Hidden-charm pentaquarks as a meson-baryon molecule with coupled-channels for $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$

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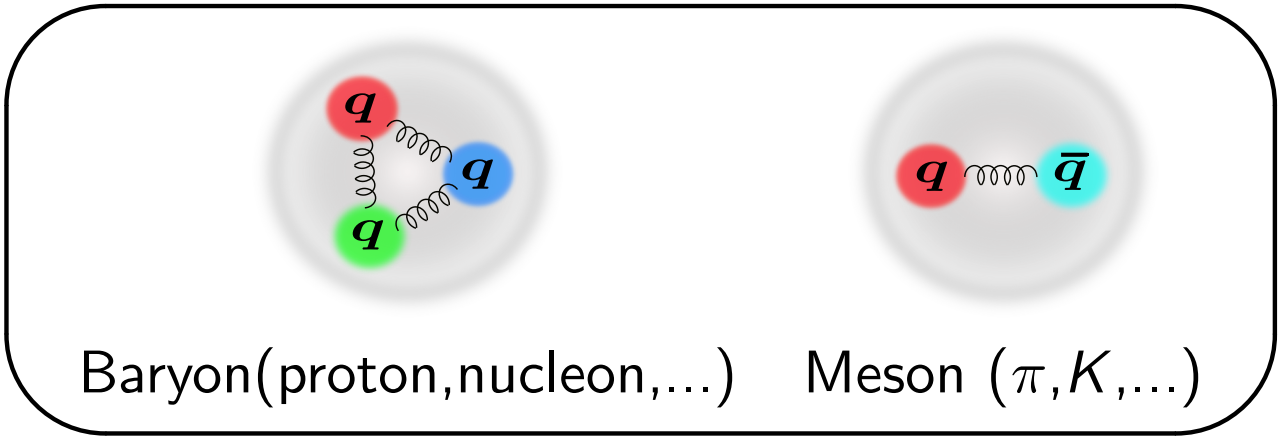
Yasuhiro Yamaguchi and Elena Santopinto ,
arXiv:1606.08330 [hep-ph].

Terzo Incontro Nazionale di Fisica Nucleare INFN2016
14-16 November 2016, Laboratori Nazionali di Frascati, Italy

Hadrons in the heavy quark region

- Hadron: Composite particle of **Quarks** and **Gluons**
- Constituent quark model (Baryon(qqq) and Meson $q\bar{q}$) has been successfully applied to the hadron spectra!



Baryon(proton,nucleon,...) Meson (π,K,...)

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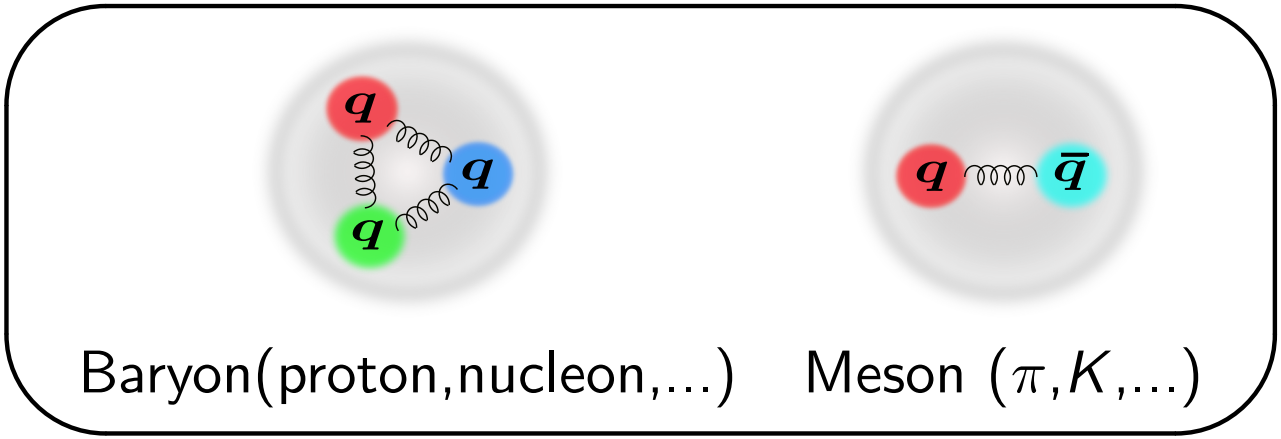
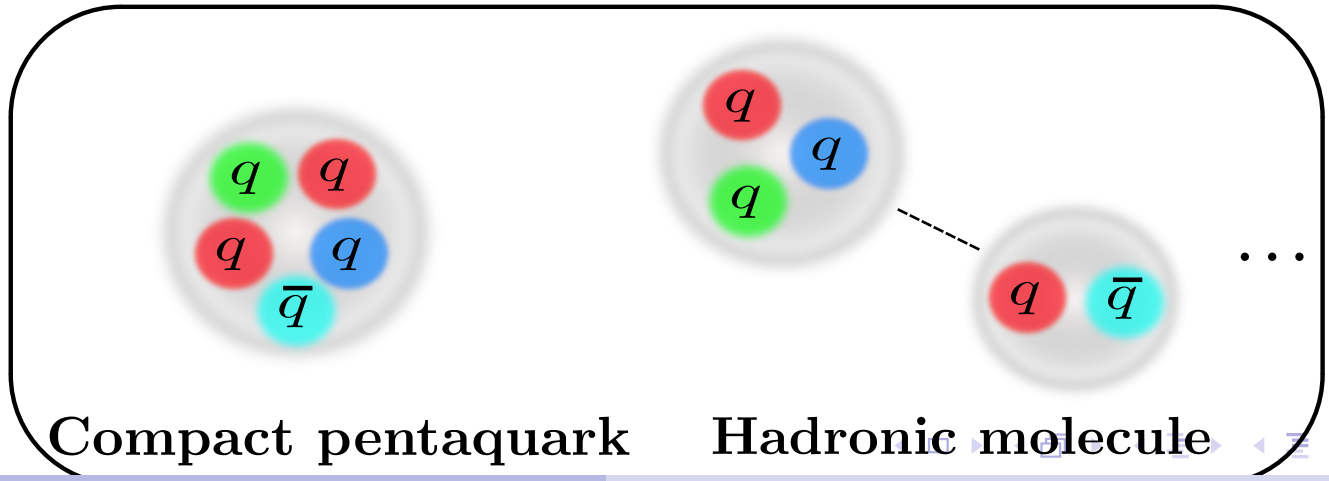


- **Exotic hadrons?** $\rightarrow$ Multiquark state



Observation of two hidden-charm pentaquarks !!

Introduction

PRL 115, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

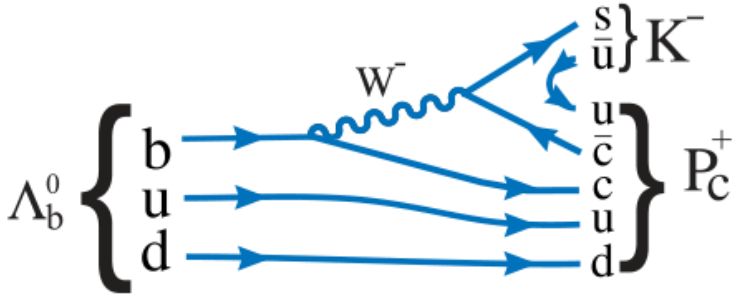
R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of ① $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of ② $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

DOI: 10.1103/PhysRevLett.115.072001 PACS numbers: 14.40.Pq, 13.25.Gv

$\Lambda_b^0 \to K^- P_c^+$ decay



$c\bar{c}uud$ Pentaquark!

