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

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in collaboration with

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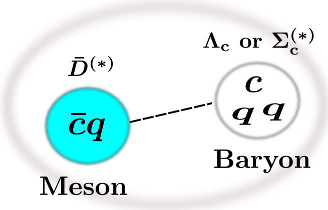
Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa in preparation

9th Workshop on Hadron physics in China and Opportunities Worldwide

Hadronic molecules of meson and baryon

1. Introduction
   - Exotic hadron
   - Hidden-charm pentaquark
2. Model setup
   - Heavy Quark Spin Symmetry and OPEP
   - Compact 5-quark potential
3. Numerical results
4. 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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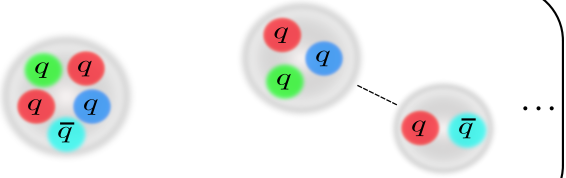
Baryon(proton,nucleon,...) Meson (π,K,...)

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



Compact pentaquark Hadronic molecule

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

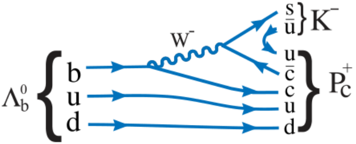
R. Aaij *et al.*[*]
(LHCb Collaboration)

(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



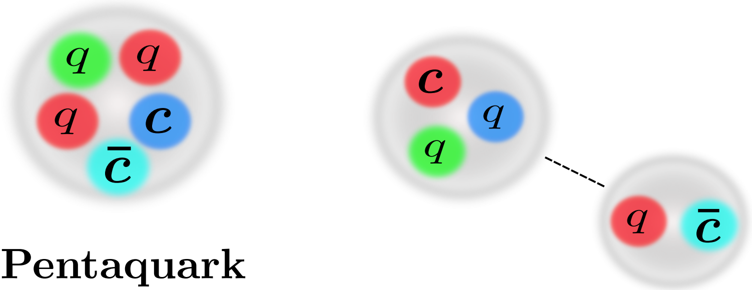
$c\bar{c}uud$
Pentaquark!

$J = 3/2, 5/2$

- 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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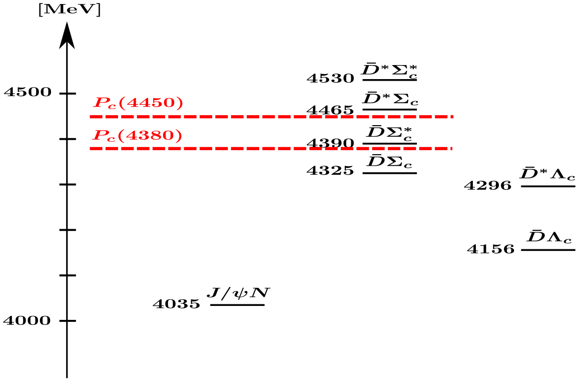
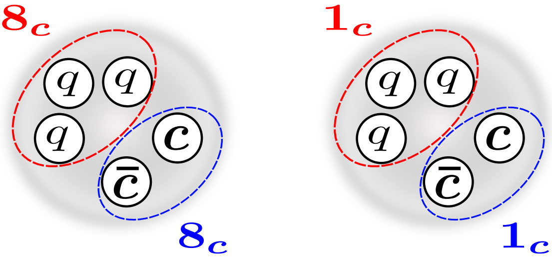
▷ Pentaquarks are close to **the meson-baryon thresholds**
$\Rightarrow$ **Hadronic molecules?**



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



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

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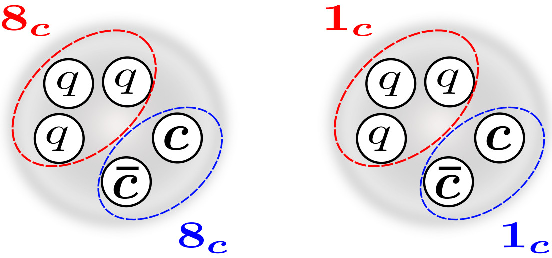

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- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

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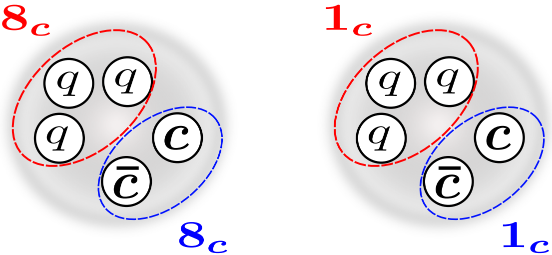

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- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!
  $\Rightarrow$ Couplings to (qqc) baryon-$(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_c$, are allowed!

