Exotic baryons as a hadronic molecule in the heavy quark region

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

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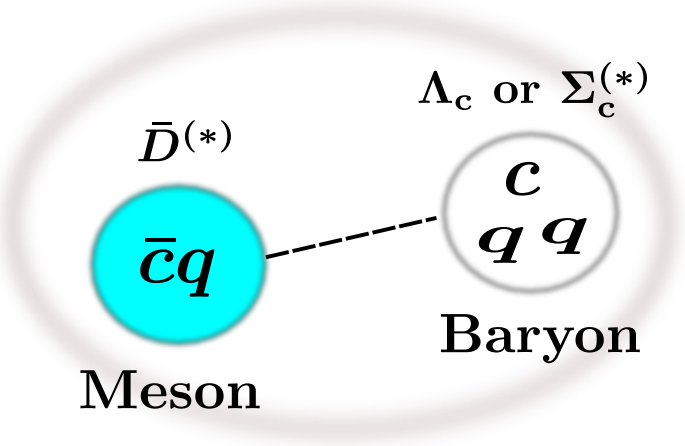
Outline

Hidden-charm pentaquarks as **a molecules**

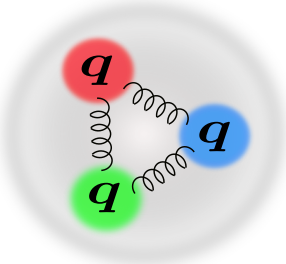
1. Introduction
   - Observed Pentaquarks
   - Heavy Quark Spin Symmetry
   - Coupled channels
2. Meson-Baryon molecules: $\bar{D}^{(*)}\Lambda_c^{(*)} - \bar{D}^{(*)}\Sigma_c^{(*)}$
3. Summary



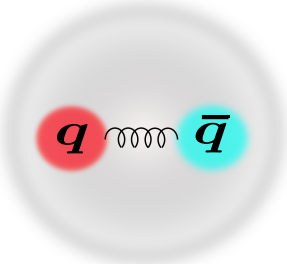
2-body system

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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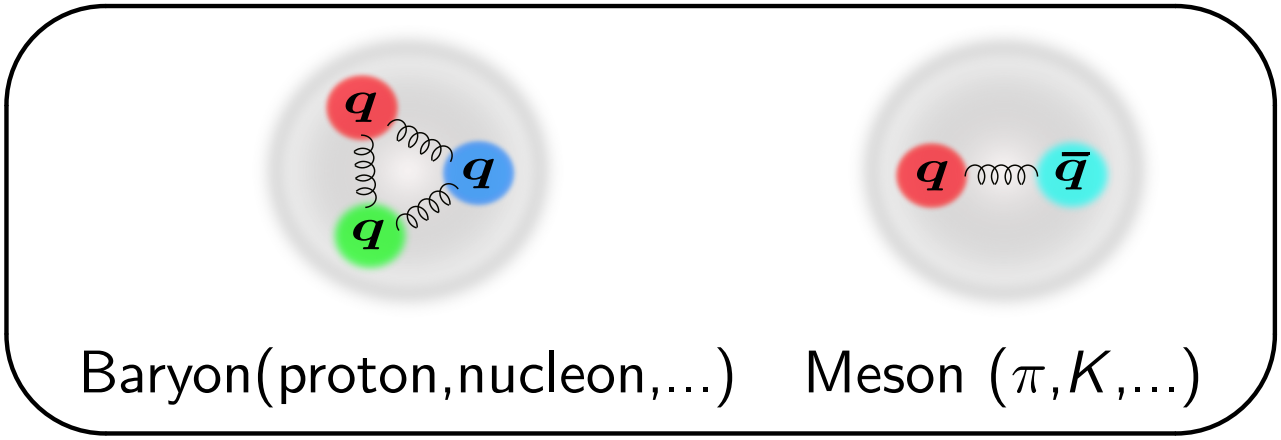
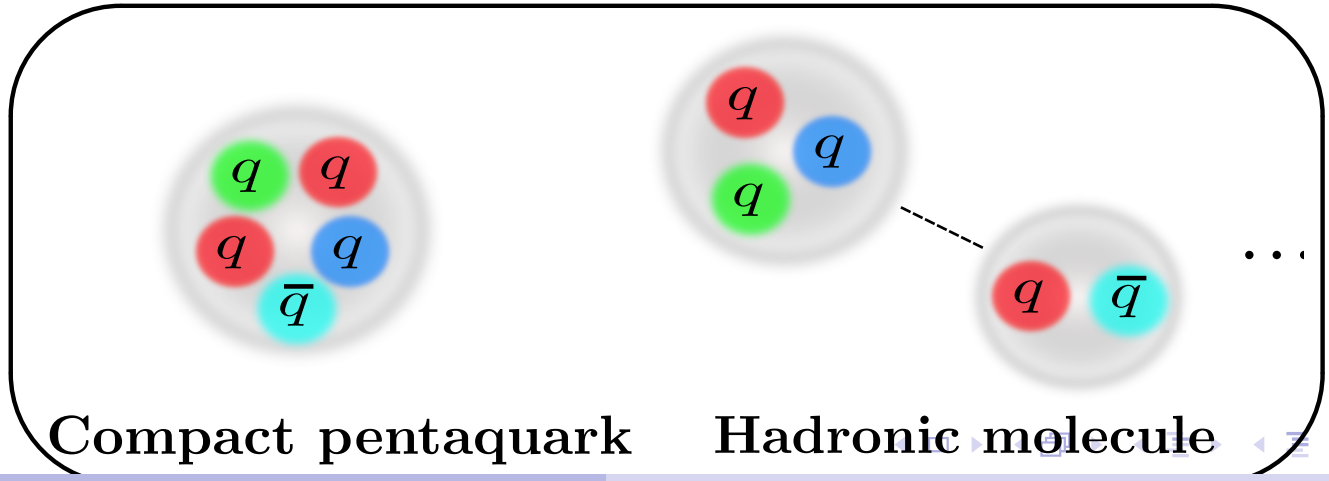


- **Exotic hadrons?** $\rightarrow$ Multiquark state



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

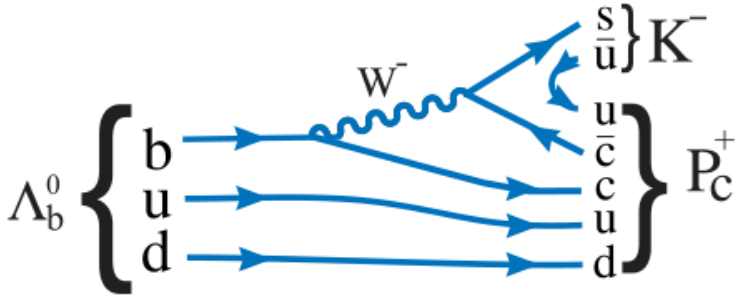
R. Aaij *et al.*[*]
(LHCb Collaboration)

(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 4380 ± 8 ± 29 MeV and a width of 205 ± 18 ± 86 MeV, while the second is narrower, with a mass of 4449.8 ± 1.7 ± 2.5 MeV and a width of 39 ± 5 ± 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

$\boxed{\Lambda_b^0 \to K^- P_c^+ \text{ decay}}$



$c\bar{c}uud$
Pentaquark!

$J = 3/2, 5/2$

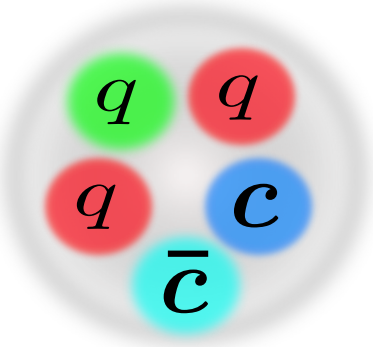
Theoretical discussions

- Compact pentaquark?
  - ▷ Quark model

    W.L.Wang *et al.*, PRC**84**(2011)015203

    G. Yang and J. Ping, (2015), arXiv:1511.09053.

    ...



