Heavy tetra and penta quarks

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APCTP Focus Program in Nuclear Physics 2021 Part I
Hadron properties in a nuclear medium from the quark and gluon degrees of freedom

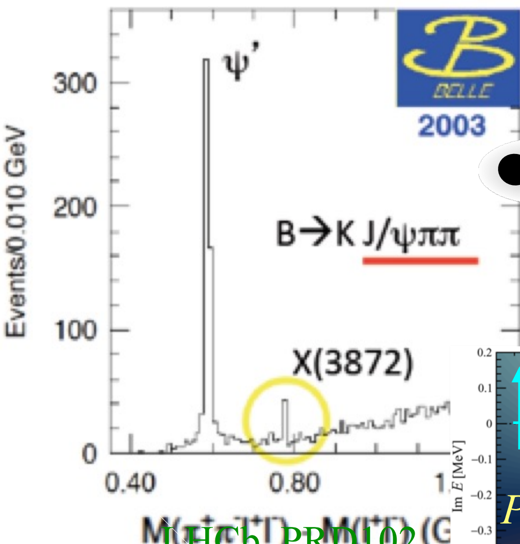
1. Introduction
2. Quasi-stable hidden charm hadron — $\bar{c}cuud$: P_c
3. Stable doubly heavy hadron — $bb\bar{u}\bar{d}$: T_{bb}
4. Summary

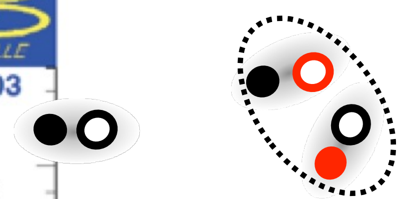
1. Introduction

Many (multi-quark) hadrons with heavy quarks

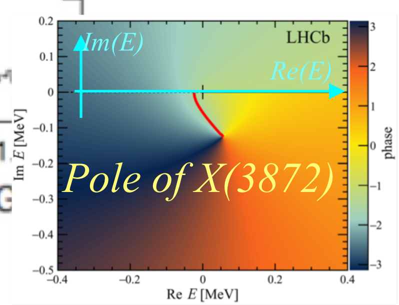
X(3872)

Belle, PRL91 (2003) 262001





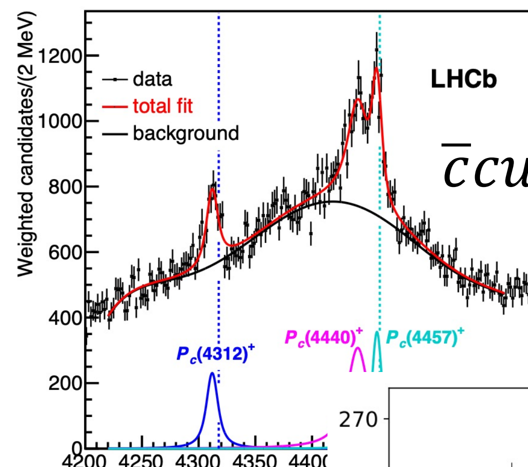
$\bar{c}c$ or $D^* - \bar{D}$

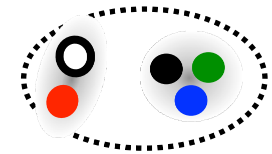


LHCb, PRD102 092005 (2020)

P_c(4310, 4460, 4520)

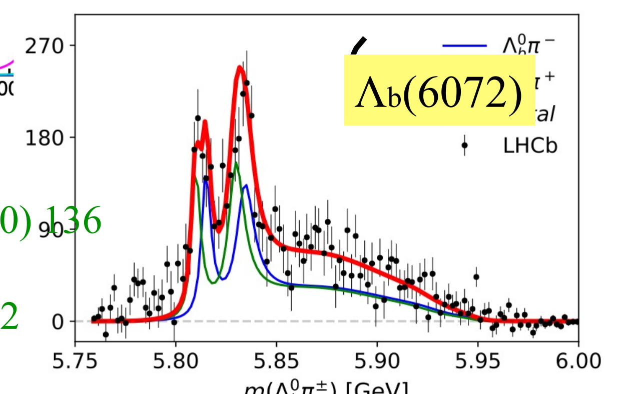
LHCb, PRL122 (2019) 222001





$\bar{c}cuud \to (\bar{c}u)(cdd$

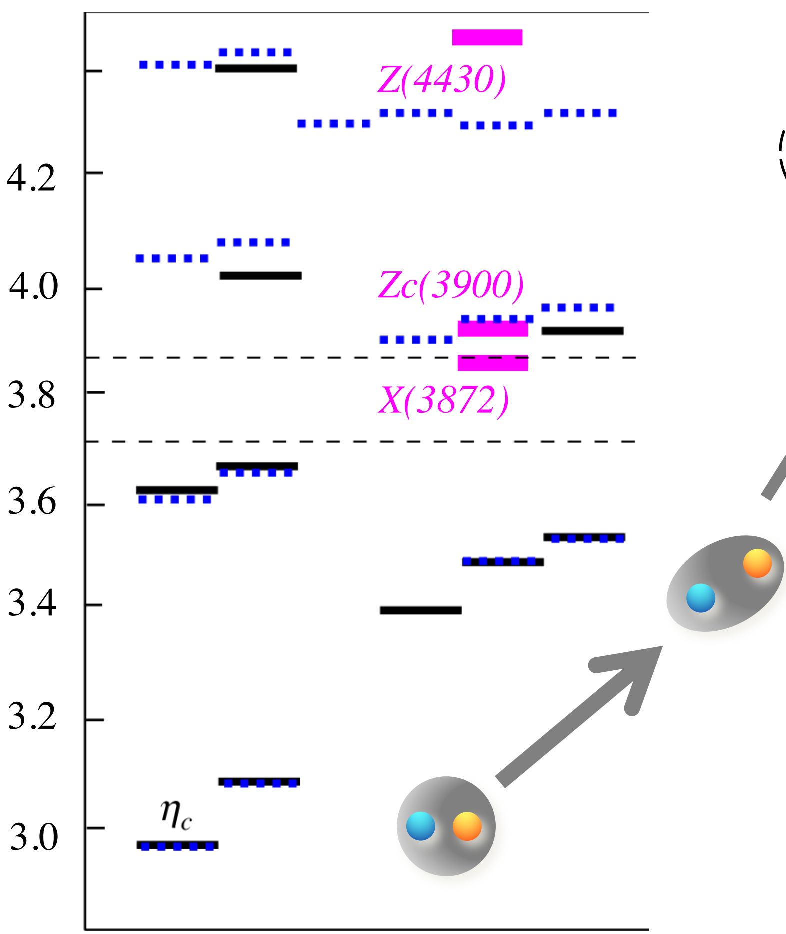
Λ_b(6072)

