Hadronic molecules with heavy quarks

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Contents

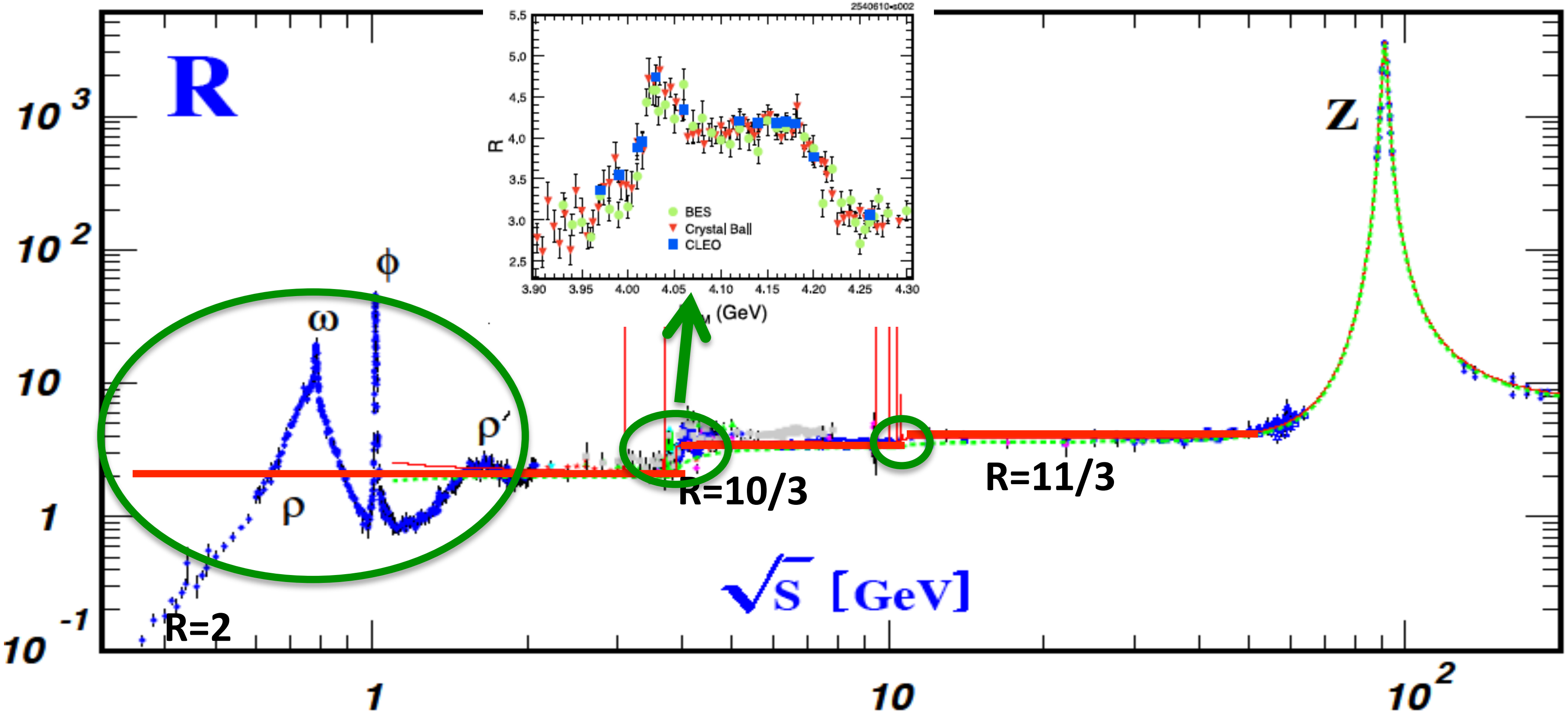
1. Introduction

— *Hadron Physics* —

- Evidence of Higgs (like) has been observed
  Low energy QCD for Hadron is perhaps least understood
- Lagrangian is simple but not easy to solve
- Long history: Experiments, Models (Empirical rules), Computer simulations (Lattice QCD, Kei SC@Kobe)
- Recent (last decade) observations has opened Unexpectedly *rich spectrum* near *thresholds* at KEK, Spring-8, J-PARCBES, RHIC, LHC, …

Hadrons are around thresholds

$$R(s) = \sigma(e^+e^- \rightarrow hadrons, s)/\sigma(e^+e^- \rightarrow \mu^+\mu^-, s).$$



1 GeV

1 GeV

GeV in Log scale

ud s

Mass generation

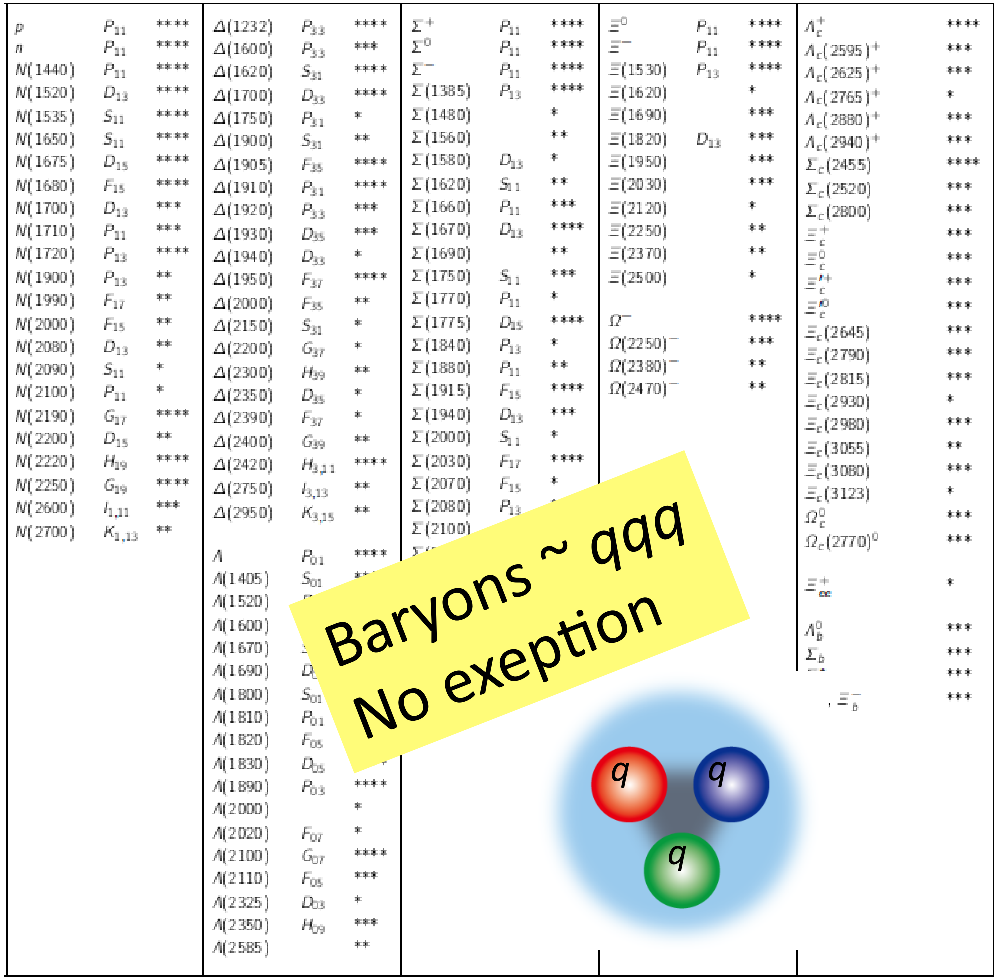
c

b

Hadrons are composite

Many resonant states

Particle data book (PDG)



p	P_{11}	****
n	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	S_{11}	*
$N(2100)$	P_{11}	*
$N(2190)$	G_{17}	****
$N(2200)$	D_{15}	**
$N(2220)$	H_{19}	****
$N(2250)$	G_{19}	****
$N(2600)$	$I_{1,11}$	***
$N(2700)$	$K_{1,13}$	**