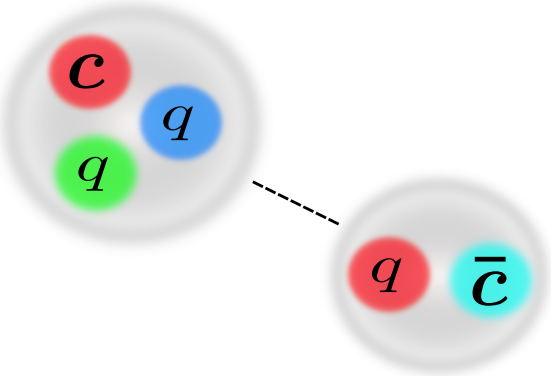
Pentaquark (Compact)

- Hadronic molecule?
  - ▷ SU(4) flavor symmetry

    J.-J.Wu *et al.*, PRL**105**(2010)232001

    C.W.Xiao *et al.*, PRD**88**(2013)056012

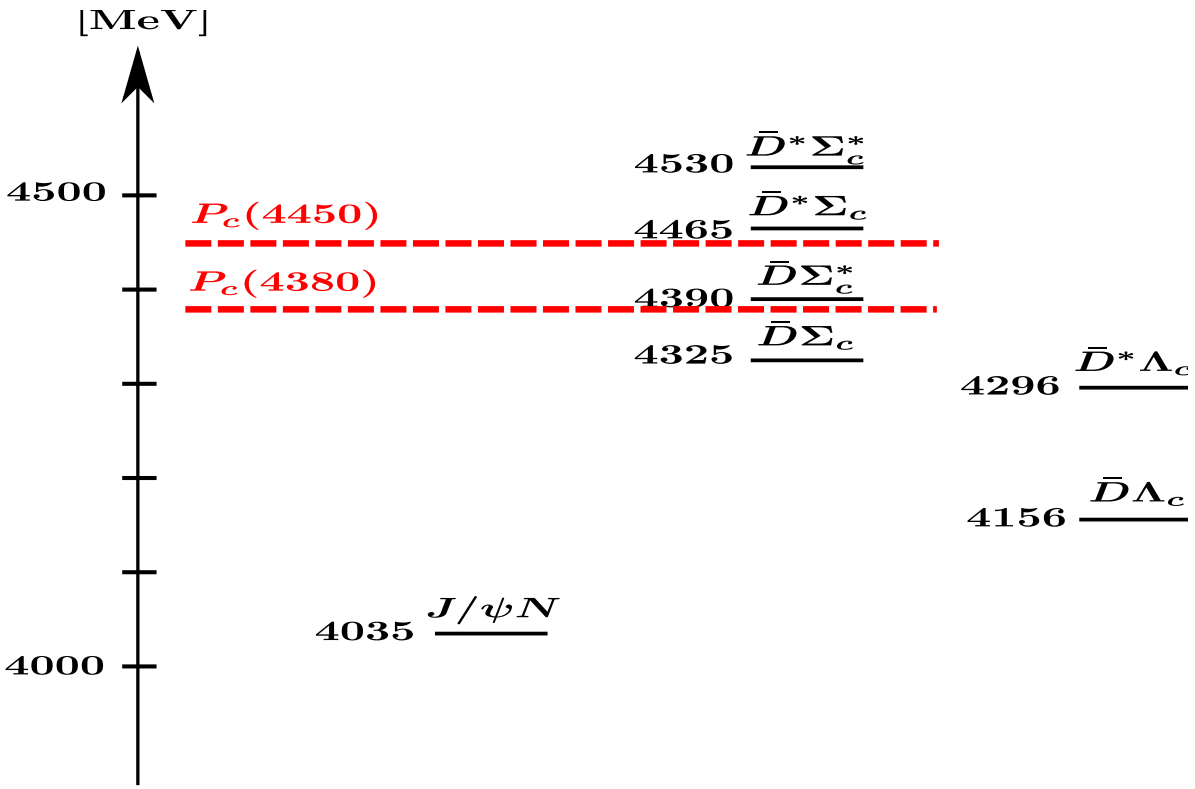
    ...



Hadronic molecule

Important issue of the heavy pentaquarks
Introduction

1. Pentaquarks are close to **the meson-baryon thresholds**
   $\Rightarrow$ **Hadronic molecules** appears near the thresholds!



2. **Heavy Quark Spin Symmetry**
   $\Rightarrow$ SU(4) symmetry is broken in the charm quark sector.

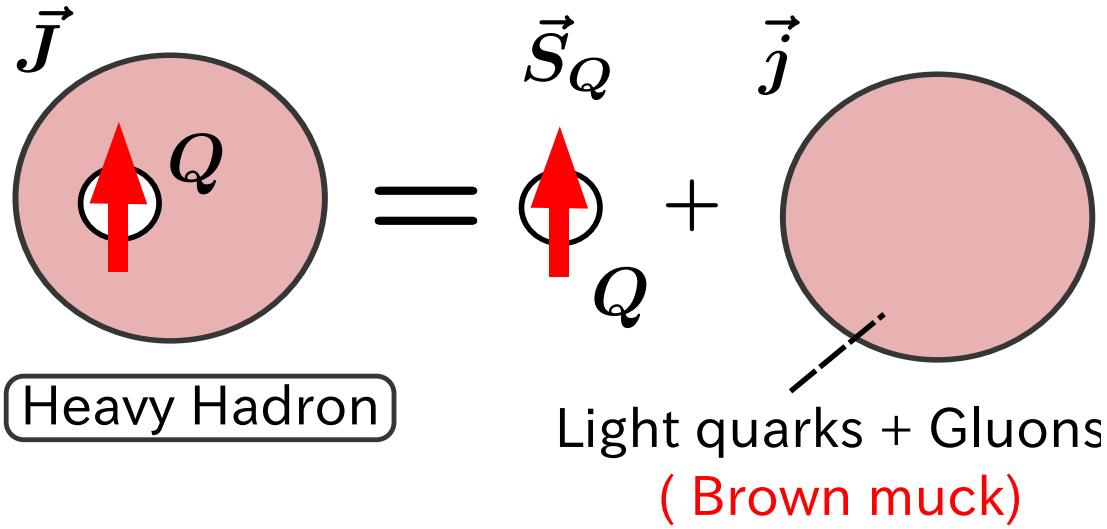
Heavy Quark Spin Symmetry (HQS)

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

- **Suppression of Spin-spin force** in $m_Q \to \infty$.