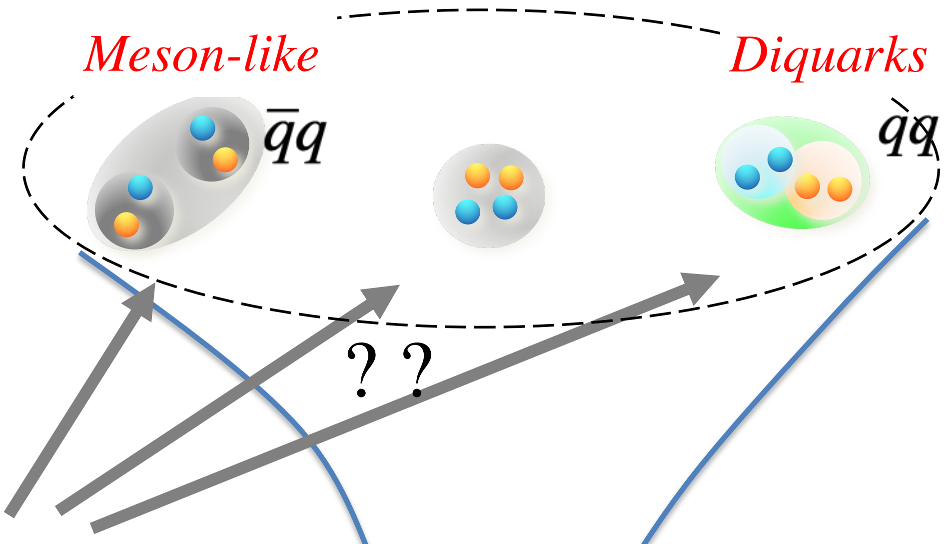


LHCb, JHEP 06 (2020) 136
Arifi et al, PRD 101 (2020) 111502

Excited states

Example: Charmonium-like states





- $\bar{q}q$ creation near threshold
- How multiquarks arranged
  - — Correlations
  - — $\bar{q}q, qq$ (diquarks)
- The role of heavy quarks Q

What to be asked

Questions:

- Do they exist?
- If they do, which ones?
- What is their internal structure?
- How best to look for them?

Marek Karliner, QNP conference, 2018@Tsukuba

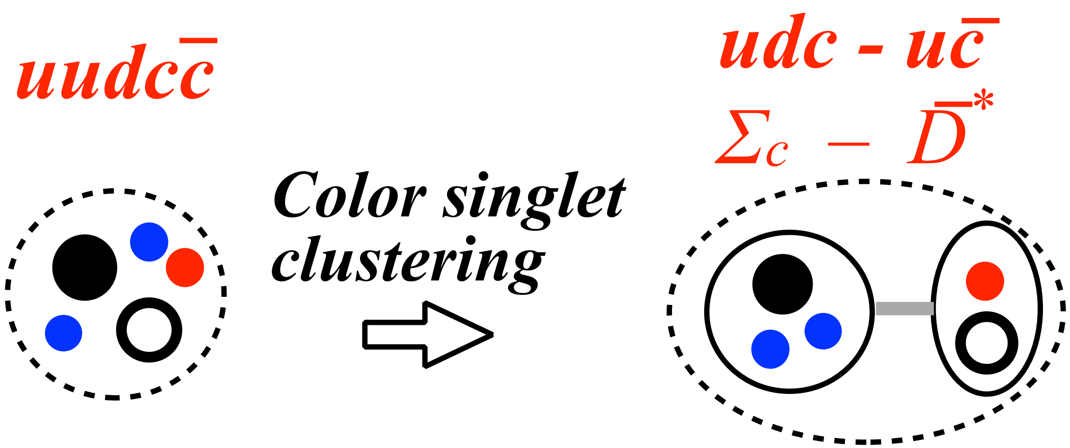
Answer in part (for multi-quark systems) in this talk:

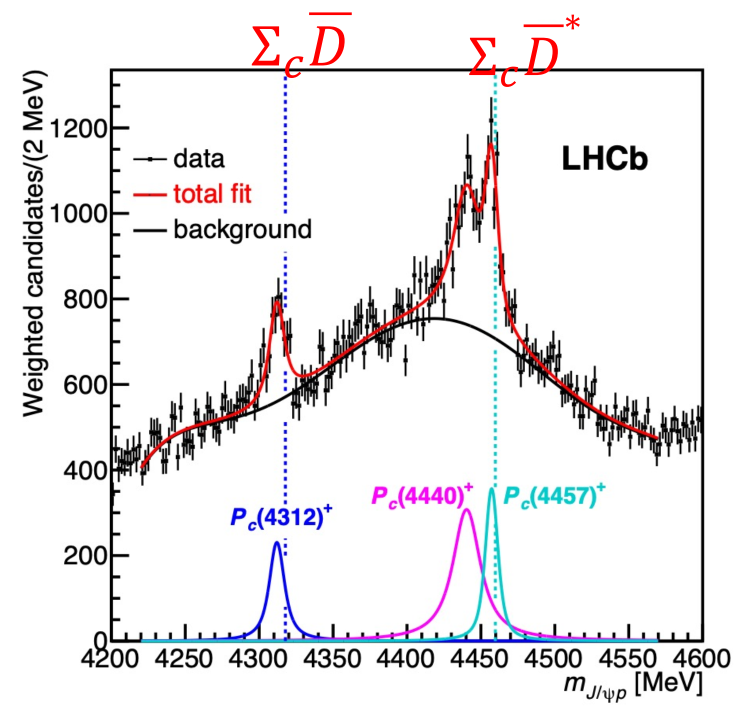
- $\bar{Q}Q$ may form quasi-stable hadrons $\rightarrow \bar{c}cuud$: $P_{\bar{c}c}$
- QQ may for stable hadrons $\rightarrow bb\overline{u}\overline{d}$: T_{bb}