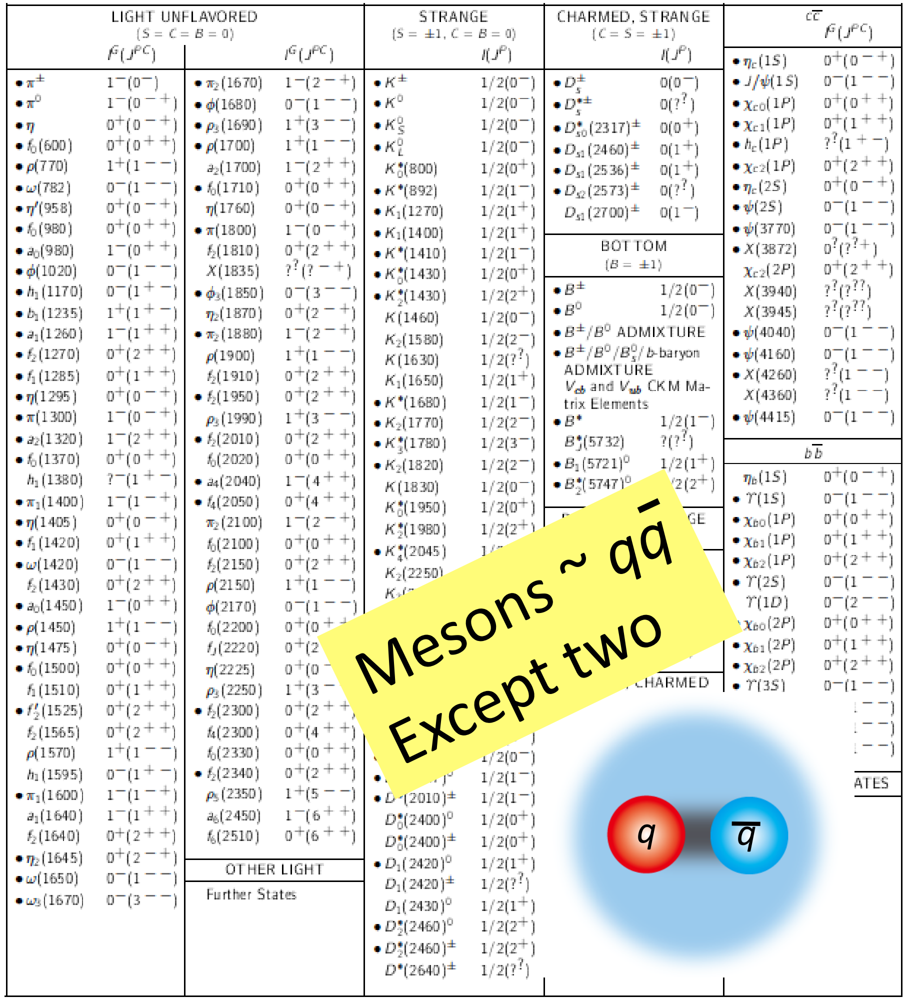
$\Delta(1232)$	P_{33}	****
$\Delta(1600)$	P_{33}	***
$\Delta(1620)$	S_{31}	****
$\Delta(1700)$	D_{33}	****
$\Delta(1750)$	P_{31}	*
$\Delta(1900)$	S_{31}	**
$\Delta(1905)$	F_{35}	****
$\Delta(1910)$	P_{31}	****
$\Delta(1920)$	P_{33}	***
$\Delta(1930)$	D_{35}	***
$\Delta(1940)$	D_{33}	*
$\Delta(1950)$	F_{37}	****
$\Delta(2000)$	F_{35}	**
$\Delta(2150)$	S_{31}	*
$\Delta(2200)$	G_{37}	*
$\Delta(2300)$	H_{39}	**
$\Delta(2350)$	D_{35}	*
$\Delta(2390)$	F_{37}	*
$\Delta(2400)$	G_{39}	**
$\Delta(2420)$	$H_{3,11}$	****
$\Delta(2750)$	$I_{3,13}$	**
$\Delta(2950)$	$K_{3,15}$	**
Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	
$\Lambda(1520)$		
$\Lambda(1600)$		
$\Lambda(1670)$		
$\Lambda(1690)$		
$\Lambda(1800)$	S_{01}	
$\Lambda(1810)$	P_{01}	
$\Lambda(1820)$	F_{05}	
$\Lambda(1830)$	D_{05}	
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	F_{07}	*
$\Lambda(2100)$	G_{07}	****
$\Lambda(2110)$	F_{05}	***
$\Lambda(2325)$	D_{03}	*
$\Lambda(2350)$	H_{09}	***
$\Lambda(2585)$		**

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
$\Sigma(1385)$	P_{13}	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	D_{13}	*
$\Sigma(1620)$	S_{11}	**
$\Sigma(1660)$	P_{11}	***
$\Sigma(1670)$	D_{13}	****
$\Sigma(1690)$		**
$\Sigma(1750)$	S_{11}	***
$\Sigma(1770)$	P_{11}	*
$\Sigma(1775)$	D_{15}	****
$\Sigma(1840)$	P_{13}	*
$\Sigma(1880)$	P_{11}	**
$\Sigma(1915)$	F_{15}	****
$\Sigma(1940)$	D_{13}	***
$\Sigma(2000)$	S_{11}	*
$\Sigma(2030)$	F_{17}	****
$\Sigma(2070)$	F_{15}	*
$\Sigma(2080)$	P_{13}	
$\Sigma(2100)$		

Ξ^0	P_{11}	****
Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	****
$\Lambda_c(2595)^+$	***
$\Lambda_c(2625)^+$	***
$\Lambda_c(2765)^+$	*
$\Lambda_c(2880)^+$	***
$\Lambda_c(2940)^+$	***
$\Sigma_c(2455)$	****
$\Sigma_c(2520)$	***
$\Sigma_c(2800)$	***
Ξ_c^+	***
Ξ_c^0	***
$\Xi_c'^+$	***
$\Xi_c'^0$	***
$\Xi_c(2645)$	***
$\Xi_c(2790)$	***
$\Xi_c(2815)$	***
$\Xi_c(2930)$	*
$\Xi_c(2980)$	***
$\Xi_c(3055)$	**
$\Xi_c(3080)$	***
$\Xi_c(3123)$	*
Ω_c^0	***
$\Omega_c(2770)^0$	***
Ξ_{cc}^+	*
Λ_b^0	***
Σ_b	***
	***
, Ξ_b^-	***

Baryons ~ qqq
No exeption



LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	$\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{+}$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2$
• $f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_0(2330)$	$0^+(0^{++})$
$h_1(1595)$	$0^-(1^{+-})$	• $f_2(2340)$	$0^+(2^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$\rho_5(2350)$	$1^+(5^{--})$
$a_1(1640)$	$1^-(1^{++})$	$a_6(2450)$	$1^-(6^{++})$
$f_2(1640)$	$0^+(2^{++})$	$f_6(2510)$	$0^+(6^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$	OTHER LIGHT	
• $\omega(1650)$	$0^-(1^{--})$	Further States	
• $\omega_3(1670)$	$0^-(3^{--})$		

STRANGE ($S = \pm1$, $C = B = 0$)	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	1/
$K_2(2250)$	
	$1/2(0^-)$
•	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
$D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D^*(2640)^\pm$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)^\pm$	$0(?^?)$
$D_{s1}(2700)^\pm$	$0(1^-)$
BOTTOM ($B = \pm1$)	
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$/2(2^+)$
GE	
CHARMED	

$c\overline{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
$\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(3945)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $X(4260)$	$?^?(1^{--})$
$X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$b\overline{b}$	
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
	$^{--})$
	$^{--})$
	$^{--})$
ATES	

