

Hidden-charm meson-baryon molecules with a short-range attraction from five quark states

Yasuhiro Yamaguchi¹

in collaboration with

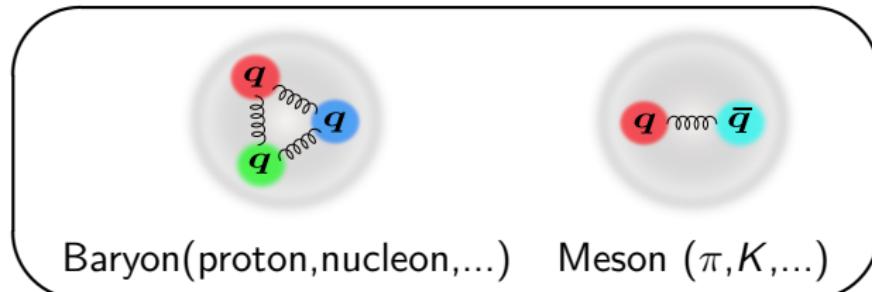
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Social Work, ⁵Showa Pharmaceutical U.

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Physics (APFB 2017)
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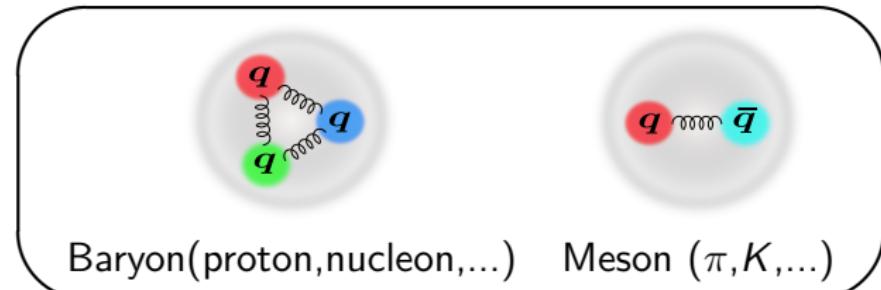
Introduction: Exotic Hadrons

- 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!

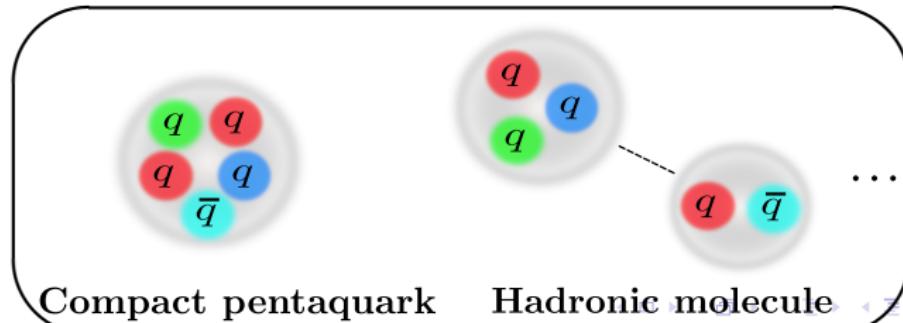


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- Exotic hadrons?** → Multiquark state



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 $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays

R. Aaij *et al.**

(LHCb Collaboration)

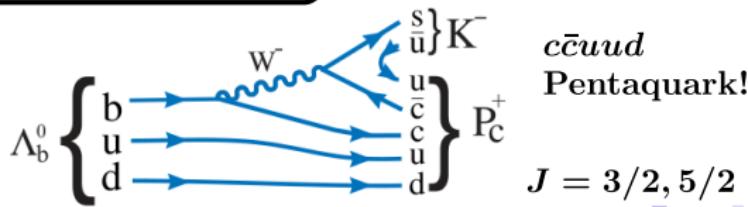
(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \rightarrow J/\psi K^- p$ 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 resonance state. The significance of each of these resonances is more than 9 standard deviations. One has a mass $\mathbf{(1)} 4380 \pm 8 \pm 29 \text{ MeV}$ and a width of $205 \pm 18 \pm 86 \text{ MeV}$, while the second is narrower, with a mass $\mathbf{(2)} 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$ and a width of $39 \pm 5 \pm 19 \text{ MeV}$. 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](https://doi.org/10.1103/PhysRevLett.115.072001)

PACS numbers: 14.40.Pq, 13.25.Gv

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



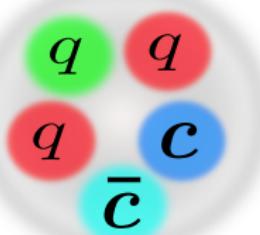
What is the structure of the pentaquarks?

Introduction

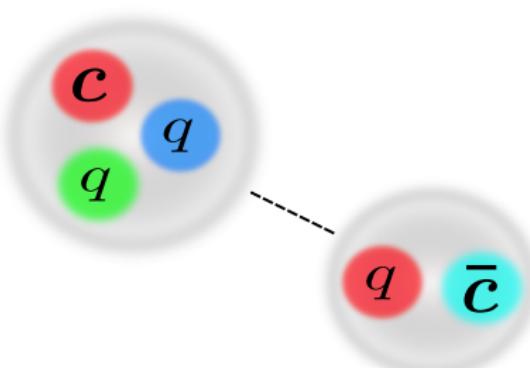
- Compact pentaquark? Hadronic molecule (Hadron cluster)?

W.L.Wang *et al.*, (2011), G. Yang, J. Ping, (2015), S.Takeuchi, M.Takizawa (2017),...