$\Rightarrow$ Decomposition of **Heavy quark spin** and **Light components**

$$\vec{J} = \vec{L} + \vec{S} = \vec{S}_Q + \vec{j}$$

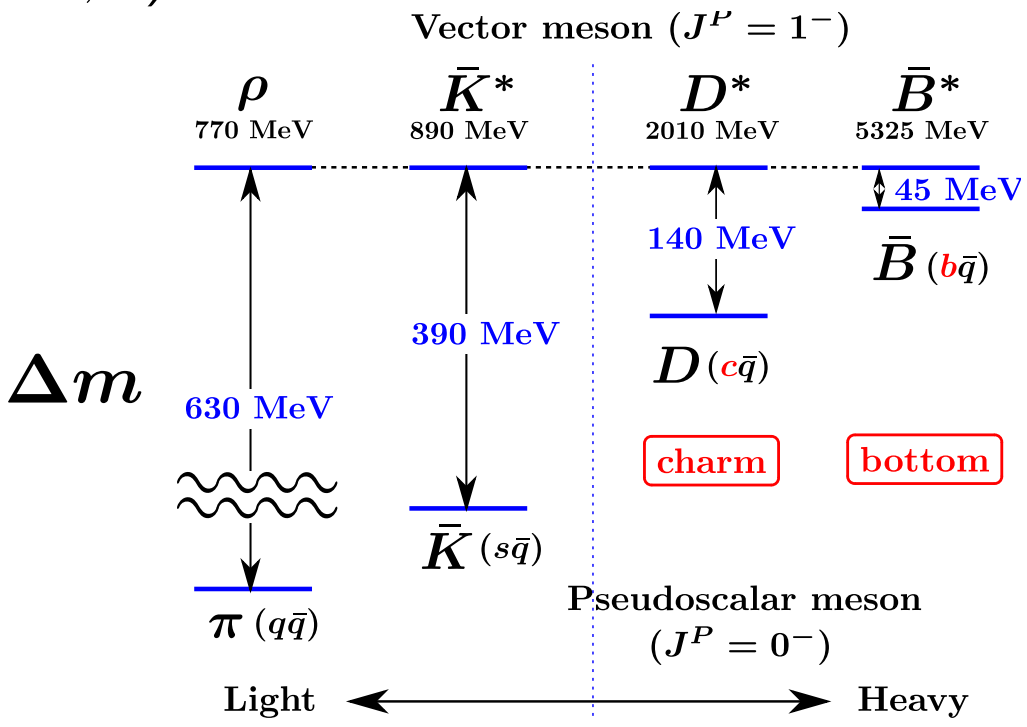


$\Rightarrow$ **Mass degeneracy** of hadrons with the different J

- Mass degeneracy of $\{D, D^*\}(Q\bar{q})$, $\{\eta_c, J/\psi\}(Q\bar{Q})$, $\{\Sigma_c, \Sigma_c^*\}(Qqq)$ (baryons)...

Mass degeneracy of heavy hadrons
Introduction

- Mass difference between vector and pseudoscalar mesons. $(Q\bar{q},\ q = u, d)$



- ▷ Δm decreases when the quark mass increases.
- ▷ Mass degeneracy of heavy baryons $\{\Sigma_c, \Sigma_c^*\}$ also appears.

Mass degeneracy of heavy hadrons
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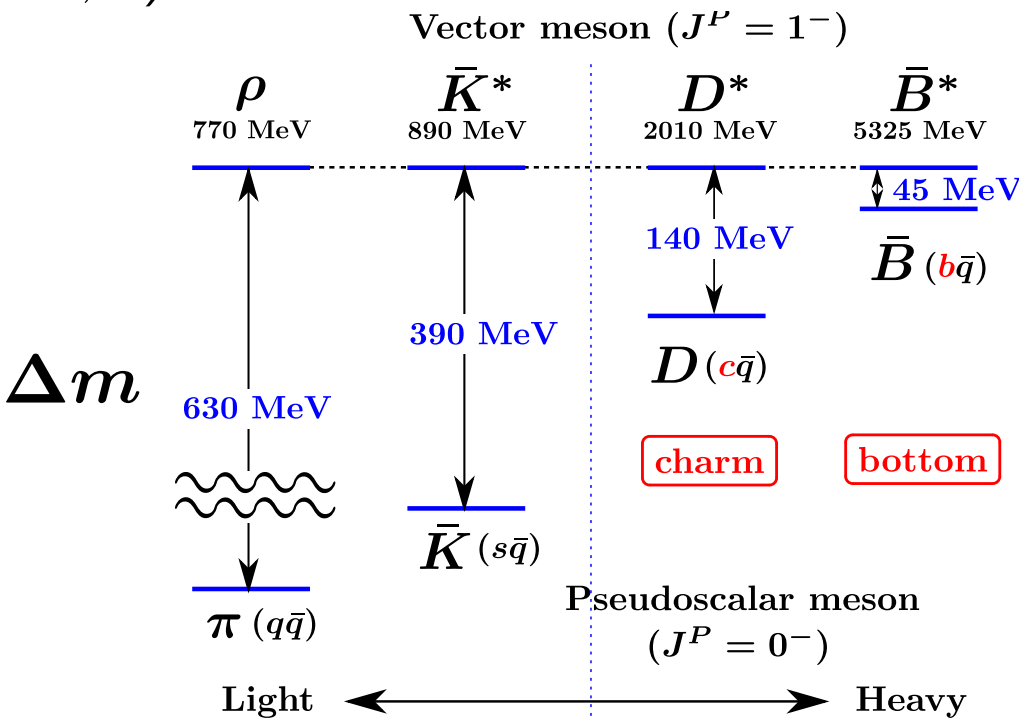


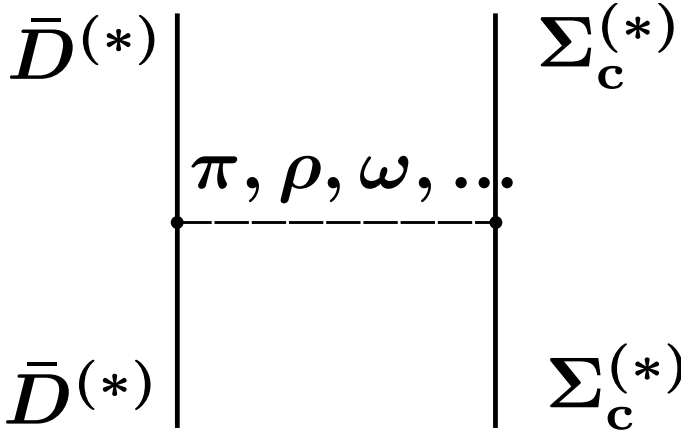
▷ Δm decreases when the quark mass increases.

▷ Mass degeneracy of heavy baryons $\{\Sigma_c, \Sigma_c^*\}$ also appears.

$\Rightarrow$ **Degeneracy of $\bar{D}\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$**

- $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$ mixing (analogous to $\Lambda N - \Sigma N$)
  $m_{\Sigma_c} - m_{\Lambda_c} \sim 170$ MeV

$\bar{D}^{(*)}\Sigma_c^{(*)}$ coupling



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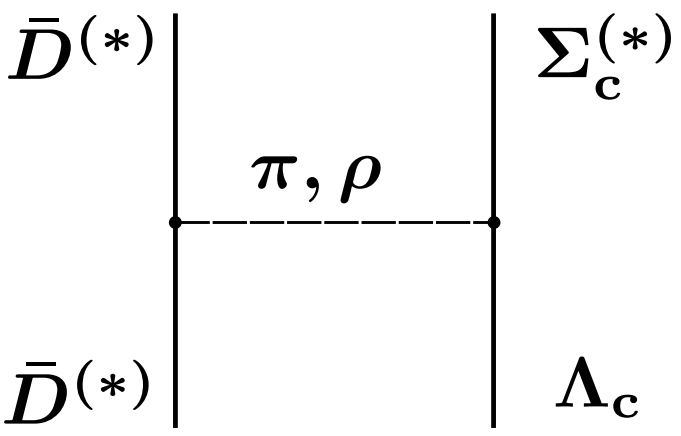

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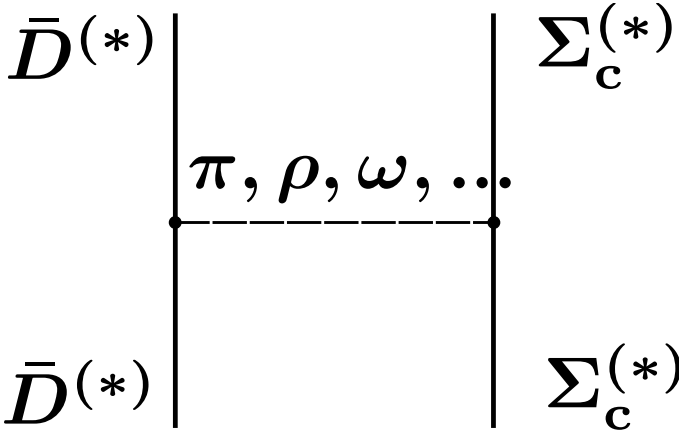