- **Hadronic molecule + Compact state**

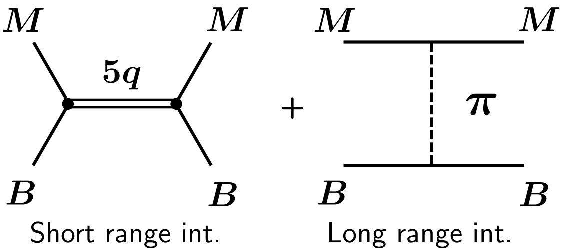
- **Hadronic molecule + Compact state**
  = Hadronic molecule with the coupling to the Compact state

Model setup in this study

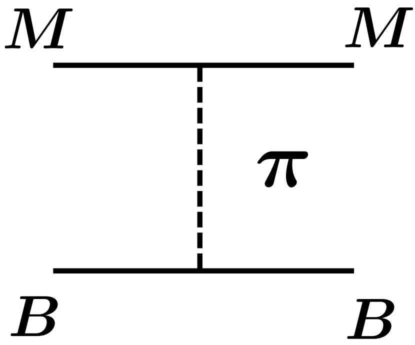
- **Hadronic molecule + Compact state**
  = Hadronic molecule with the coupling to the Compact state
- The coupling to the Compact state

  ⇒ 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

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

Heavy Quark Spin Symmetry

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

$$\Downarrow$$

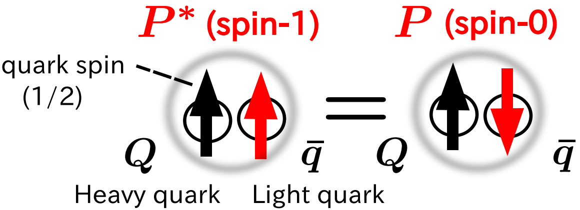
1. Coupled channels of MB
2. Tensor force

Heavy Quark Spin Symmetry (HQS) N.Isgur,M.B.Wise,PLB**232**(1989)113

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

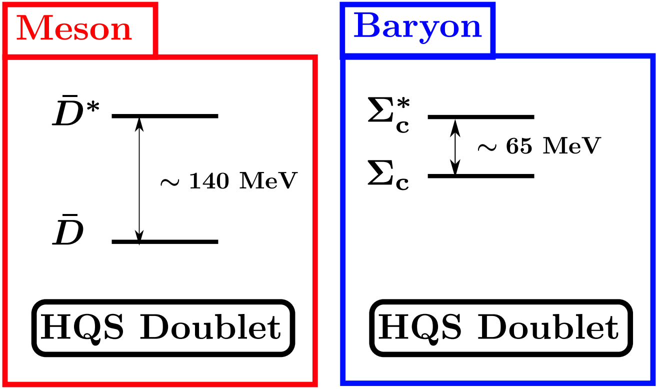
  $\Rightarrow$ **Mass degeneracy** of hadrons with the different J

- e.g. $Q\bar{q}$ meson



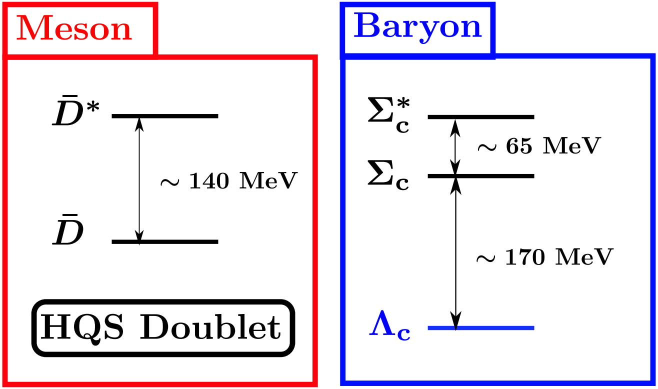
$\Rightarrow$ Mass degeneracy of spin-0 and spin-1 states!

- $\bar{D}-\bar{D}^*$ 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 $\bar{D}^*\Sigma_c^*$!

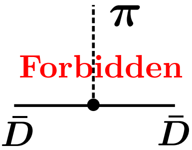
- $\bar{D} - \bar{D}^*$ and $\Sigma_c - \Sigma_c^*$ mixings due to the HQS



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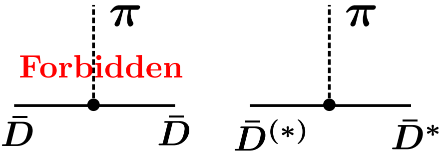

- $\bar{D} - \bar{D}^*$ mixing introduces the **π exchange (OPEP)**

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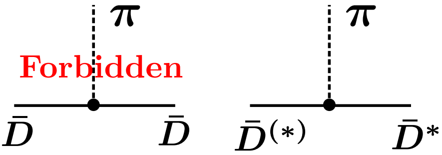

- $\bar{D} - \bar{D}^*$ mixing introduces the **π exchange (OPEP)**
- Importance in NN: **Driving force to bind Nuclei**
  $\rightarrow$ **Tensor force** mixing S and $D-$waves