2. Quasi-stable hidden charm hadron

— $\bar{c}cuud$: $P_{\bar{c}c}$ —

Peaks near thresholds of $\Sigma_c D$ and $\Sigma_c D^*$

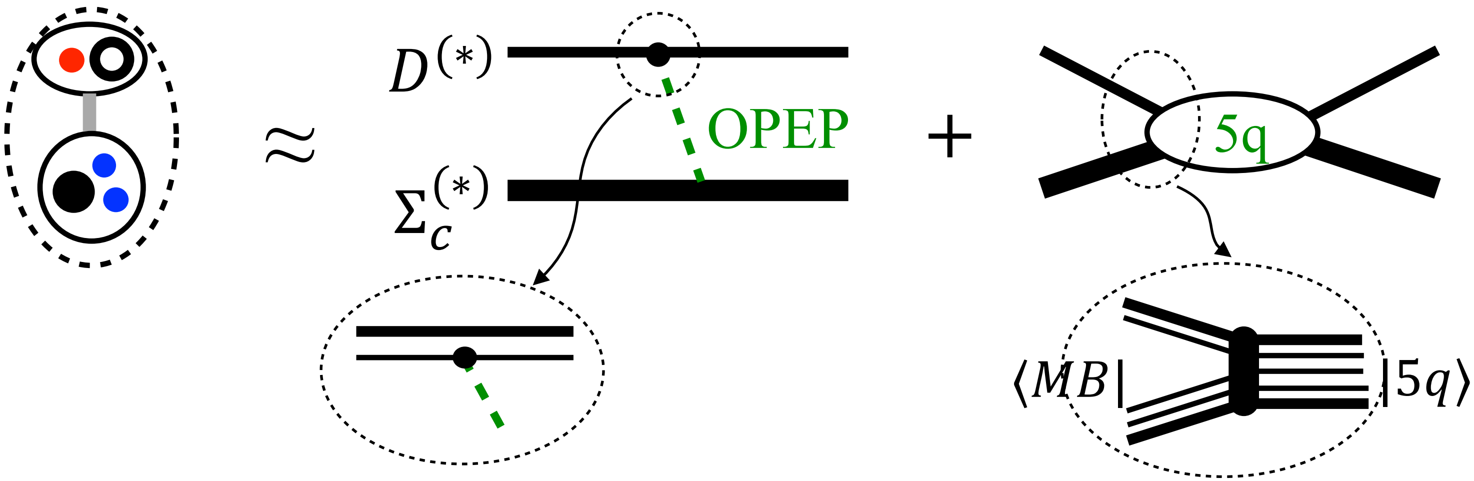




Near threshold
Molecular state

$\Sigma_c^{(*)} D^{(*)}$ molecules

Yamaguchi et al, *PRD* 101 (2020) 9, 091502; *PRD* 96 (2017) 11, 114031



πqq coupling + WF of $D^{(*)}$

Controlled parameter

$$V^{OPEP}_{MB\to MB} = \frac{g^2}{(2f_\pi)^2}\frac{3\vec{\sigma}_1\cdot\hat{q}\,\vec{\sigma}_2\cdot\hat{q} - \vec{\sigma}_1\cdot\vec{\sigma}_2}{\vec{q}^2+m_\pi^2}$$

SD coupling: important for the deuteron

S-factor

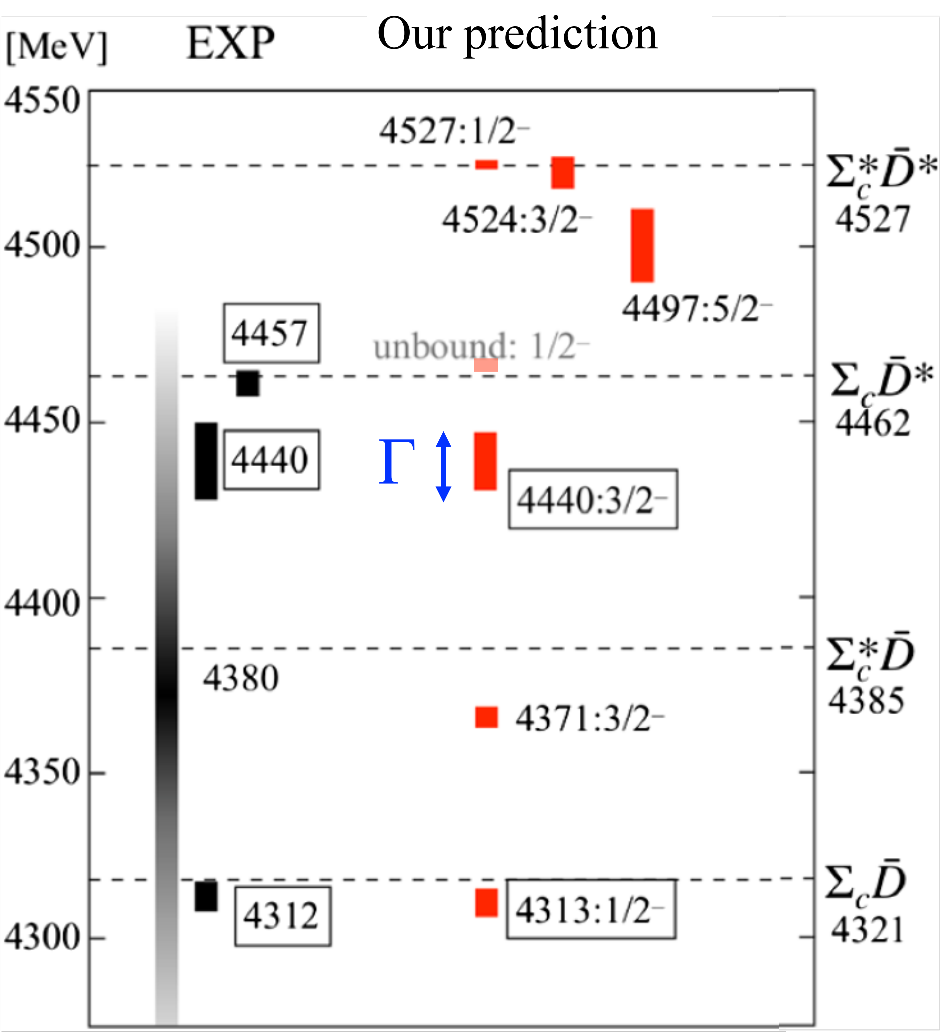
One parameter

$$V^{5q}_{MB\to MB} \sim f\sum_{5q}\frac{\langle MB|5q\rangle\langle 5q|MB\rangle}{E-E_{5q}}$$