Mesons ~ $q\bar{q}$
Except two

But all of them seem excitations of minimum number (2 or 3) of valence quarks

But why not exotics such as

- Gluon excitations (glueballs, hybrids, …)
- Hadrons of more quarks,

  tetraquarks, pentaquarks, …
- Multi-hadron hadrons (hadronic molecules)

  other than atomic nuclei

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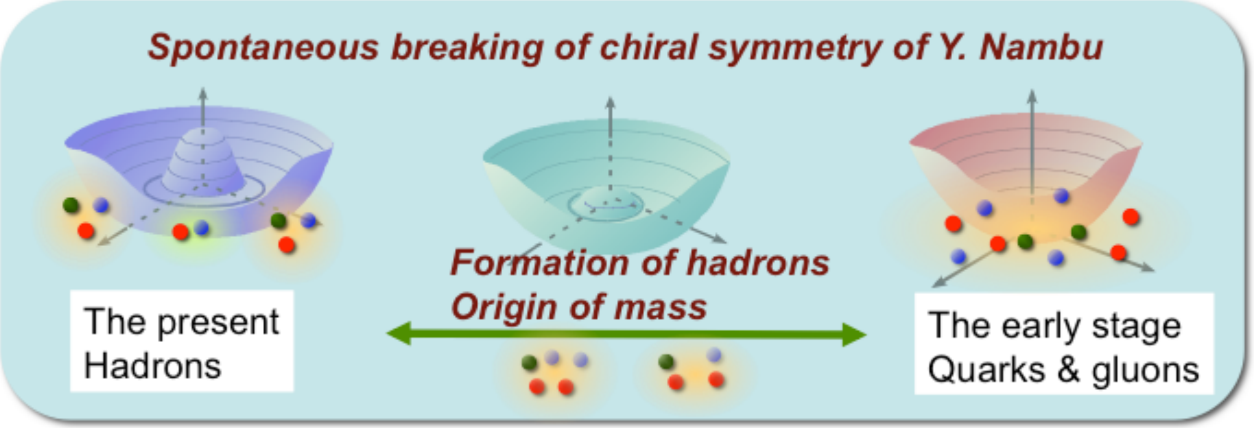
Variety of flavors (Heavy quarks) may be a good probe

Nambu’s SSBχ & Yukawa’s pion

(1) Light bare quarks
=> *Massive constituent quarks*

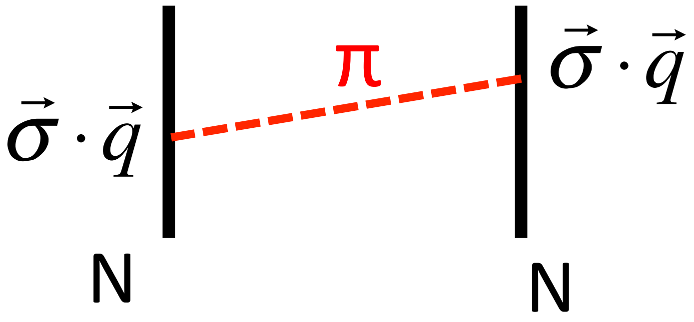
(2) Appearance of the *massless pion*



OPEP

Long range *tensor force*

spin and orientation dependent



Nambu’s SSBχ & Yukawa’s pion

(1) Light bare quarks

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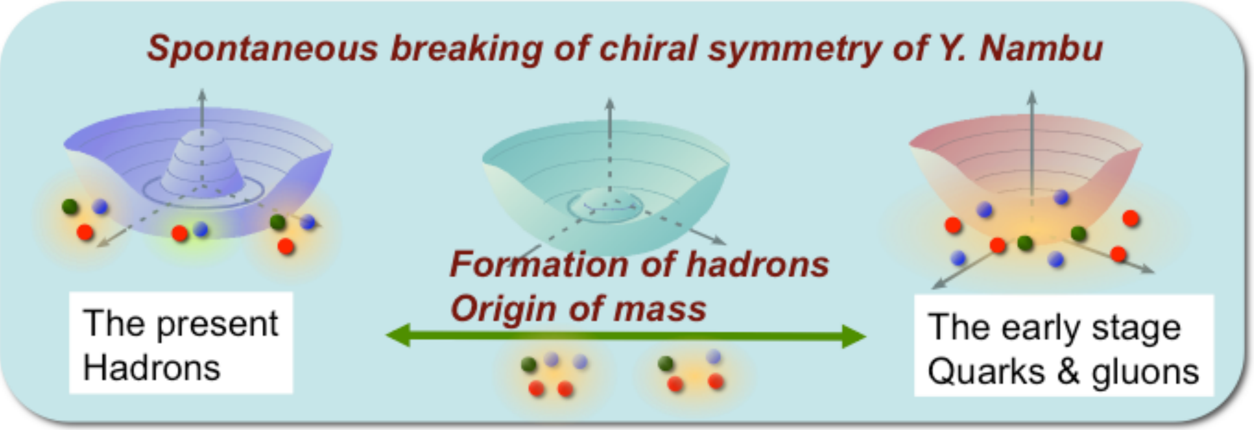
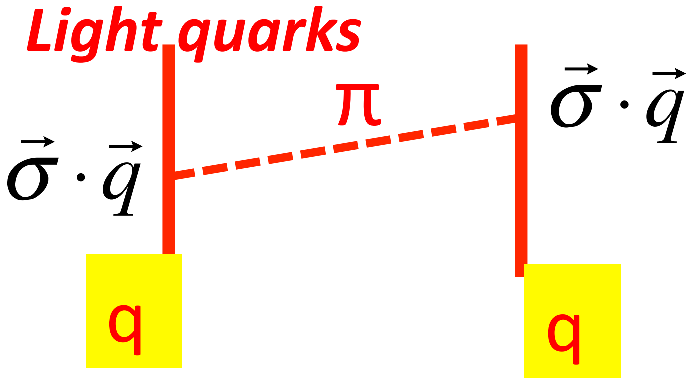


OPEP

Long range ***tensor force***

spin and orientation dependent



2. Exotic hadrons with many quarks

Near flavor thresholds

e+e- collider at 11.5 GeV (CM)

Mesons

X(3872)

State	Mass (MeV)	Width (MeV)	Decay	Production
Ys(2175)	2175±8	58±26	ff_0	ISR
X(3872)	3871.84±0.33	<0.95	J/ypp, J/yg	B decay
X(3872)	3872.8 +0.7/-0.6	3.9 +2.8/-1.8	$D^{*0}D^0$	B decay
Z(3940)	3929±5	29±10	DD	gg
X(3940)	3942±9	37±17	DD*	Double-charm
Y(3940)	3942±17	87±34	J/yw	B decay
Y(4008)	4008 +82/-49	226 +97/-80	J/ypp	ISR
Z(4051)$^+$	4051 +24/-43	82 +51/-28	pc_{c1}	B decay
X(4160)	4156±29	139 +113/-65	D*D*	Double-charm
Z(4248)$^+$	4248 +185/-45	177 +320/-72	pc_{c1}	B decay
Y(4260)	4264±12	83±22	J/ypp	ISR
Y(4350)	4361±13	74±18	y'pp	ISR
Z(4430)$^+$	4433±5	45 +35/-18	y'p	B decay
Y(4660)	4664±12	48±15	y'pp	ISR
Y_b(10890)	10889.6±2.3	54.7 +8.9/-7.6	ppϒ(nS)	e^+e^- annihilation
Y(3915)	3915±4	17±10	J/yw	gg
X(4350)	4350 +4.7/-5.1	13 +18/-14	J/yf	gg
h_b(1P)	9898.3±1.5		MM(pp)	ϒ(5S) /Y_b decay
h_b(2P)	10259.3 +1.6/-1.2		MM(pp)	ϒ(5S) /Y_b decay
Z_b(10610)	10608.4±2.0	15.6±2.5	(ϒ(nS) or h_b)p	ϒ(5S) /Y_b decay
Z_b(10650)	10653.2±1.5	14.4±3.2	(ϒ(nS) or h_b)p	ϒ(5S) /Y_b decay