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

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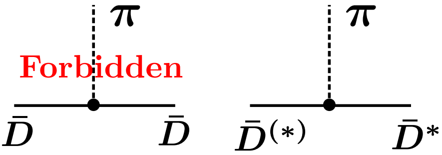

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- **Strong Attraction** in $\bar{D}N$ and $D\bar{D}^*$

S.Yasui and K.Sudoh PRD**80**(2009)034008, S. Ohkoda, *et.al.*,PRD**86**(2012)014004

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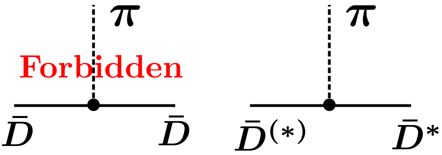

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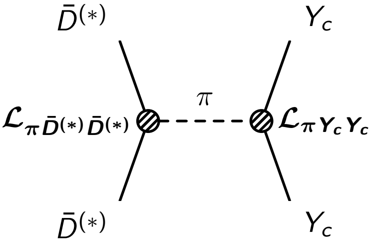
Important role in $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$?

$\bar{D}^{(*)}Y_c$ Interaction: Long range force

- One pion exchange potential

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



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

Y_c: Λ_c, Σ_c or Σ_c^*

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

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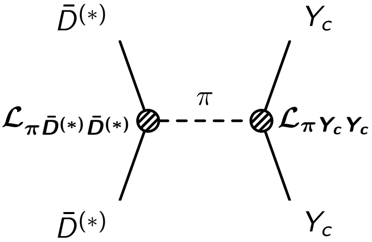

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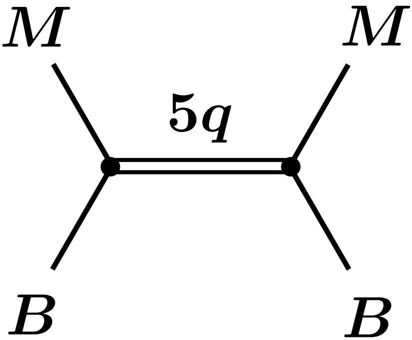
$$V^{\pi}_{\bar{D}^{(*)} Y_c - \bar{D}^{(*)} Y_c} = G \left[\vec{\mathcal{O}}_1 \cdot \vec{\mathcal{O}}_2 C(r) + S_{\mathcal{O}_1 \mathcal{O}_2} T(r) \right]$$

Comments

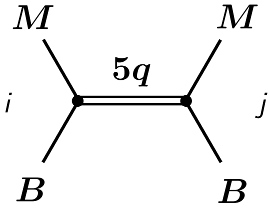
- Couplings to the $\ell \neq 0$ state due to Tensor operator $S_{\mathcal{O}_1 \mathcal{O}_2}$
- Strong attraction from Tensor function $T(r)$

2. Short range force: 5-quark potential



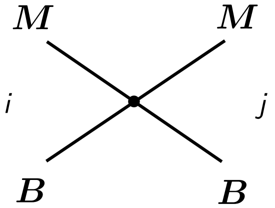
Model: 5-quark potential

- 5-quark potential ⇒ s-channel diagram...But



Model: 5-quark potential

- 5-quark potential $\Rightarrow$ **Local Gaussian potential** is employed



$$\Rightarrow -f\, S_i S_j e^{-\alpha r^2}$$

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

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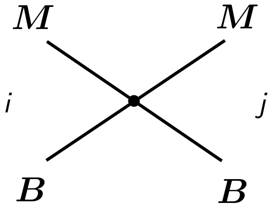

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Channel $i, j = \bar{D}^{(*)}\Lambda_c,\ \bar{D}^{(*)}\Sigma_c^{(*)}$ with $S-$wave

Free Parameters

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

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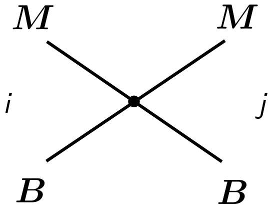

$\Rightarrow -f\, S_i S_j e^{-\alpha r^2}$

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Free Parameters

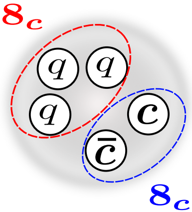
Strength $\boldsymbol{f}$ and Gaussian para. $\boldsymbol{\alpha}$
($f-$dependence of E will be shown. $\alpha = 1$ fm^{-2})

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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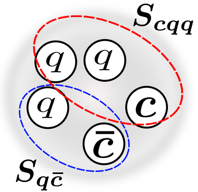

