\ \vec{\sigma} \cdot \vec{q}\ \vec{T} \cdot \vec{\pi}$

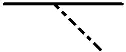
$D^* \to D^*\pi$



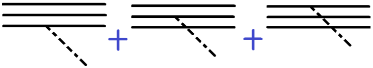
$g_{D^*D^*\pi}\ \vec{\epsilon} \cdot \vec{q}\ \vec{\tau} \cdot \vec{\pi}$

Heavy quark and chiral symmetry c.f. quark model

$N \to N\pi$

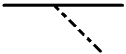


$g_{NN\pi}\ \vec{\sigma}\cdot\vec{q}\ \vec{\tau}\cdot\vec{\pi}$

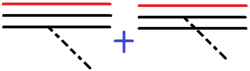


$g_{qq\pi}\sum_{i=1}^{3}\vec{\sigma}_i\cdot\vec{q}\ \vec{\tau}_i\cdot\vec{\pi}$

$\Sigma_c \to \Sigma_c\pi$

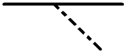


$g_{\Sigma_c\Sigma_c\pi}\ \vec{\sigma}\cdot\vec{q}\ \vec{T}\cdot\vec{\pi}$

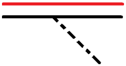


$g_{qq\pi}\sum_{i=1}^{2}\vec{\sigma}_i\cdot\vec{q}\ \vec{\tau}_i\cdot\vec{\pi}$

$D^* \to D^*\pi$



$g_{D^*D^*\pi}\ \vec{\epsilon}\cdot\vec{q}\ \vec{\tau}\cdot\vec{\pi}$



$g_{qq\pi}\vec{\sigma}_1\cdot\vec{q}\ \vec{\tau}_1\cdot\vec{\pi}$

Heavy quark and chiral symmetry c.f. quark model

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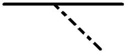
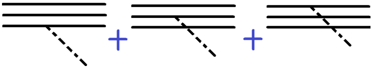
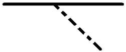


$g_{NN\pi}\ \vec{\sigma} \cdot \vec{q}\ \vec{\tau} \cdot \vec{\pi}$

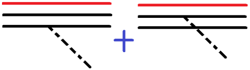


$g_{qq\pi} \sum_{i=1}^{3} \vec{\sigma}_i \cdot \vec{q}\ \vec{\tau}_i \cdot \vec{\pi}$

$\Sigma_c \to \Sigma_c \pi$

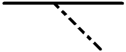


$g_{\Sigma_c \Sigma_c \pi}\ \vec{\sigma} \cdot \vec{q}\ \vec{T} \cdot \vec{\pi}$

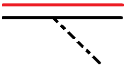


$g_{qq\pi} \sum_{i=1}^{2} \vec{\sigma}_i \cdot \vec{q}\ \vec{\tau}_i \cdot \vec{\pi}$

$D^* \to D^* \pi$



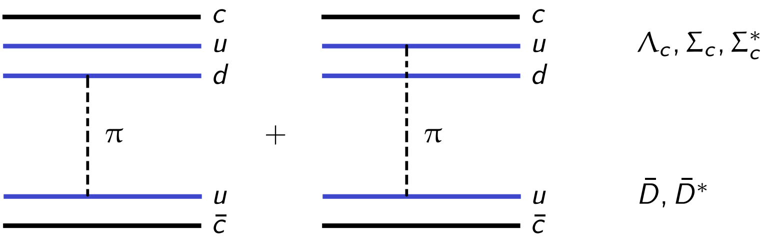
$g_{D^* D^* \pi}\ \vec{\epsilon} \cdot \vec{q}\ \vec{\tau} \cdot \vec{\pi}$



$g_{qq\pi} \vec{\sigma}_1 \cdot \vec{q}\ \vec{\tau}_1 \cdot \vec{\pi}$

Both approaches have the same generic form $g\ \vec{\Sigma} \cdot \vec{q} \vec{T} \cdot \vec{\pi}$

One-pion exchange potential



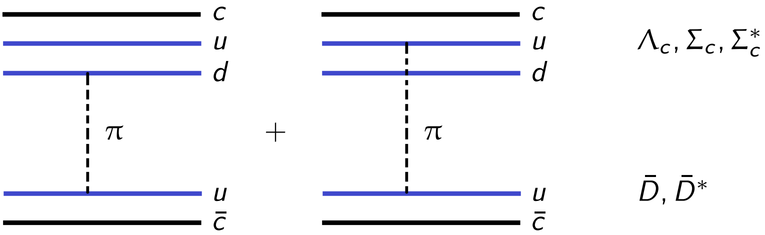
Coupled-channels, mixing angular momenta and particles, e.g.

$$\Sigma_c \bar{D}^* ({}^2\mathrm{S}_{1/2}) \to \Sigma_c \bar{D}^* ({}^4\mathrm{D}_{1/2})$$
$$\Sigma_c \bar{D}^* ({}^2\mathrm{S}_{1/2}) \to \Lambda_c \bar{D} ({}^2\mathrm{S}_{1/2})$$

but first consider first elastic channels only

- $\Lambda_c \Lambda_c \pi$ vertex is forbidden (isospin)
- $\bar{D} \bar{D} \pi$ vertex is forbidden (spin-parity)

One-pion exchange potential



Coupled-channels, mixing angular momenta and particles, e.g.

$$\Sigma_c \bar{D}^* (^2S_{1/2}) \to \Sigma_c \bar{D}^* (^4D_{1/2})$$
$$\Sigma_c \bar{D}^* (^2S_{1/2}) \to \Lambda_c \bar{D} (^2S_{1/2})$$

but first consider first elastic channels only

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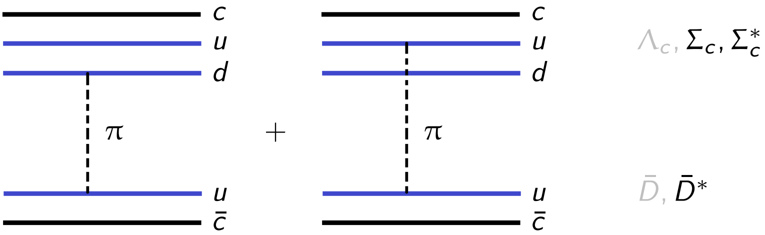
- $\bar{D} \bar{D} \pi$ vertex is forbidden (spin-parity)

One-pion exchange potential



Coupled-channels, mixing angular momenta and particles, e.g.