Zb(10610)

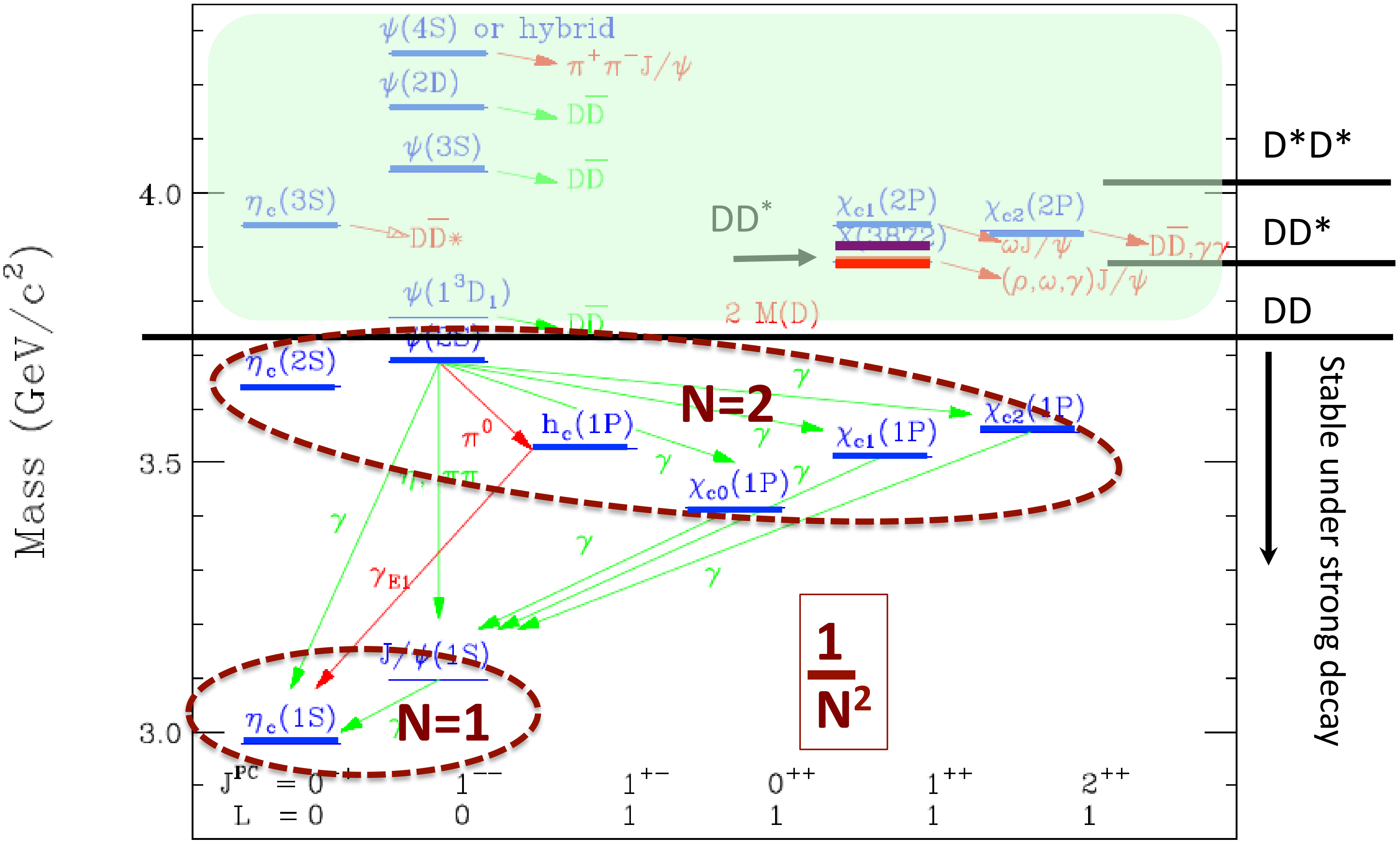
Zb(10650)

Zc(3900), Phys. Rev. Lett. 110, 252001 (2013)

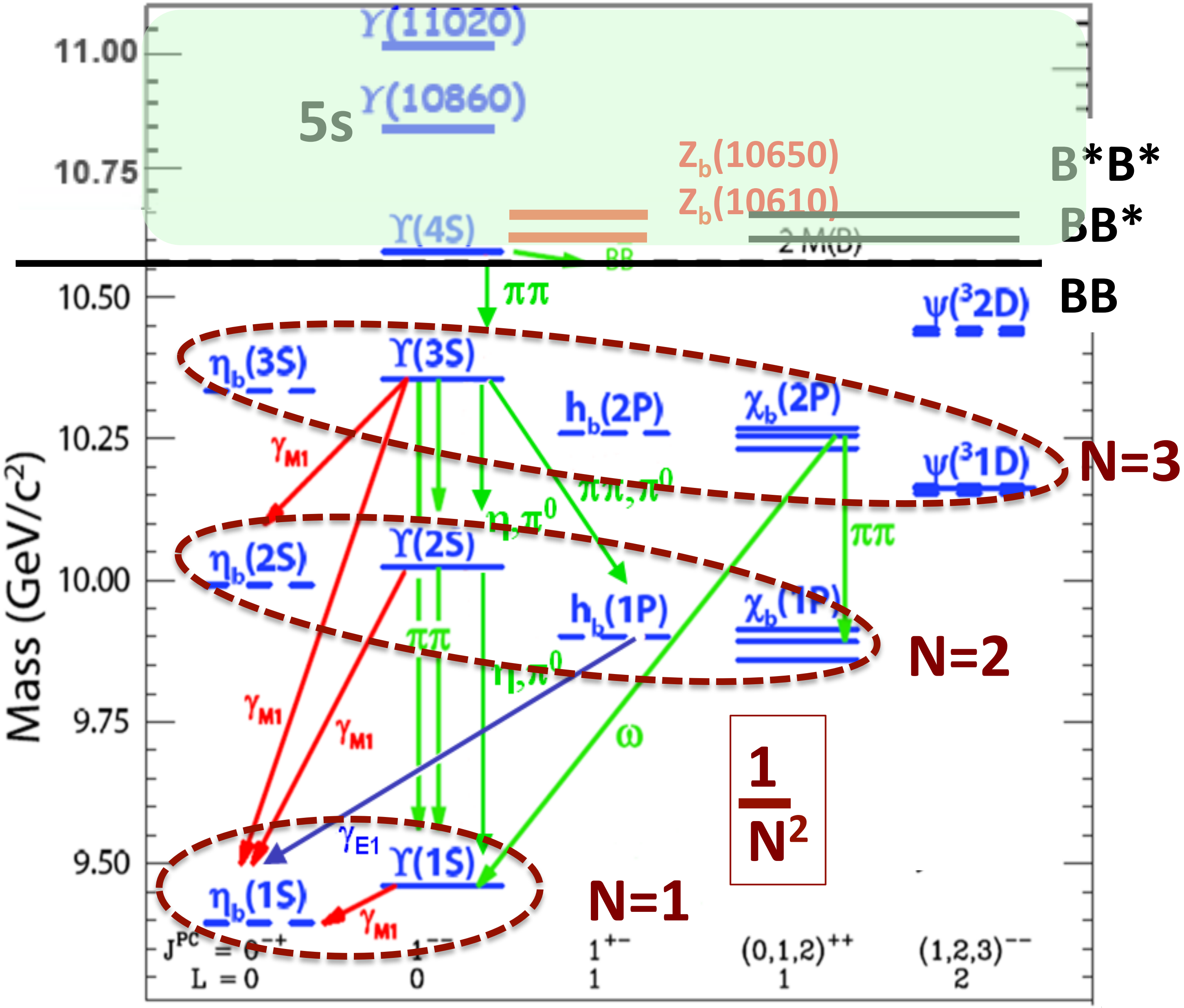
C quark spectroscopy

🟥 Z(4430)