Both OPEP (2nd order) and 5q: attraction

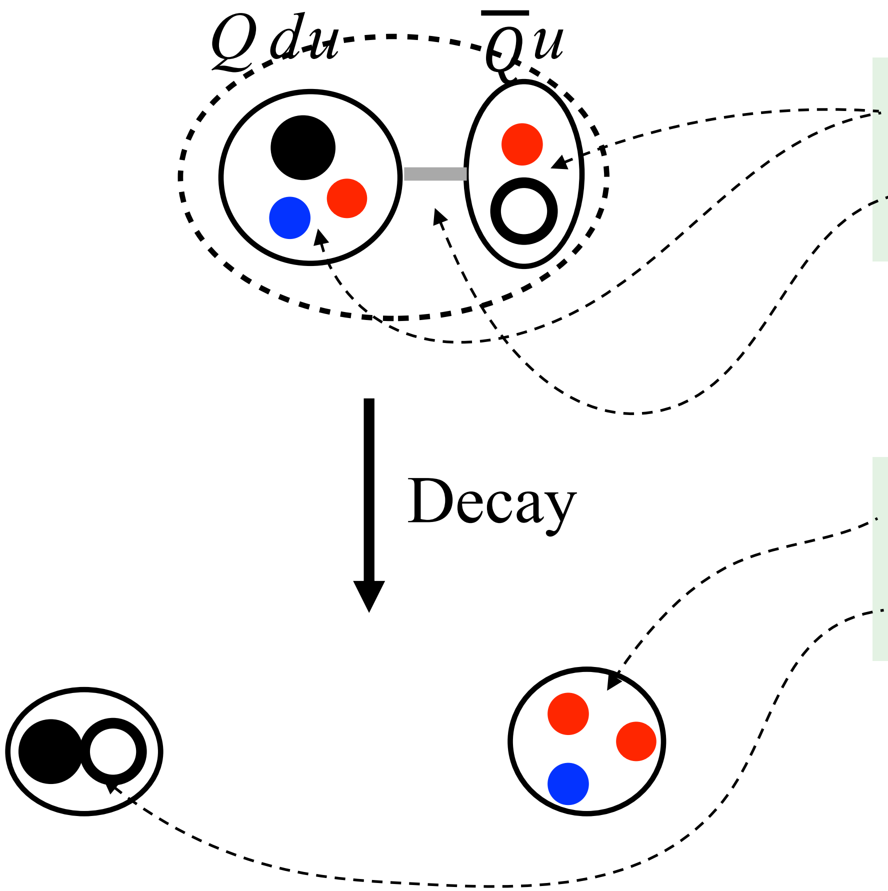
OPEP: Spin splittings

Result



- $\Sigma_c D$ singlet and $\Sigma_c D^*$ doublet well agree with data with predicted spin-parity
- $\Sigma_c^* D$ singlet and $\Sigma_c^* D^*$ triplet are predicted
- OPEP and 5q interactions are both important for binding
- Widths and spin-splittings are due to OPEP
- Decay into $J/\psi p$: Open charm → Hidden charm

A feature — Rearrange of $Q\bar{Q}qqq$



Binding strength

$\sim \Lambda_{QCD}$: Colored light degrees

~10 MeV: Colorless hadrons

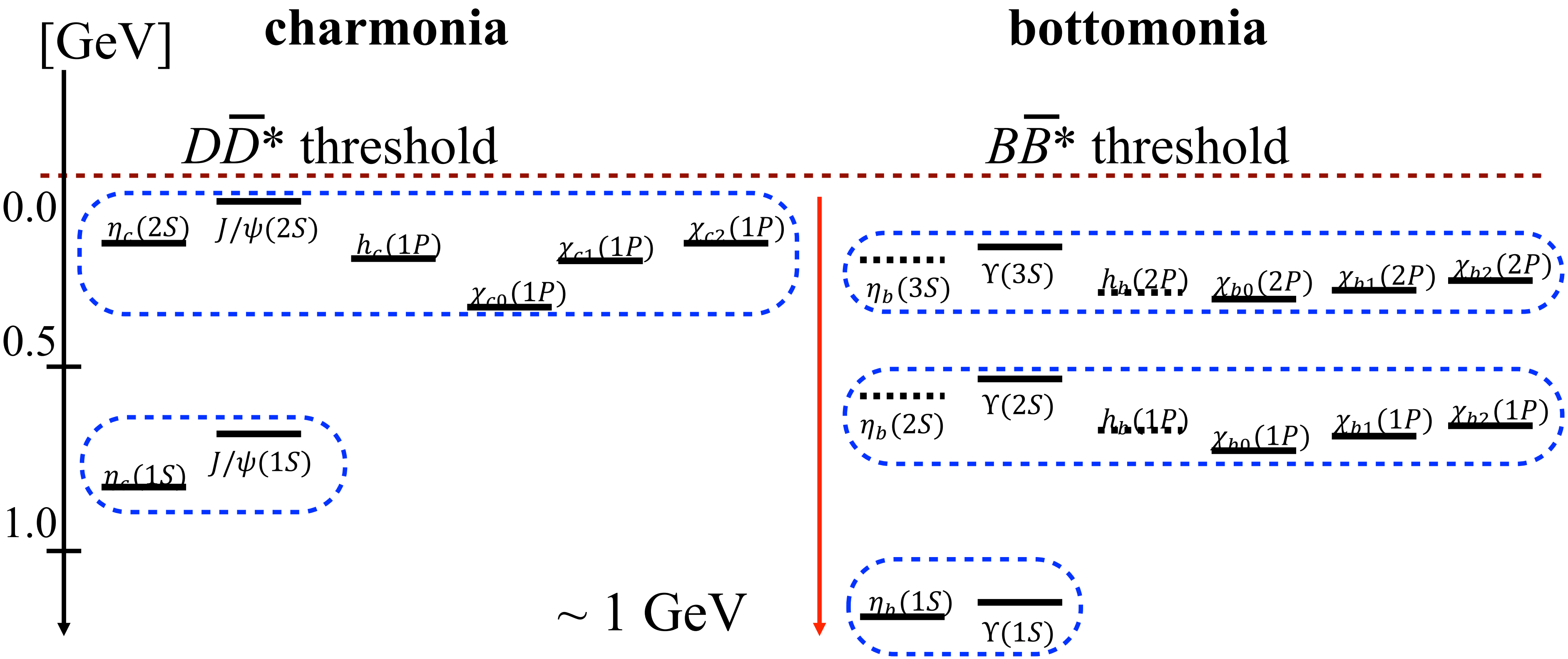
$\sim \Lambda_{QCD}$: Colored light degrees