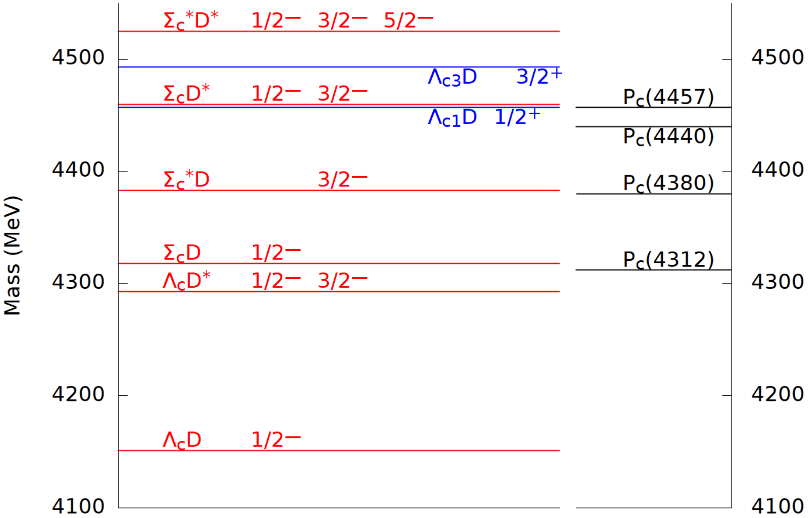
$$\Sigma_c \bar{D}^* ({}^2\mathrm{S}_{1/2}) \to \Sigma_c \bar{D}^* ({}^4\mathrm{D}_{1/2})$$

$$\Sigma_c \bar{D}^* ({}^2\mathrm{S}_{1/2}) \to \Lambda_c \bar{D} ({}^2\mathrm{S}_{1/2})$$

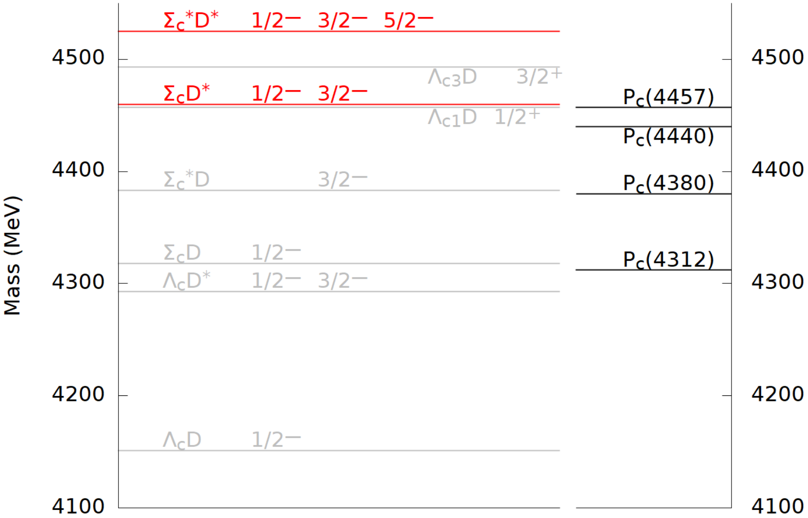
but first consider first elastic channels only

- $\Lambda_c \Lambda_c \pi$ vertex is forbidden (isospin)
- $\bar{D}\bar{D}\pi$ vertex is forbidden (spin-parity)

Restricting the spectrum



Restricting the spectrum



One-pion exchange potential

From couplings $g\,\vec{\Sigma}\cdot\vec{q}\,\vec{T}\cdot\vec{\pi}$,

$$V(\vec{r}) = \left[V_C(r)\vec{\Sigma}_1\cdot\vec{\Sigma}_2 + V_T(r)\mathrm{S}_{12}(\hat{r})\right]\vec{T}_1\cdot\vec{T}_2$$

e.g. $\Sigma_c\bar{D}^*$ with $I=1/2$, $J^P=3/2^-$:

$$\begin{array}{cccc} & |^4\mathrm{S}_{3/2}\rangle & |^2\mathrm{D}_{3/2}\rangle & |^4\mathrm{D}_{3/2}\rangle \\ \langle^4\mathrm{S}_{3/2}| & -\frac{8}{3}V_C & -\frac{8}{3}V_T & -\frac{16}{3}V_T \\ \langle^2\mathrm{D}_{3/2}| & -\frac{8}{3}V_T & +\frac{16}{3}V_C & +\frac{8}{3}V_T \\ \langle^4\mathrm{D}_{3/2}| & -\frac{16}{3}V_T & +\frac{8}{3}V_T & -\frac{8}{3}V_C \end{array}$$

One-pion exchange potential

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$$V(\vec{r}) = \left[V_C(r)\vec{\Sigma}_1\cdot\vec{\Sigma}_2 + V_T(r)\mathrm{S}_{12}(\hat{r})\right]\vec{T}_1\cdot\vec{T}_2$$

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	$\vert{}^4\mathrm{S}_{3/2}\rangle$	$\vert{}^2\mathrm{D}_{3/2}\rangle$	$\vert{}^4\mathrm{D}_{3/2}\rangle$
$\langle{}^4\mathrm{S}_{3/2}\vert$	$-\frac{8}{3}V_C$	$-\frac{8}{3}V_T$	$-\frac{16}{3}V_T$
$\langle{}^2\mathrm{D}_{3/2}\vert$	$-\frac{8}{3}V_T$	$+\frac{16}{3}V_C$	$+\frac{8}{3}V_T$
$\langle{}^4\mathrm{D}_{3/2}\vert$	$-\frac{16}{3}V_T$	$+\frac{8}{3}V_T$	$-\frac{8}{3}V_C$