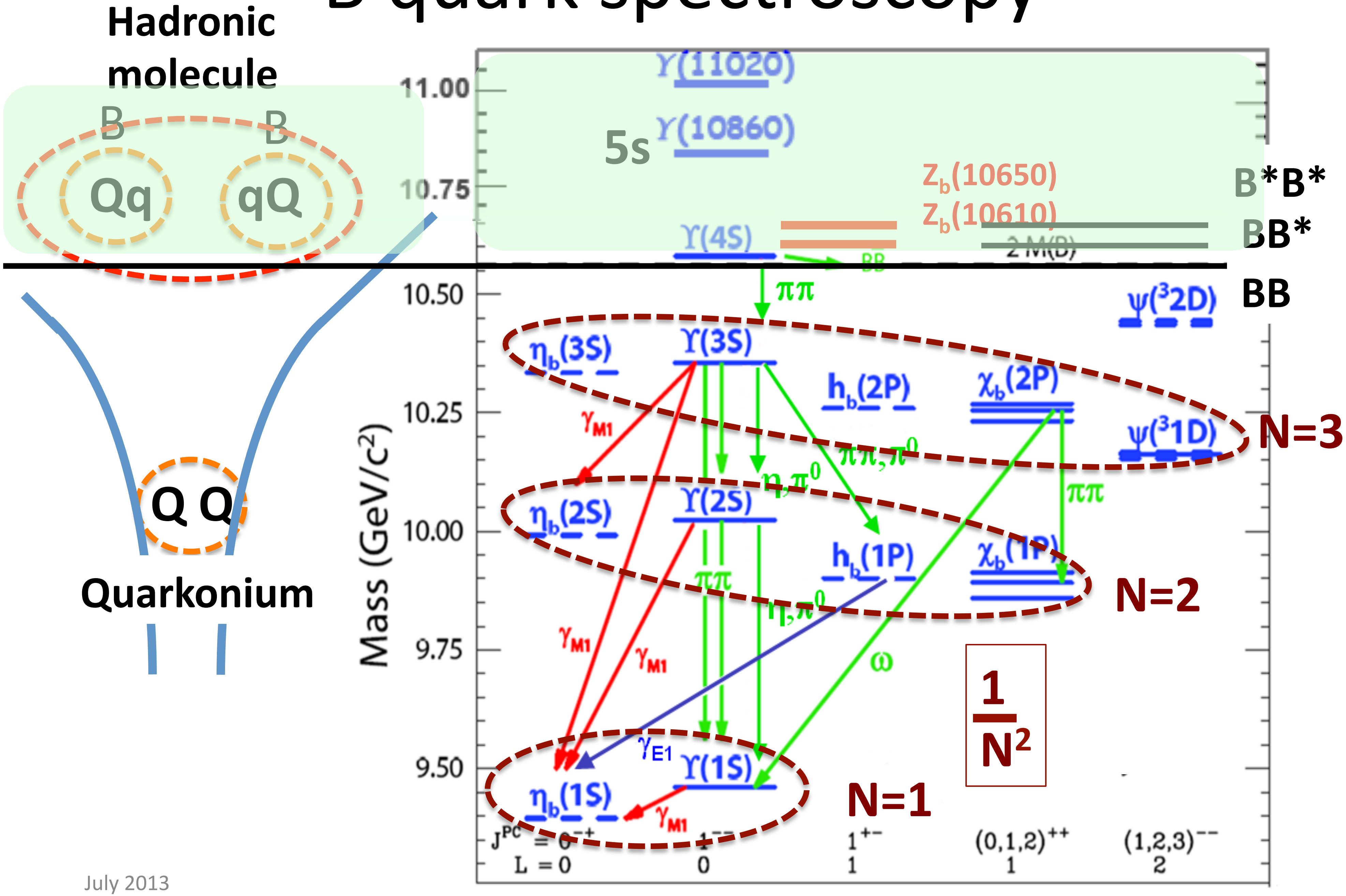
🟪 $Z_c(3900)$



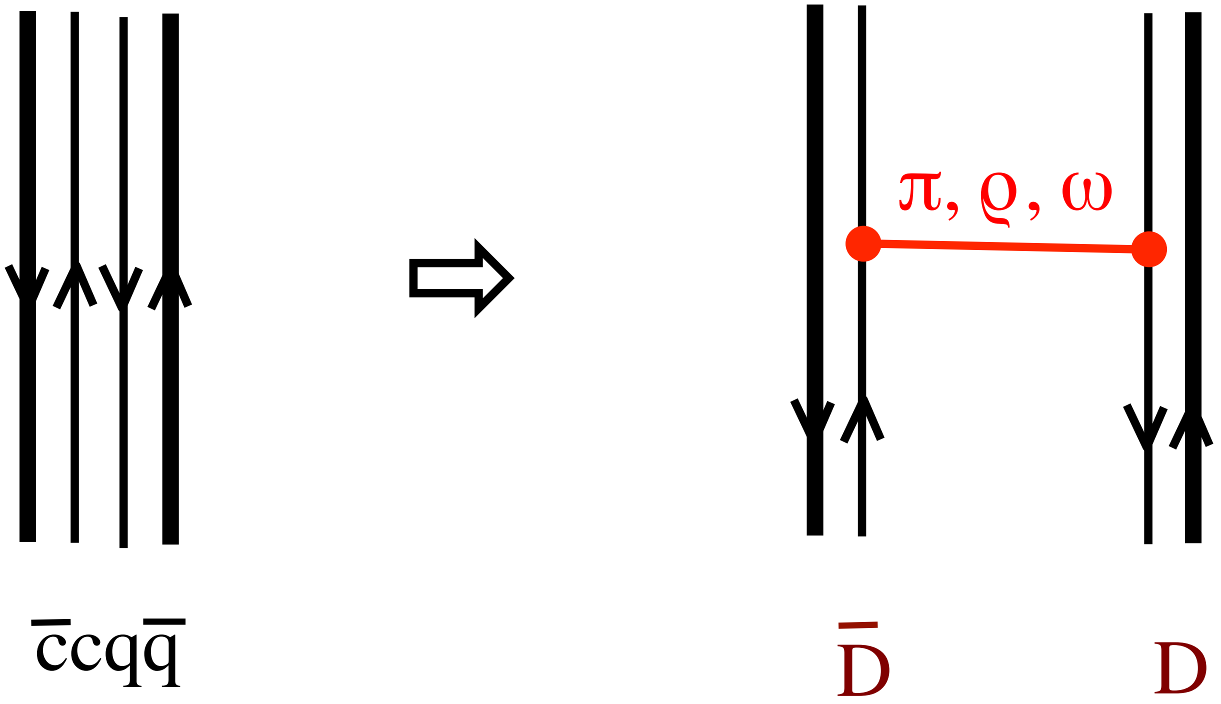
B quark spectroscopy



B quark spectroscopy



Clusterized multiquarks and interactions



Multiquarks (with light flavor) rearrange into hadrons
Chiral dynamics among light quarks