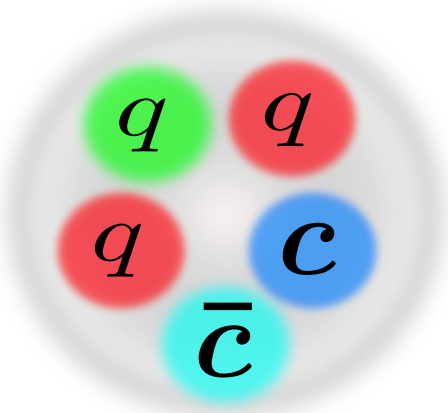
$J = 3/2, 5/2$

What is the structure of the pentaquarks?
Introduction

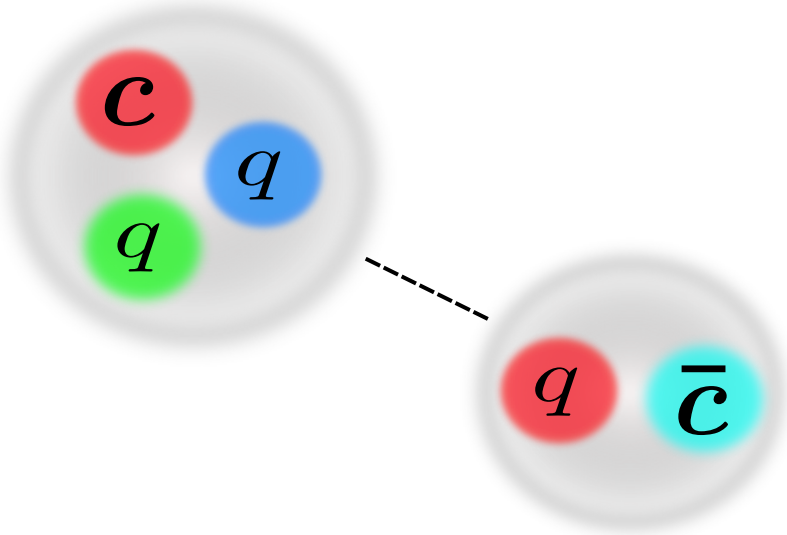
- Compact pentaquark? Hadronic molecule?

  W.L.Wang *et al.*, (2011), G. Yang and J. Ping, (2015)

  J.-J.Wu *et al.*, (2010), C.W.Xiao *et al.*, (2013)



Pentaquark (Compact)



Hadronic molecule

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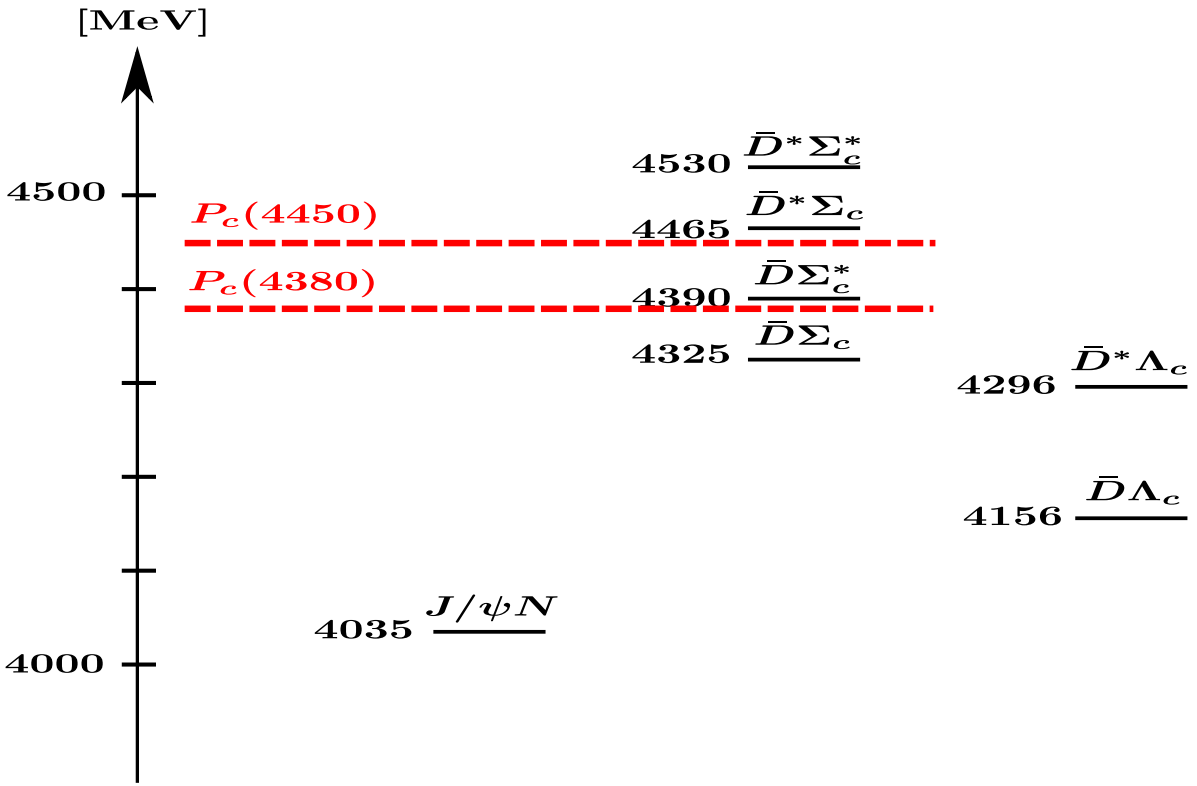
▷ Pentaquarks are close to **the meson-baryon thresholds**
$\Rightarrow$ **Hadronic molecules** are a loosely bound state of hadrons.



Important issue of the heavy pentaquarks
Introduction

Heavy Quark Spin Symmetry

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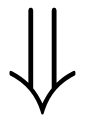
Charm (c), Bottom (b), Top (t)

Heavy Quark Spin Symmetry

Charm (c), Bottom (b), Top (t)

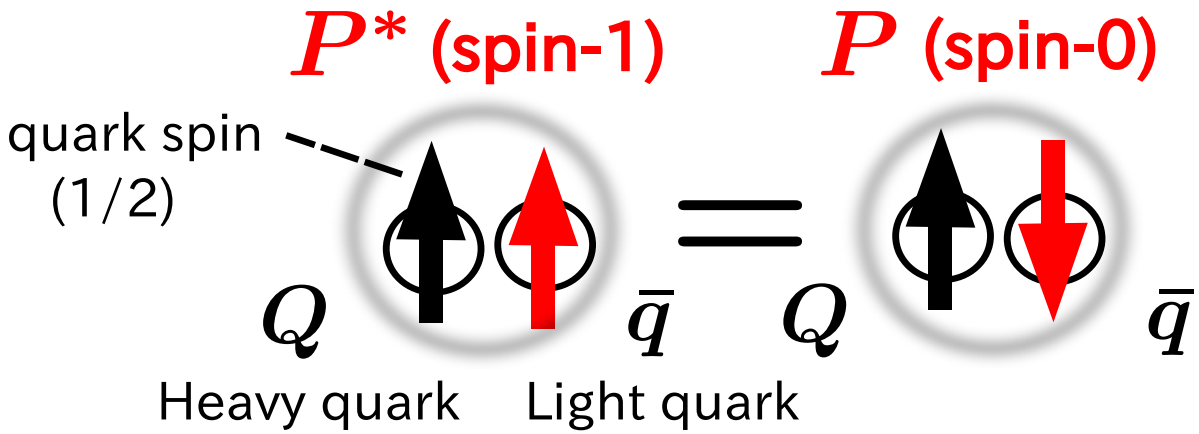


1. Coupled channels of MB
2. Tensor force

Heavy Quark Spin Symmetry (HQS)