$J^P = 1/2^-$

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

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

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

$\Rightarrow$ 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

$$V^{5q}_{ij}(r) = -f\mathbf{S_i}\mathbf{S_j}e^{-\alpha r^2}$$

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

$$V^{5q}_{ij}(r) = -f\mathbf{S_i}\mathbf{S_j}e^{-\alpha r^2}$$

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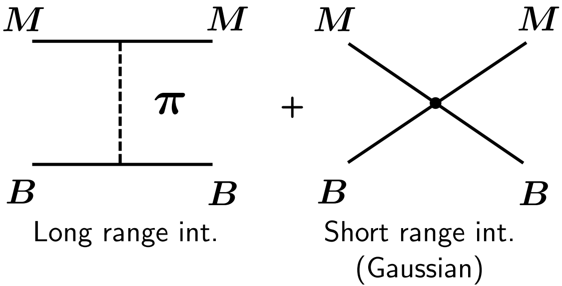
J		$S_{c\bar{c}}$	S_{3q}	$\bar{D}\Lambda_c$	$\bar{D}^*\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
1/2	(i)	0	1/2	0.4	**0.6**	−0.4	—	0.2	**−0.6**
	(ii)	1	1/2	**0.6**	−0.4	0.2	—	**−0.6**	−0.3
	(iii)	1	3/2	0.0	0.0	**−0.8**	—	−0.5	0.3
3/2	(i)	0	3/2	—	0.0	—	**−0.5**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

- **Large S_i** will play an important role.

Numerical Results in 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)

Coupled-channels

Channels	$\bar{D}Y_c(^{2S+1}L)$	
$1/2^-$	$\bar{D}\Lambda_c(^2S)$, $\bar{D}^*\Lambda_c(^2S)$, $\bar{D}\Sigma_c(^2S)$, $\bar{D}\Sigma_c^*(^4D)$, $\bar{D}^*\Sigma_c(^2S,^4D)$, $\bar{D}^*\Sigma_c^*(^2S,^4D,^6D)$	(10 ch)
$3/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^4S,^2D,^4D)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4S)$, $\bar{D}^*\Sigma_c(^4S,^2D,^4D)$, $\bar{D}^*\Sigma_c^*(^4S,^2D,^4D,^6D,^6G)$	(14 ch)
$5/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^2D,^4D,^4G)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4D)$, $\bar{D}^*\Sigma_c(^2D,^4D,^4G)$, $\bar{D}^*\Sigma_c^*(^6S,^2D,^4D,^6D,^4G,^6G)$	(15 ch)

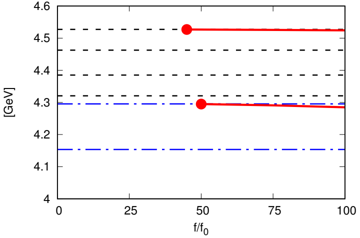
Coupled-channels

Channels	$\bar{D}Y_c(^{2S+1}L)$	
$1/2^-$	$\bar{D}\Lambda_c(^2S)$, $\bar{D}^*\Lambda_c(^2S)$,	
	$\bar{D}\Sigma_c(^2S)$, $\bar{D}\Sigma_c^*(^4D)$,	
	$\bar{D}^*\Sigma_c(^2S,^4D)$, $\bar{D}^*\Sigma_c^*(^2S,^4D,^6D)$	(10 ch)
$3/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^4S,^2D,^4D)$,	
	$\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4S)$,	
	$\bar{D}^*\Sigma_c(^4S,^2D,^4D)$, $\bar{D}^*\Sigma_c^*(^4S,^2D,^4D,^6D,^6G)$	(14 ch)
$5/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^2D,^4D,^4G)$,	
	$\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4D)$,	
	$\bar{D}^*\Sigma_c(^2D,^4D,^4G)$, $\bar{D}^*\Sigma_c^*(^6S,^2D,^4D,^6D,^4G,^6G)$	(15 ch)

- ***$J/\psi N$* channel is absent...** (Future Work)
- The $5q$ potential works in the $S-$wave states.

- Charm $\bar{D}Y_c$ for $\boldsymbol{J^P = 1/2^-}$, $5q-$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

$\Rightarrow$ **States** appear with V^{5q}

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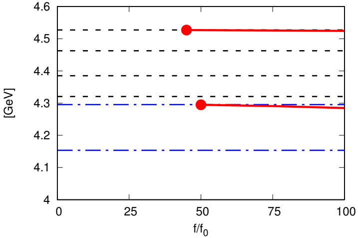
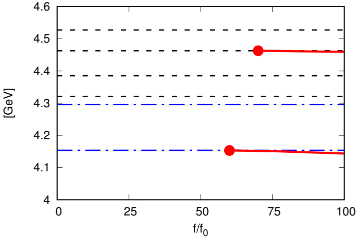
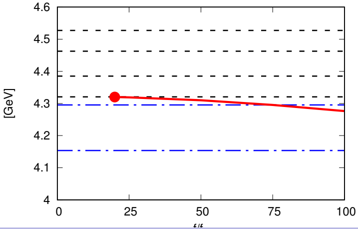


(ii) $(S_{c\bar{c}}, S_{3q}) = (1, \frac{1}{2})$



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



- OPEP + V^{5q}
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$f-$dependence of energies for $J^P = 1/2^-$