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



Pentaquark
(Compact)



Hadronic molecule

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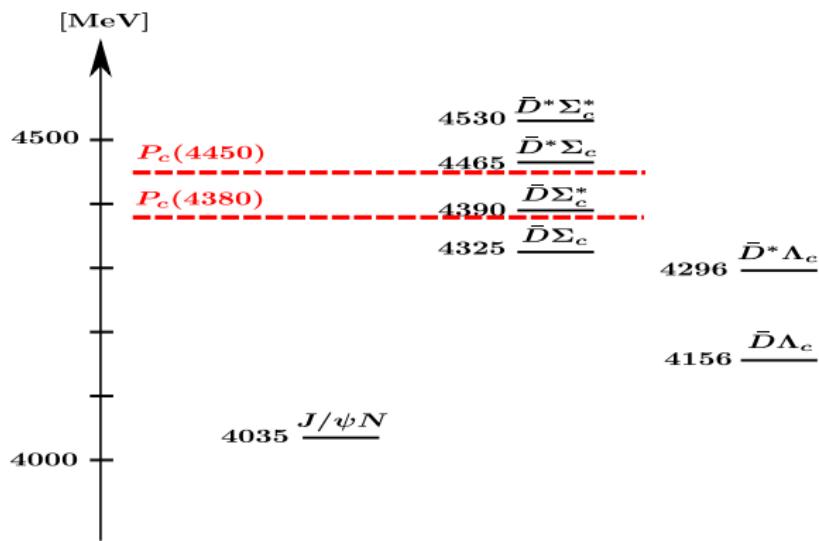
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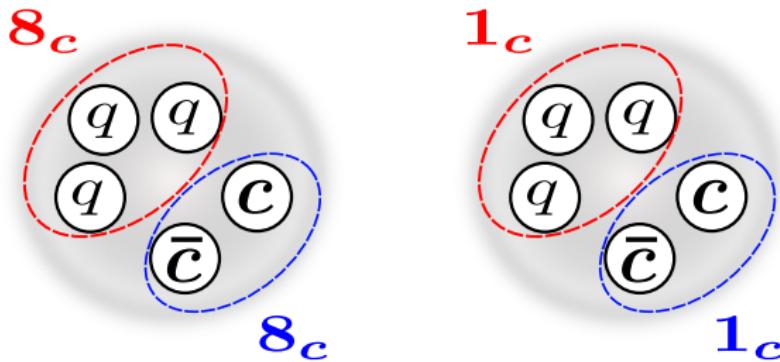
- Pentaquarks are close to **the meson-baryon thresholds**
⇒ **Hadronic molecules?**



Compact state: 5-quark configuration

Introduction

- S. Takeuchi and M. Takizawa, PLB**764** (2017) 254-259.
 P_c states by the quark cluster model
- 5-quark configuration

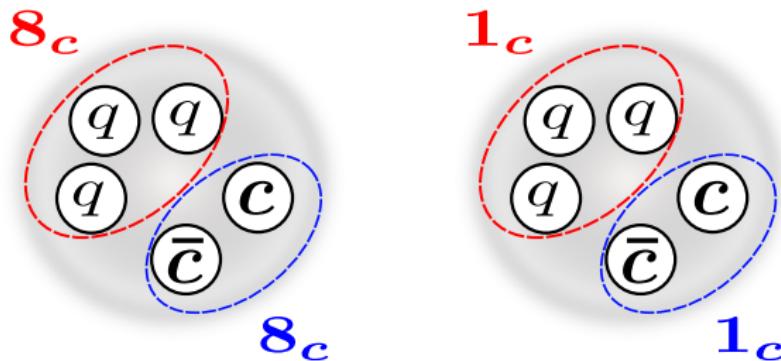


$$S_{q^3} = 1/2, 3/2, \quad S_{c\bar{c}} = 0, 1 \quad S_{q^3} = 1/2, \quad S_{c\bar{c}} = 0, 1$$

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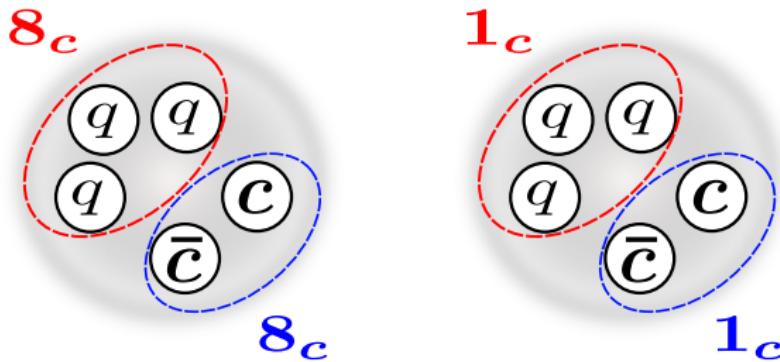
$$S_{q^3} = 1/2, \textcolor{red}{3/2}, S_{c\bar{c}} = 0, 1 \quad S_{q^3} = 1/2, S_{c\bar{c}} = 0, 1$$

- $[q^3 8_c 3/2]$: Color magnetic int. is attractive!

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- $[q^3 8_c 3/2]$: Color magnetic int. is attractive!
⇒ Couplings to (qqc) baryon-($q\bar{c}$) meson, e.g. $\bar{D}\Sigma_c$, are allowed!

Model setup in this study

Introduction

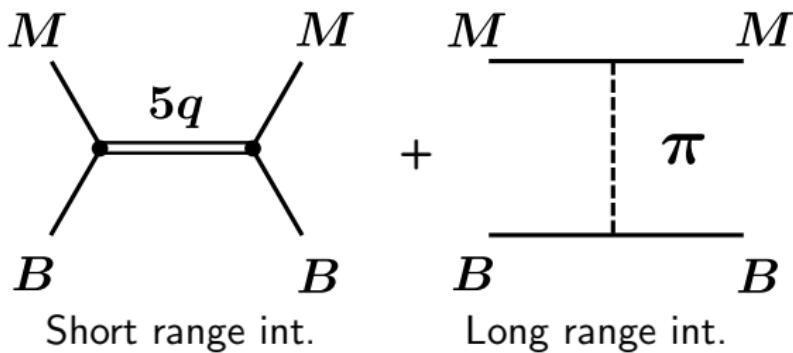
- Hadronic molecule + Compact state

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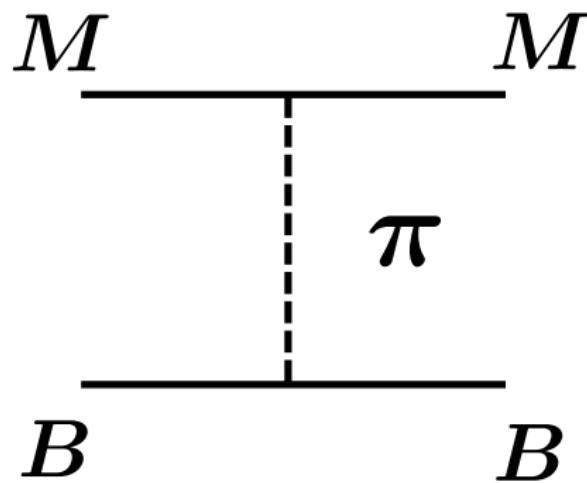
Introduction