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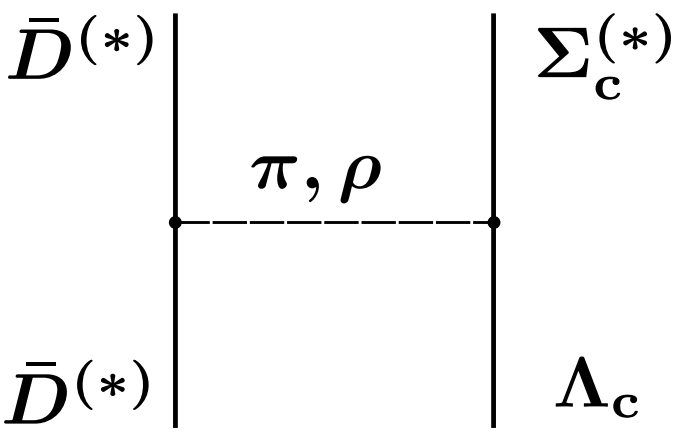

$\Rightarrow$ $\bar{D}\Lambda_c, \bar{D}^*\Lambda_c, \bar{D}\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$ (**6 thresholds!**)

Coupled channels of the hidden-charm pentaquark
Introduction

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  $m_{\Sigma_c} - m_{\Lambda_c} \sim 170$ MeV

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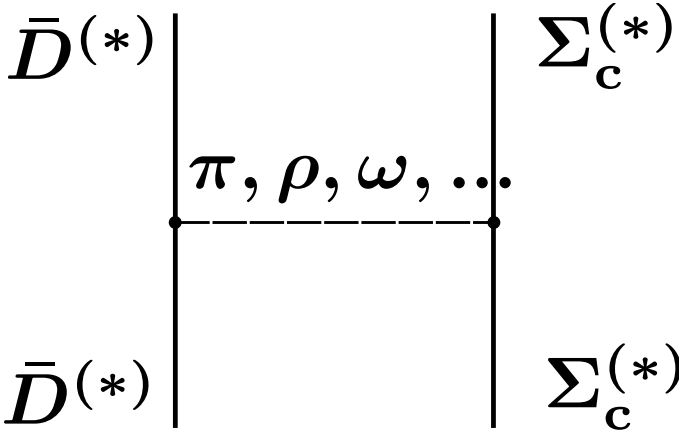
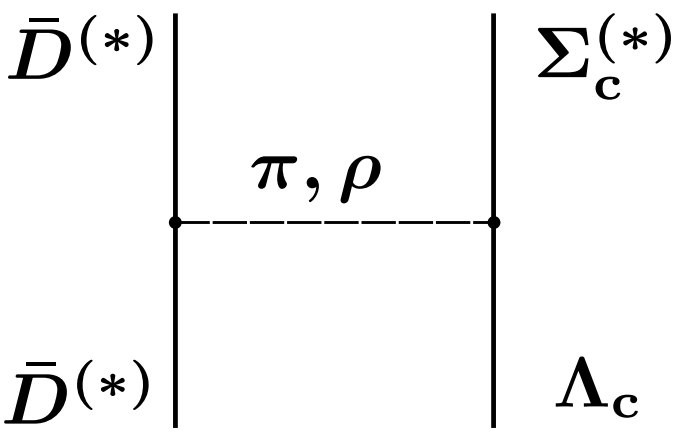


$\bar{D}^{(*)}\Lambda_c^{(*)} - \bar{D}^{(*)}\Sigma_c^{(*)}$ coupling

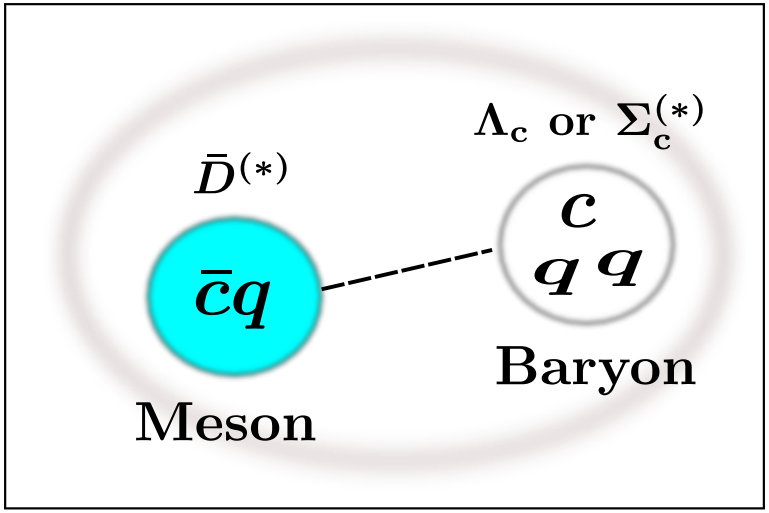


$\Rightarrow$ $\bar{D}\Lambda_c, \bar{D}^*\Lambda_c, \bar{D}\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$ (**6 thresholds!**)

- Coupling to a state with $\ell \neq 0$ ($D-$wave,...)
  $\Rightarrow$ **Tensor force producing a strong attraction!**

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

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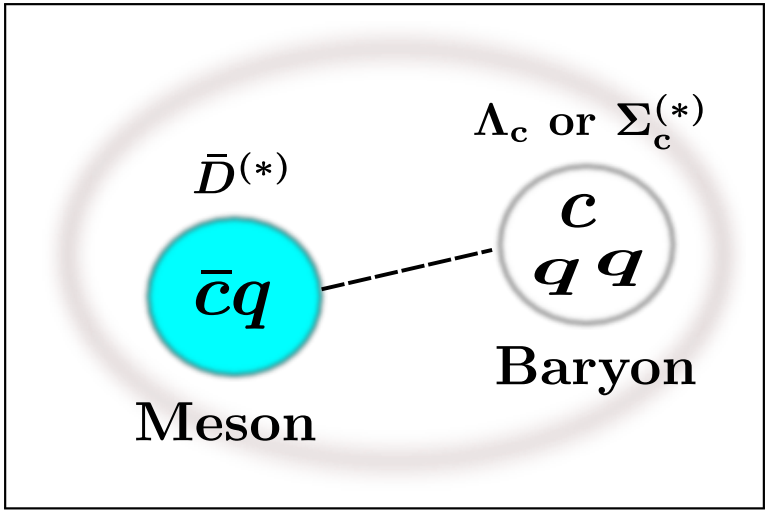

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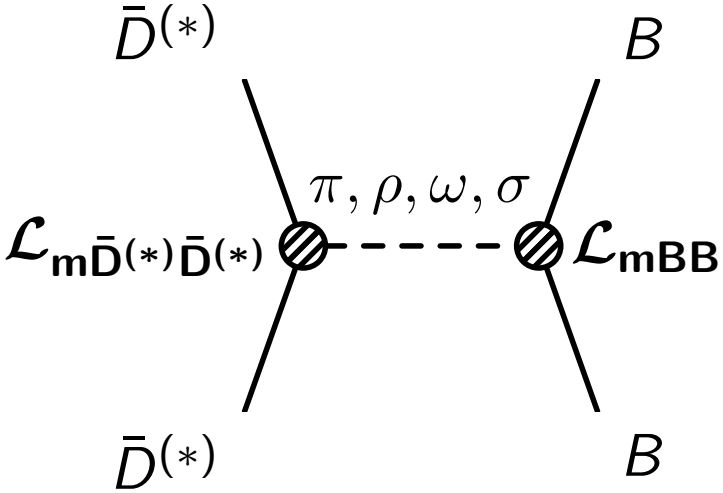
▷ Coupling to the state with $\ell \neq 0$

