Molecules of hadrons bound by pion exchange: application to LHCb pentaquarks

Tim Burns

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

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

	$P_c(4380)^+$	$P_c(4450)^+$
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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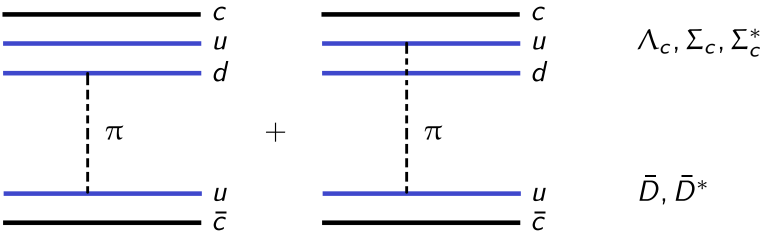
Hidden-charm molecules

- 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)
- . . .

One-pion exchange potential



Potential mixes particles and angular momenta, e.g.

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

but the pattern is driven by diagonal blocks of fixed particles.

Note

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

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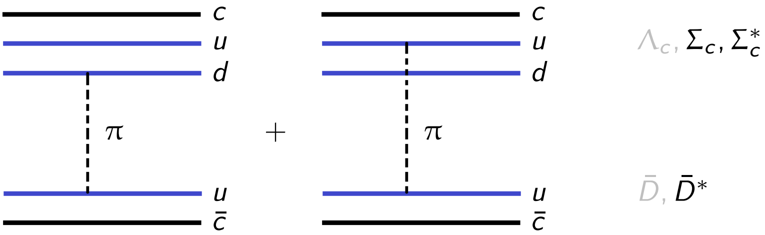

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Quark models and heavy-quark chiral Lagrangians give

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

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Coefficents are model-independent; e.g. $\Sigma_c \bar{D}^*$ in $1/2(3/2^-)$:

	$\vert{}^4S_{3/2}\rangle$	$\vert{}^2D_{3/2}\rangle$	$\vert{}^4D_{3/2}\rangle$
$\langle{}^4S_{3/2}\vert$	$-\frac{8}{3}V_C$	$-\frac{8}{3}V_T$	$-\frac{16}{3}V_T$
$\langle{}^2D_{3/2}\vert$	$-\frac{8}{3}V_T$	$+\frac{16}{3}V_C$	$+\frac{8}{3}V_T$
$\langle{}^4D_{3/2}\vert$	$-\frac{16}{3}V_T$	$+\frac{8}{3}V_T$	$-\frac{8}{3}V_C$

and relative strengths fixed by HQ symmetry.

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Central and tensor potentials with form factor cutoff

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Central and tensor potentials with form factor cutoff

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

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\langle^2D_{3/2}| & -\frac{8}{3}V_T & +\frac{16}{3}V_C & +\frac{8}{3}V_T \\
\langle^4D_{3/2}| & -\frac{16}{3}V_T & +\frac{8}{3}V_T & -\frac{8}{3}V_C
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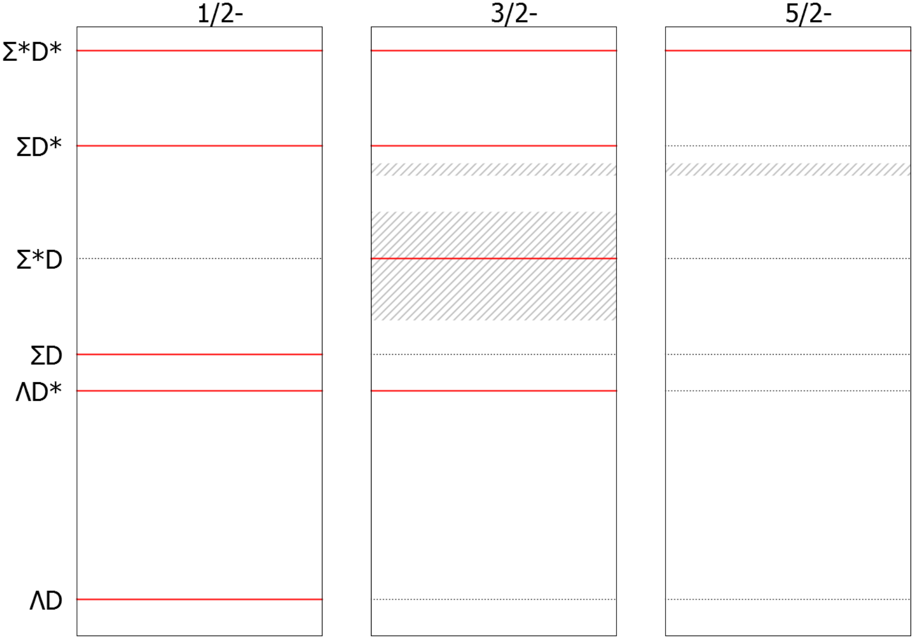
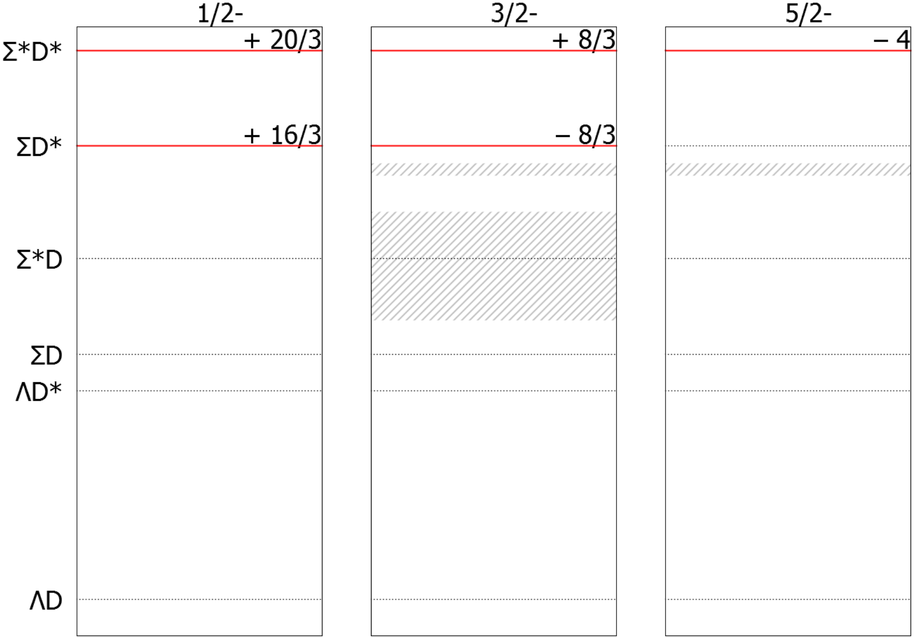
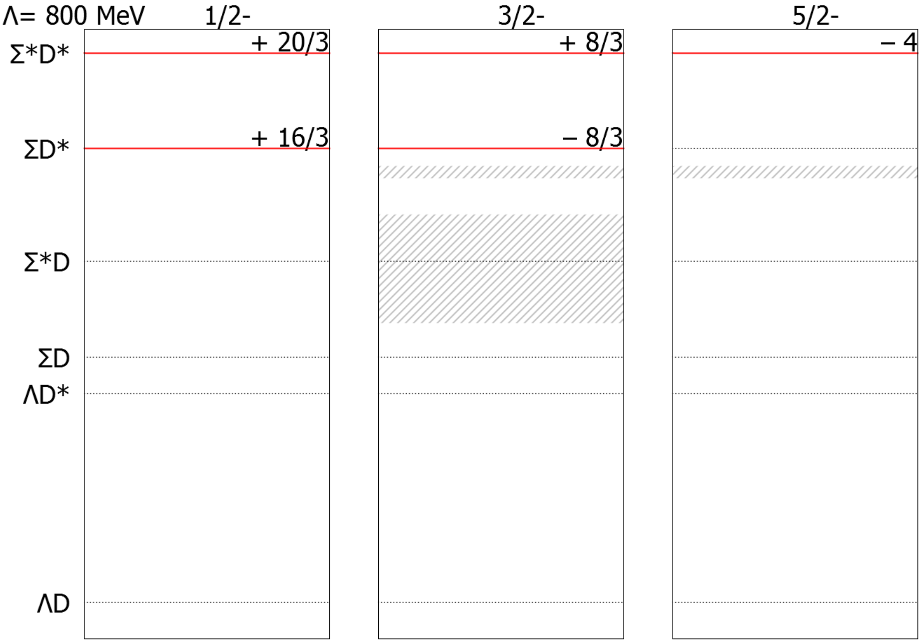
For channels with S-waves, binding is driven by coefficient of $V_C(r)$ (and unlike for NN, this can be positive. . .)