- Hadronic molecule + Compact state
- The coupling to the Compact state
 - ⇒ As **a short range** interaction between hadrons
- **Long range** interaction: One pion exchange potential (OPEP)

Interaction of hadrons (M and B)



1. Long range force: One pion exchange potential



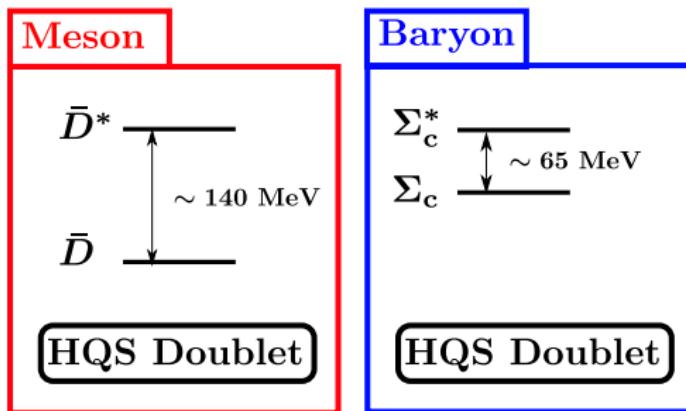
Heavy Quark Spin Symmetry and Mass degeneracy

Introduction

Heavy Quark Spin Symmetry (HQS)

N.Isgur,M.B.Wise,PLB232(1989)113

- **Suppression of Spin-spin force** in $m_Q \rightarrow \infty$.
⇒ **Mass degeneracy** of hadrons with the different J
- $\bar{D}(0^-) - \bar{D}^*(1^-)$ and $\Sigma_c(1/2^+) - \Sigma_c^*(3/2^+)$ mixings



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

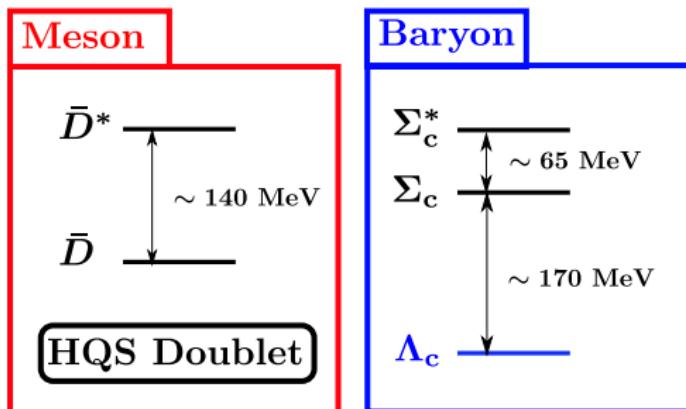
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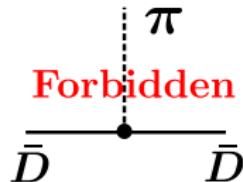
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- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!
- In addition, **Λ_c (cqq)**: $\bar{D}\Lambda_c$ and $\bar{D}^*\Lambda_c$ channels

$\bar{D} - \bar{D}^*$ mixing and the OPEP

- Absence of $\bar{D}\bar{D}\pi$ vertex due to **the parity conservation**



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- Importance in NN : **Driving force to bind Nuclei**
→ **Tensor force** mixing S and D -waves

$\bar{D} - \bar{D}^*$ mixing and the OPEP

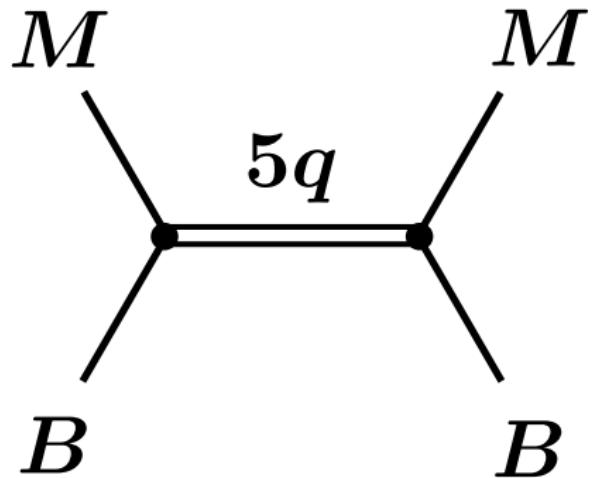
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- $\bar{D} - \bar{D}^*$ mixing introduces the **π exchange (OPEP)**
- Importance in NN : **Driving force to bind Nuclei**
→ **Tensor force** mixing S and D -waves
- One pion exchange potential (OPEP) in $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$
$$V_{\bar{D}^{(*)}Y_c - \bar{D}^{(*)}Y_c}^\pi = G \left[\vec{\mathcal{S}}_1 \cdot \vec{\mathcal{S}}_2 C(r) + S_{S_1 S_2} T(r) \right]$$

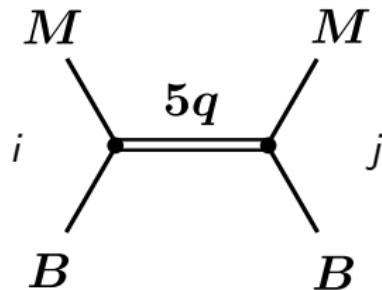
Important role in $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$?