The full-coupled channel analysis has never 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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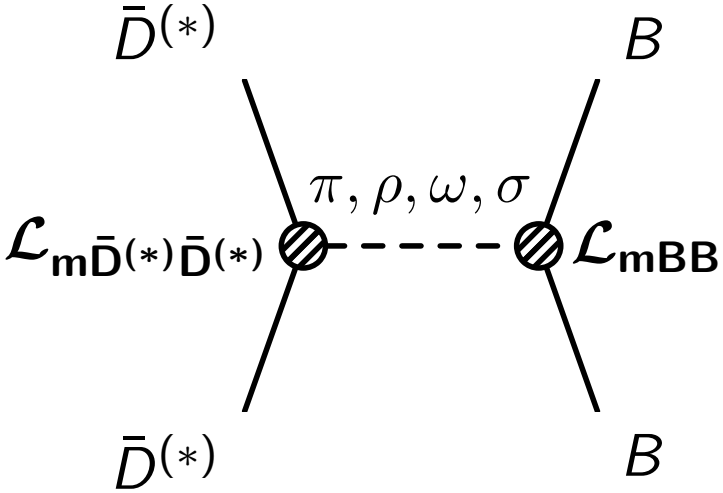

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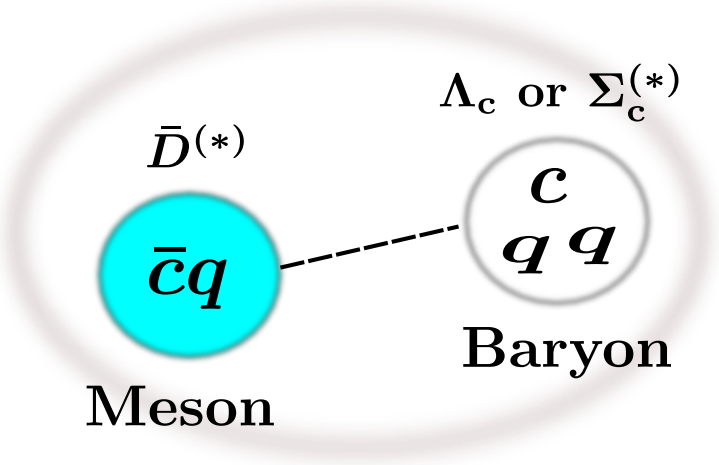
- Form factor with common cutoff $\Lambda \leftarrow$ Free parameter

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

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



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

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

<u>Bound state and Resonance</u>

- 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

Determination of cutoff Λ by observed P_c^+

- Narrow resonance $P_c^+(4450)$ (12σ)

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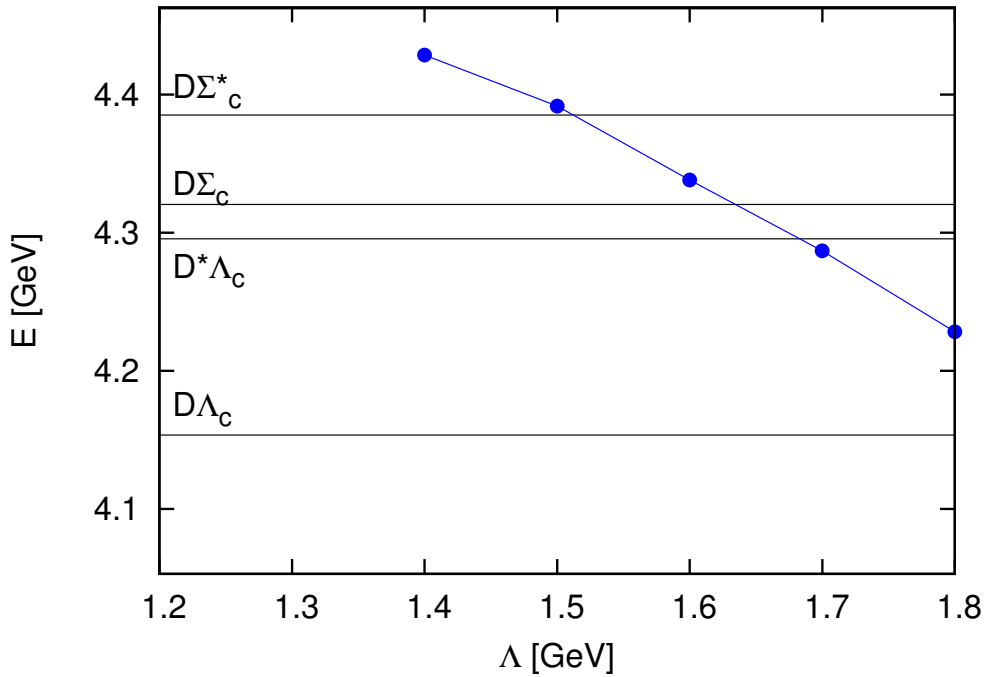

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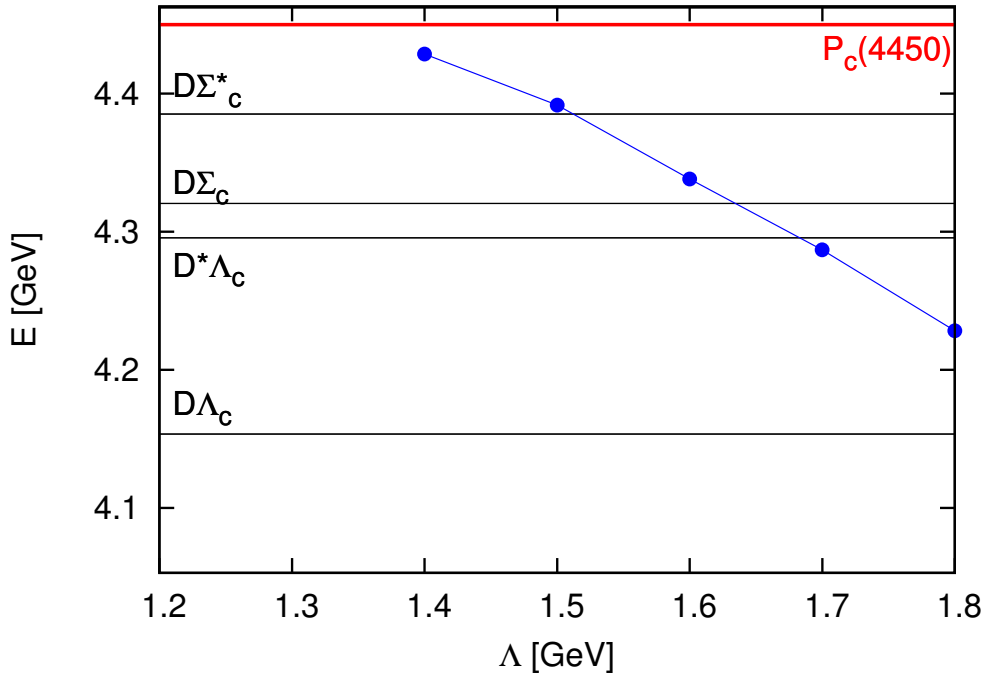