1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD


1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD


1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4


Λ= 800 MeV
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4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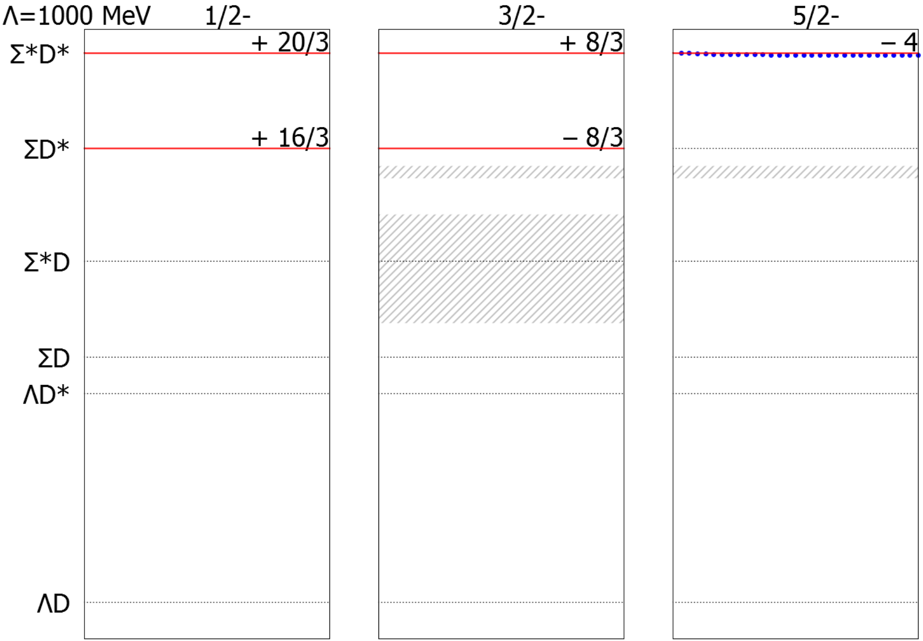