$\sim M_Q$: Heavy quark mass

Very large binding

$M(P_c) > M(J/\psi) + M(p)$ $Q\bar{Q}qqq$ survive quasi-stably

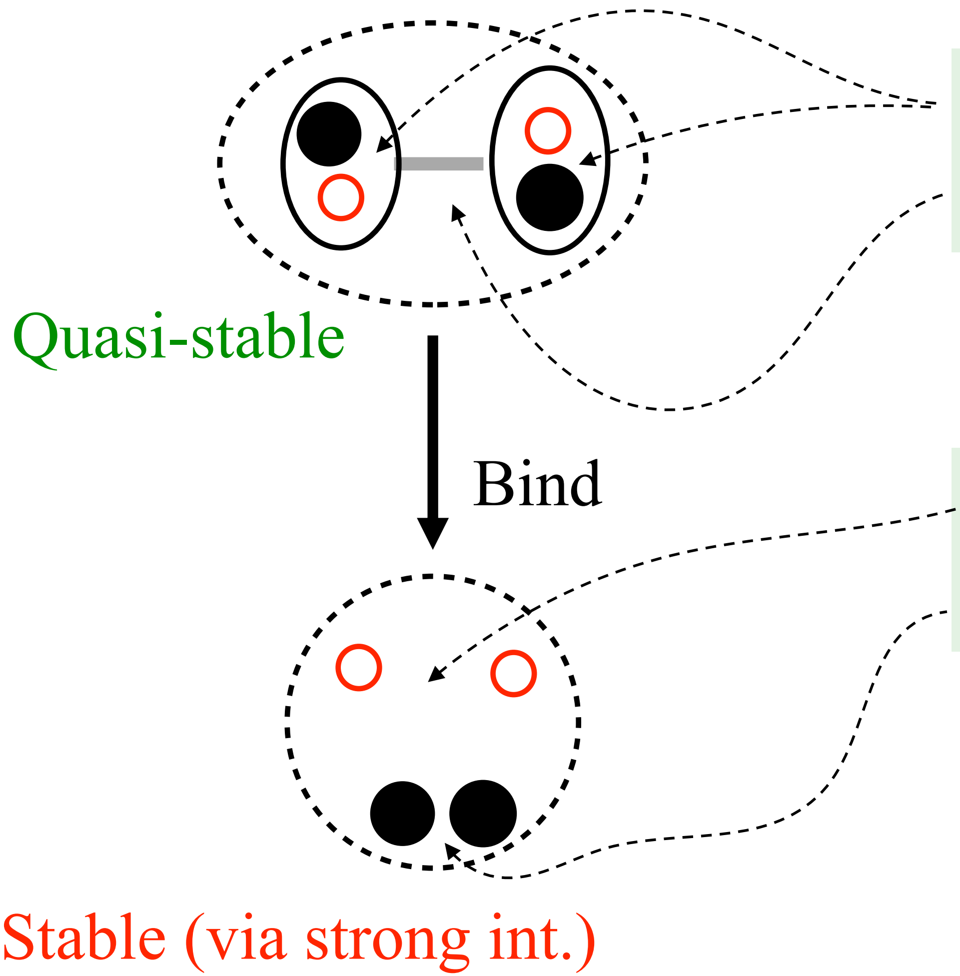
Strongly bound quarkonium



Strong $\bar{Q}Q$ attraction → 1/2 for QQ

3. Stable doubly heavy hadron

— $bb\overline{u}\overline{d}$: T_{bb} —



Binding strength

$\sim \Lambda_{QCD}$: Colored light degrees

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$\sim M_Q$: Heavy quark mass

Very large binding

M. Karliner, J.L. Rosner
Phys. Rev. D 90(9) (2014) 094007

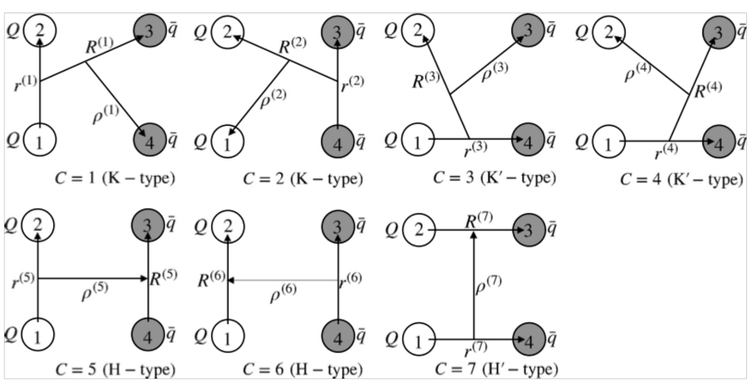
Stable $QQ'\overline{qq}'$

Q. Meng et al, PLB 814 (2021) 136095

Quark model solved precisely

$$H = \sum_i^4 \left(m_i + \frac{\boldsymbol{p}_i^2}{2m_i}\right) - T_G - \frac{3}{16}\sum_{i<j=1}^4 \sum_a^8 \left((\lambda_i^a \cdot \lambda_j^a) V_{ij}(\boldsymbol{r}_{ij})\right)$$

$$V_{ij}(\boldsymbol{r}) = -\frac{\kappa}{r} + \lambda r^p - \Lambda + \frac{2\pi\kappa'}{3m_i m_j}\frac{\exp(-r^2/r_0^2)}{\pi^{3/2} r_0^3}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$