Central and tensor potentials with form factor cutoff

One-pion exchange potential

From couplings $g\,\vec{\Sigma}\cdot\vec{q}\,\vec{T}\cdot\vec{\pi}$,

$$V(\vec{r}) = \left[V_C(r)\vec{\Sigma}_1\cdot\vec{\Sigma}_2 + V_T(r)\mathrm{S}_{12}(\hat{r})\right]\vec{T}_1\cdot\vec{T}_2$$

e.g. $\Sigma_c\bar{D}^*$ with $I=1/2$, $J^P=3/2^-$:

$$\begin{array}{cccc}
 & |{}^4\mathrm{S}_{3/2}\rangle & |{}^2\mathrm{D}_{3/2}\rangle & |{}^4\mathrm{D}_{3/2}\rangle \\
\langle{}^4\mathrm{S}_{3/2}| & -\frac{8}{3}V_C & -\frac{8}{3}V_T & -\frac{16}{3}V_T \\
\langle{}^2\mathrm{D}_{3/2}| & -\frac{8}{3}V_T & +\frac{16}{3}V_C & +\frac{8}{3}V_T \\
\langle{}^4\mathrm{D}_{3/2}| & -\frac{16}{3}V_T & +\frac{8}{3}V_T & -\frac{8}{3}V_C
\end{array}$$

Central and tensor potentials with form factor cutoff

Model-independent coefficients, fixed by HQ and isospin symmetry

One-pion exchange potential

From couplings $g\,\vec{\Sigma}\cdot\vec{q}\,\vec{T}\cdot\vec{\pi}$,

$$V(\vec{r}) = \left[V_C(r)\vec{\Sigma}_1\cdot\vec{\Sigma}_2 + V_T(r)\mathrm{S}_{12}(\hat{r})\right]\vec{T}_1\cdot\vec{T}_2$$

e.g. $\Sigma_c\bar{D}^*$ with $I=1/2$, $J^P=3/2^-$:

	$\lvert{}^4\mathrm{S}_{3/2}\rangle$	$\lvert{}^2\mathrm{D}_{3/2}\rangle$	$\lvert{}^4\mathrm{D}_{3/2}\rangle$
$\langle{}^4\mathrm{S}_{3/2}\rvert$	$-\frac{8}{3}V_C$	$-\frac{8}{3}V_T$	$-\frac{16}{3}V_T$
$\langle{}^2\mathrm{D}_{3/2}\rvert$	$-\frac{8}{3}V_T$	$+\frac{16}{3}V_C$	$+\frac{8}{3}V_T$
$\langle{}^4\mathrm{D}_{3/2}\rvert$	$-\frac{16}{3}V_T$	$+\frac{8}{3}V_T$	$-\frac{8}{3}V_C$

Central and tensor potentials with form factor cutoff

Model-independent coefficients, fixed by HQ and isospin symmetry

Larger isospin $\implies$ weaker potential; e.g. $V_{I=3/2} = -\frac{1}{2}V_{I=1/2}$

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$\langle{}^4\mathrm{S}_{3/2}\rvert$	$-\frac{8}{3}V_C$	$-\frac{8}{3}V_T$	$-\frac{16}{3}V_T$
$\langle{}^2\mathrm{D}_{3/2}\rvert$	$-\frac{8}{3}V_T$	$+\frac{16}{3}V_C$	$+\frac{8}{3}V_T$
$\langle{}^4\mathrm{D}_{3/2}\rvert$	$-\frac{16}{3}V_T$	$+\frac{8}{3}V_T$	$-\frac{8}{3}V_C$

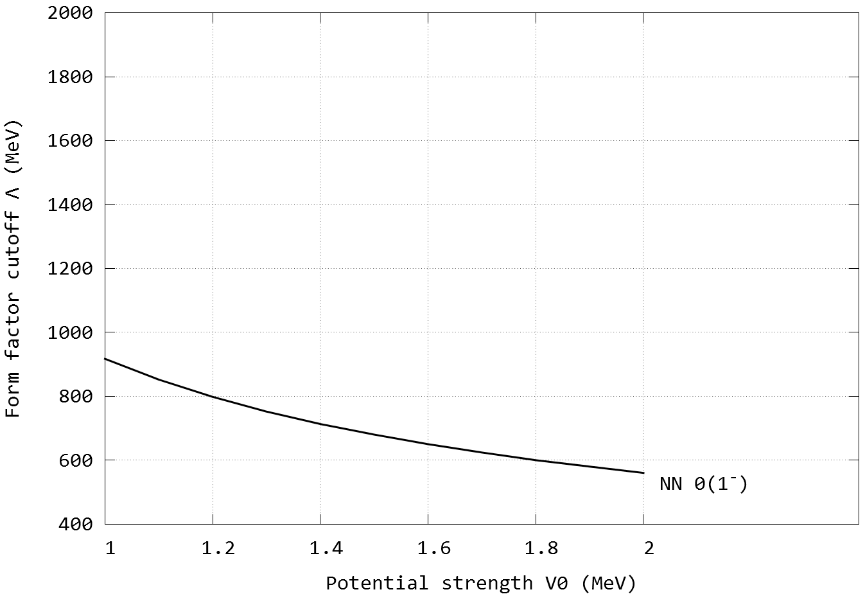
Central and tensor potentials with form factor cutoff

Model-independent coefficients, fixed by HQ and isospin symmetry

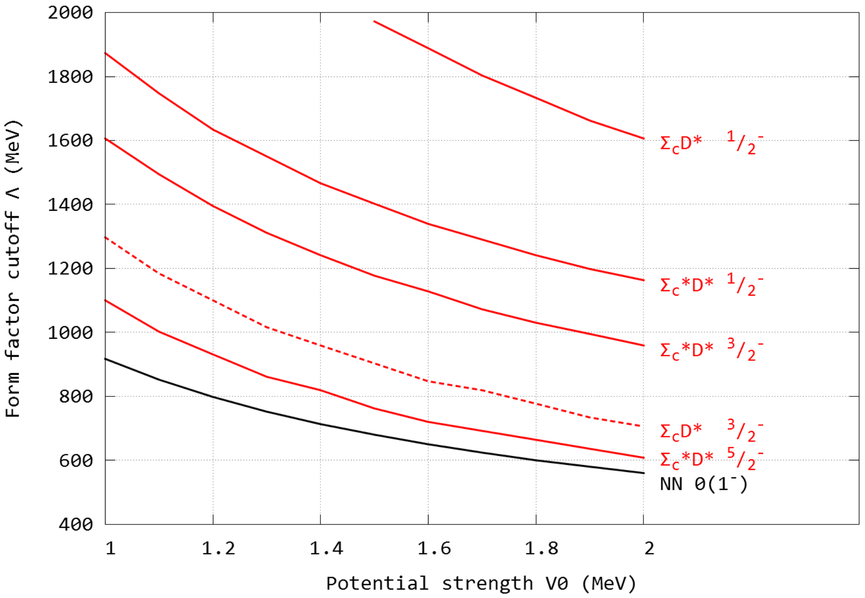
Larger isospin $\Longrightarrow$ weaker potential; e.g. $V_{I=3/2} = -\frac{1}{2}V_{I=1/2}$