2. Short range force: 5-quark potential



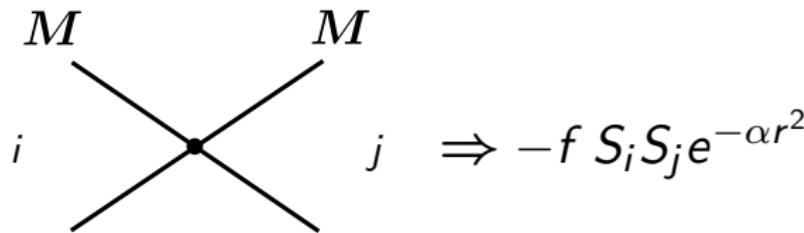
Model: 5-quark potential

- 5-quark potential \Rightarrow s-channel diagram...But



Model: 5-quark potential

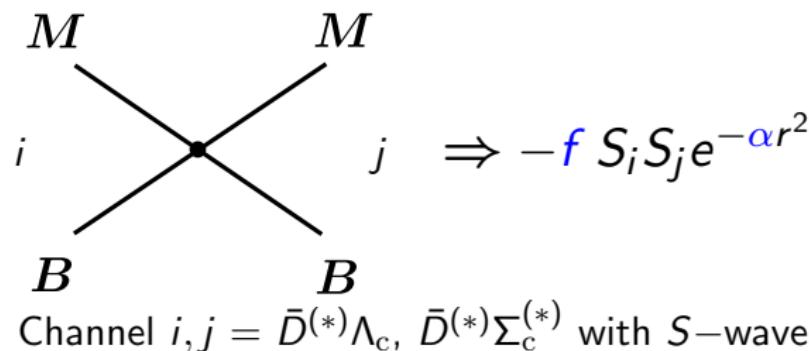
- 5-quark potential \Rightarrow Local Gaussian potential is employed
Massive M_{5q} (few hundred MeV above $\bar{D}^*\Sigma_c^*$) \rightarrow Attractive



Channel $i, j = \bar{D}^{(*)}\Lambda_c, \bar{D}^{(*)}\Sigma_c^{(*)}$ with S -wave

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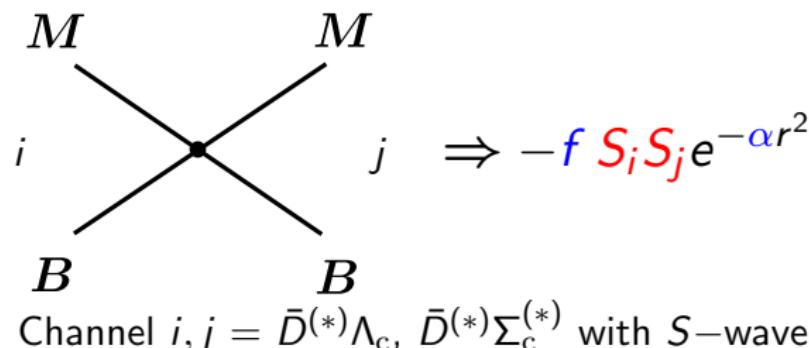


Free Parameters

Strength f and Gaussian para. α
(f -dependence of E will be shown. $\alpha = 1 \text{ fm}^{-2}$)

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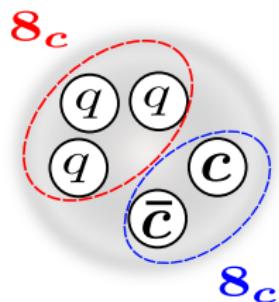
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Relative strength S_i

Spectroscopic factors \Rightarrow determined by the spin structure of $5q$

Spectroscopic factors S_i

- S-factor is determined by the spin structure of the $5q$ state
- Several $5q$ states with S_{3q} and $S_{c\bar{c}}$ configuration
e.g. for $J^P = 1/2^-$, (i), (ii), (iii)

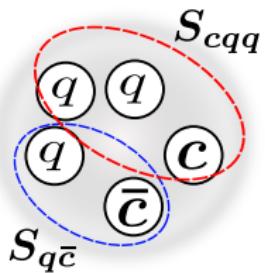


$$J^P = 1/2^-$$

	(i)	(ii)	(iii)
$S_{c\bar{c}}$	0	1	1
S_{3q}	1/2	1/2	3/2

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S_{3q}	1/2	1/2	3/2

- **Overlap** of the spin wavefunctions of 5-quark state and $\bar{D}Y_c$

$$S_i = \langle (\bar{D}Y_c)_i | 5q \rangle$$

⇒ Relative strength of couplings to $\bar{D}Y_c$ channel

Spectroscopic factor S_i

- 5q-configuration: 8_c qqq and 8_c $c\bar{c}$ with S -wave

$$V_{ij}^{5q}(r) = -f \mathbf{S}_i \mathbf{S}_j e^{-\alpha r^2}$$

Table: Spectroscopic factors S_i for each meson-baryon channel.

J		$S_{c\bar{c}}$	S_{3q}	$\bar{D}\Lambda_c$	$\bar{D}^*\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
1/2	(i)	0	1/2	0.4	0.6	-0.4	—	0.2	-0.6
	(ii)	1	1/2	0.6	-0.4	0.2	—	-0.6	-0.3
	(iii)	1	3/2	0.0	0.0	-0.8	—	-0.5	0.3
3/2	(i)	0	3/2	—	0.0	—	-0.5	0.6	-0.7
	(ii)	1	1/2	—	0.7	—	0.4	-0.2	-0.5
	(iii)	1	3/2	—	0.0	—	-0.7	-0.8	-0.2
5/2	(i)	1	3/2	—	—	—	—	—	-1.0

Spectroscopic factor S_i

- 5q-configuration: 8_c qqq and 8_c $c\bar{c}$ with S -wave

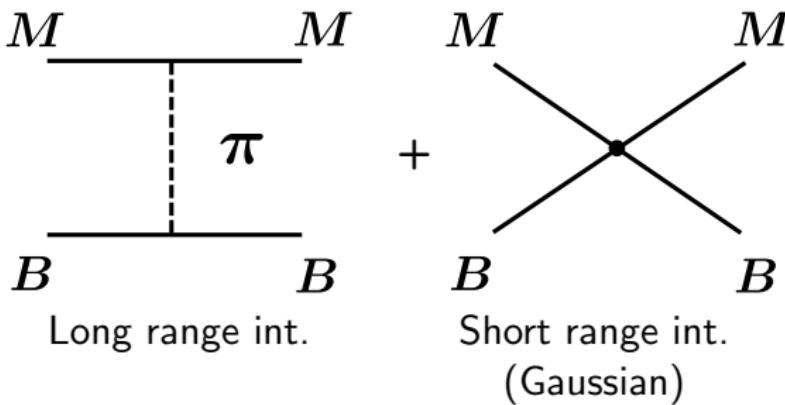
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3/2	(i)	0	3/2	—	0.0	—	-0.5	0.6	-0.7
	(ii)	1	1/2	—	0.7	—	0.4	-0.2	-0.5
	(iii)	1	3/2	—	0.0	—	-0.7	-0.8	-0.2
5/2	(i)	1	3/2	—	—	—	—	—	-1.0

- Large S_i will play an important role.