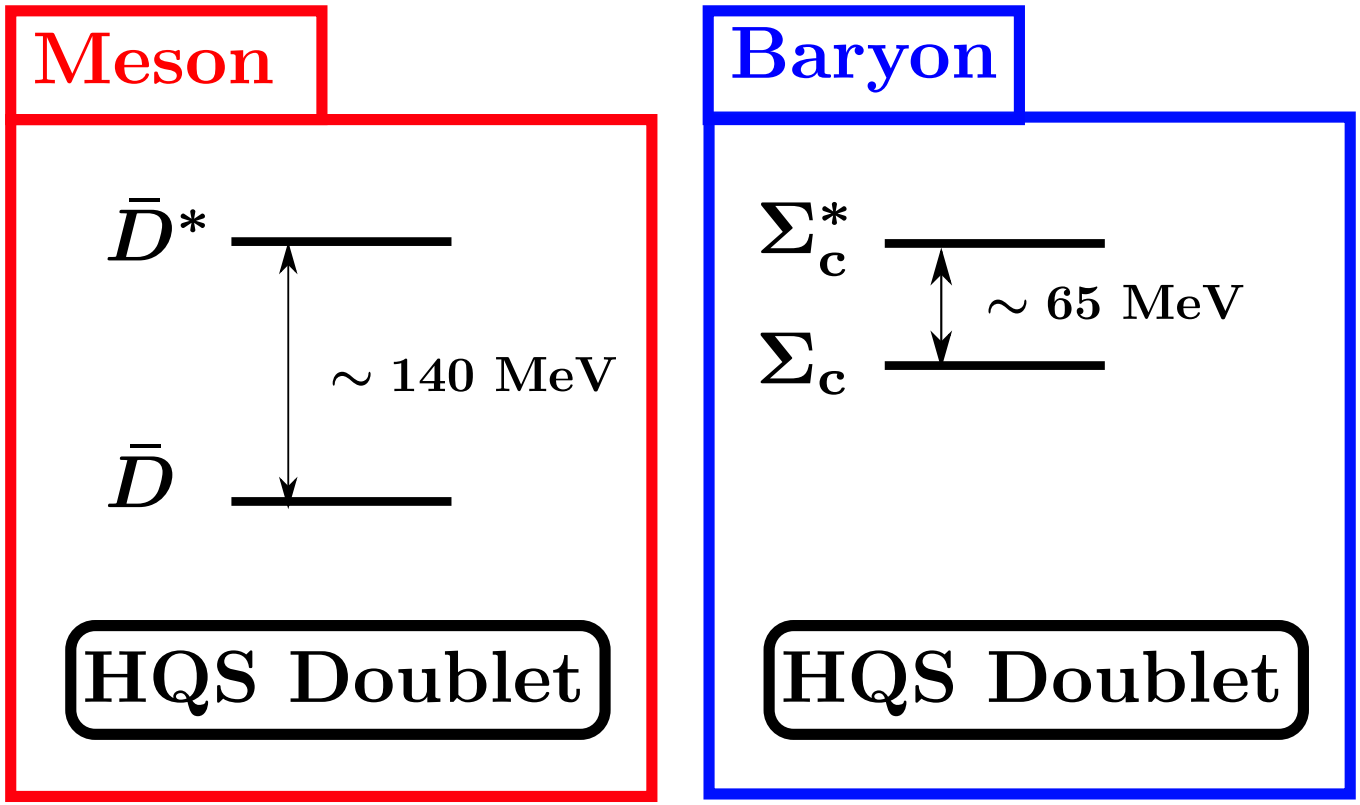
N.Isgur,M.B.Wise,PLB**232**(1989)113

- **Suppression of Spin-spin force** in $m_Q \to \infty$.
- e.g. $Q\bar{q}$ meson $\Rightarrow$ Mass degeneracy of spin-0 and spin-1 states!



$\Rightarrow$ **Mass degeneracy** of hadrons with the different J

- $\bar{D} - \bar{D}^*$ and $\Sigma_c - \Sigma_c^*$ mixings due to the HQS



- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!

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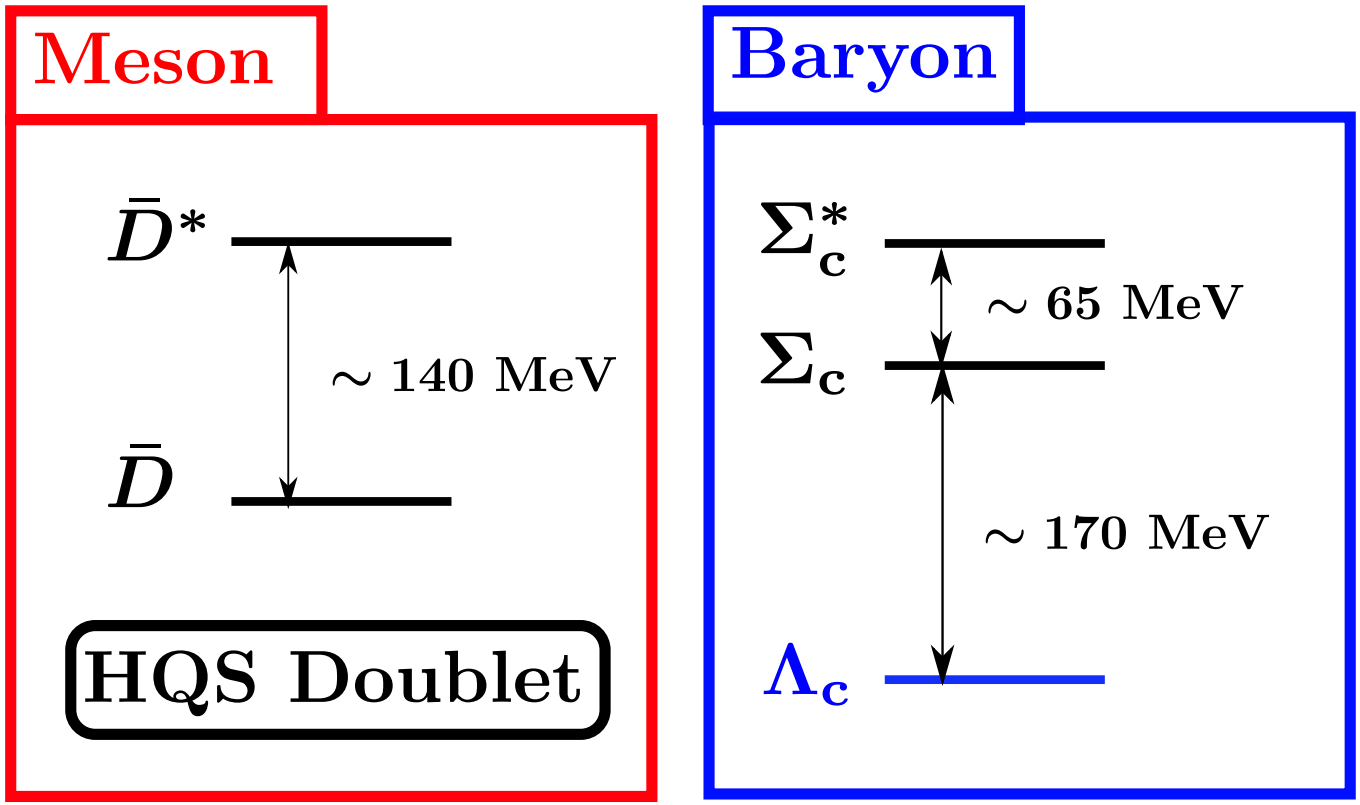

- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!
- In addition, $\boldsymbol{\Lambda_c}$ **(*cqq*)**: $\bar{D}^{(*)}\Lambda_c$ channel?

- 6 meson-baryon components

  (1) $\bar{D}\Lambda_c$, (2) $\bar{D}^*\Lambda_c$, (3) $\bar{D}\Sigma_c$, (4) $\bar{D}\Sigma_c^*$, (5) $\bar{D}^*\Sigma_c$, (6) $\bar{D}^*\Sigma_c^*$

$\Rightarrow$ These components are mixed by...**Tensor force!**

- 6 meson-baryon components

$$(1)\ \bar{D}\Lambda_c,\ (2)\ \bar{D}^*\Lambda_c,\ (3)\ \bar{D}\Sigma_c,\ (4)\ \bar{D}\Sigma_c^*,$$
$$(5)\ \bar{D}^*\Sigma_c,\ (6)\ \bar{D}^*\Sigma_c^*$$

$\Rightarrow$ These components are mixed by...**Tensor force!**

Tensor force $\Rightarrow$ Mixing of states with different ℓ

$$V^{tensor}(r) = g\mathbf{S}_{12}(\hat{\mathbf{r}})\left(3 + \mathbf{mr} + \mathbf{m}^2\mathbf{r}^2\right)\frac{\mathbf{e}^{-\mathbf{mr}}}{\mathbf{r}^3}$$

- $\boldsymbol{S_{12}(\hat{r}) = \left[3(\vec{\mathcal{O}}_1 \cdot \hat{r})(\vec{\mathcal{O}}_2 \cdot \hat{r}) - \vec{\mathcal{O}}_1 \cdot \vec{\mathcal{O}}_2\right]}$ $\rightarrow$ $S-D$ mixing
- $\boldsymbol{T(r)}$ $\rightarrow$ Strong attraction