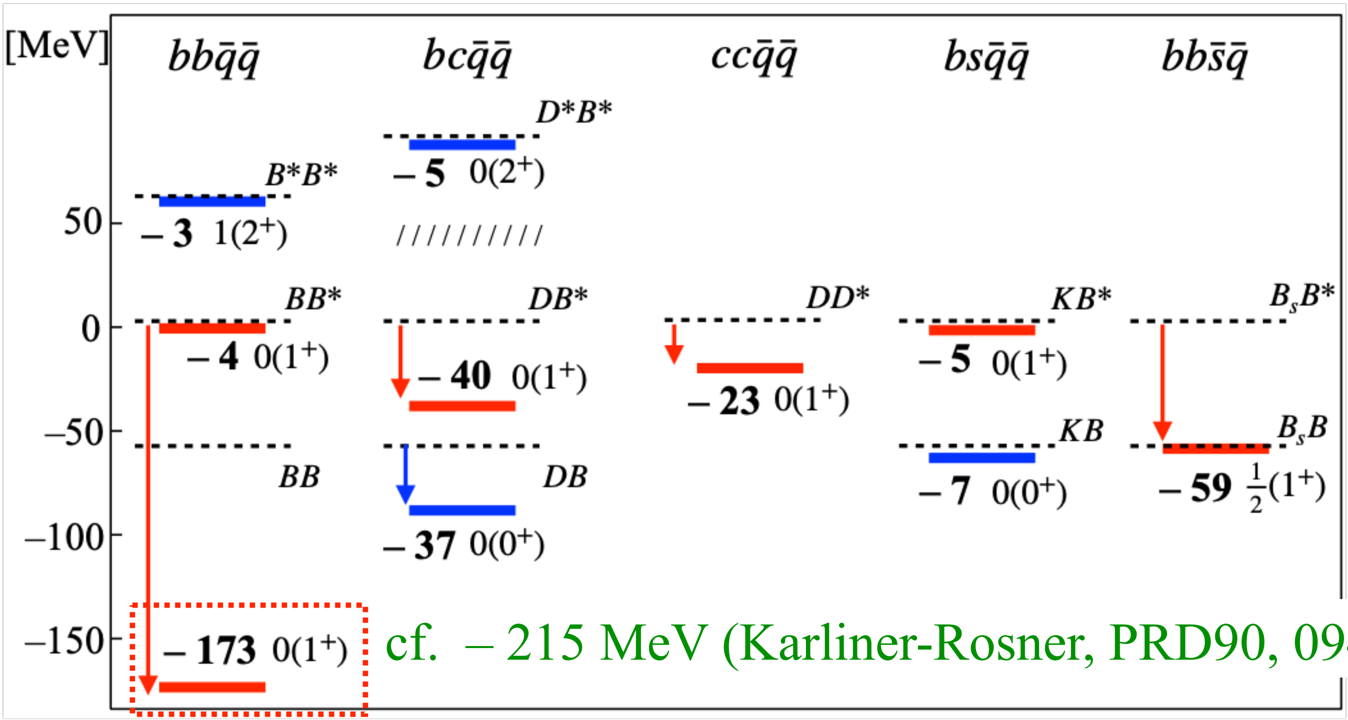


Conventional mesons

Table 1
The parameters of the Hamiltonian and the calculated masses (Cal) of heavy mesons compared with their experimental values (Exp).

Parameters		Masses (MeV)		
			Cal	Exp
$m_{u,d}$ (GeV)	0.277	$\eta_b(0^-)$	9375	9399
m_s (GeV)	0.593	$\Upsilon(1^-)$	9433	9460
m_c (GeV)	1.826	$\eta_c(0^-)$	2984	2984
m_b (GeV)	5.195	$J/\psi(1^-)$	3102	3097
p	2/3	$B^-(0^-)$	5281	5279
κ	0.4222	$B^{*-}(1^-)$	5336	5325
κ'	1.7925	$B_s(0^-)$	5348	5367
λ (GeV$^{5/3}$)	0.3798	$B_s^*(1^-)$	5410	5415
Λ (GeV)	1.1313	$D^-(0^-)$	1870	1870
A (GeV^{B-1})	1.5296	$D^{*-}(1^-)$	2018	2010
B	0.3263			

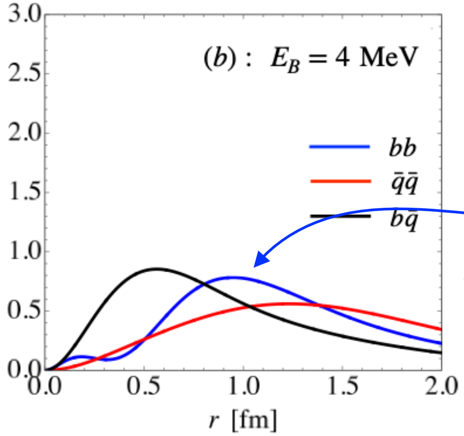
Stable $QQ'\overline{qq}'$

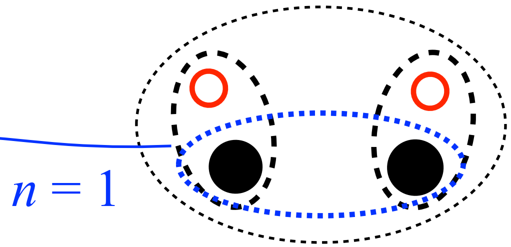


cf. – 215 MeV (Karliner-Rosner, PRD90, 094007)

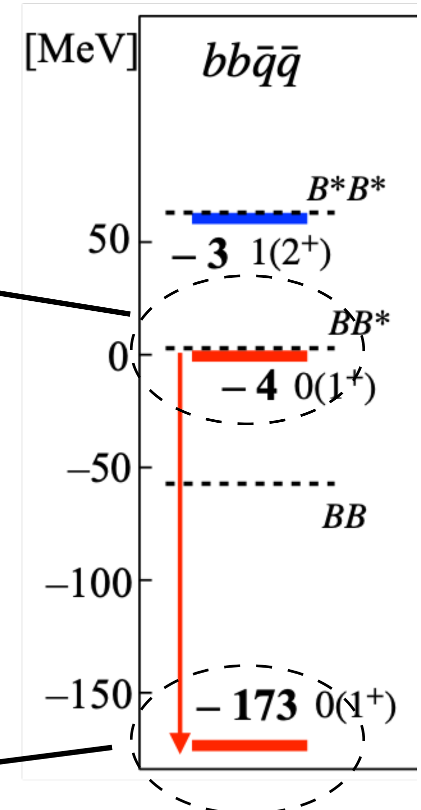
	$I(J^P)$	This work	[23]	lattice calculations			[27]
$bb\bar{q}\bar{q}$	$0(1^+)$	−173	−189 ± 13	−143 ± 34	–	−186 ± 15	−128 ± 26
$bc\bar{q}\bar{q}$	$0(1^+)$	−40	–	–	13 ± 3	–	–
$cc\bar{q}\bar{q}$	$0(1^+)$	−23	–	−23 ± 11	–	–	–
$bs\bar{q}\bar{q}$	$0(1^+)$	−5	–	–	16 ± 2	–	–
$bb\bar{s}\bar{q}$	$\frac{1}{2}(1^+)$	−59	−98 ± 10	−87 ± 32	–	–	–