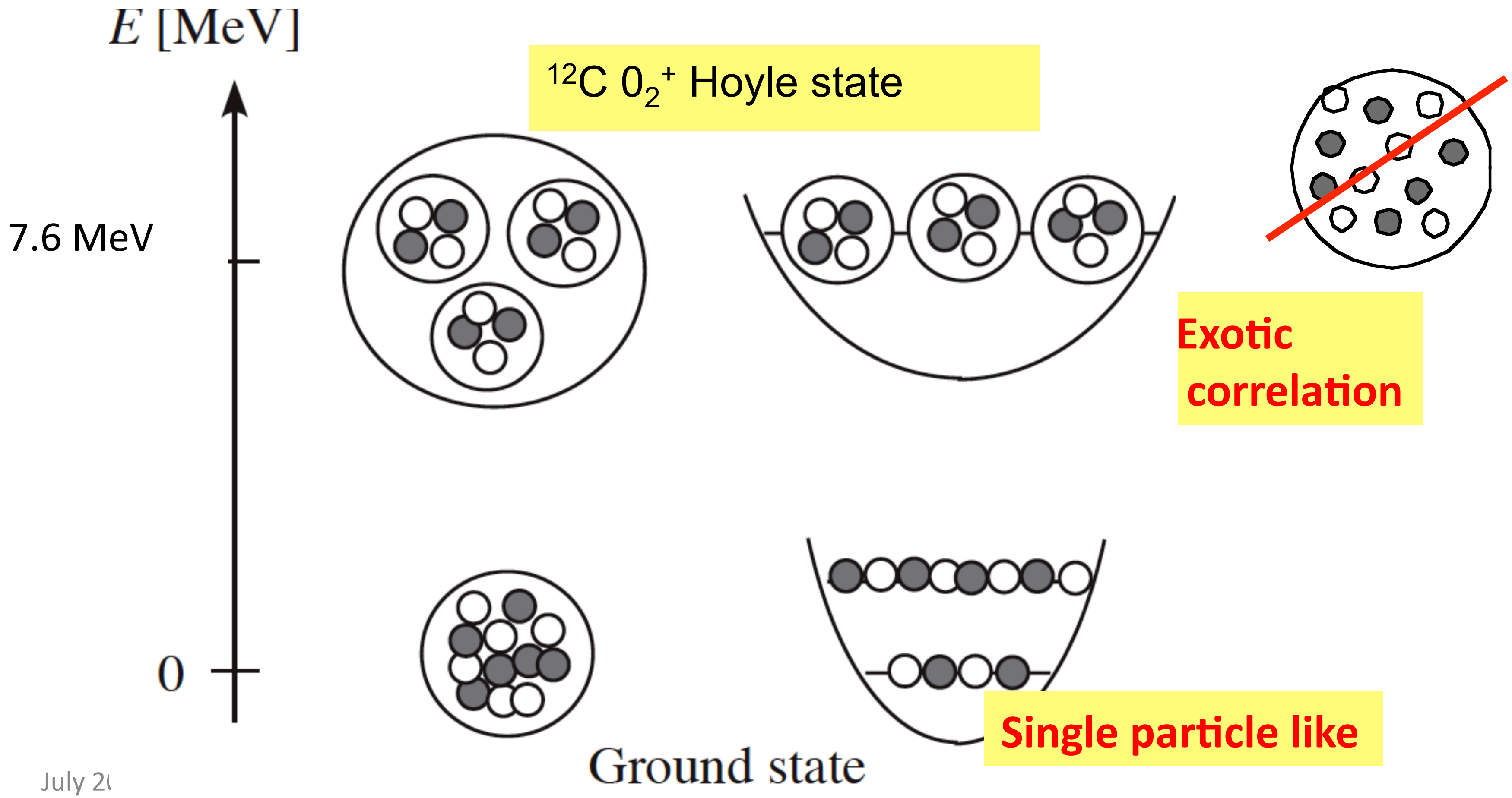
Two issues

(1) qq^{bar} creation near the threshold → Multiquark configuration

(2) **Rearrangements of the multiquark configuration → Clustering**

M. Itoh et al, PRC84,054308(2011) "Physics Viewpoint"
(RCNP experiment)

Talk by S. Ershov



$^{12}C\ 0_2^+$ Hoyle state

Exotic correlation

Single particle like

3. Hadronic molecules with heavy quarks

(1) $D^{bar}N$ and BN

(2) Z_b and related states

(1) $D^{bar}N$ and BN

Another form of ***exotic*** baryons
Hadronic molecules

Yamaguchi, Yamaguchi, Yasui and Hosaka
Phys.Rev.D84:014032,2011,
D85,054003,2012
Ohkoda, Yamaguchi, Sudoh, Yasui and Hosaka
arXiv:1210.3170, in PRD
Phys.Rev. D86: 034019, 2012
D86: 014004, 2012

OPEP induced HQ molecules

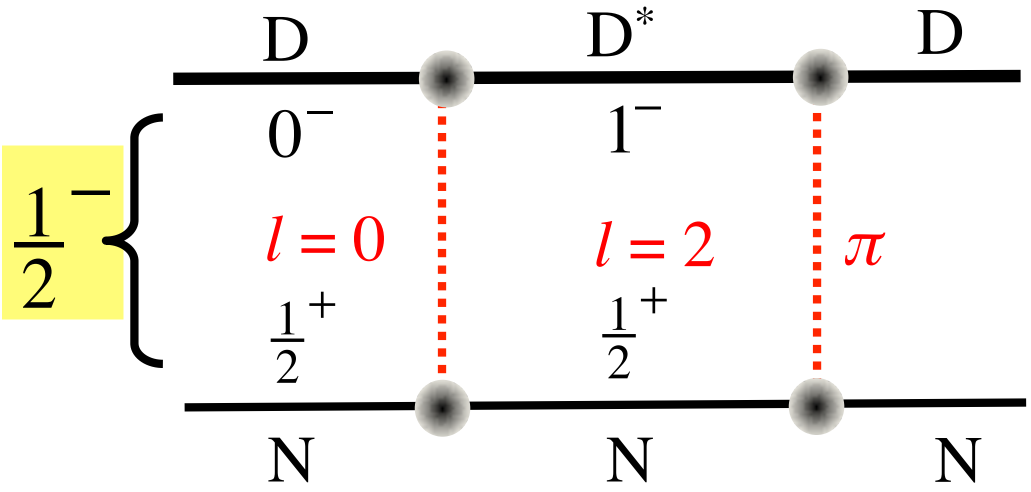
Loosely bound or resonance of $\bar{D}$N ($\bar{c}$qqqq)

- **Heavy Q symmetry**: $\bar{D} \sim \bar{D}^*$ → Coupled channel of $\bar{D}$N and $\bar{D}^*$N

Yasui-Sudoh, PRD80, 034008, 2009
Yamaguchi-Ohkoda-Yasui and Hosaka, PRD84:014032,2011

- ***Tensor of OPEP***

$$m_{K^*} - m_K \sim 400\ MeV$$
$$m_{D^*} - m_D \sim 140\ MeV$$
$$m_{B^*} - m_B \sim 35\ MeV$$

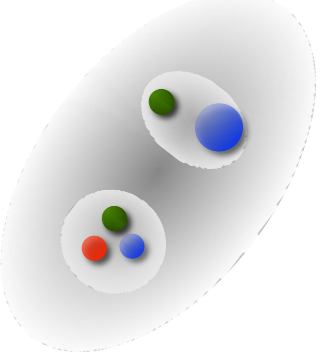


- **Short range**

		qq	qq^{bar}(annihilation)
π	+	ϱ(attraction)	attraction
	+	ω(repulsion)	attraction