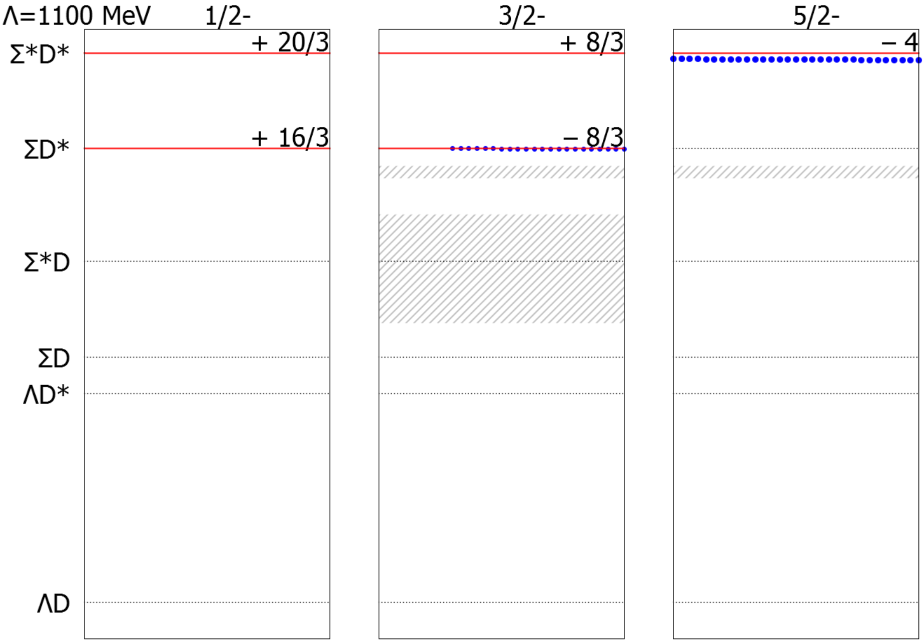
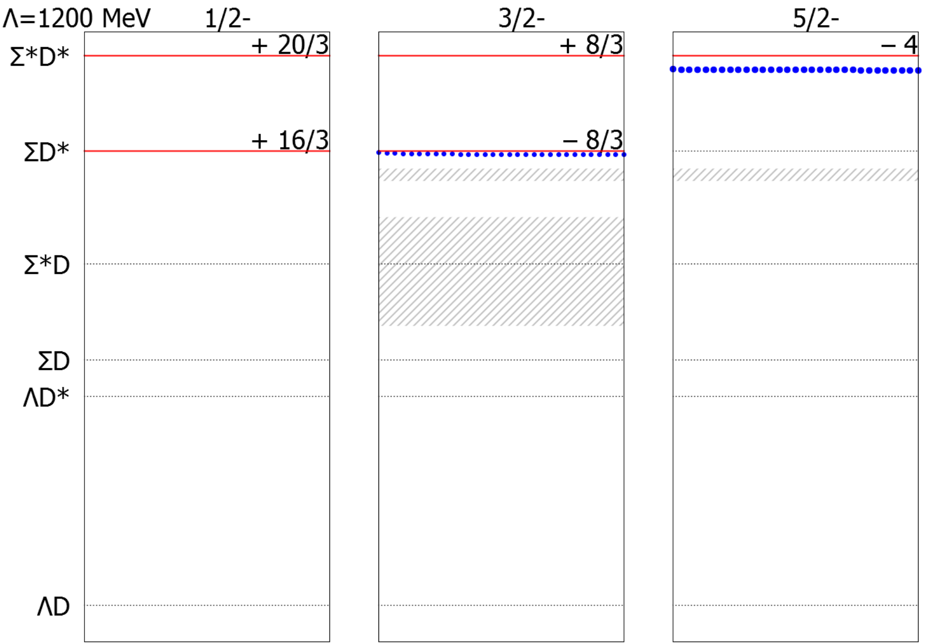
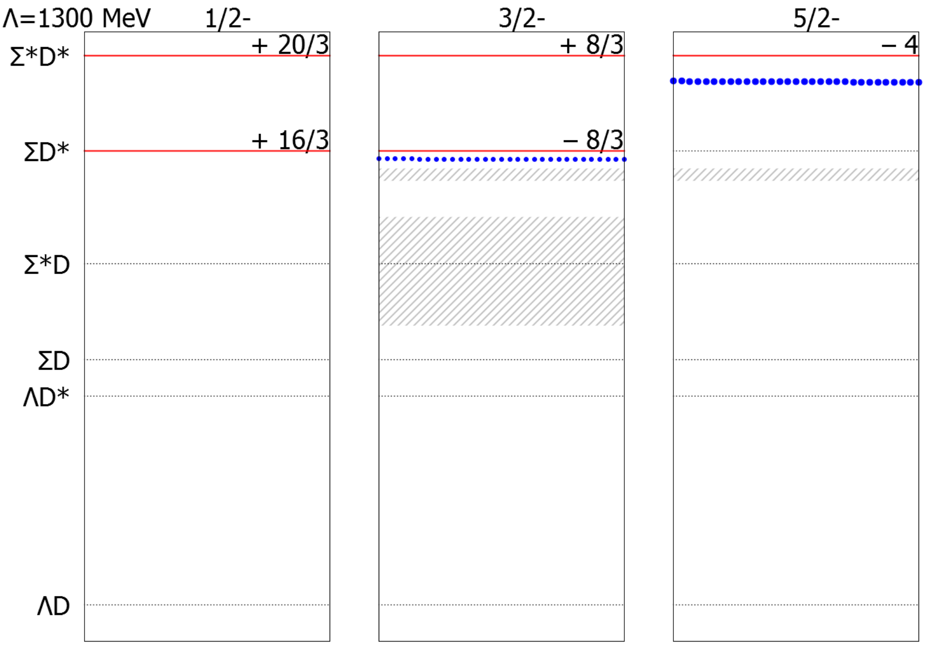
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4

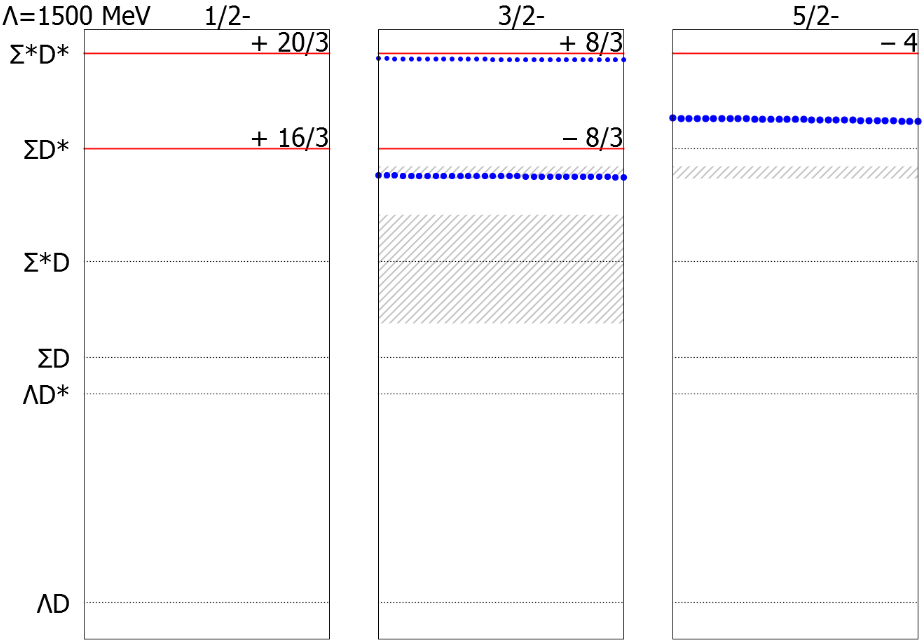

Λ=1000 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
+ 16/3
− 8/3
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD


Λ=1100 MeV
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4


Λ=1200 MeV
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4

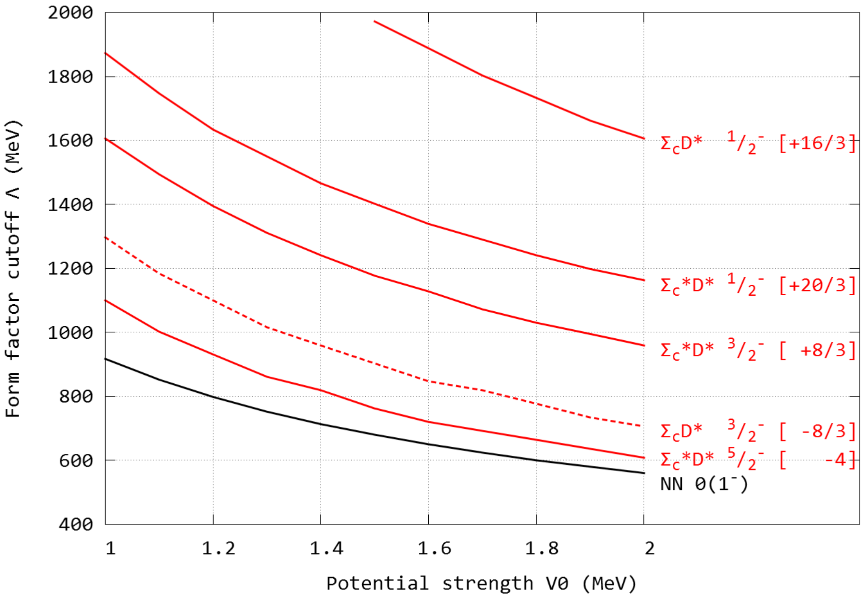


Λ=1300 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
+ 16/3
− 8/3
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD

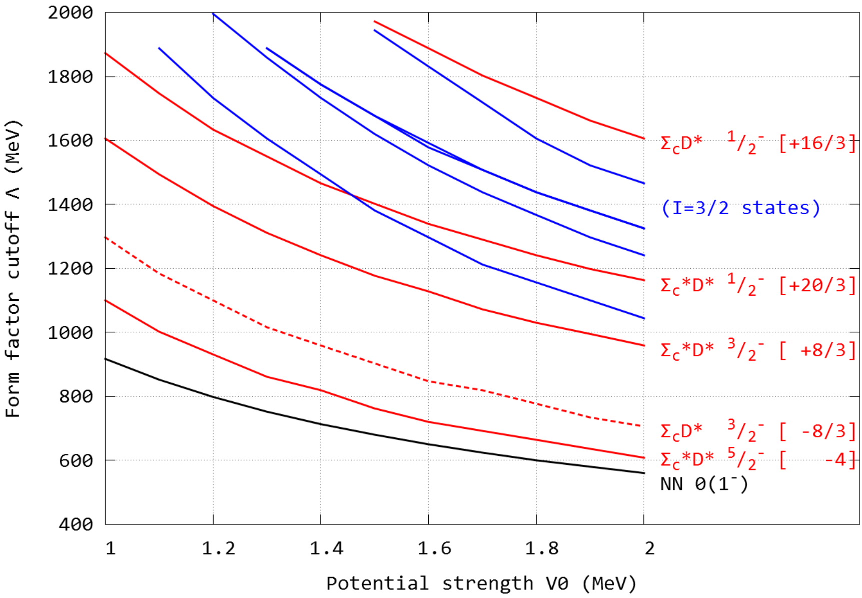


Λ=1500 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD

Critical form factor



Critical form factor



Conventional wisdom

"Molecules exist close to S-wave thresholds"

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- Only for certain quantum numbers
- "Few" states exist $\Leftrightarrow$ all are "near" threshold
- "Many" states exist $\Leftrightarrow$ some are more deeply bound
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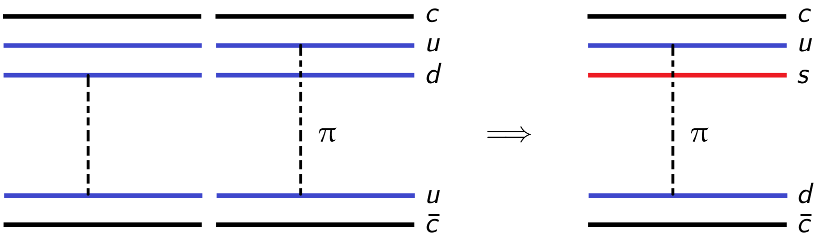
P-wave states? (e.g $1/2^+$, $3/2^+$, $5/2^+$)

- Possible, but with much larger cut-off, implying many more states overall
- Pattern is driven by coefficient of V_T.
- States near wrong thresholds for $P_c(4380)$, $P_c(4450)$.

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

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

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 $P_c(4450)$

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

The P_c states have mixed isospin:

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

They should decay also 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 mixing: predicted $5/2^-$ states

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

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

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

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

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

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Reason for absence at LHCb?

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

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

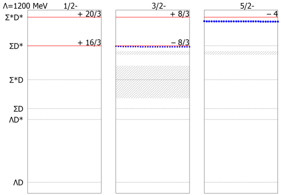
$$\Xi_c^{*0} \bar{D}^{*0} = 4652.9 \pm 0.6$$
$$\Xi_c^{*+} D^{*-} = 4656.2 \pm 0.7$$

Mixed 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.
$\implies I = 1$ decay enhanced.