Pattern of binding driven by coefficient of $V_C(r)$ in S-wave

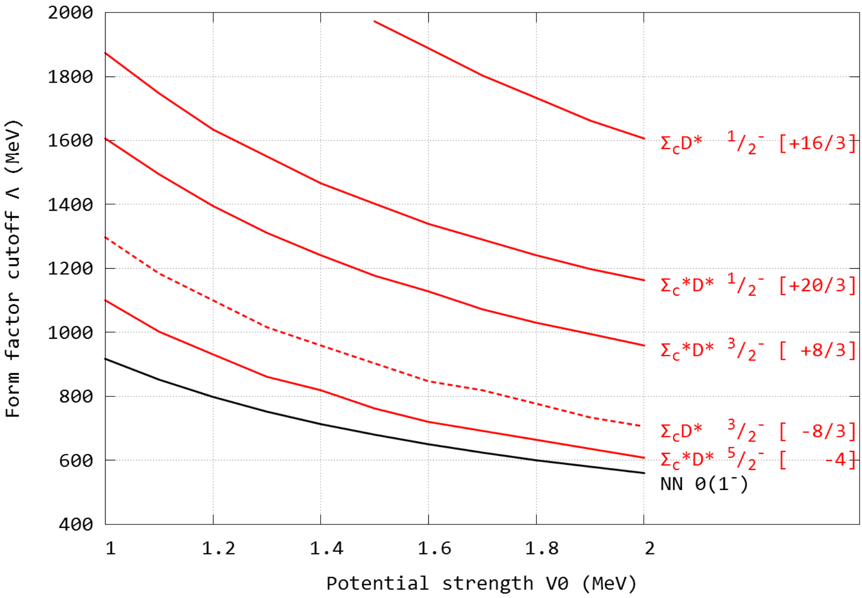
Critical form factor



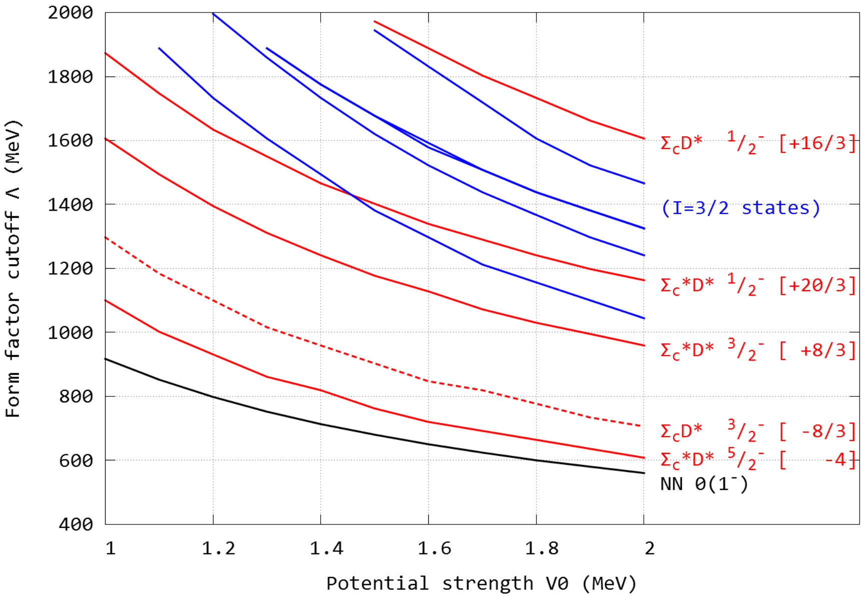
Critical form factor



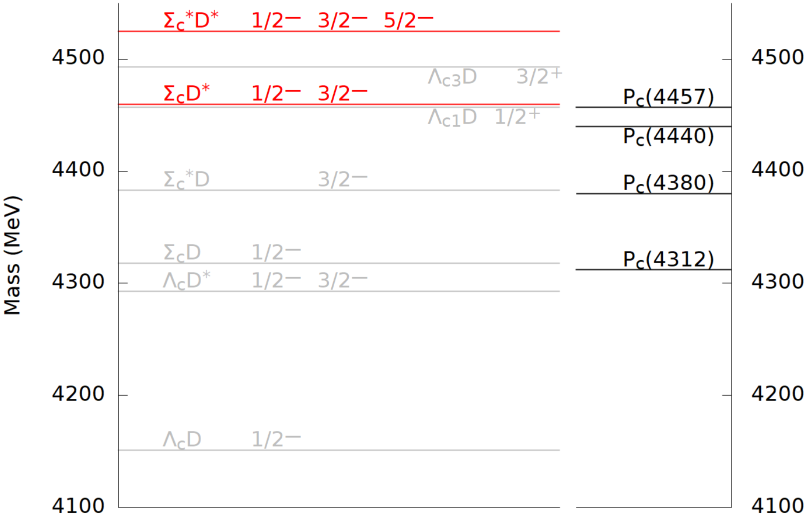
Critical form factor



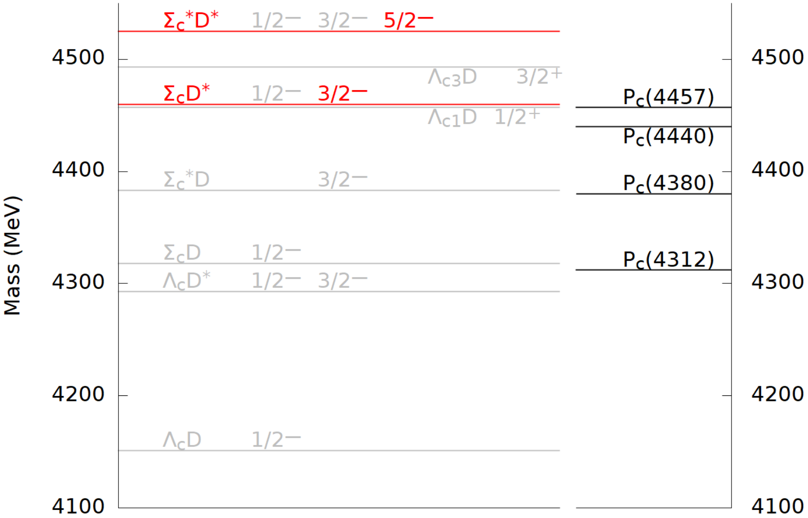
Critical form factor



Restricting the spectrum

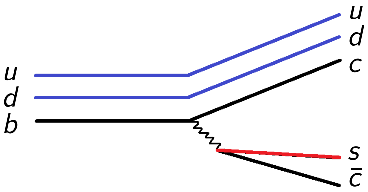


Restricting the spectrum



Production
and
particle coupled-channels