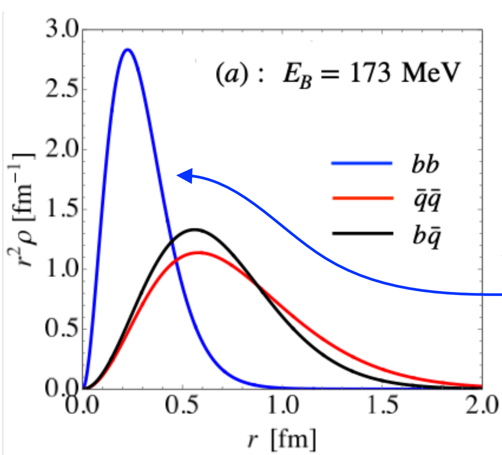
Structure



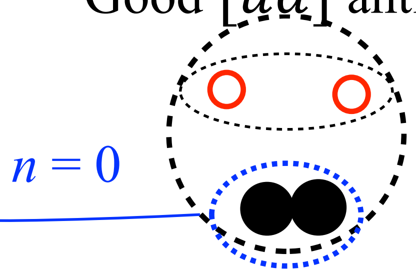


BB^* ***molecule***





Good $[\overline{u}\overline{d}]$ antidiquark

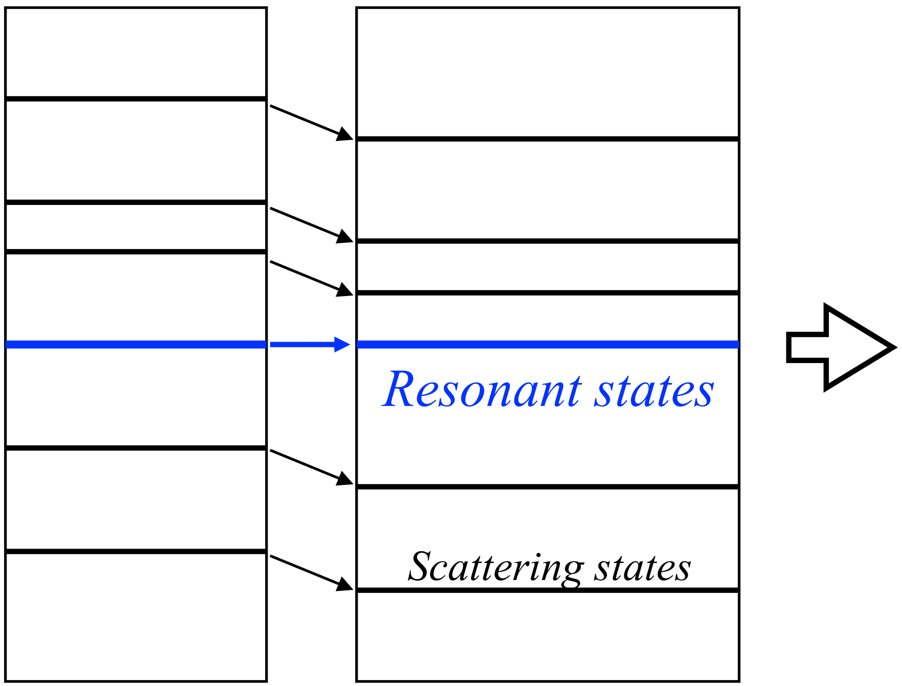


$\{bb\}$ heavy compact diquark of $J^P_{QQ} = 1^+$

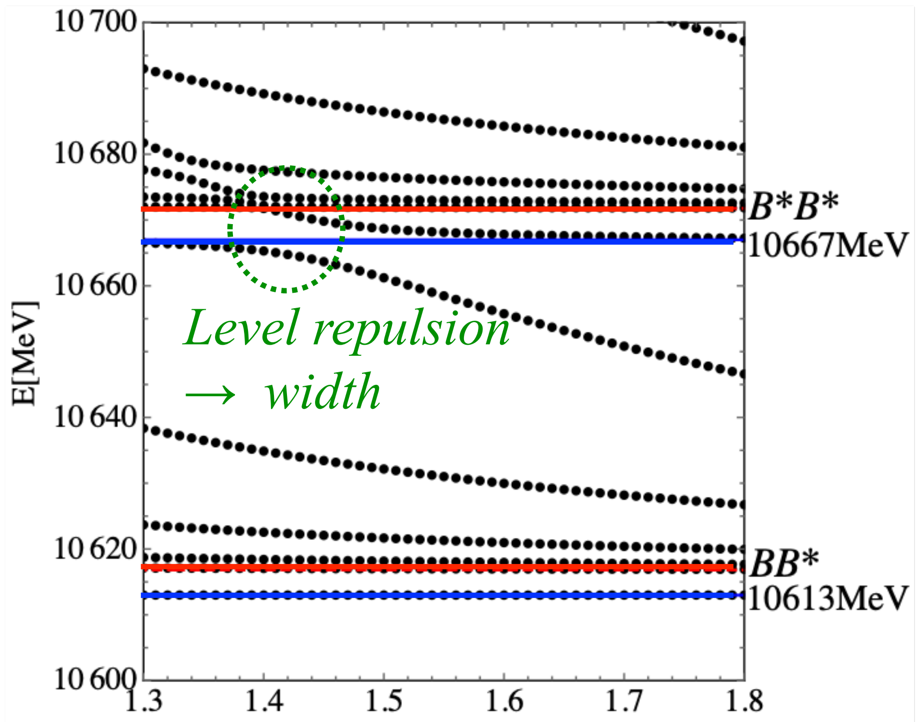
Compact Quasi-3-body

Resonant $bb\overline{qq}$

Technical issue = *scaling by α*



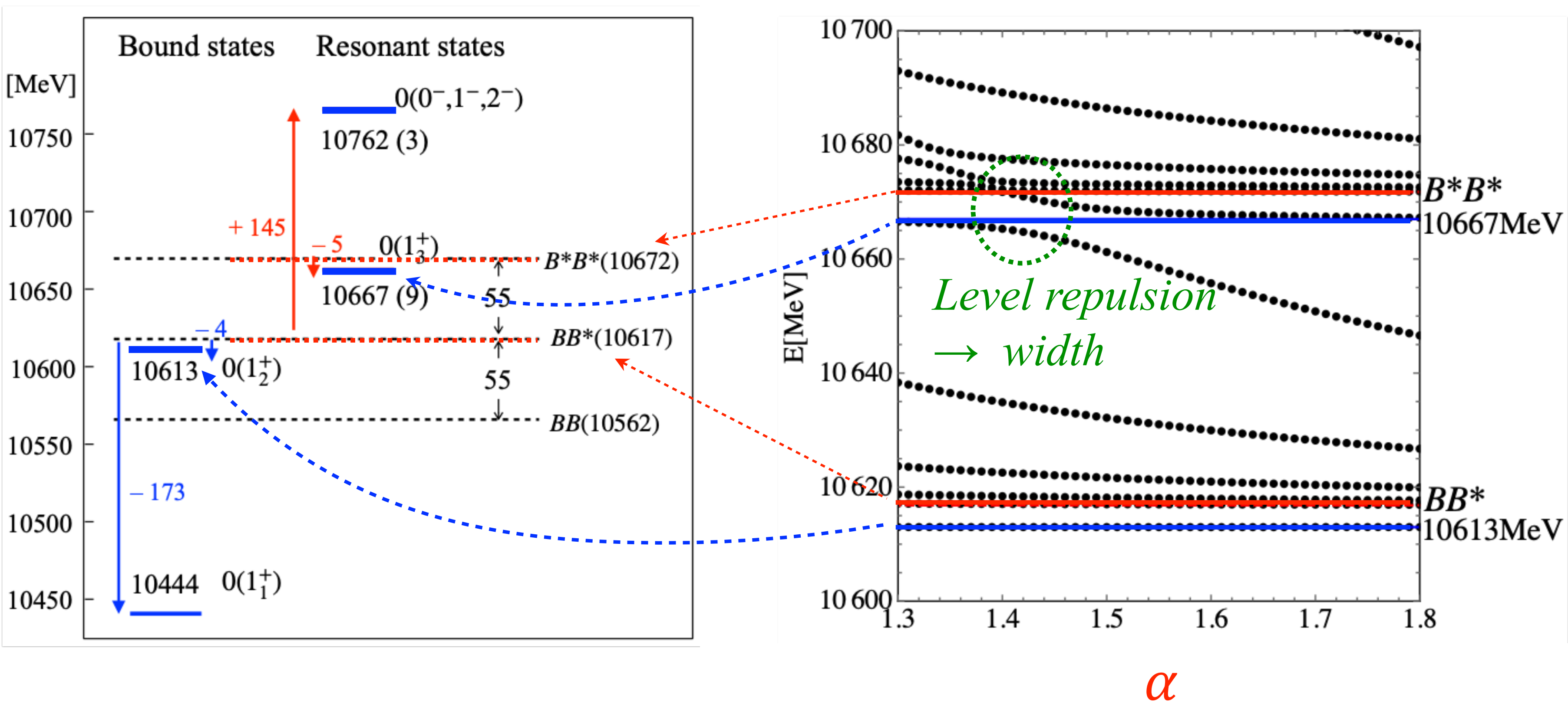
α *increase*



α

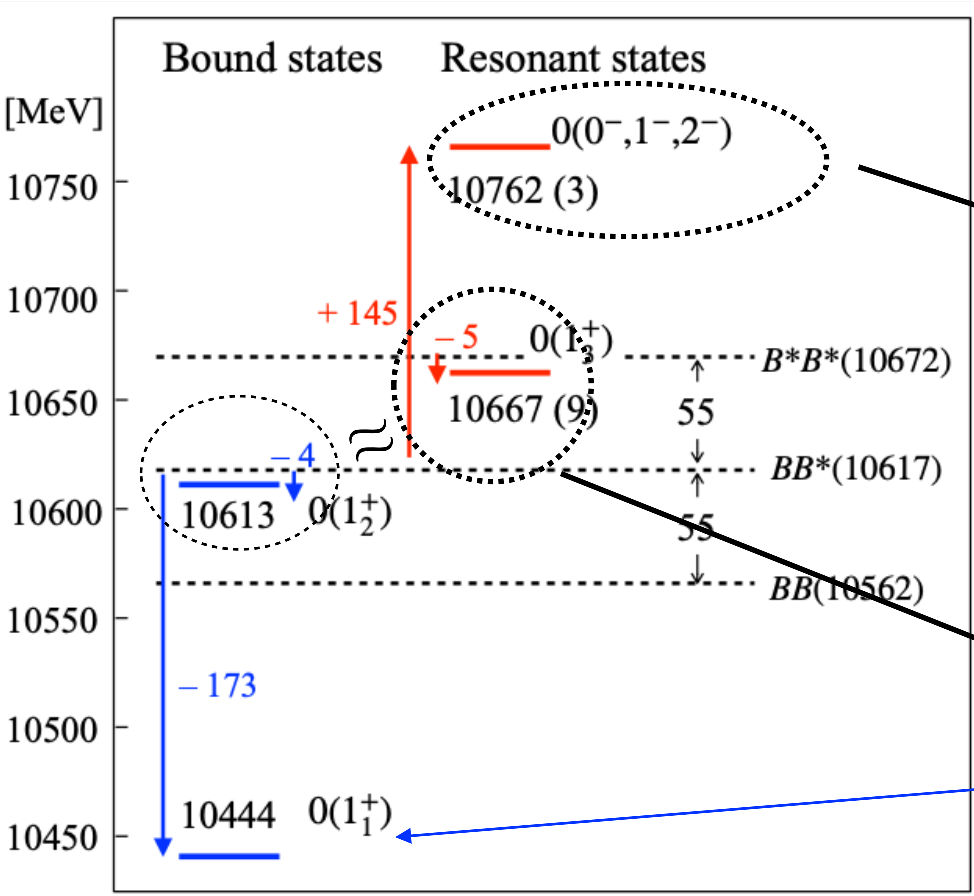
Resonant $bb\overline{qq}$

Technical issue = *scaling by α*



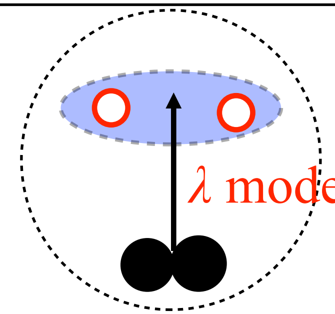
One 1^+ and three degenerate $0^-, 1^-, 2^-$ states

Resonant $bb\overline{qq}$

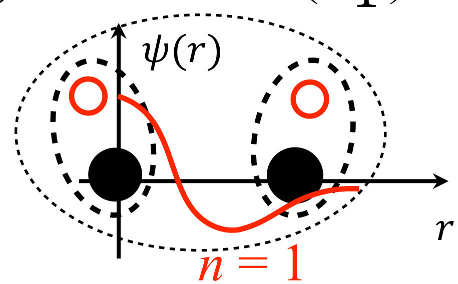


Heavy quark triplet of
$bb(1^+) + [\overline{qq}]_{\text{good}}(0^+)$ in p-wave ($L = 1$

$1 + 1 = 0, 1, 2$



Molecular of BB^* or B^*B^* with
$[bb]_{\bar{3}}$ of one radial node $n = 1$
orthogonal to $10444(1_1^+)$ of $n = 0$



4. Summary

Partially answer to the questions:

- Do they exist?
- If they do, which ones?
- What is their internal structure?
- How best to look for them?

1. P_c's as $\Sigma_c^{(*)} D^{(*)}$ molecules

Predicted spin-parity and other states ($\Sigma_c^{*} D^{(*)}$)

2. Bound and resonant $QQ'\overline{qq}'$ states are predicted
3. Role of heavy quarks

$Q\overline{Q}$: Quasi-stable molecular states

QQ: Compact or molecular like stable states