Tensor force in NN ($^3S_1 - ^3D_1$)

- Tensor force is important in Deuteron, $NN(^3S_1 - ^3D_1)$

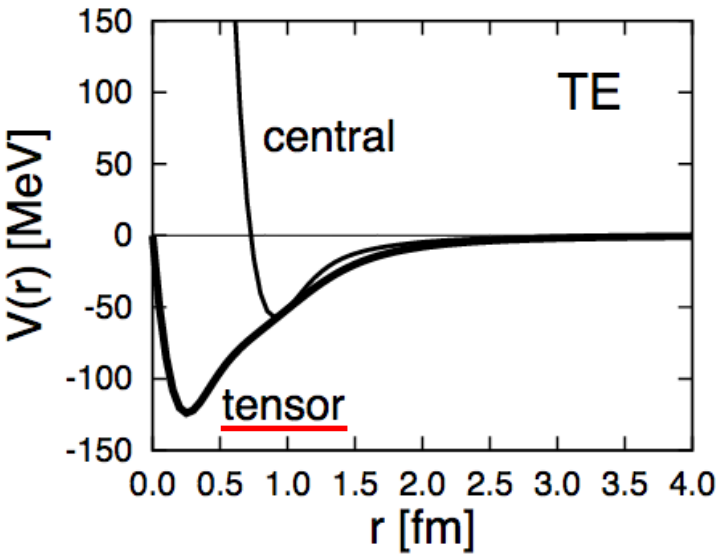

Table 2 Deuteron properties using the AV8' nucleon-nucleon potential.

Energy	−2.24 [MeV]
Kinetic	19.88
(SS)	11.31
(DD)	8.57
Central	−4.46
(SS)	−3.96
(DD)	−0.50
Tensor	−16.64
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LS	−1.02

K. Ikeda, T. Myo, K. Kato and H. Toki, Lect. Notes Phys. **818**, 165 (2010).

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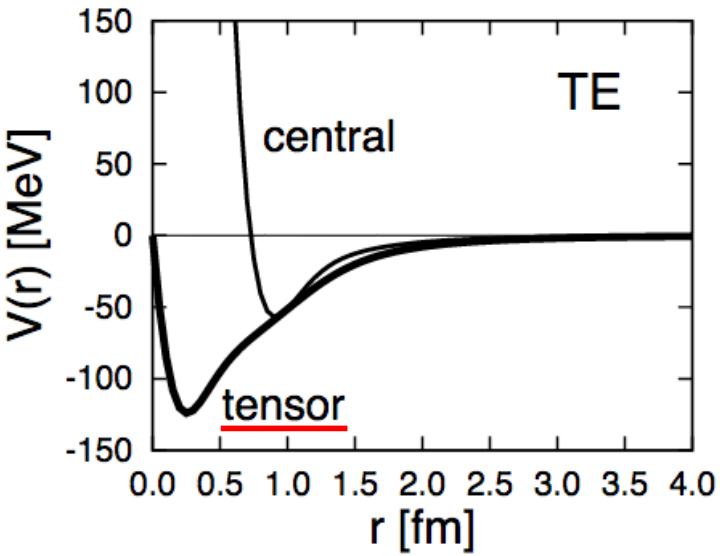

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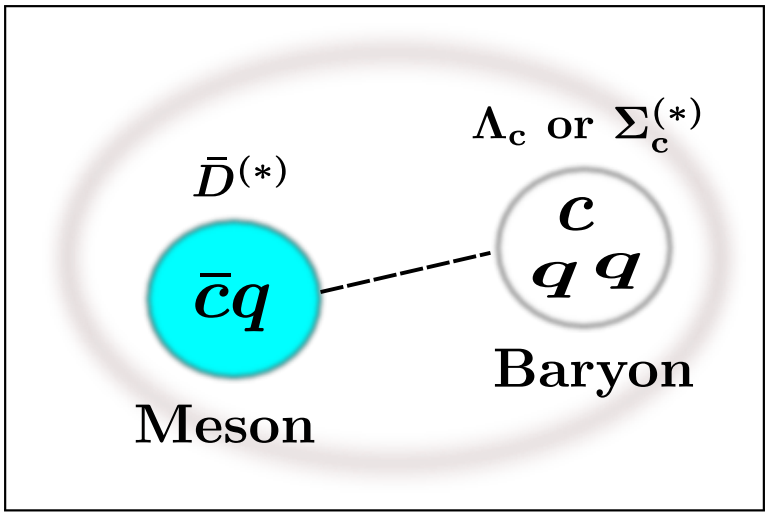
- Tensor force in $S - D$ component produces **the strong attraction**!
- Couplings to the states with $\ell \neq 0$ are needed!

Main Subject: Pentaquarks

- Hadronic molecules formed by **hidden-charm meson-baryon**.



- Bound and resonant states of $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$
  - ▷ Coupling to $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, and $\bar{D}^*\Sigma_c^*$
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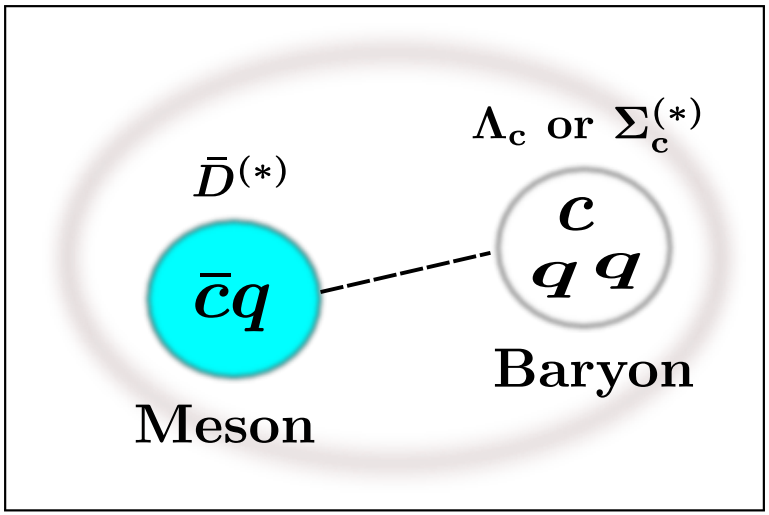

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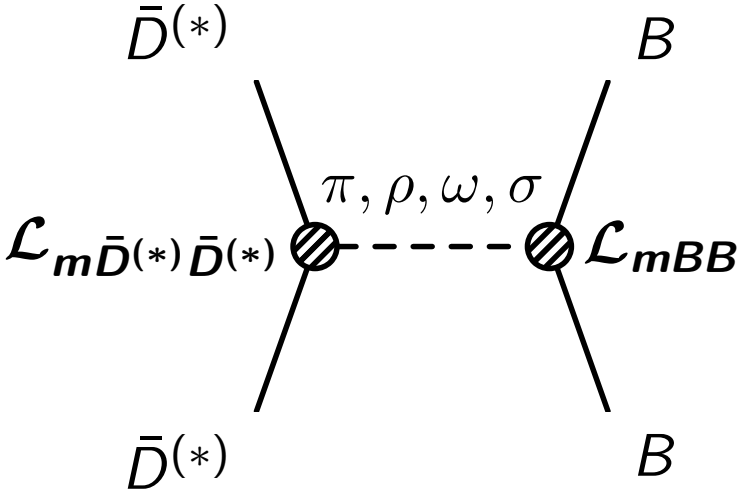
The full-coupled channel analysis has never been performed so far !