Production favours Λ_c-flavoured components



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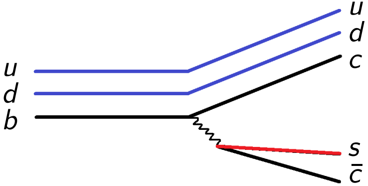

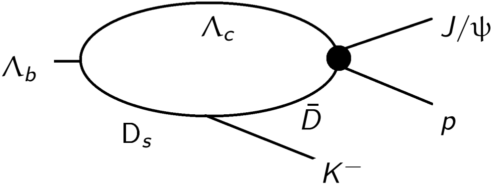

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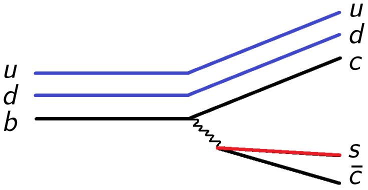

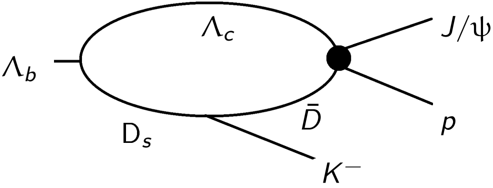

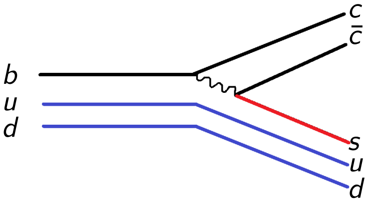

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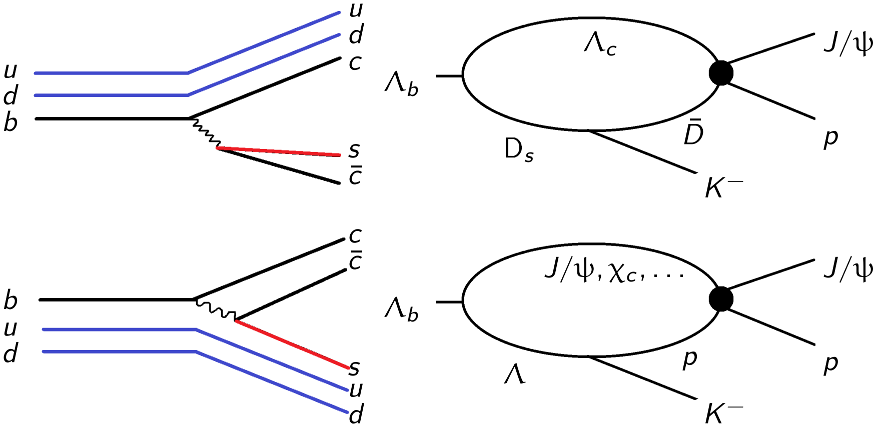
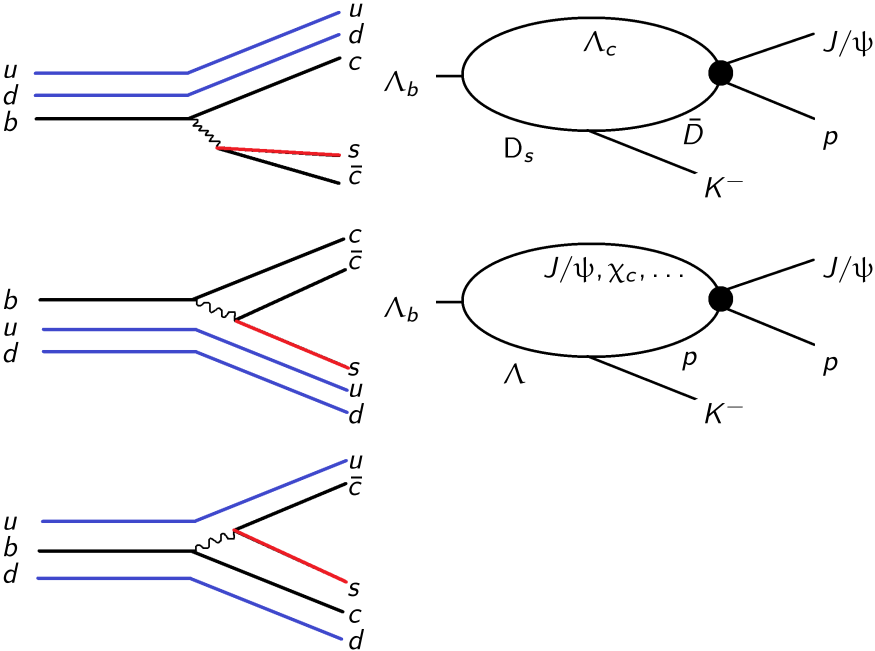