Numerical Results for Hidden-charm sector

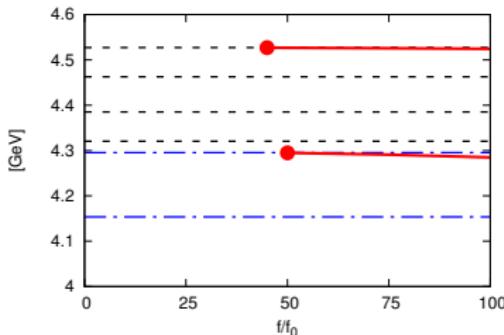


Bound state and Resonance

- Coupled-channel Schrödinger equation for $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ (6 MB components).
- OPEP and Short range Gaussian potential
- For $J^P = 1/2^-, 3/2^-, 5/2^-$ (Negative parity)

f -dependence of energies for $J^P = 1/2^-$

- Charm $\bar{D}Y_c$ for $J^P = 1/2^-$, $5q$ -states (i), (ii), (iii)
(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{1}{2})$

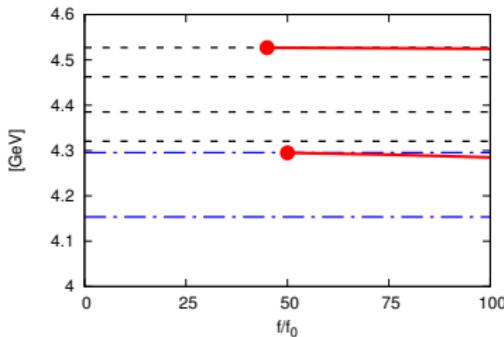


- OPEP + V^{5q}
 - OPEP is not enough to produce states
- ⇒ **States** appear with V^{5q}

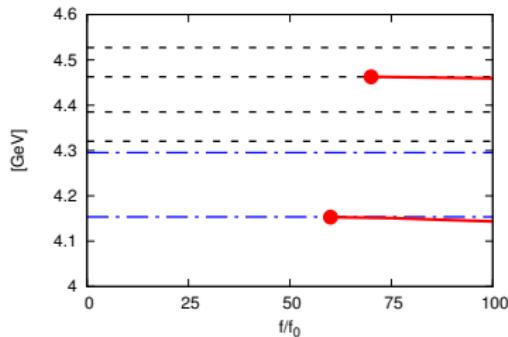
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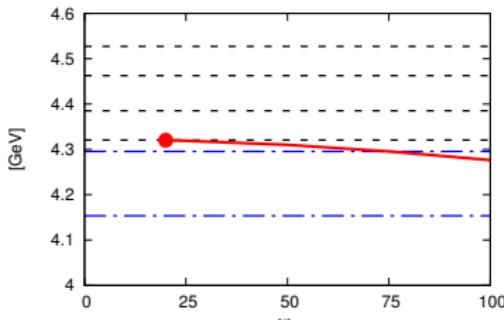
(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{1}{2})$



(ii) $(S_{c\bar{c}}, S_{3q}) = (1, \frac{1}{2})$



(iii) $(S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})$

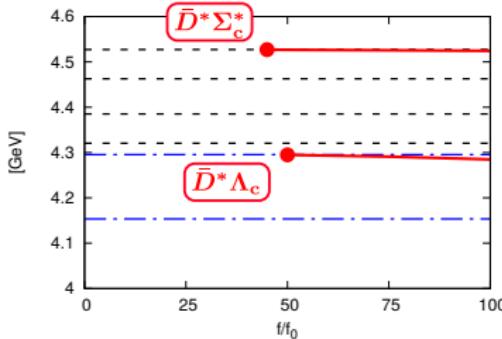


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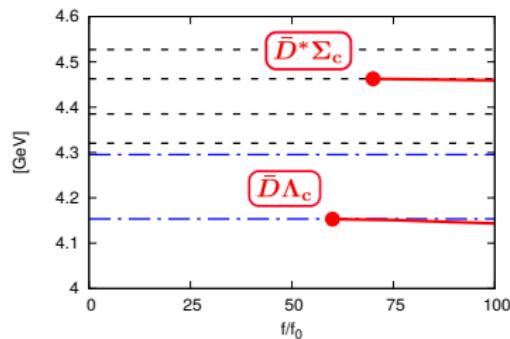
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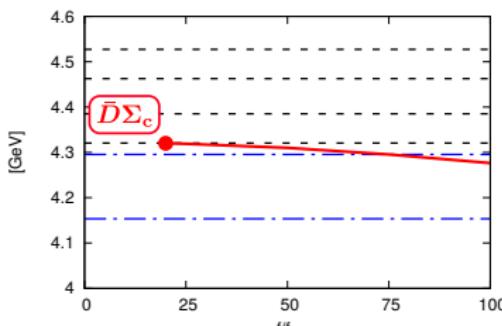
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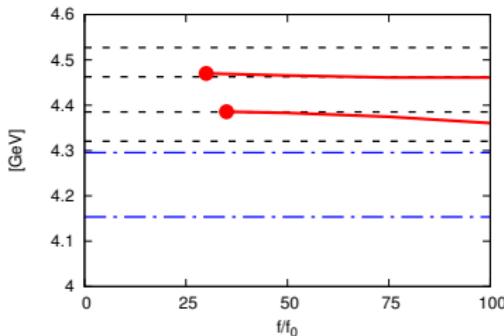