$\bar{D}^{(*)}B$ Interaction: Meson exchange potential

- Effective Lagrangian with heavy quark symmetry

R. Casalbuoni *et al.*, Phys.Rept.**281** (1997)145, Y.-R.Liu and M.Oka, PRD**85**(2012)014015



$\bar{D}^{(*)}$: $\bar{D}$ or $\bar{D}^*$

B: Λ_c, Σ_c or Σ_c^*

m: π, ρ, ω or σ

Fig: Meson exchange diagram

$$V^{\pi}_{\bar{D}^{(*)}B-\bar{D}^{(*)}B} = G\left[\vec{\mathcal{O}}_1 \cdot \vec{\mathcal{O}}_2 C(r) + S_{\mathcal{O}_1\mathcal{O}_2} T(r)\right]$$

$C(r)$: Central force, $T(r)$: Tensor force

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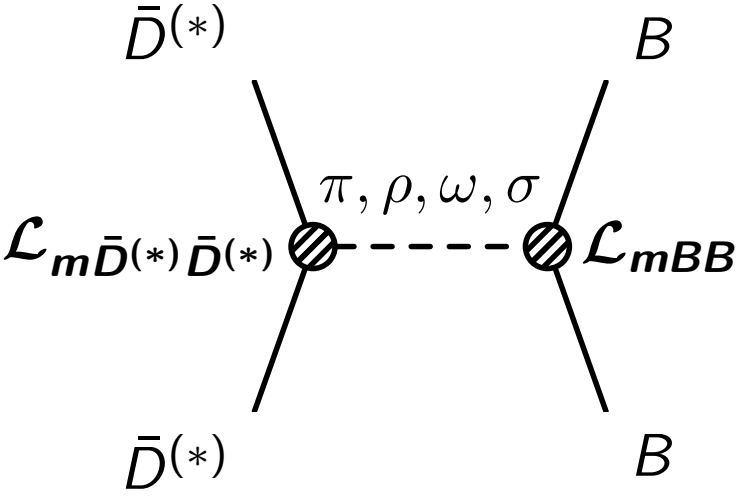

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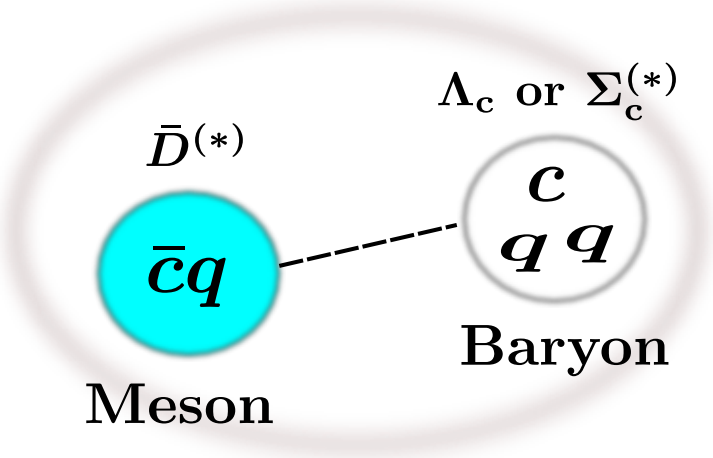
$C(r)$: Central force, $T(r)$: Tensor force

- Form factor with common cutoff $\Lambda \leftarrow$ Free parameter

$$F(\Lambda, \vec{q}\,) = \frac{\Lambda^2 - m_\alpha^2}{\Lambda^2 + |\vec{q}\,|^2} \quad \text{(fixed by the observed mass of } P_c\text{)}$$

Results of $\bar{D}^{(*)}B$ states (2-body)



$\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$

Exotic states ($c\bar{c}qqq$)

Bound state and Resonance

- We solve the coupled-channel Schrödinger equations with $J^P = 3/2^{\pm}, 5/2^{\pm}$ and isospin $I = 1/2$.
- Interaction: $\pi\rho\omega\sigma$ exchange potentials

Numerical results

- Observed Pentaquarks; $P_c^+(4380)$ and $P_c^+(4450)$
- J^P assignment by LHCb;
  $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$, $(5/2^+, 3/2^-)$

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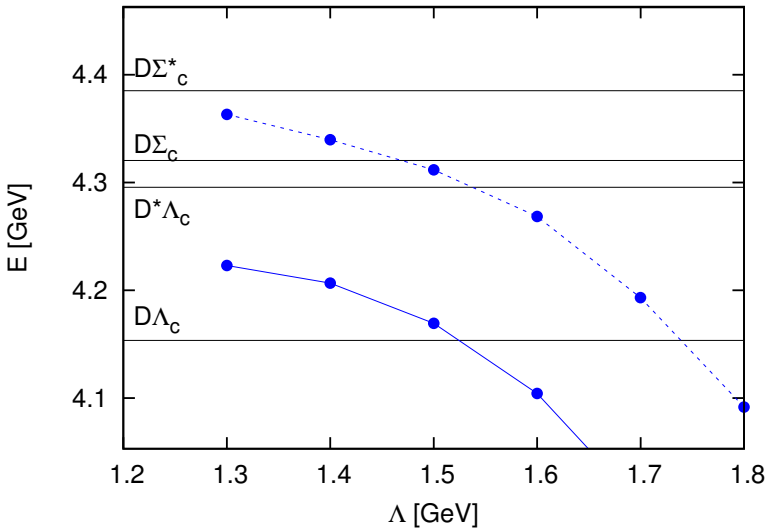
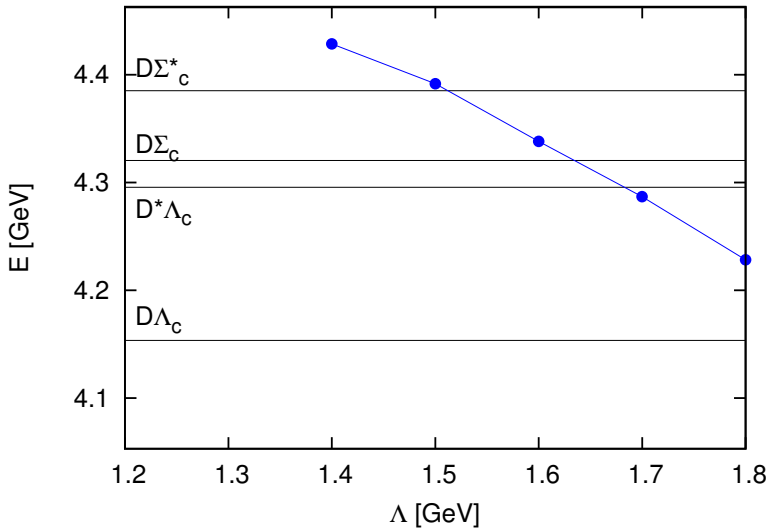
$J^P = 3/2^+$



$J^P = 5/2^-$



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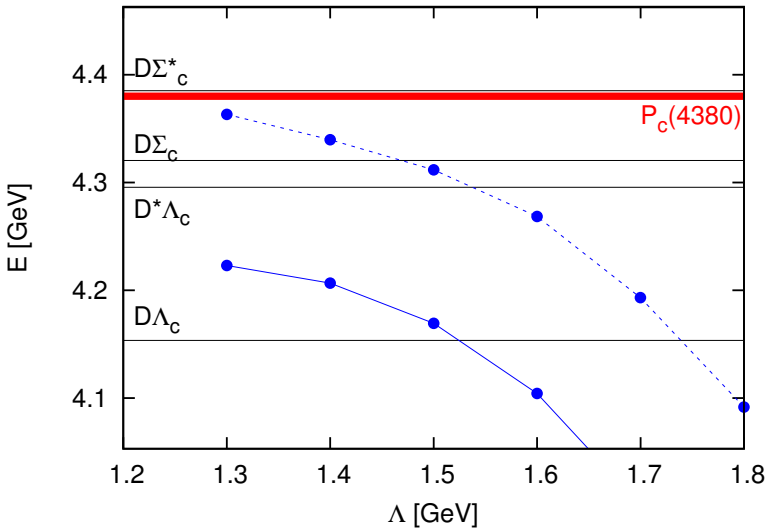

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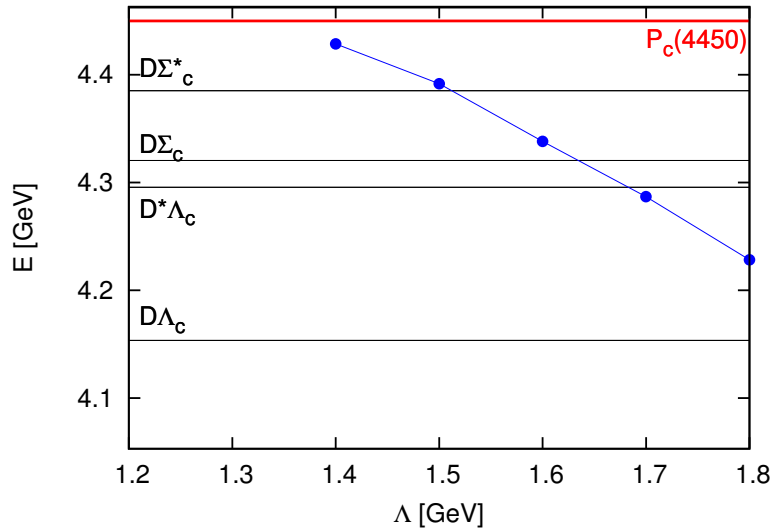