$P_c^+(4450)$: $M = 4449.8 \pm 1.7 \pm 2.5$ MeV

$J^P = 5/2^-$ state: $M = 4428.6$ MeV in **$\Lambda = 1400$ MeV**

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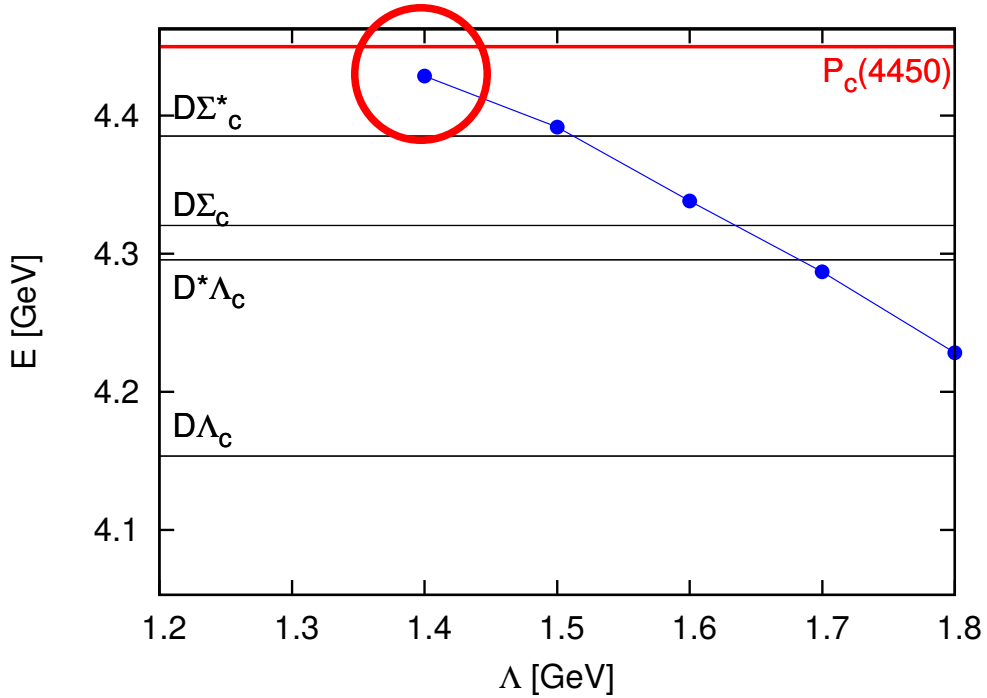

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$$\boxed{\text{Cutoff } \Lambda = 1400 \text{ MeV}, \ J^P \text{ of } P_c^+(4450) = 5/2^-}$$

What is J^P of $P_c^+(4380)$?

- $P_c^+(4450)$: $J^P = 5/2^- \Rightarrow J^P$ of $P_c^+(4380)$ is **$3/2^+$!**

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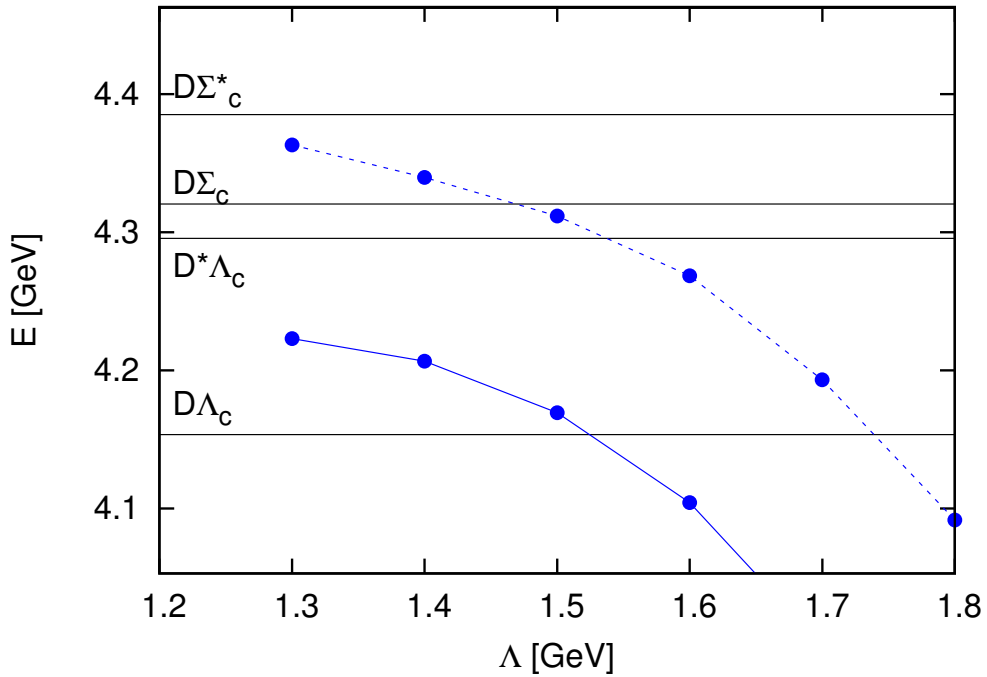

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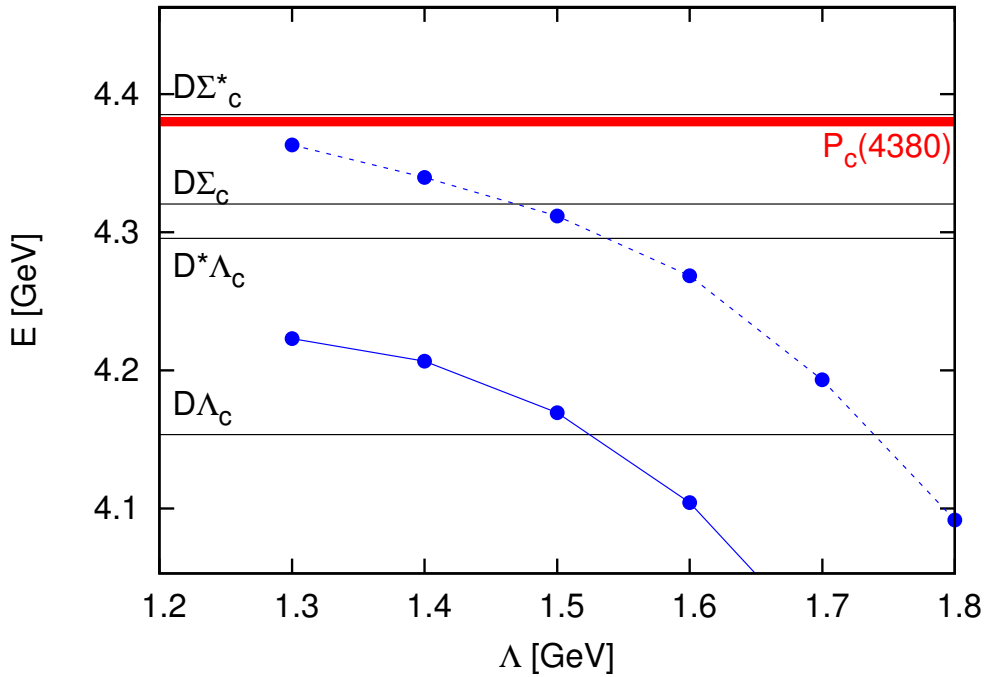

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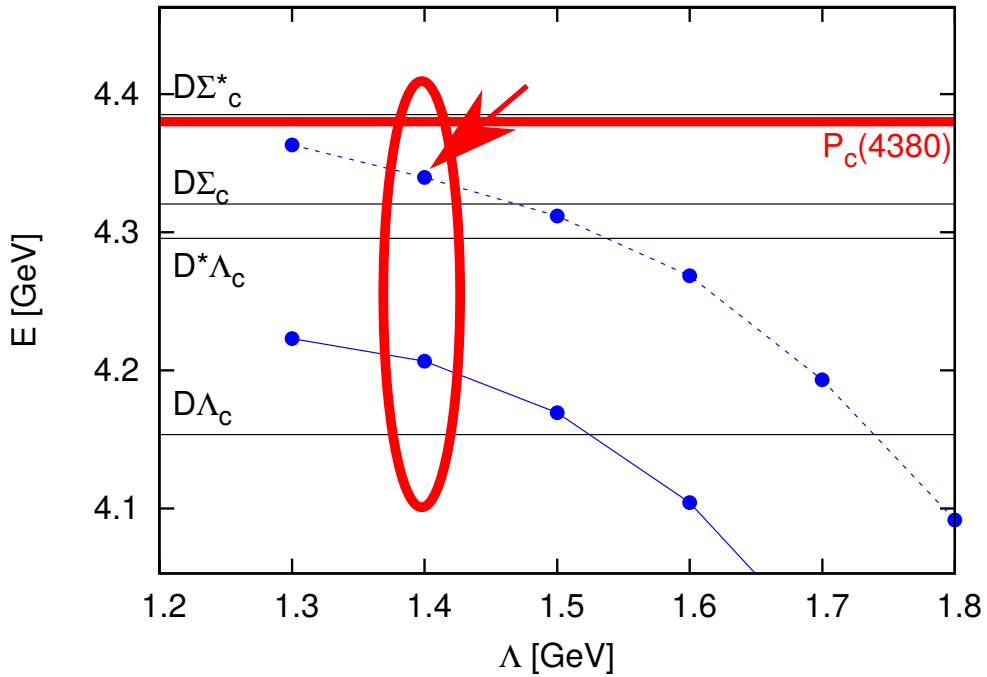