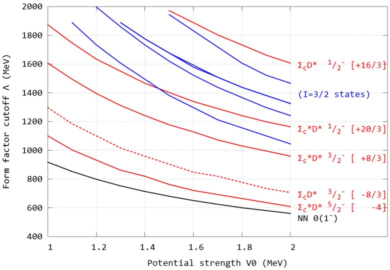
Conclusions

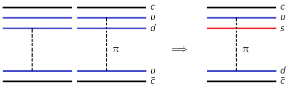


- Binding in certain $I(J^P)$ only
- $3/2^-$ $\Sigma_c \bar{D}^* = P_c(4450)$?
- $5/2^-$ $\Sigma_c^* \bar{D}^*$ with D-wave decay

Pattern is

- easily understood
- parameter insensitive
- generic

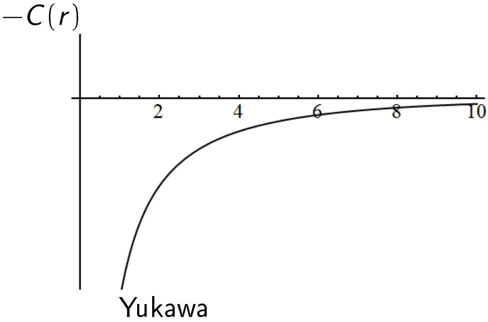




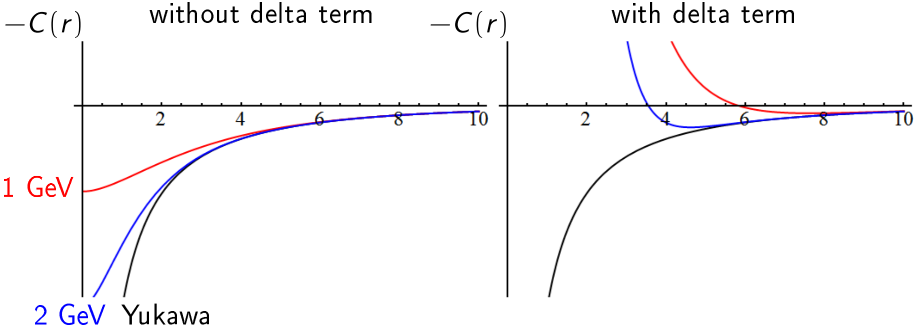
- Predict $\Xi_c^* \bar{D}^*$ $0(5/2^-)$ partner
- All states are isospin mixtures