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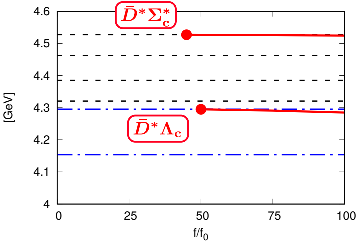

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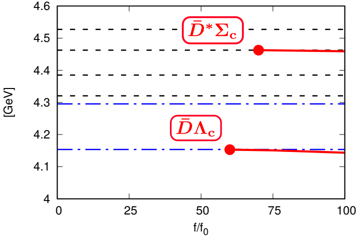
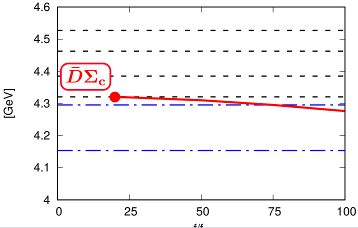


(iii) $(S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})$



- OPEP + V^{5q}
- OPEP is not enough to produce states

$\Rightarrow$ **States** appear with V^{5q}

$\Leftrightarrow$ **Large S-factor**

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

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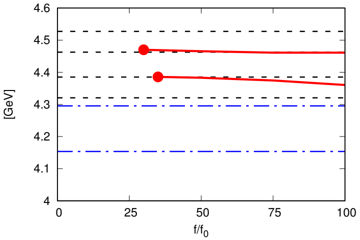
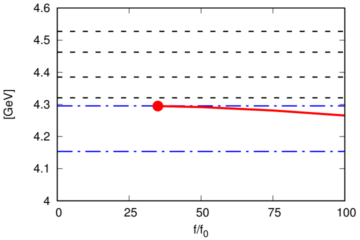
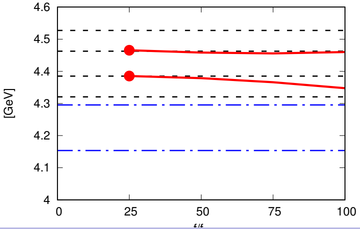


(ii) $(S_{c\bar{c}}, S_{3q}) = (1, \frac{1}{2})$



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



- OPEP + V^{5q}

⇒ **States** appear with V^{5q}

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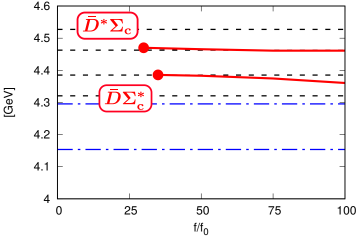

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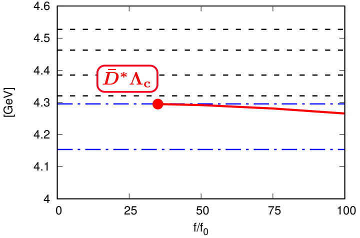

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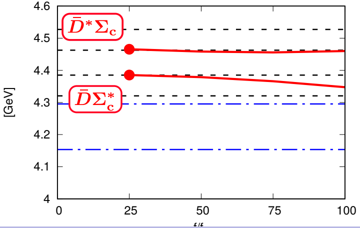

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$\Leftrightarrow$ **Large S-factor**

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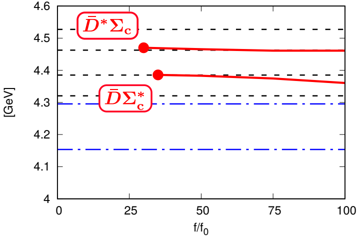

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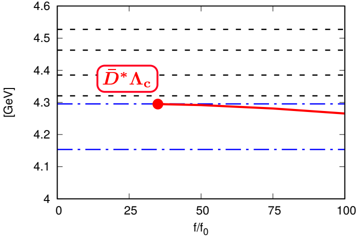

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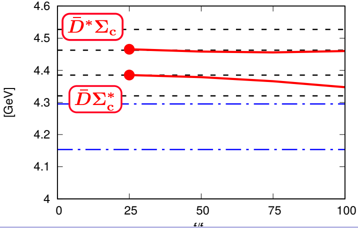


- OPEP + V^{5q}

$\Rightarrow$ **States** appear with V^{5q}

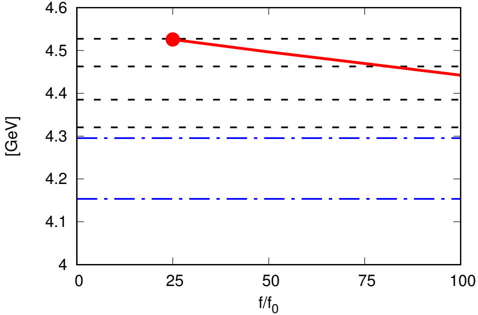
$\Leftrightarrow$ **Large S-factor**

- $P_c(4380)$? (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 $\boldsymbol{J^P = 5/2^-}$, One $5q$ state