Production favours Λ_c-flavoured components



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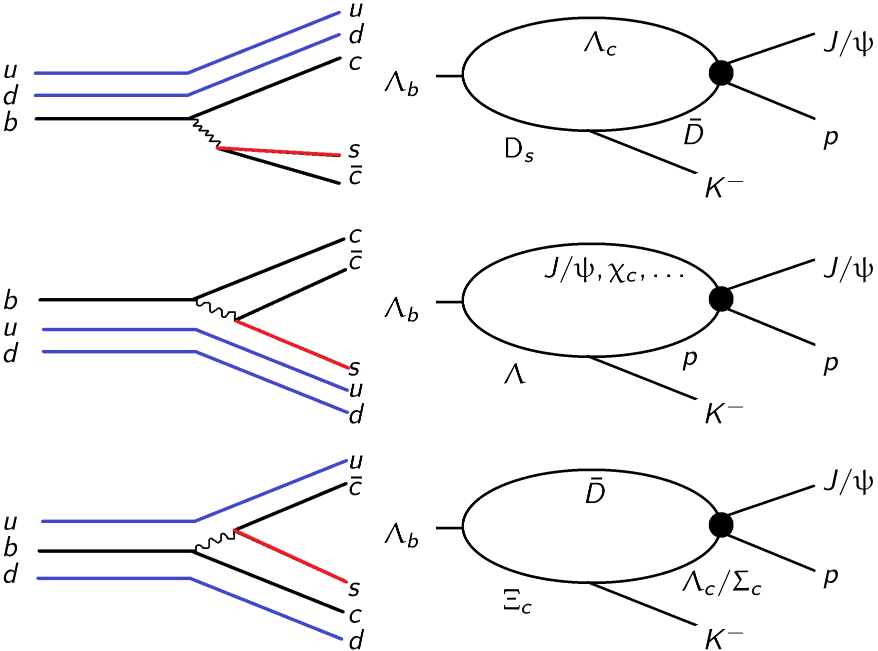
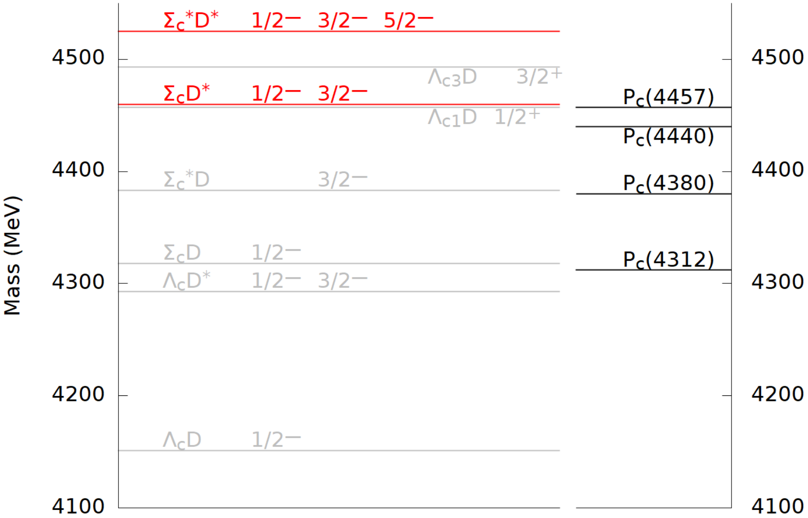


Including particle coupled-channel effects



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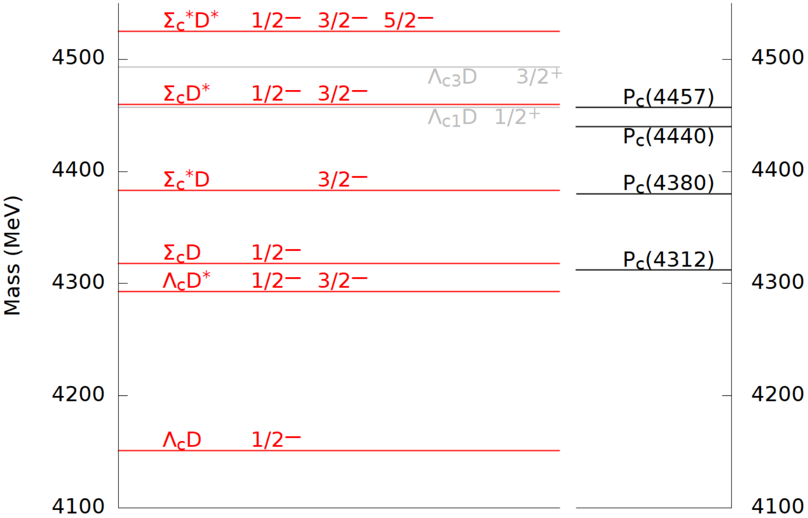

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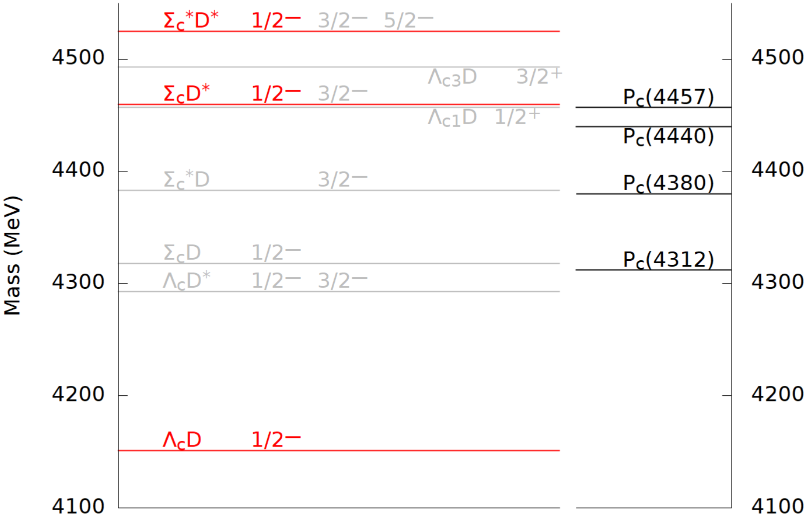