Backup slides

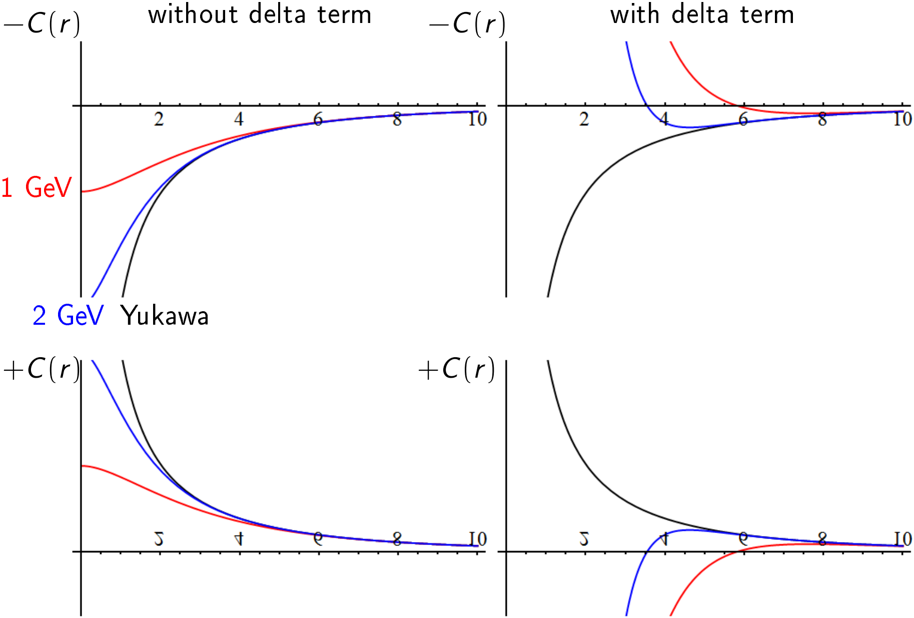
Central potential

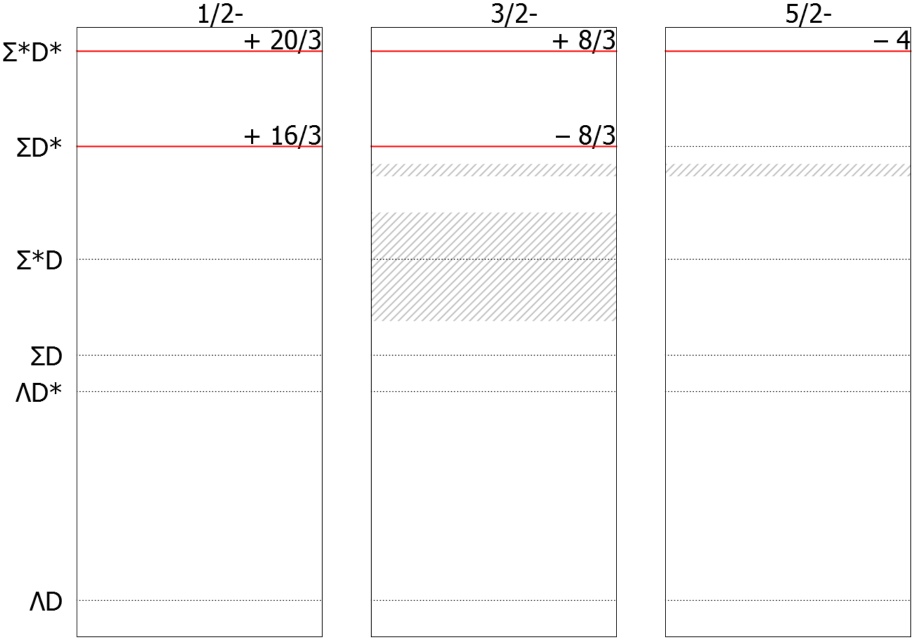


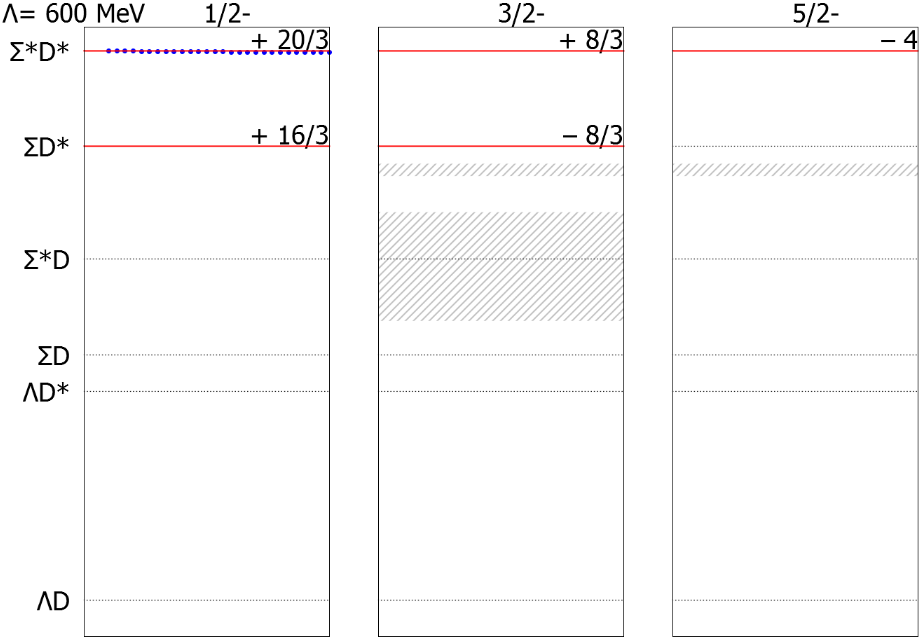
Central potential



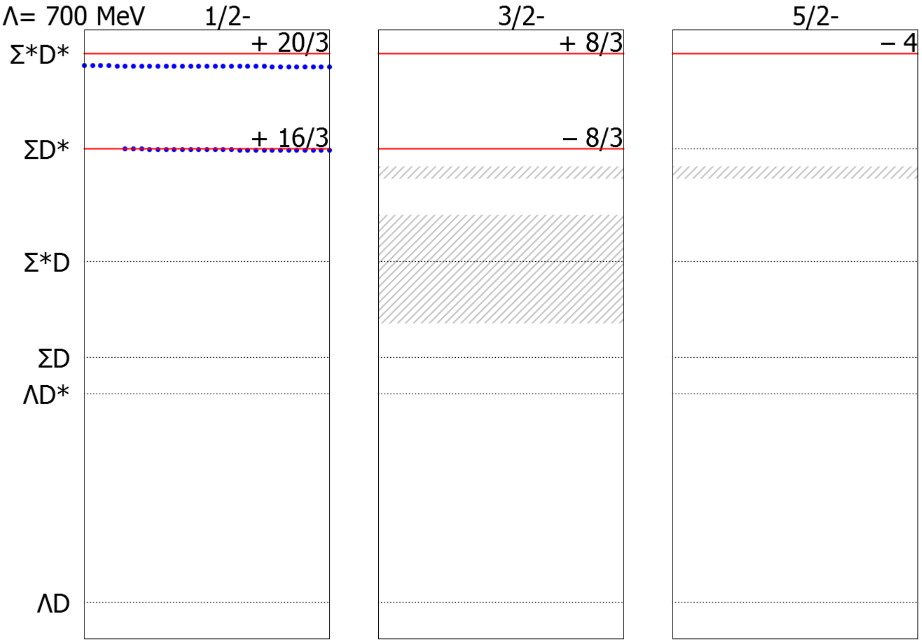
Central potential



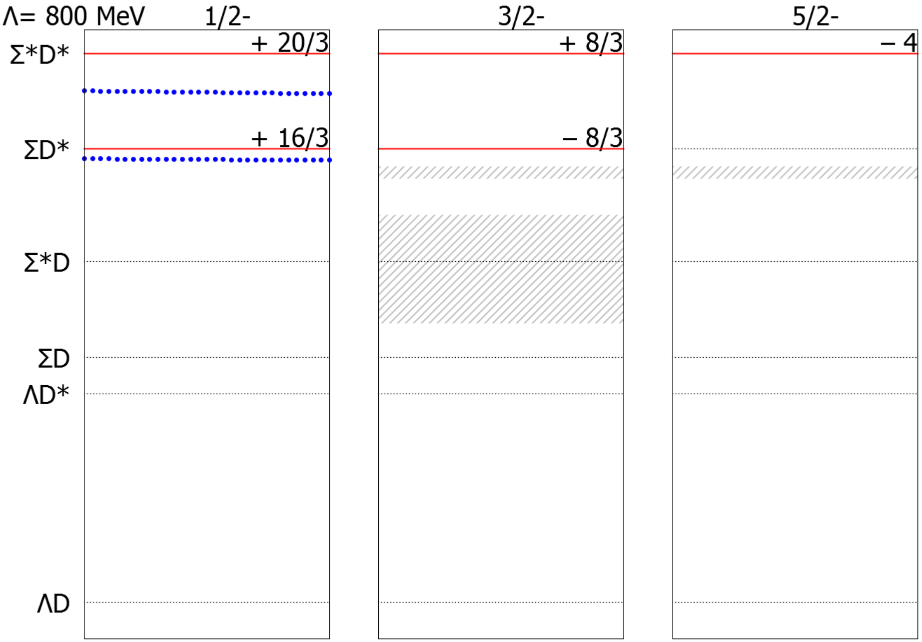

1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
+ 16/3
− 8/3
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD



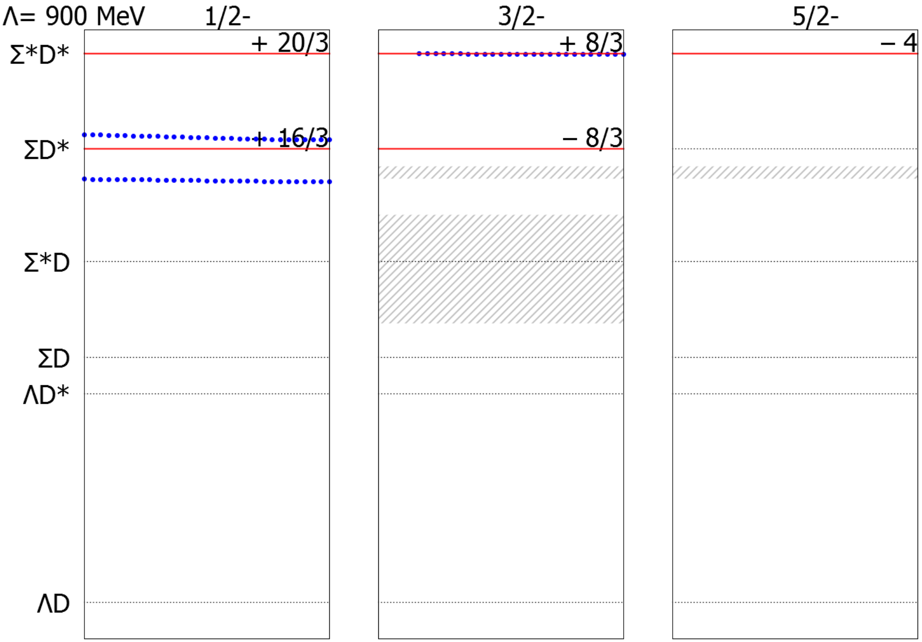
Λ= 600 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
+ 16/3
− 8/3
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD



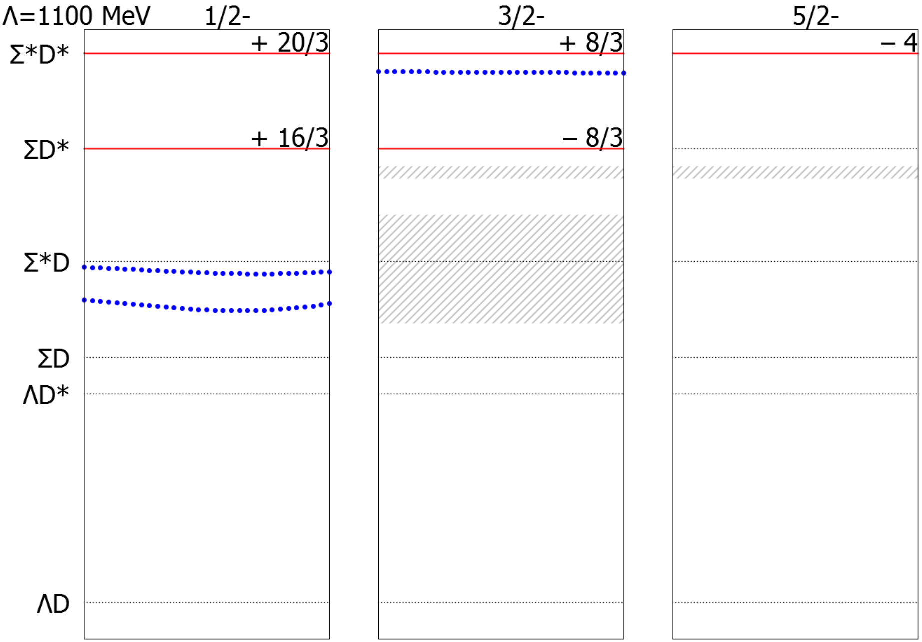
Λ= 700 MeV
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4