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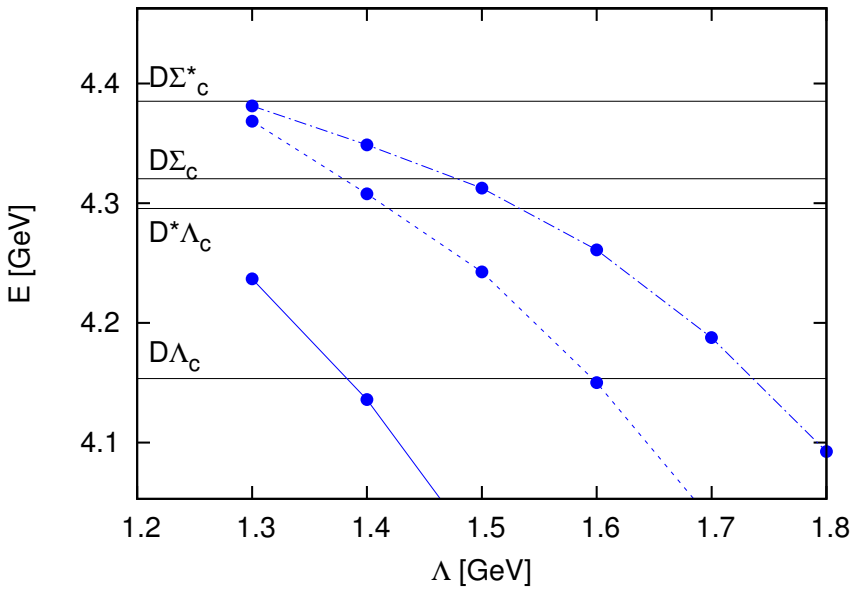
$P_c^+(4380)$: $\mathbf{J^P = 3/2^+}$ $P_c^+(4450)$: $\mathbf{J^P = 5/2^-}$

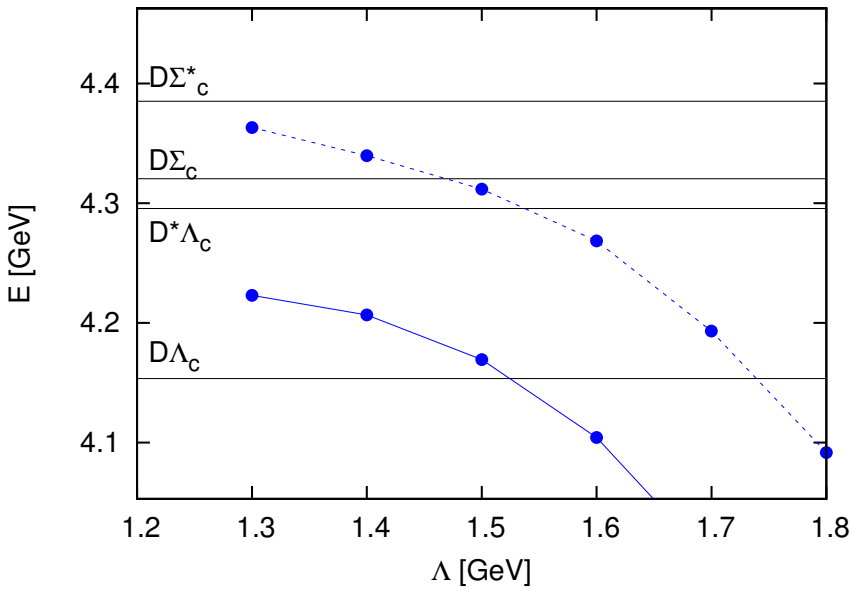
Cutoff $\Lambda = 1400$ MeV

Other predicted states

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



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



- In $\Lambda = 1400$ MeV,

  $J^P = 3/2^-$: 4136.0 MeV, 4307.9 MeV and 4348.7 MeV

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New states are predicted!

(can be decayed to $J/\psi p$, $\bar{D}^{(*)}\Lambda_c$,...)

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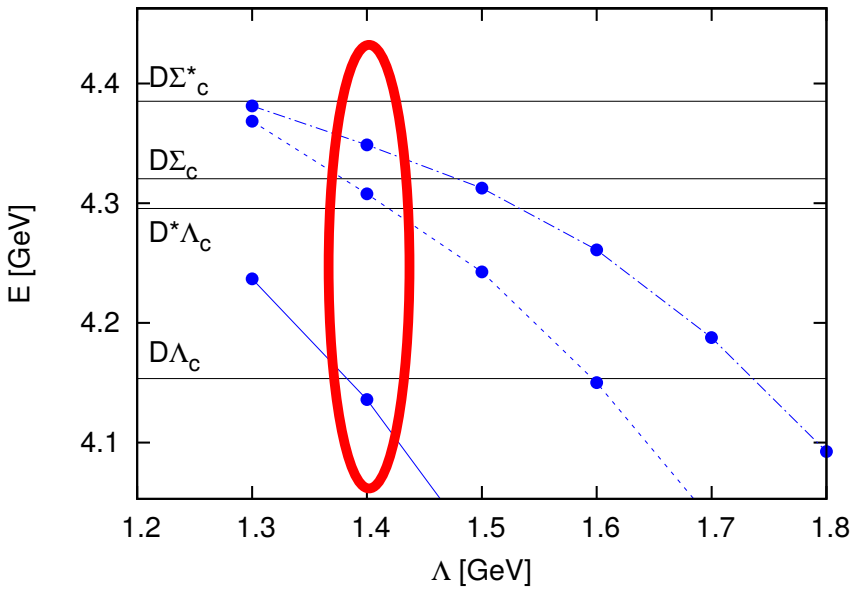

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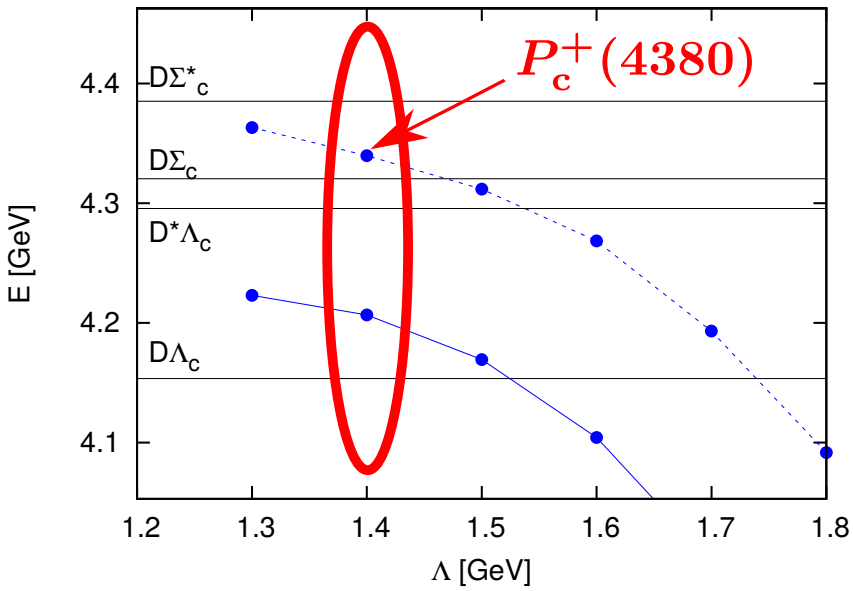

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Summary

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

$\Downarrow$

- **Meson-baryon thresholds** closed to the observed pentaquarks are considered.
  $\rightarrow$ **Full-coupled channel analysis** of $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$
- The meson exchange potential respecting to **the heavy quark spin symmetry** is employed.
- The J^P assignment of $P_c^+(4380)$ and $P_c^+(4450)$ is **$3/2^+$** and **$5/2^-$**, respectively.
- New states are predicted in $J^P = 3/2^\pm$.