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- ⇒ States appear with V^{5q}
- ↔ Large S-factor

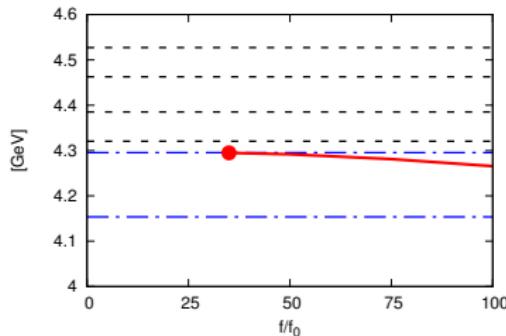
f -dependence of energies for $J^P = 3/2^-$

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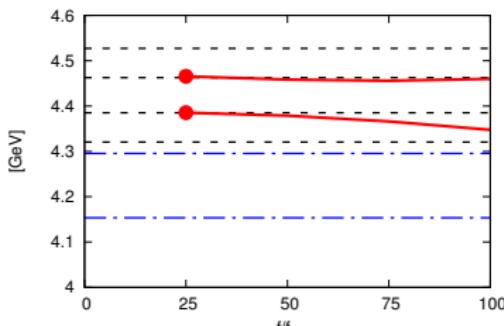
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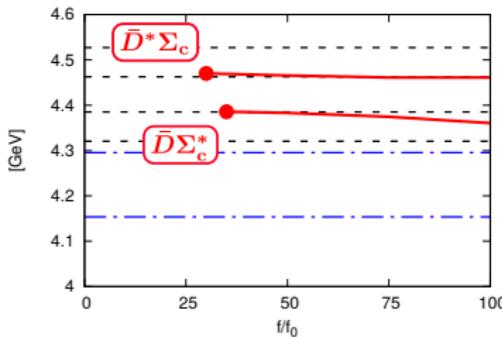
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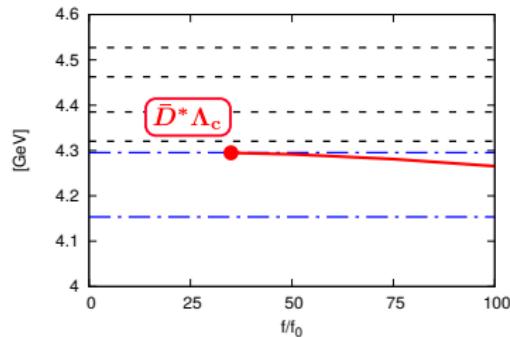
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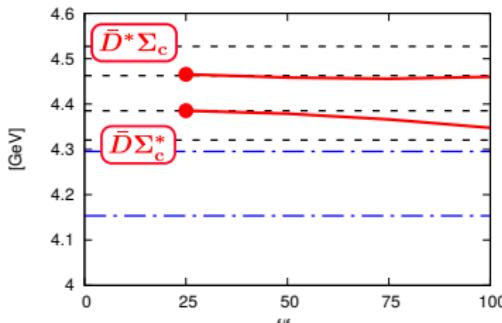
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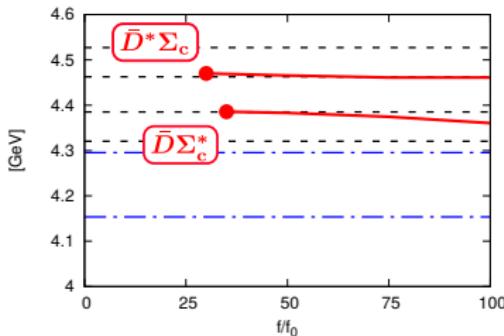


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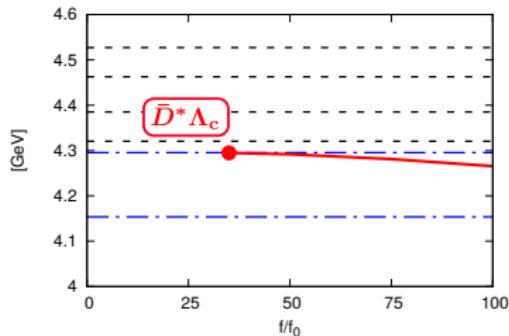
f -dependence of energies for $J^P = 3/2^-$

- Charm $\bar{D}Y_c$ for $J^P = 3/2^-$, 5q-states (i), (ii), (iii)

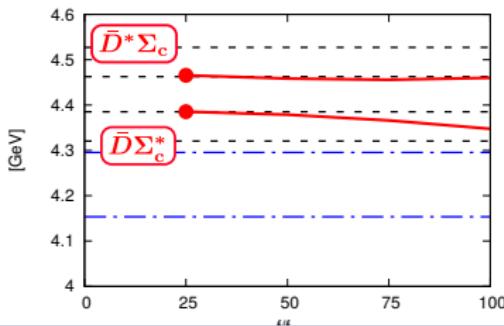
$$(i) (S_{c\bar{c}}, S_{3q}) = (0, \frac{3}{2})$$



$$(ii) (S_{c\bar{c}}, S_{3q}) = (1, \frac{1}{2})$$



$$(iii) (S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})$$

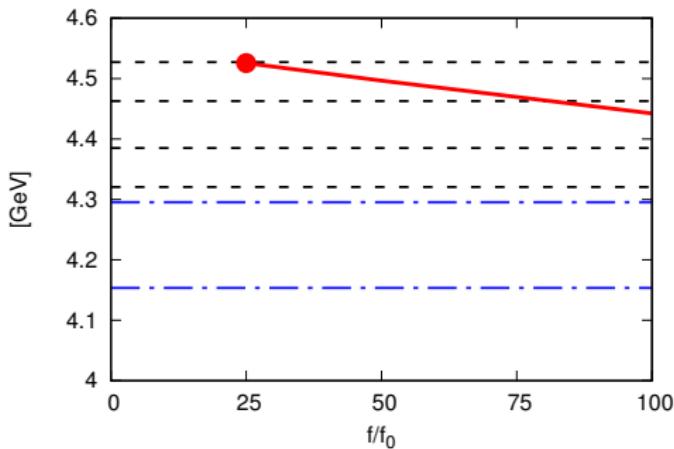


- OPEP + V^{5q}
- ⇒ States appear with V^{5q}
- ↔ Large S-factor
- $P_c(4380)?$ (below $\bar{D}\Sigma_c^*$)
- $P_c(4450)?$ (below $\bar{D}^*\Sigma_c$)