$P_c^+(4380)$: **$J^P = 3/2^+$** $P_c^+(4450)$: **$J^P = 5/2^-$**
Cutoff $\Lambda = 1400$ MeV

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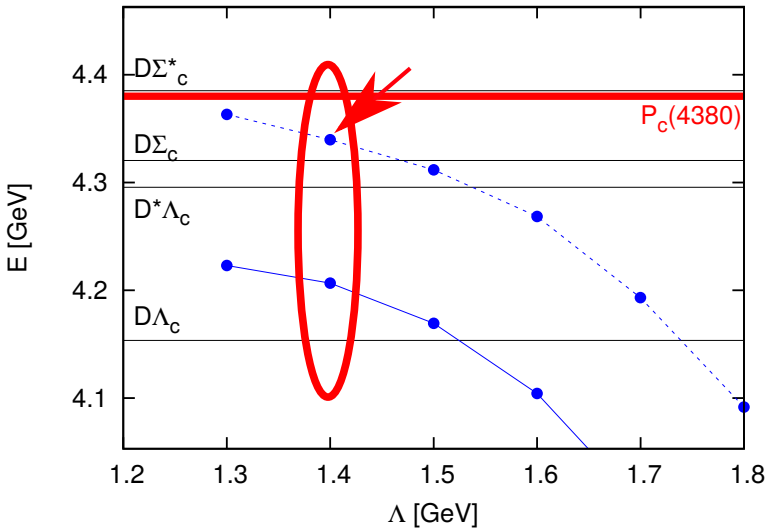
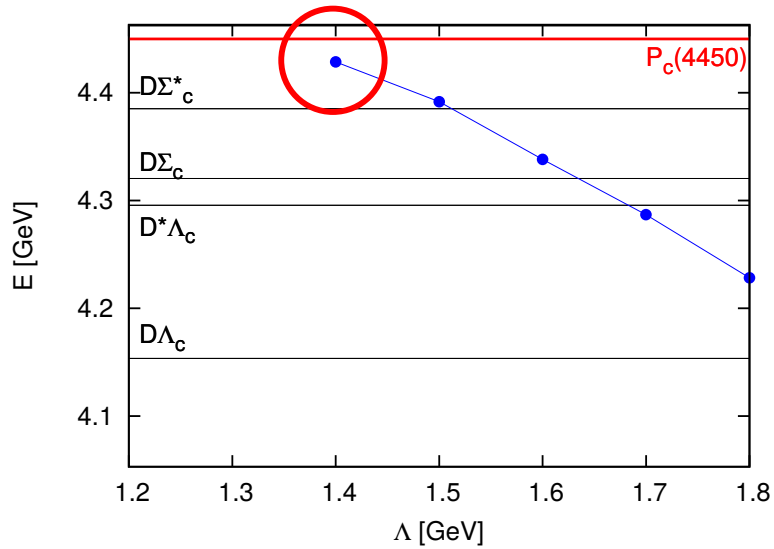


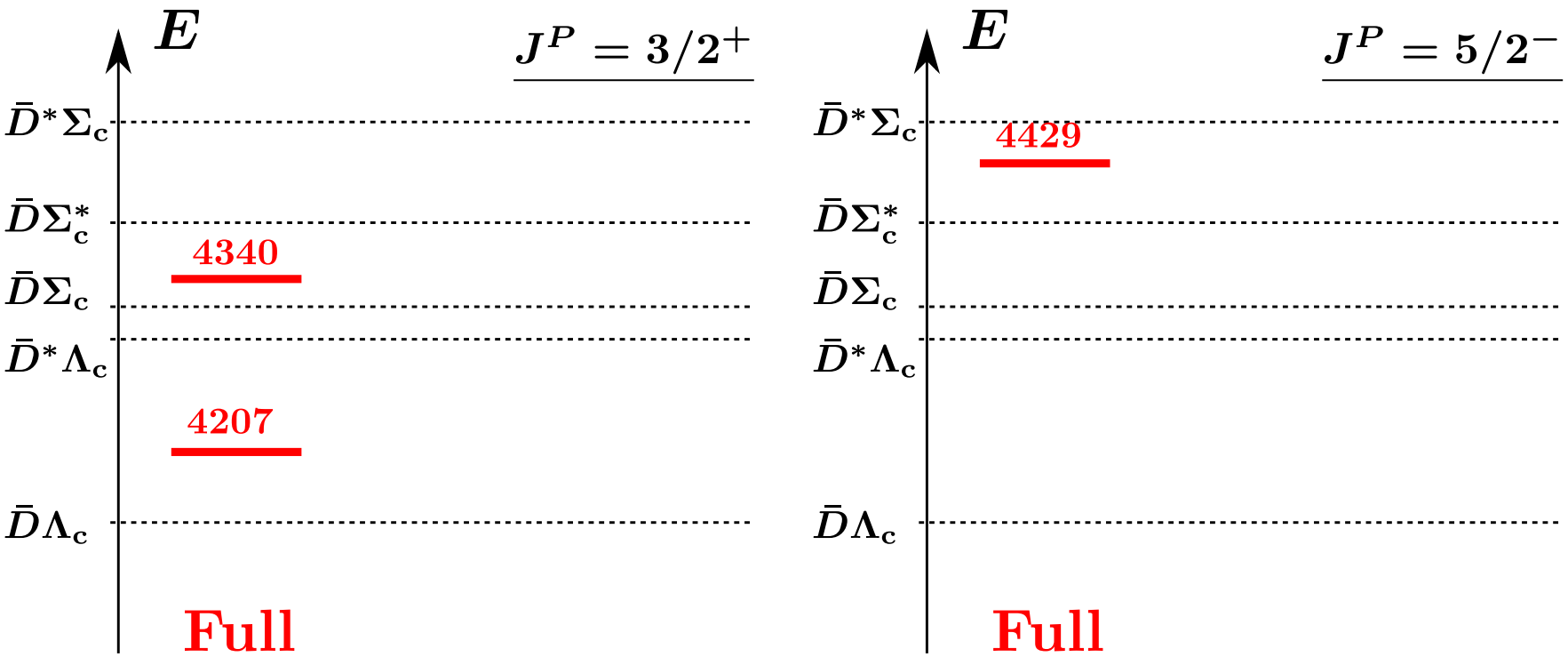
$J^P = 5/2^-$



$P_c^+(4380)$: **$J^P = 3/2^+$** $\quad$ $P_c^+(4450)$: **$J^P = 5/2^-$**
Cutoff $\Lambda = 1400$ MeV

Channel-coupling effects

- Obtained mass with **Full channel coupling**, **without** $\bar{D}^{(*)}\Lambda_c$ and **without** $\ell > 0$ $(\ell > 1)$