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



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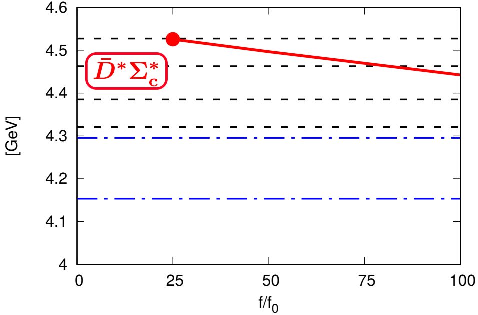
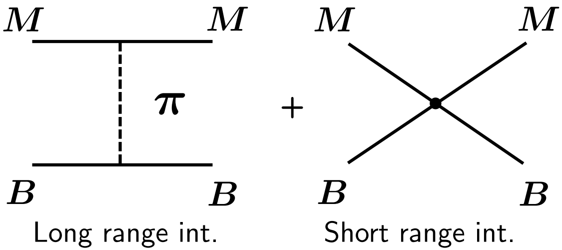


Summary of the hidden-charm sector

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

Numerical results in Hidden-bottom sector



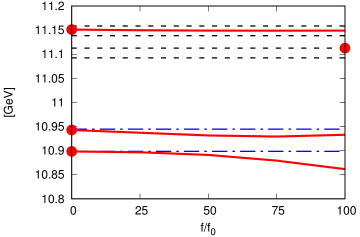
Bound state and Resonance

- Coupled-channel Schrödinger equation for $B\Lambda_{\rm b}$, $B^*\Lambda_{\rm b}$, $B\Sigma_{\rm b}$, $B\Sigma_{\rm b}^*$, $B^*\Sigma_{\rm b}$, $B^*\Sigma_{\rm b}^*$ (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 $\boldsymbol{J^P = 1/2^-}$, $5q-$states (i), (ii), (iii)

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



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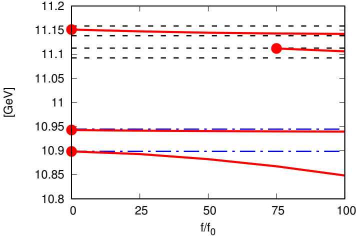

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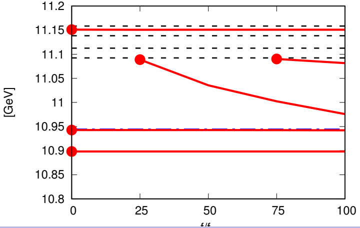

- OPEP produces **the states**!
- **Importance of OPEP**
  $B - B^*$, $\Sigma_\mathrm{b} - \Sigma_\mathrm{b}^*$ mixing
- **Many states** close to the thresholds

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

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

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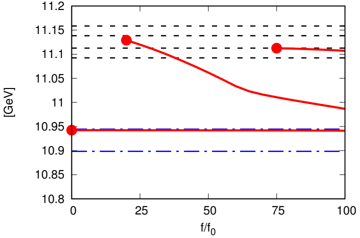

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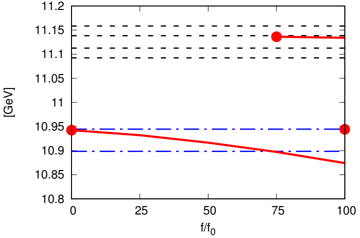
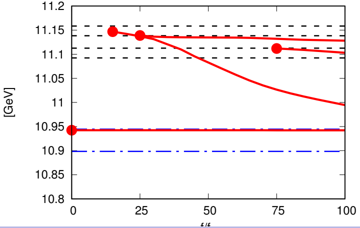


(iii) $(S_{b\bar{b}}, S_{3q}) = (1, \frac{3}{2})$

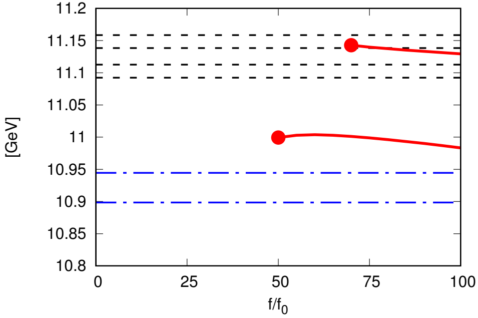


- OPEP produces **the states**!
- **Importance of OPEP (mixing effect)**
- **Many states** close to the thresholds

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

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

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



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

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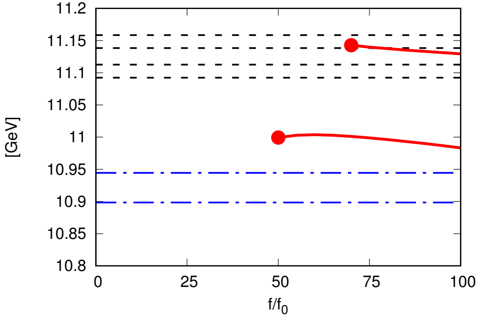


Summary of the hidden-bottom sector

- OPEP plays the major role. $\Leftarrow$ **Mixing effect**
- Many states are obtained.
- Difference between Charm and Bottom sectors

Summary

Subject: Hidden-charm meson-baryon molecules

⇓

- Introducing **6 meson-baryon components**:
  Multiplet of the HQS, $\bar{D}\Sigma_{\rm c}, \bar{D}\Sigma_{\rm c}^{*}, \bar{D}^{*}\Sigma_{\rm c}, \bar{D}^{*}\Sigma_{\rm c}^{*}$ + $\bar{D}\Lambda_c, \bar{D}^{*}\Lambda_c$
- 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.