f -dependence of energies for $J^P = 5/2^-$

- Charm $\bar{D}Y_c$ for $J^P = 5/2^-$, One $5q$ state

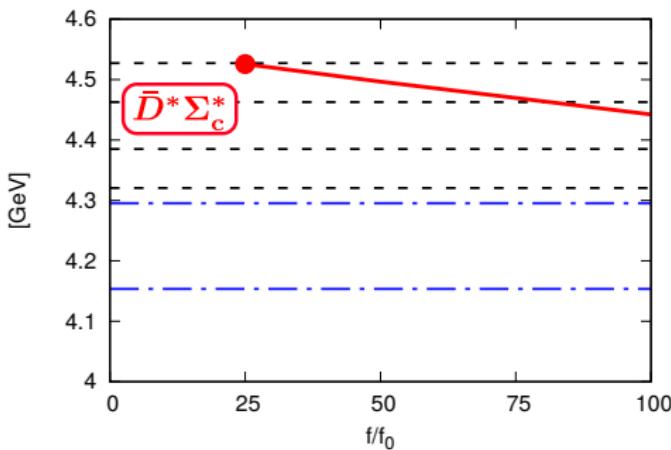
$$(S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})$$



f -dependence of energies for $J^P = 5/2^-$

- Charm $\bar{D}Y_c$ for $J^P = 5/2^-$, One $5q$ state

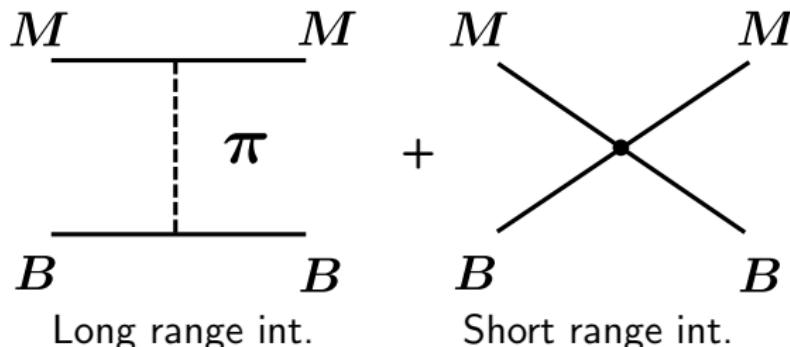
$$(S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})$$



Summary of the hidden-charm sector

- OPEP is not strong enough to produce a state.
- The importance of the $5q$ potential
⇒ States below the MB thresholds ← **large S -factor**

Numerical Results for Hidden-bottom sector



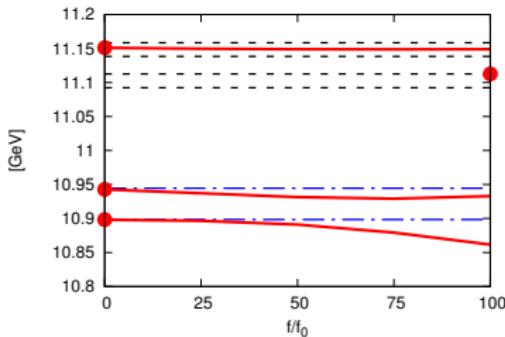
Bound state and Resonance

- Coupled-channel Schrödinger equation for $B\Lambda_b$, $B^*\Lambda_b$, $B\Sigma_b$, $B\Sigma_b^*$, $B^*\Sigma_b$, $B^*\Sigma_b^*$ (6 MB components).
- For $J^P = 1/2^-$, $3/2^-$, $5/2^-$ (Negative parity)

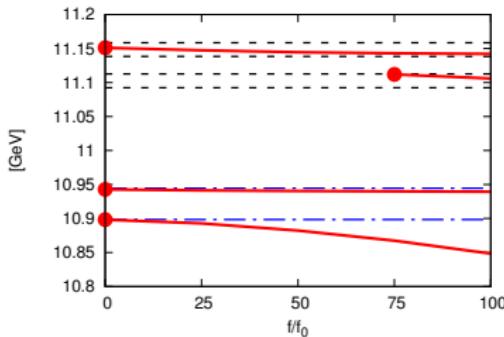
f -dependence of energies for $J^P = 1/2^-$ ($b\bar{b}$)

- Bottom BY_b for $J^P = 1/2^-$, 5q-states (i), (ii), (iii)

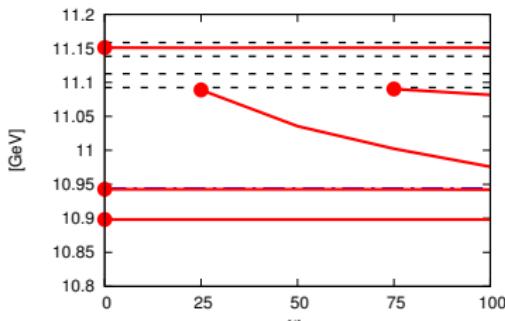
(i) $(S_{b\bar{b}}, S_{3q}) = (0, \frac{1}{2})$



(ii) $(S_{b\bar{b}}, S_{3q}) = (1, \frac{1}{2})$



(iii) $(S_{b\bar{b}}, S_{3q}) = (1, \frac{3}{2})$

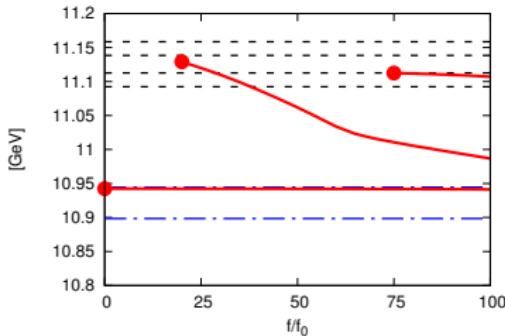


- OPEP produces **the states!**
- Importance of OPEP**
 $B - B^*$, $\Sigma_b - \Sigma_b^*$ mixing
- Many states** close to the thresholds