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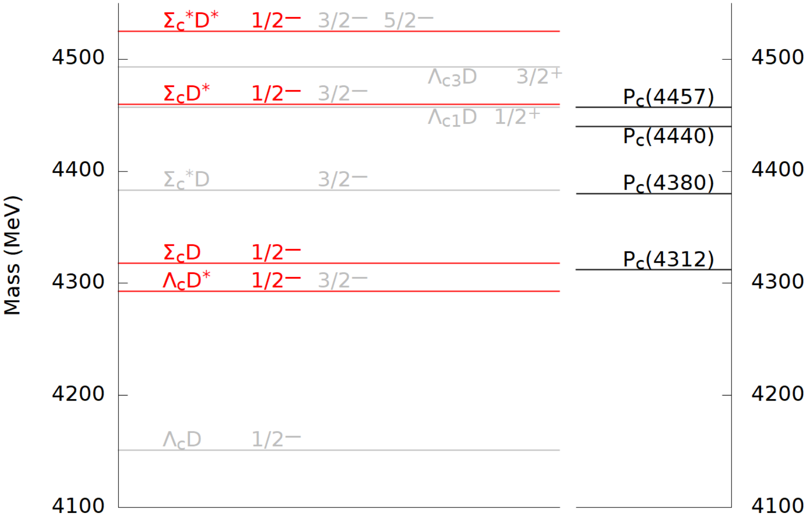

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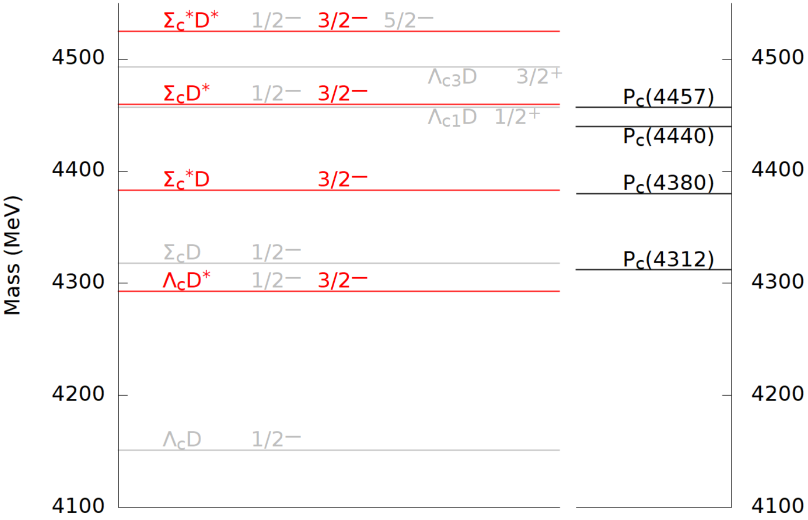

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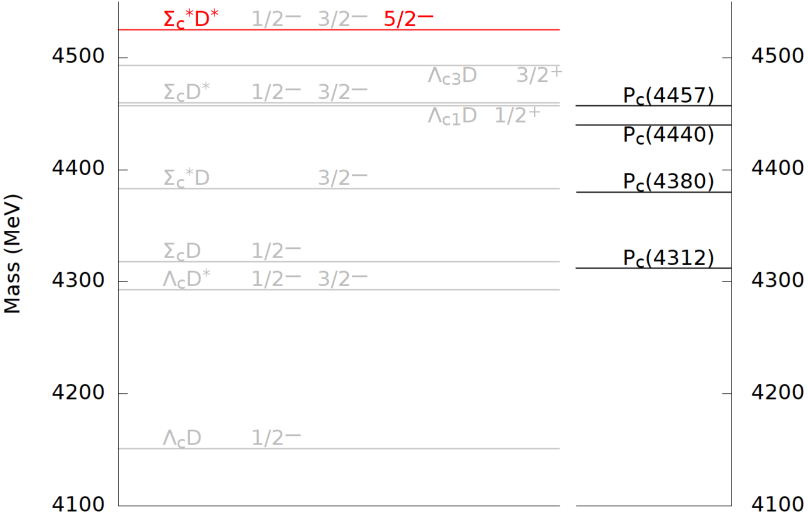
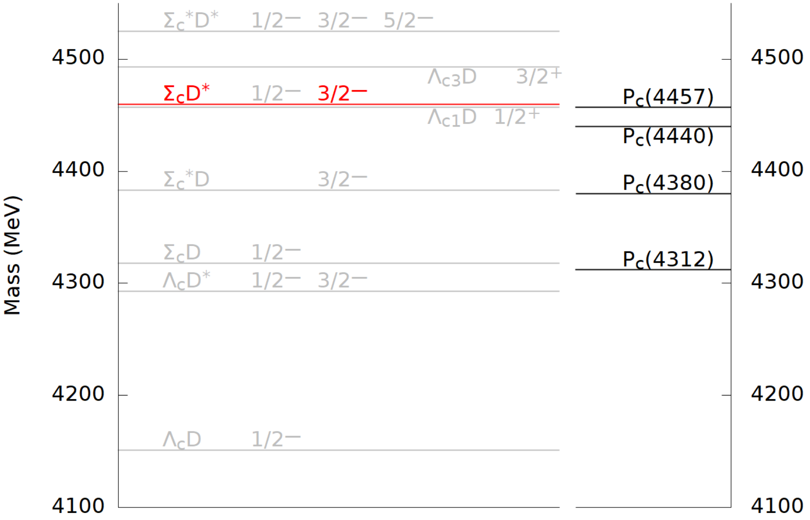
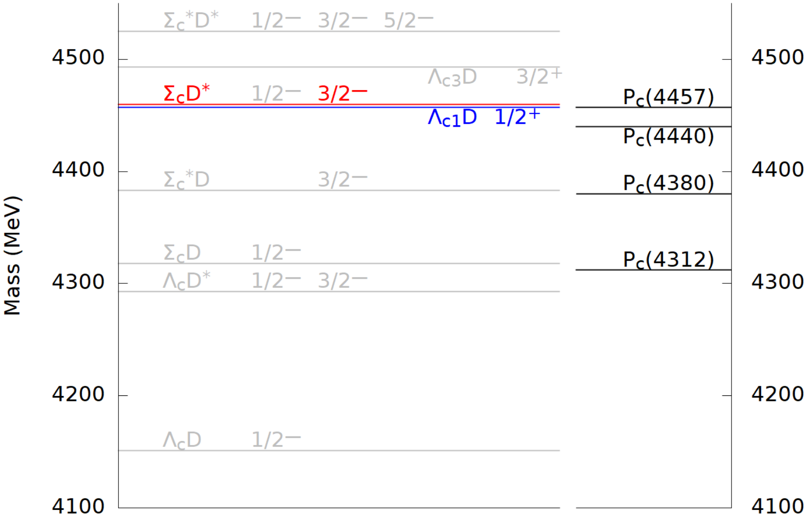