Outlook

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

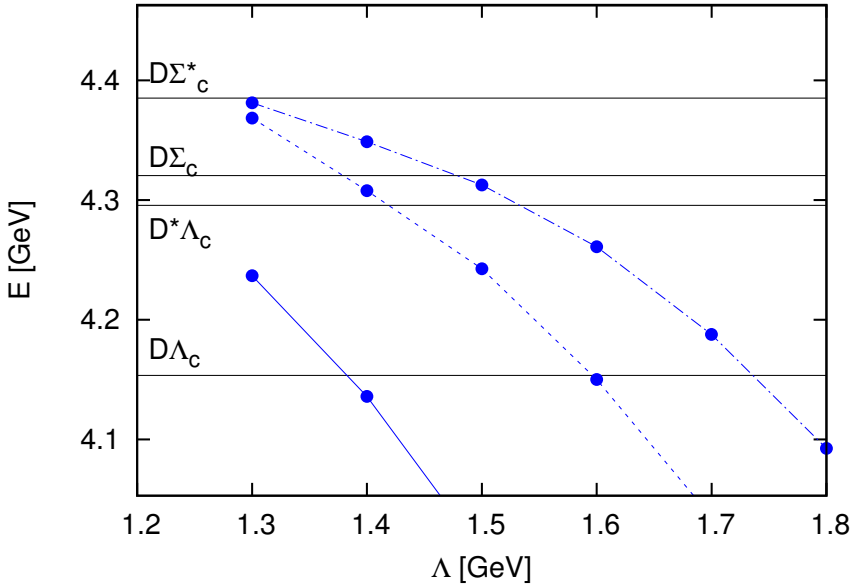
Yasuhiro Yamaguchi and Elena Santopinto , arXiv:1606.08330 [hep-ph]

Back up

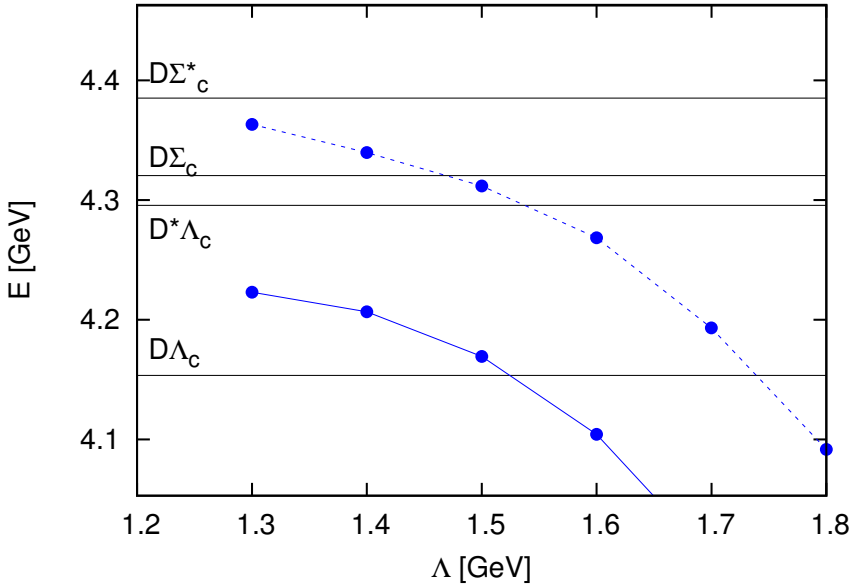
Coupled-Channels

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)
	$\bar{D}\Lambda_c(4153.5)$, $\bar{D}^*\Lambda_c(4295.5)$, $\bar{D}\Sigma_c(4320.5)$, $\bar{D}\Sigma_c^*(4385.1)$, $\bar{D}^*\Sigma_c(4462.5)$, $\bar{D}^*\Sigma_c^*(4527.1)$

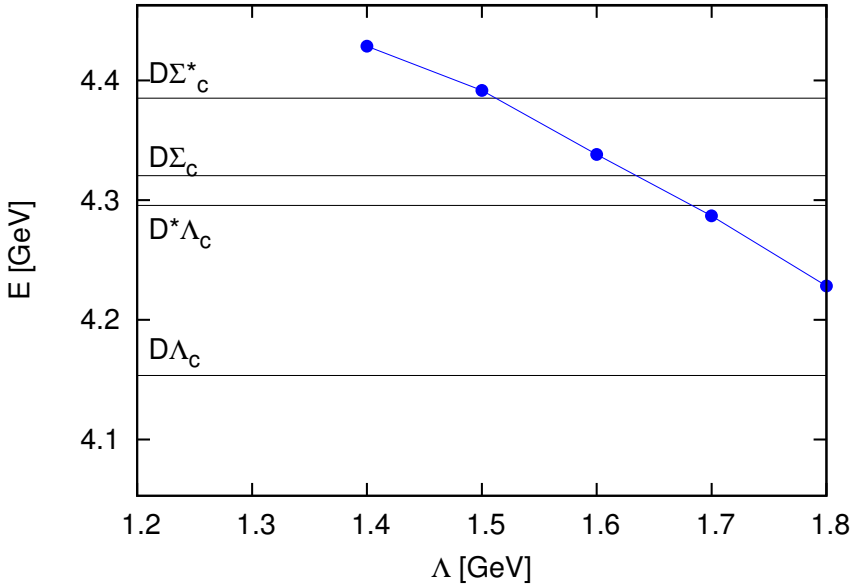
(i) $J^P = 3/2^-$



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



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



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

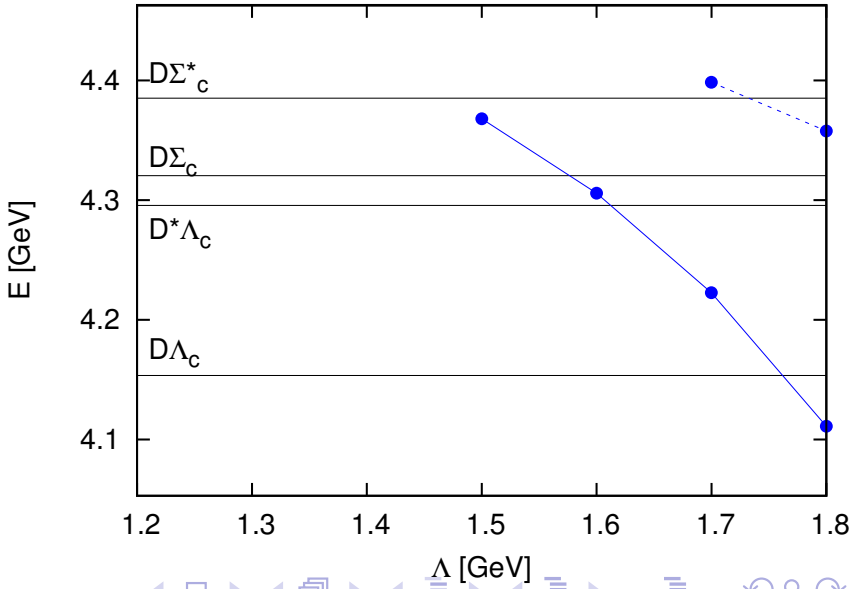


Table : Obtained masses with full channel coupling (Full), without $\bar{D}^{(*)}\Lambda_c$ (w/o $\bar{D}^{(*)}\Lambda_c$) and without large orbital angular momentum ℓ (w/o $\ell > 0$ or w/o $\ell > 1$) in $\Lambda = 1400$ MeV.

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