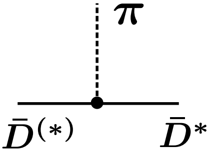
Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa in preparation.

Back up

$\bar{D}^{(*)} Y_c$ Interaction: Long range force

- Effective Lagrangians: Heavy hadron and Pion

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



▷ Heavy meson: $\bar{D}^{(*)}\bar{D}^{(*)}\pi$

$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi}\mathrm{Tr}\left[H\gamma_\mu\gamma_5\partial^\mu\hat{\pi}\bar{H}\right], \quad H = \frac{1+\not{v}}{2}\left[D^*_\mu\gamma^\mu - D\gamma_5\right]$$

$\bar{D}^{(*)} Y_c$ Interaction: Long range force

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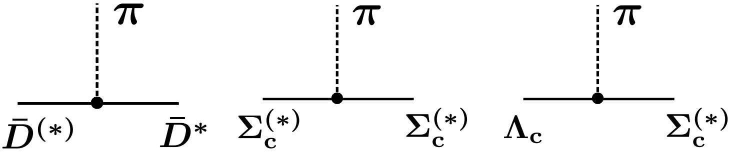

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▷ Heavy baryon: $\Sigma_c^{(*)}\Sigma_c^{(*)}\pi,\ \Lambda_c\Sigma_c^{(*)}\pi$

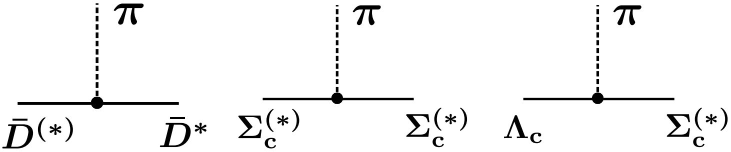
$$\mathcal{L}_{\pi BB} = -\frac{3}{4f_\pi}g_1(iv_\kappa)\varepsilon^{\mu\nu\lambda\kappa}\mathrm{tr}\left[\bar{S}_\mu\partial_\nu\hat{\pi}S_\lambda\right] - \frac{g_4}{2f_\pi}\mathrm{tr}\left[\bar{S}^\mu\partial_\mu\hat{\pi}\Lambda_c\right] + \mathrm{H.c.},$$

$$S_\mu = \Sigma^*_{c\mu} - \frac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma_5\Sigma_c, \quad g_\pi = 0.59, g_1 = 1.00, g_4 = 1.06$$

$\bar{D}^{(*)}Y_c$ Interaction: Long range force

- Effective Lagrangians: Heavy hadron and Pion

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



▷ Heavy meson: $\bar{D}^{(*)}\bar{D}^{(*)}\pi$

$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi}\mathrm{Tr}\left[H\gamma_\mu\gamma_5\partial^\mu\hat{\pi}\bar{H}\right], \quad \mathbf{H} = \frac{\mathbf{1}+\not{v}}{\mathbf{2}}\left[\mathbf{D}^*_\mu\gamma^\mu - \mathbf{D}\gamma_5\right]$$

▷ Heavy baryon: $\Sigma_c^{(*)}\Sigma_c^{(*)}\pi$, $\Lambda_c\Sigma_c^{(*)}\pi$

$$\mathcal{L}_{\pi BB} = -\frac{3}{4f_\pi}g_1(iv_\kappa)\varepsilon^{\mu\nu\lambda\kappa}\mathrm{tr}\left[\bar{S}_\mu\partial_\nu\hat{\pi}S_\lambda\right] - \frac{g_4}{2f_\pi}\mathrm{tr}\left[\bar{S}^\mu\partial_\mu\hat{\pi}\Lambda_c\right] + \mathrm{H.c.},$$

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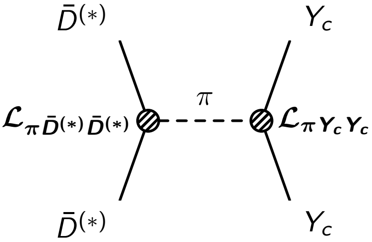
Form factor

- To take into account the hadron structure, the form factor is introduced.