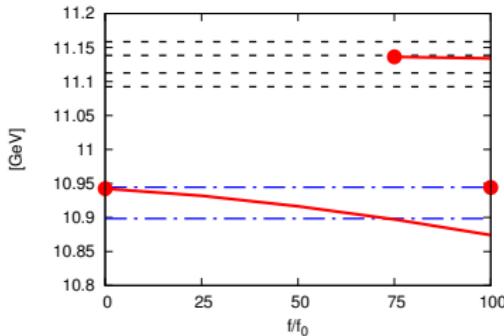
f -dependence of energies for $J^P = 3/2^-$ ($b\bar{b}$)

- Bottom BY_b for $J^P = 3/2^-$, 5q-states (i), (ii), (iii)

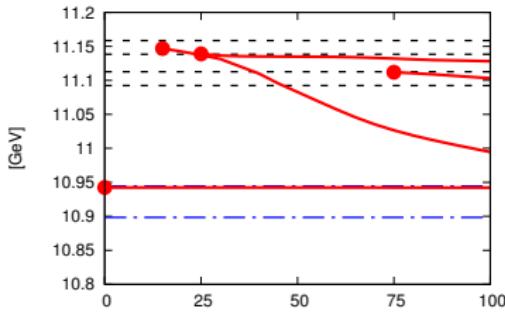
(i) $(S_{b\bar{b}}, S_{3q}) = (0, \frac{3}{2})$



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(iii) $(S_{b\bar{b}}, S_{3q}) = (1, \frac{3}{2})$

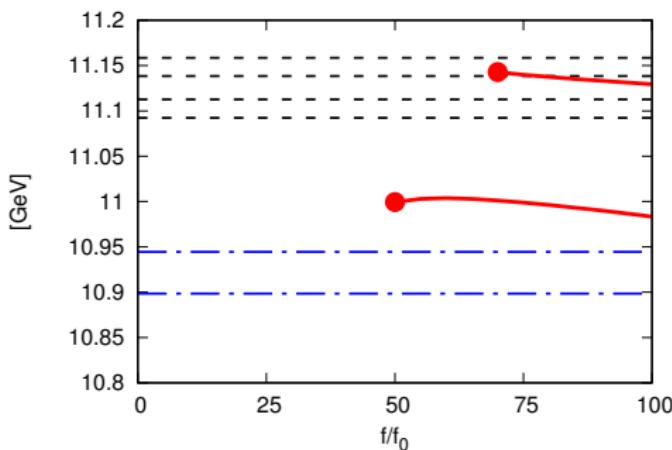


- OPEP produces **the states!**
- Importance of OPEP (mixing effect)**
- Many states close to the thresholds**

f -dependence of energies for $J^P = 5/2^-$ ($b\bar{b}$)

- Bottom BY_b for $J^P = 5/2^-$, One $5q$ -state

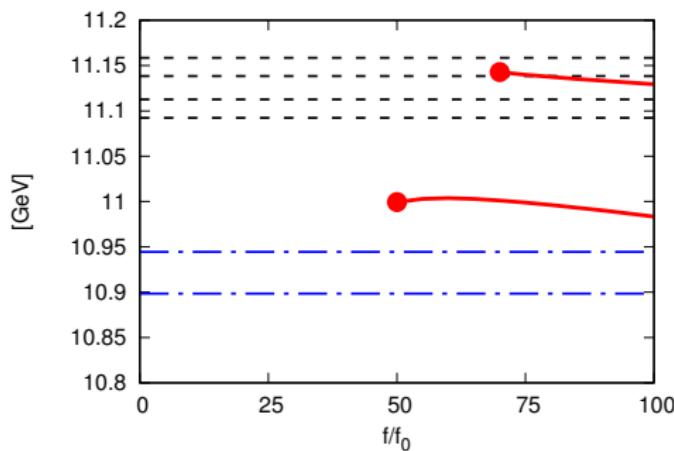
$$(S_{b\bar{b}}, S_{3q}) = (1, \frac{3}{2})$$



f -dependence of energies for $J^P = 5/2^-$ ($b\bar{b}$)

- Bottom BY_b for $J^P = 5/2^-$, One $5q$ -state

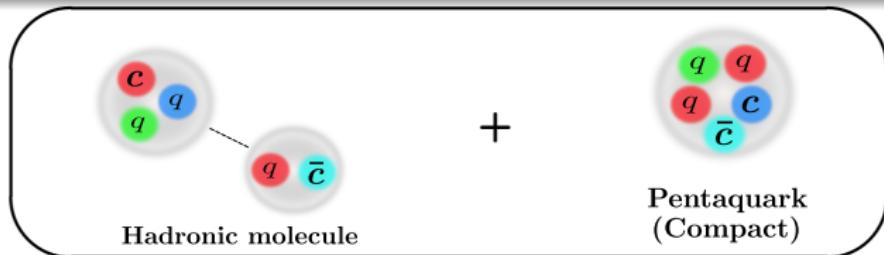
$$(S_{b\bar{b}}, S_{3q}) = (1, \frac{3}{2})$$



Summary of the hidden-bottom sector

- OPEP is strong enough to produce state. \Leftarrow **Mixing effect**
- Many states are obtained.
- Difference between Charm and Bottom sectors

Summary



- Introducing **6 meson-baryon components**:
Multiplet of the HQS, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ + $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$
- Interaction: **OPEP** as a long range int., and
the compact 5-quark potential as a short range int.
- By solving the coupled-channel Schrödinger equation for $\bar{D}Y_c$,
the bound and resonant states are studied.
- For the hidden-charm, the OPEP is not enough to produce
the states. **Importance of the $5q$ potential**.
- For the bottom sector, **the OPEP is enhanced** because of
the mixing effect. OPEP + $5q$ potential produces many
states.