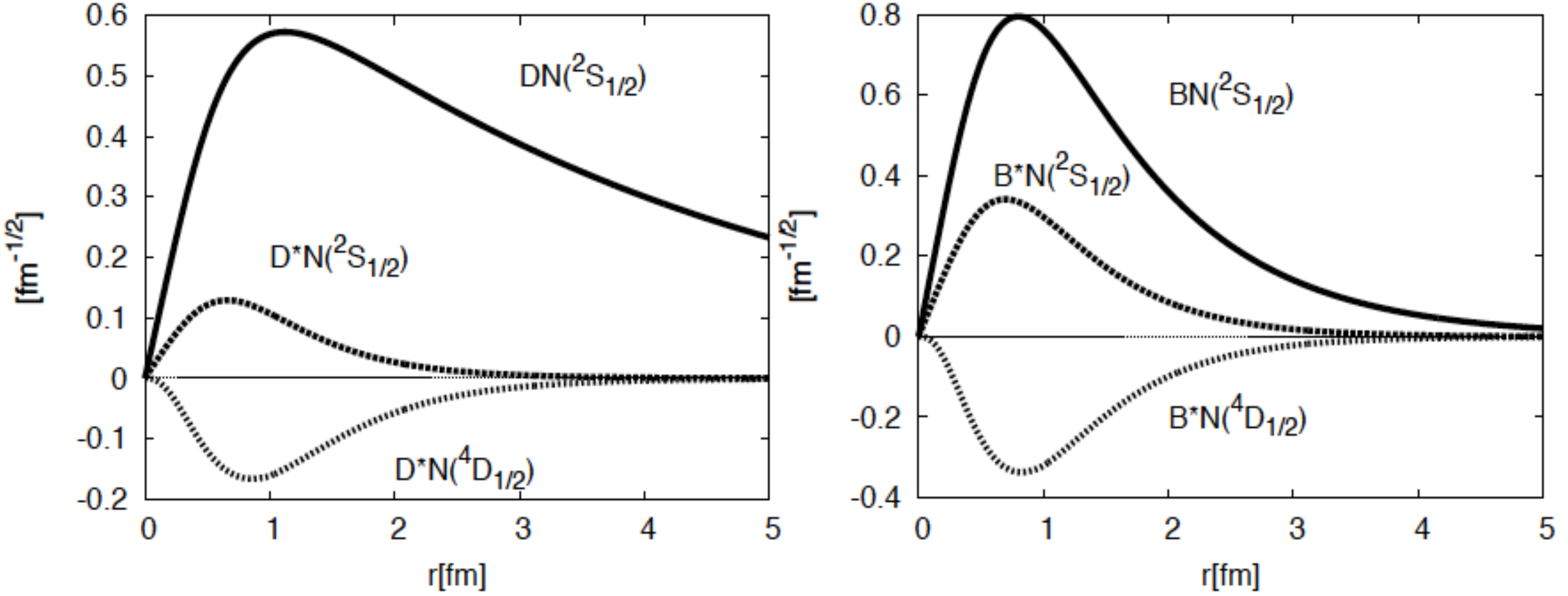
Loosely bound states: $I, J^P = 0, 1/2^-$

$\bar{Q}q$-qqq



	$\bar{D}N(\pi)$	$\bar{D}N(\pi\rho\omega)$	$BN(\pi)$	$BN(\pi\rho\omega)$
E_B [MeV]	1.60	2.14	19.50	23.04
$\langle r^2\rangle^{\frac{1}{2}}$ [fm]	3.5	3.2	1.3	1.2