The new doublet of states

The role of $\Lambda_{c1}\bar{D}$



The role of $\Lambda_{c1}\bar{D}$



The role of $\Lambda_{c1}\bar{D}$

$$\Sigma_c \bar{D}^* \to \Sigma_c \bar{D}^* \quad V(\vec{r}) = \left[V_C(r) \vec{\Sigma}_1 \cdot \vec{\Sigma}_2 + V_T(r) S_{12}(\hat{r}) \right] \vec{T}_1 \cdot \vec{T}_2$$

$$\Lambda_{c1} \bar{D} \to \Sigma_c \bar{D}^* \quad V(\vec{r}) = V_V(r) \vec{\Sigma}_2 \cdot \hat{r} \; \vec{T}_1 \cdot \vec{T}_2$$

Access to opposite parity states with S-wave components:

	$\Sigma_c \bar{D}^*$	$\Lambda_{c1} \bar{D}$
$1/2^-$	$^2S_{1/2}$ $^4D_{1/2}$	unbound
$3/2^-$	$^4S_{3/2}$ $^2D_{3/2}$ $^4D_{3/2}$	$P_c(4440)$

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$$\Sigma_c\bar{D}^* \to \Sigma_c\bar{D}^* \quad V(\vec{r}) = \left[V_C(r)\vec{\Sigma}_1\cdot\vec{\Sigma}_2 + V_T(r)S_{12}(\hat{r})\right]\vec{T}_1\cdot\vec{T}_2$$

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$3/2^-$	${}^4S_{3/2}$ ${}^2D_{3/2}$ ${}^4D_{3/2}$		$P_c(4440)$
$1/2^+$		${}^2S_{1/2}$	

The role of $\Lambda_{c1}\bar{D}$

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$1/2^+$	$^2P_{1/2}$ $^4P_{1/2}$	$^2S_{1/2}$	

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Access to opposite parity states with S-wave components:

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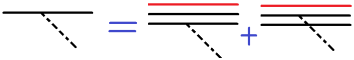
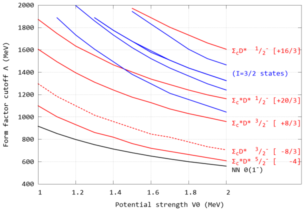
$1/2^-$	$^2S_{1/2}$ $^4D_{1/2}$	$^2P_{1/2}$	unbound
$3/2^-$	$^4S_{3/2}$ $^2D_{3/2}$ $^4D_{3/2}$	$^2P_{3/2}$	$P_c(4440)$
$1/2^+$	$^2P_{1/2}$ $^4P_{1/2}$	$^2S_{1/2}$	$P_c(4457)$

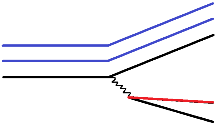
Conclusions



Quark model and Lagrangians based on HQ and chiral symmetry give the same OPE potential.

Patterns of binding are readily understood in terms of model-independent numerical factors





Production favours Λ_c channels, implying coupled channel effects for observed states, and supporting the absence of $5/2^-$ state

Conclusions

A restricted spectrum emerges, with unambigious J^P quantum numbers which can be tested in experiment:

$$\begin{array}{lll} P_c(4457) & 1/2^+ & \Lambda_{c1}\bar{D}\ (+\Sigma_c\bar{D}^*) \\ P_c(4440) & 3/2^- & \Sigma_c\bar{D}^*\ (+\Lambda_{c1}\bar{D}) \\ P_c(4380) & 3/2^- & \Sigma_c^*\bar{D}\ (+\ldots) \\ P_c(4312) & 1/2^- & \Sigma_c\bar{D}+\Lambda_c D^* \end{array}$$

States have mixed isopsin:

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

but $|\frac{3}{2},\frac{3}{2}\rangle$ partners not expected.

Compact pentaquark scenarios have model-dependent masses, and many more states, with all possible I and J^P.

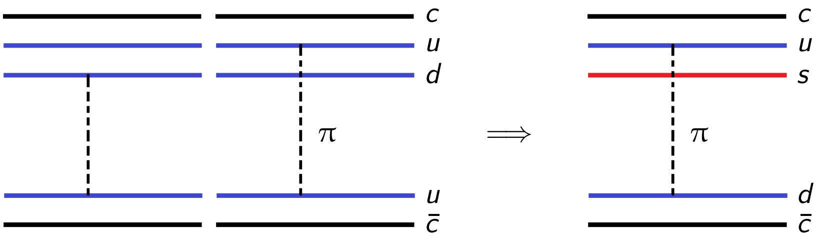
More molecules, and isospin mixing

$\Xi_c^* \bar{D}^*$ 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 $\Lambda_b \to J/\psi \Lambda \eta$, and $\Xi_b \to J/\psi \Lambda K^-$ (LHCb run II).

Isospin mixing: $P_c(4380)$ and $P_c(4457)$

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

Isospin-conserving interactions give $|I, I_3\rangle$ 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 $P_c(4457)$

$$P_c(4380) = 4380 \pm 8 \pm 29 \qquad P_c(4457) = 4457.3 \pm 0.6^{+4.1}_{-1.7}$$

$$\Sigma_c^{*+}\bar{D}^0 = 4382.3 \pm 2.4 \qquad \Sigma_c^{+}\bar{D}^{*0} = 4459.9 \pm 0.5$$

$$\Sigma_c^{*++}D^- = 4387.5 \pm 0.7 \qquad \Sigma_c^{++}D^{*-} = 4464.24 \pm 0.23$$

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:

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

$$J/\psi p : J/\psi\Delta^+ : \eta_c\Delta^+ = \cos^2\phi : 10\sin^2\phi : 6\sin^2\phi \quad [P_c(4457)]$$

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.

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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.

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

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

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

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.
$\Longrightarrow \; I = 1$ decay enhanced.