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

Y_c: Λ_c, Σ_c or Σ_c^*

- Form factor with the cutoffs Λ_D, Λ_{Y_c}
  $\rightarrow$ Fixed by the hadron size ratio, $\Lambda_D = 1.35\Lambda_N$, $\Lambda_{Y_c} \sim \Lambda_N$

$$F(\Lambda, \vec{q}\,) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + |\vec{q}\,|^2}, \quad \frac{r}{r_N} = \frac{\Lambda_N}{\Lambda}, \Lambda_N = 837 \text{ MeV}.$$

S.Yasui,K.Sudoh,PRD**80** (2009) 034008, Y.Yamaguchi,*et al.* PRD**84**(2011)014032

Model: Parameters f and α

- $V_{ij}^{5q}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1$ fm^{-2} (Assumption),

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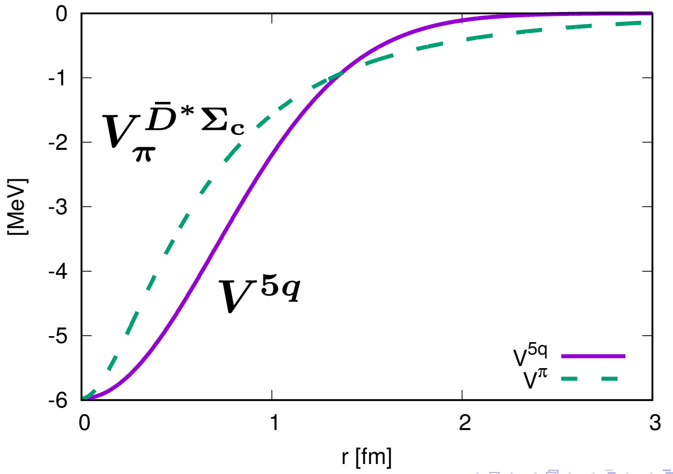
$\Rightarrow$ Parameters: $\alpha = 1$ fm^{-2} (Assumption),

$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**



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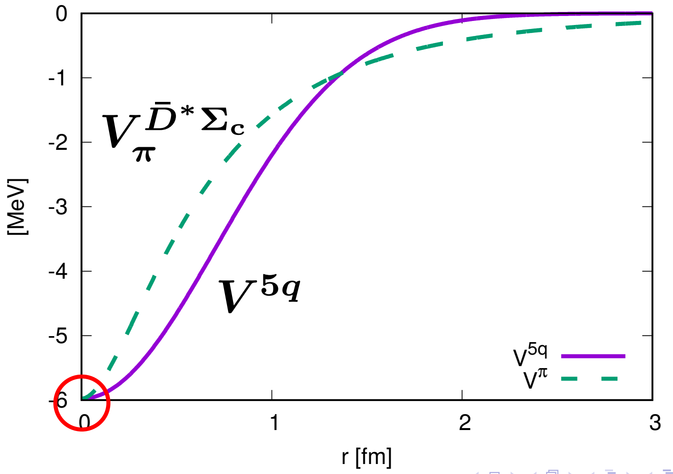

Model: Parameters f and α

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$\Rightarrow$ Parameters: $\alpha = 1$ fm^{-2} (Assumption),

$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**

Volume integral $\mathcal{V}(q=0) = \int dr^3 V(r)$

$$\left|\mathcal{V}^{5q}(0)\right| \sim \frac{1}{4}\left|\mathcal{V}_\pi^{\bar{D}^*\Sigma_c}(0)\right|$$

Model: Parameters f and α

- $V_{ij}^{5q}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1\ \mathrm{fm}^{-2}$ (Assumption),
$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**

Volume integral $\mathcal{V}(q=0) = \int dr^3 V(r)$

$$\left|\mathcal{V}^{5q}(0)\right| \sim \frac{1}{4}\left|\mathcal{V}_\pi^{\bar{D}^*\Sigma_c}(0)\right| \sim \frac{1}{15}\left|\mathcal{V}_\pi^{NN}(0)\right| \sim \frac{1}{880}\left|\mathcal{V}_\sigma^{NN}(0)\right|$$

($\mathcal{V}_\pi^{NN}$: Central force of OPEP in NN, $\mathcal{V}_\sigma^{NN}(0)$: σ exchange in NN)

Model: Parameters f and α

- $V^{5q}_{ij}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1\ \mathrm{fm}^{-2}$ (Assumption),
$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**

Volume integral $\mathcal{V}(q=0) = \int dr^3 V(r)$

$$\left|\mathcal{V}^{5q}(0)\right| \sim \frac{1}{4}\left|\mathcal{V}_\pi^{\bar{D}^*\Sigma_c}(0)\right| \sim \frac{1}{15}\left|\mathcal{V}_\pi^{NN}(0)\right| \sim \frac{1}{880}\left|\mathcal{V}_\sigma^{NN}(0)\right|$$

($\mathcal{V}_\pi^{NN}$: Central force of OPEP in NN, $\mathcal{V}_\sigma^{NN}(0)$: σ exchange in NN)

$\Rightarrow$ **Small contribution of V^{5q}**...
We will see the f dependence of the energy spectrum
($\boldsymbol{f_0}$: reference value)