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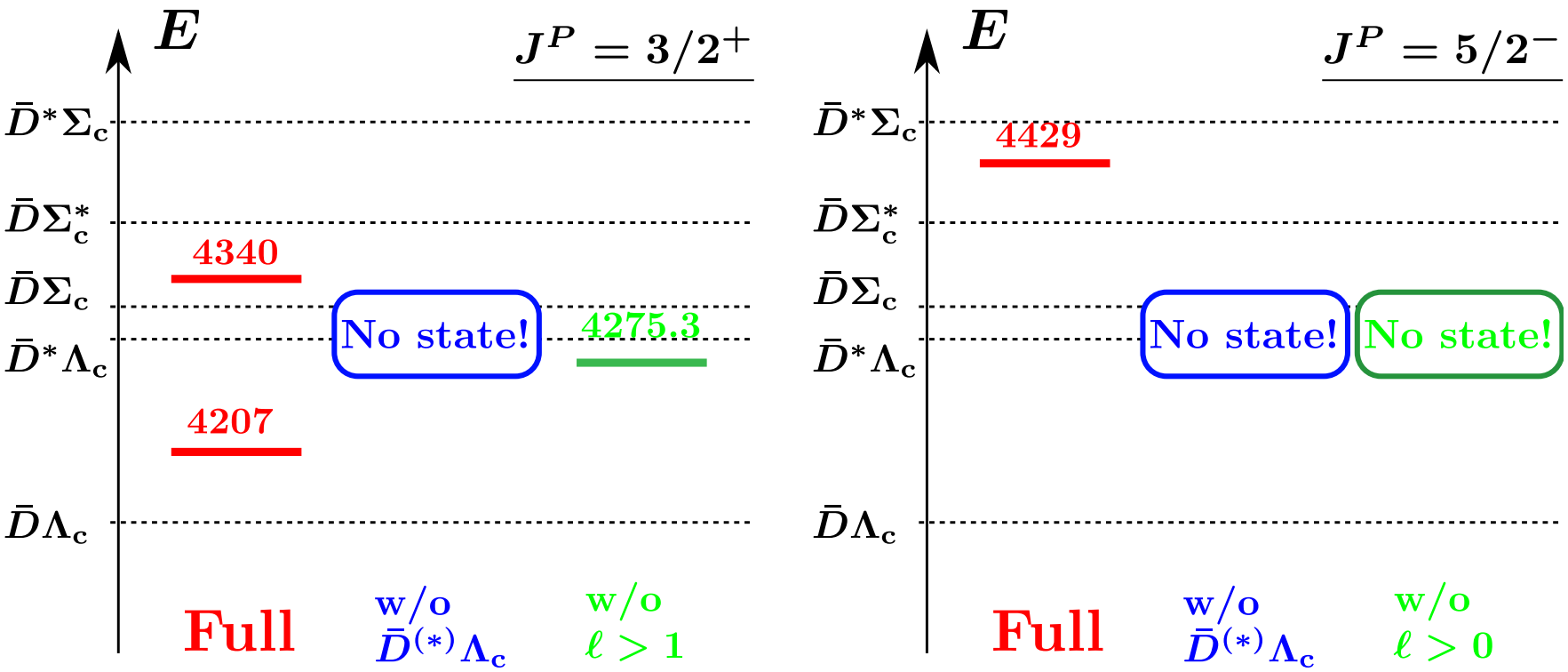

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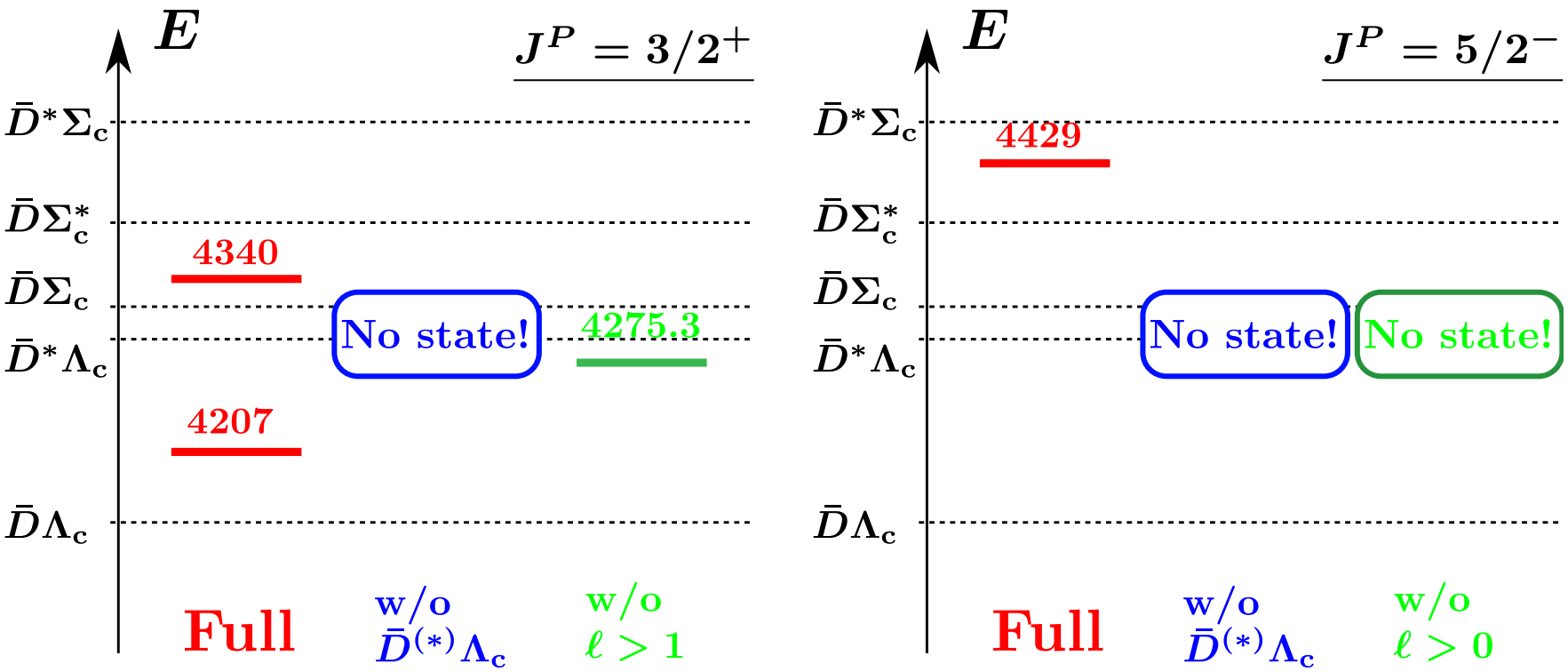


- **$\bar{D}^{(*)}\Lambda_c$ and $\ell > 0$ ($\ell > 1$)** components are not negligible.

Summary

Subject: Hidden-charm meson-baryon molecules with full-channel coupling

$\Downarrow\Downarrow$

- Observed Pentaquarks are close to the **Meson-baryon thresholds**.
  $\rightarrow$ **Hadronic molecules** are considered.
- Heavy Quark Spin Symmetry induces the coupled-channel analysis of $\boldsymbol{\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}}$.
- Tensor force induces the couplings to the states with $\boldsymbol{\ell \neq 0}$.
- Resonances of the $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$ are obtained.
- The J^P assignment of $P_c^+(4380)$ and $P_c^+(4450)$ is $\boldsymbol{3/2^+}$ and $\boldsymbol{5/2^-}$, respectively.

Outlook

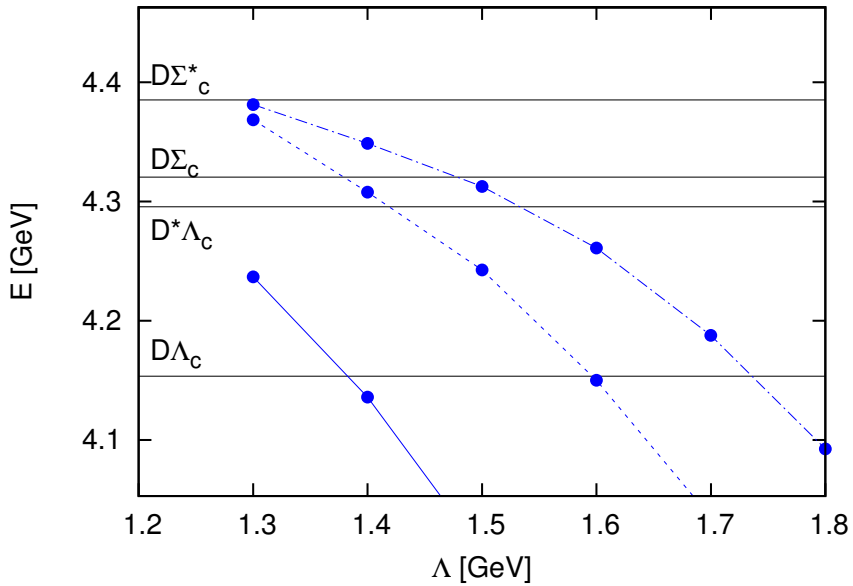
- Coupling to $J/\psi p$, cutoff Λ, $1/m_Q$ correction,...