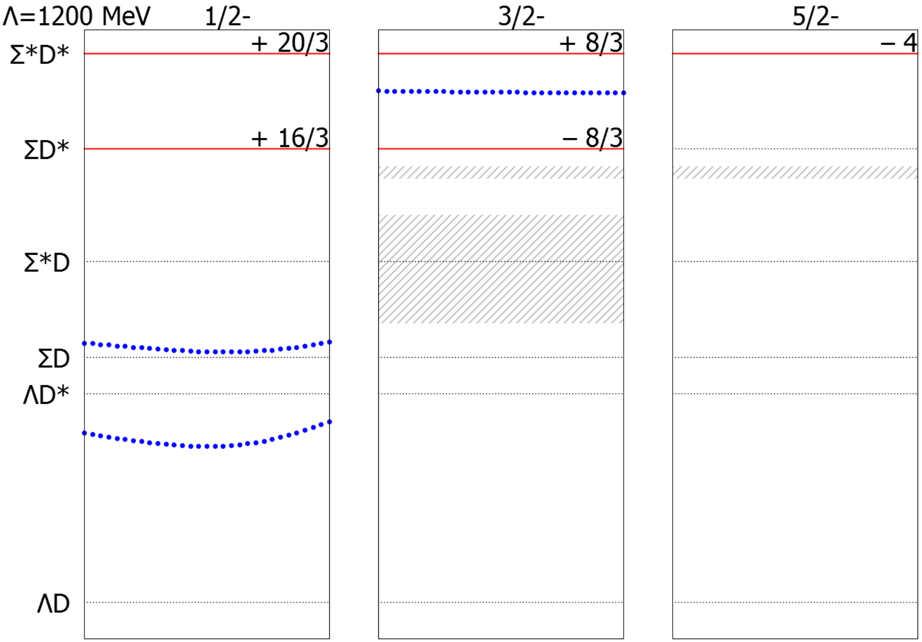


Λ= 800 MeV
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4

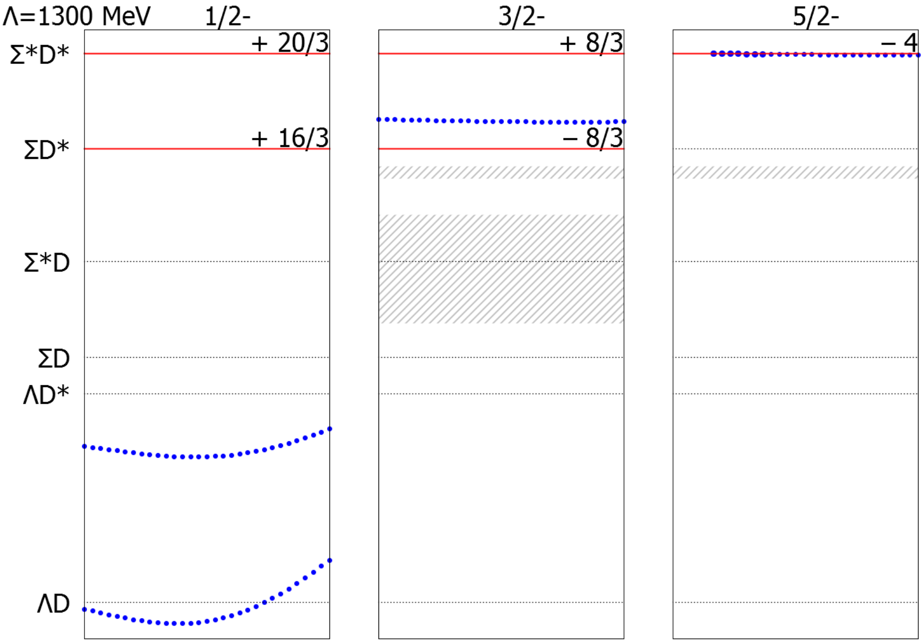


Λ= 900 MeV
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4

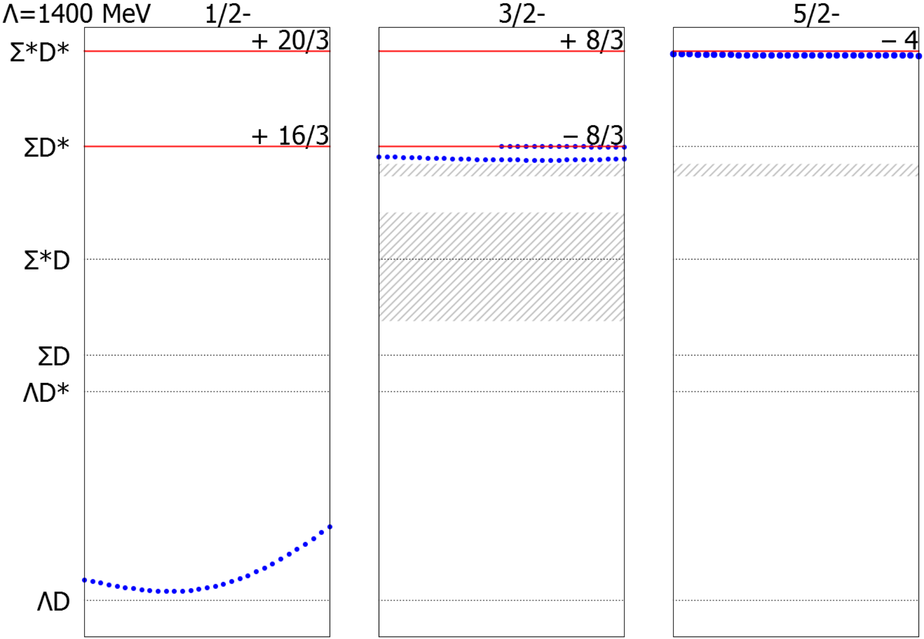

Λ=1100 MeV
1/2-
3/2-
5/2-
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD
+ 20/3
+ 16/3
+ 8/3
− 8/3
− 4

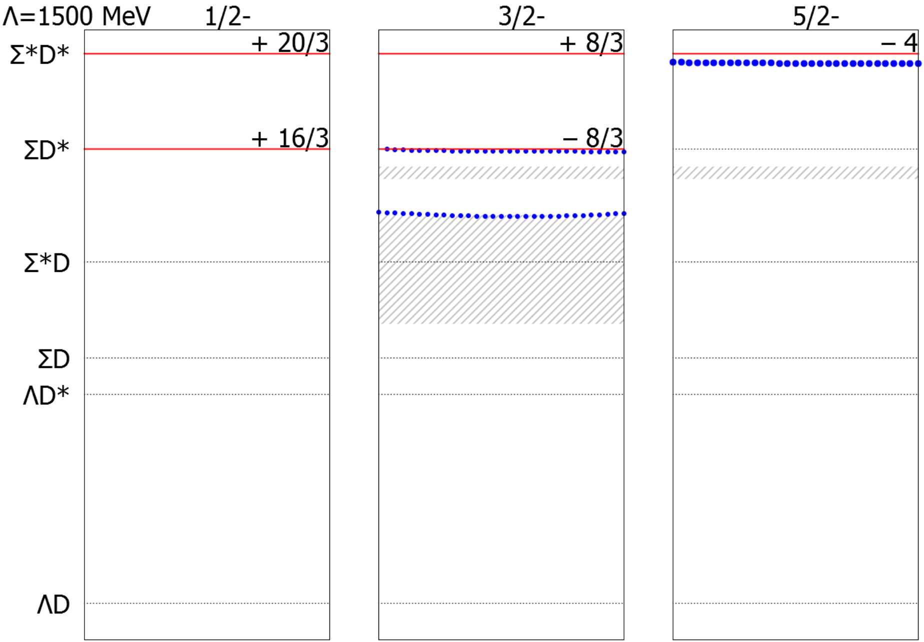


Λ=1200 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
Σ*D*
+ 16/3
− 8/3
ΣD*
Σ*D
ΣD
ΛD*
ΛD



Λ=1300 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
+ 16/3
− 8/3
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD


Λ=1400 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
+ 16/3
− 8/3
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD



Λ=1500 MeV
1/2-
3/2-
5/2-
+ 20/3
+ 8/3
− 4
+ 16/3
− 8/3
Σ*D*
ΣD*
Σ*D
ΣD
ΛD*
ΛD