Back up

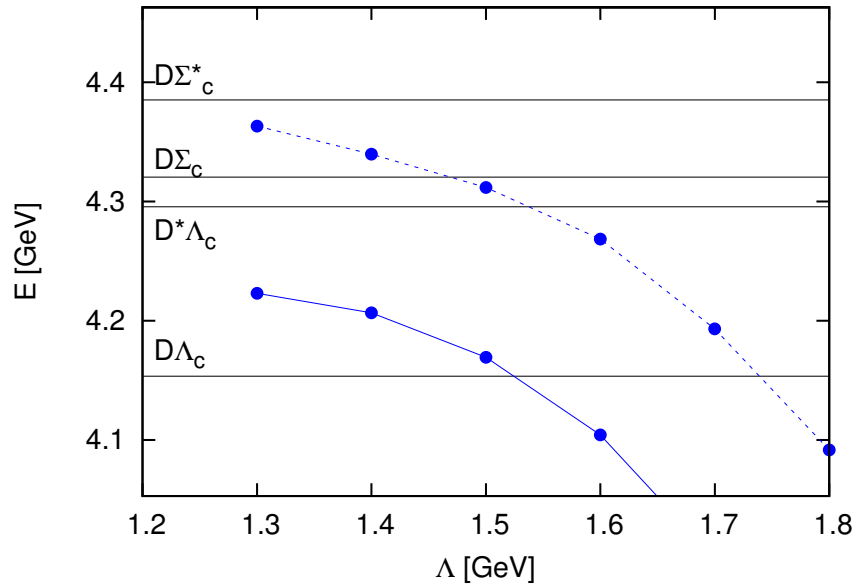
Coupled-Channels

J^P	Channels
$3/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^4S,^2D,^4D)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4S,^4D)$, $\bar{D}^*\Sigma_c(^4S,^2D,^4D)$, $\bar{D}^*\Sigma_c^*(^4S,^2D,^4D,^6D,^6G)$
$3/2^+$	$\bar{D}\Lambda_c(^2P)$, $\bar{D}^*\Lambda_c(^2P,^4P,^4F)$, $\bar{D}\Sigma_c(^2P)$, $\bar{D}\Sigma_c^*(^4P,^4F)$, $\bar{D}^*\Sigma_c(^2P,^4P,^4F)$, $\bar{D}^*\Sigma_c^*(^2P,^4P,^6P,^4F,^6F)$
$5/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^2D,^4D,^4G)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4D,^4G)$, $\bar{D}^*\Sigma_c(^2D,^4D,^4G)$, $\bar{D}^*\Sigma_c^*(^6S,^2D,^4D,^6D,^4G,^6G)$
$5/2^+$	$\bar{D}\Lambda_c(^2F)$, $\bar{D}^*\Lambda_c(^4P,^2F,^4F)$, $\bar{D}\Sigma_c(^2F)$, $\bar{D}\Sigma_c^*(^4P,^4F)$, $\bar{D}^*\Sigma_c(^4P,^2F,^4F)$, $\bar{D}^*\Sigma_c^*(^4P,^6P,^2F,^4F,^6F,^6H)$
	Thresholds (MeV)
	$\bar{D}\Lambda_c(4153.5)$, $\bar{D}^*\Lambda_c(4295.5)$, $\bar{D}\Sigma_c(4320.5)$, $\bar{D}\Sigma_c^*(4385.1)$, $\bar{D}^*\Sigma_c(4462.5)$, $\bar{D}^*\Sigma_c^*(4527.1)$

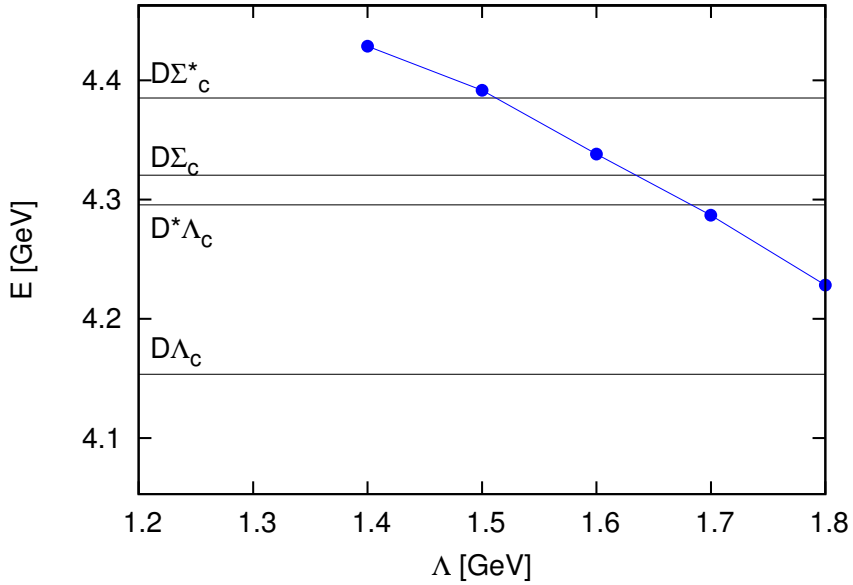
(i) $J^P = 3/2^-$



(ii) $J^P = 3/2^+$



(iii) $J^P = 5/2^-$



(iv) $J^P = 5/2^+$

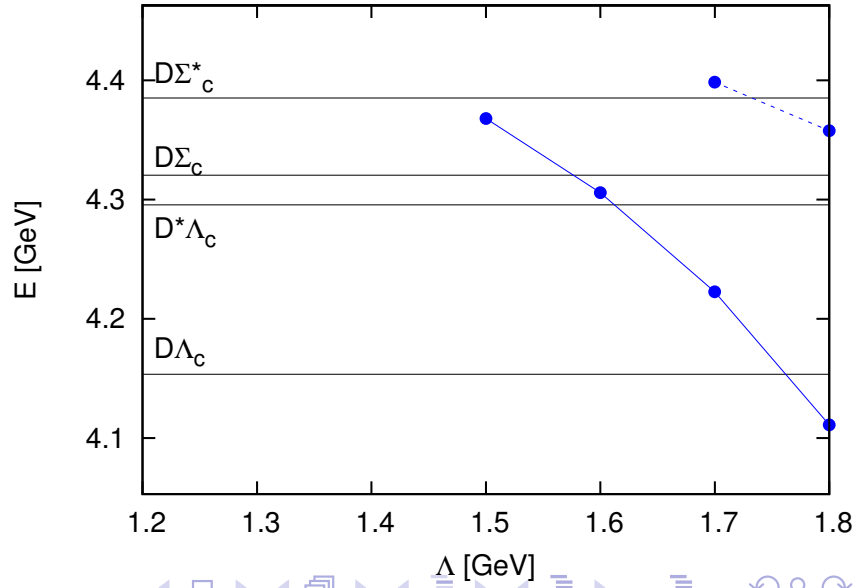


Table: Obtained masses with full channel coupling (Full), without $\bar{D}^{(*)}\Lambda_c$ (w/o $\bar{D}^{(*)}\Lambda_c$) and without large orbital angular momentum ℓ (w/o $\ell > 0$ or w/o $\ell > 1$) in $\Lambda = 1400$ MeV.

J^P	Channels	Mass [MeV]
$3/2^-$	Full	4136.0, 4307.9, 4348.7
	w/o $\bar{D}^{(*)}\Lambda_c$	4278.4, 4400.4
	w/o $\ell > 0$	4220.4, 4376.6
$3/2^+$	Full	4206.7, 4339.7
	w/o $\bar{D}^{(*)}\Lambda_c$	—
	w/o $\ell > 1$	4275.3
$5/2^-$	Full	4428.6
	w/o $\bar{D}^{(*)}\Lambda_c$	—
	w/o $\ell > 0$	—

Table: Comparison of the lowest mass of hidden-charm meson-baryon molecules with $I(J^P) = 1/2(3/2^-)$ by this work with the early works. The obtained masses are shown in the second column in the unit of MeV. The value of this work is in $\Lambda = 1400$ MeV. The third column gives the channels which are considered in those works.

Ref.	Mass [MeV]	Channels
This work	4136.0	$\bar{D}\Lambda_c, \bar{D}^*\Lambda_c, \bar{D}\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$
PRL**105**(2010)232001	4415	$\bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$ with only S-wave
PRC**84**(2010)015202	4454	$\bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$ with only S-wave
PRD88(2013)056012	4334.5	$J/\psi N, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c^*$ with only S-wave