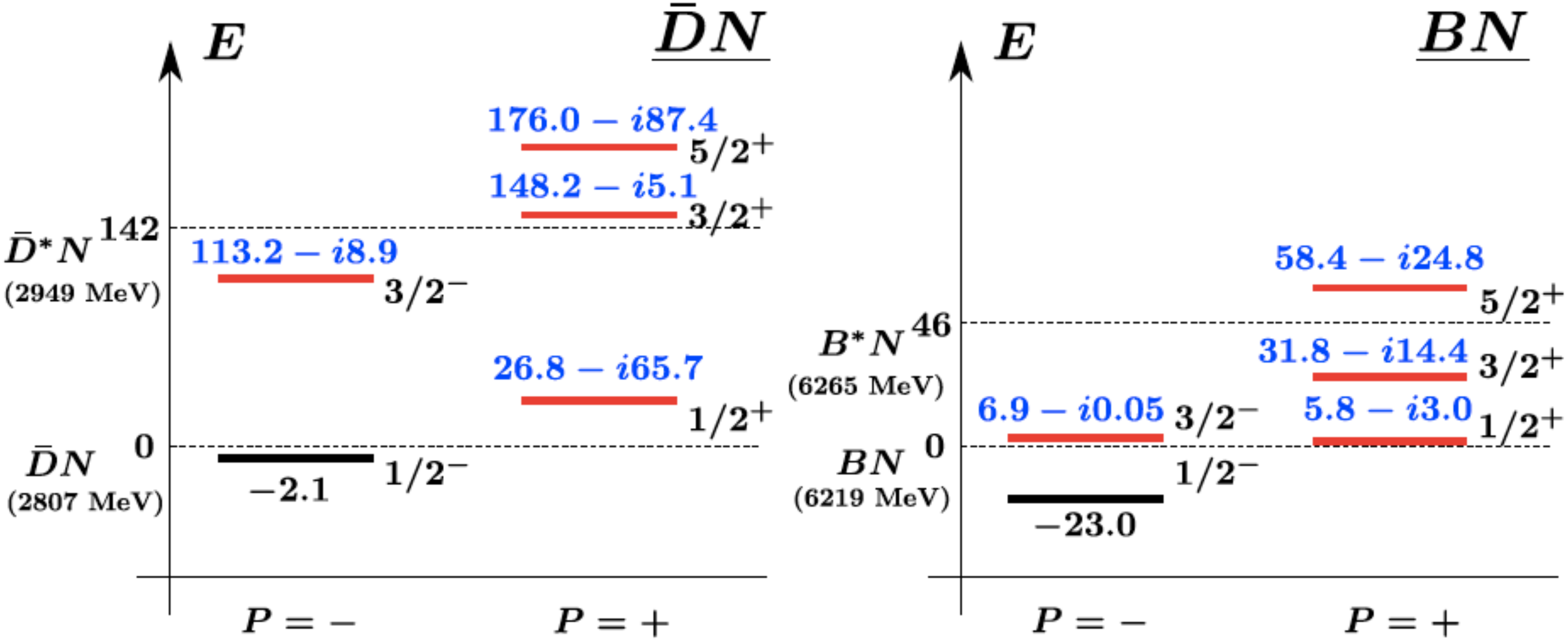
DN **Three coupled-channels** BN



More low-lying states

Yamaguchi et al, D85,054003,2012

Various states near the thresholds



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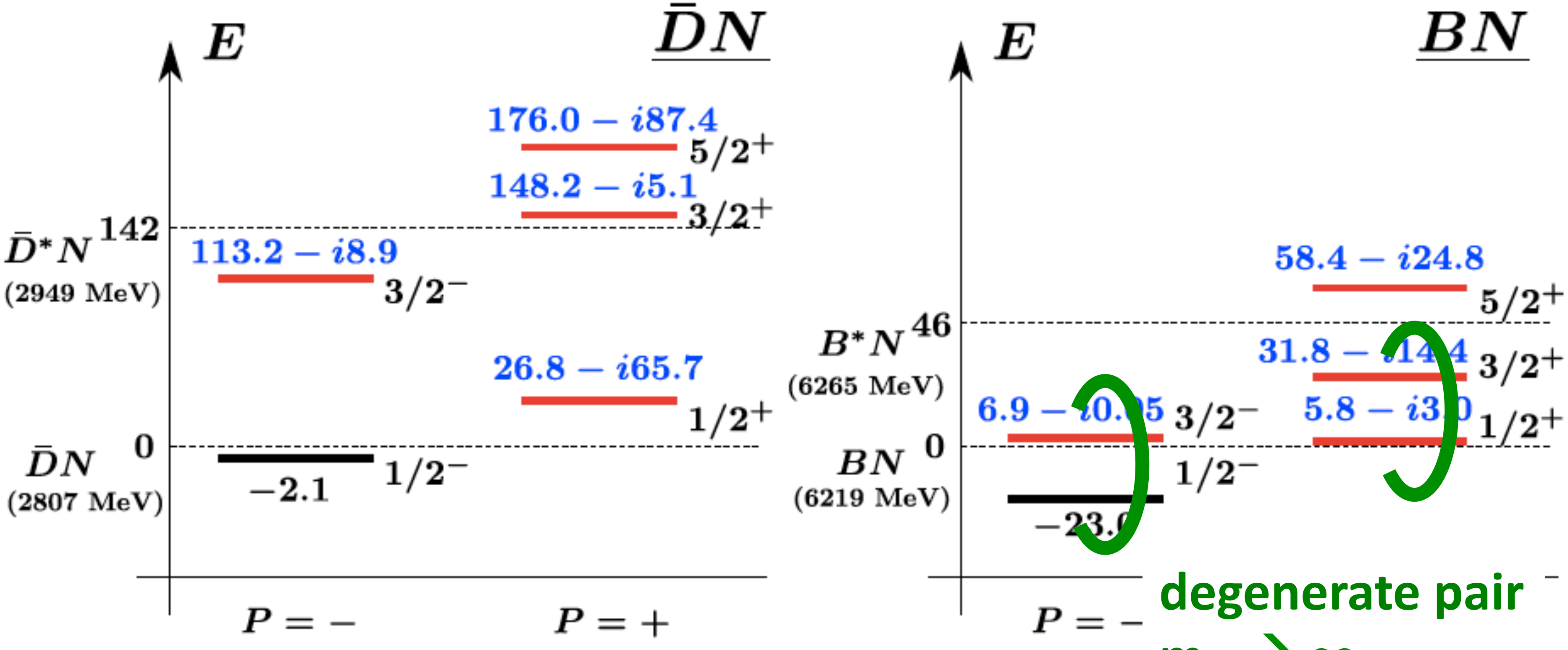


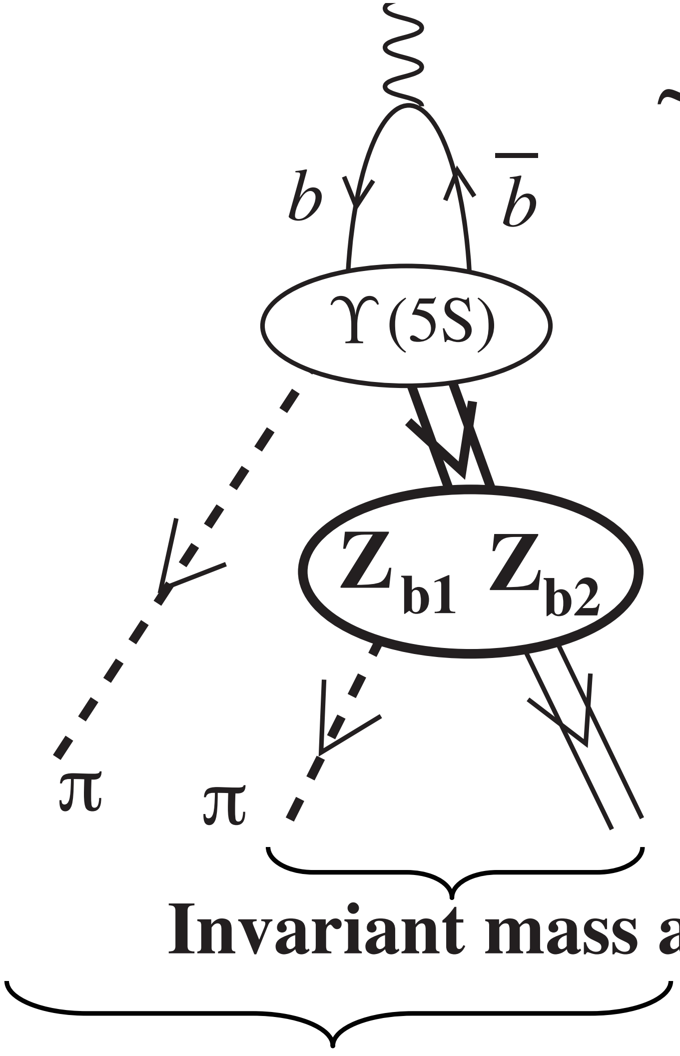
degenerate pair

$m_Q \rightarrow \infty$

(2) Z_b(10610, 10650) and related states

arXiv:1105.4583v1 [hep-ex];
PRL 108, 032001 (2012)

$I^G(J^P) = 1^+(1^+)$



~11 GeV

10860

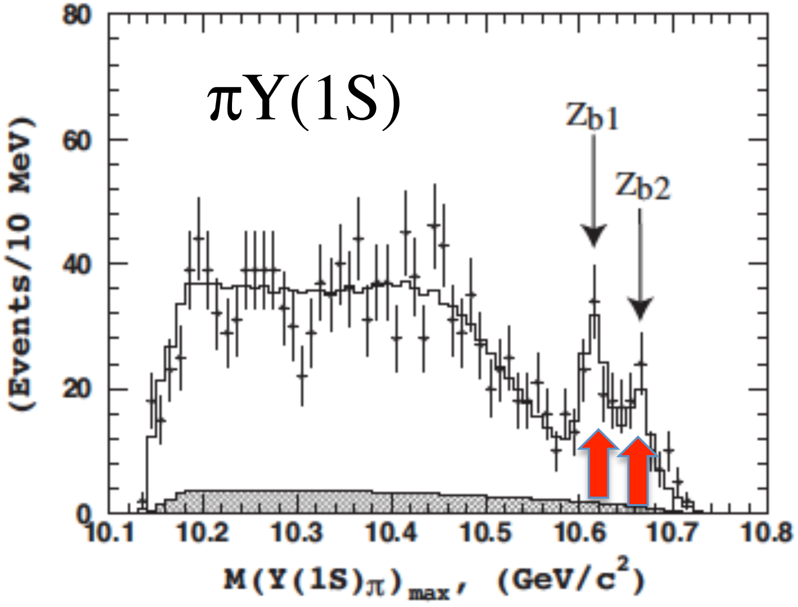
10653, 10608

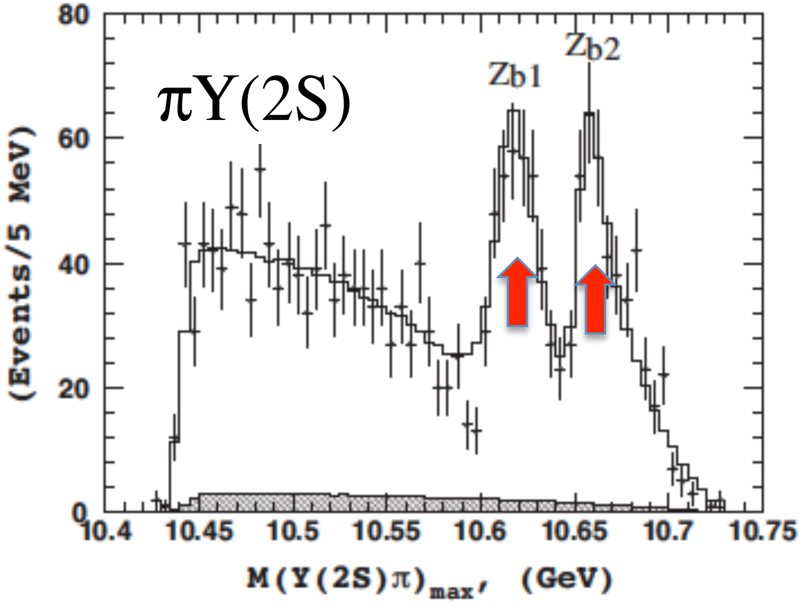
Υ(3S, 10355) h_b(2P, 10259)
Υ(2S, 10023) h_b(1P, 9898)
Υ(1S, 9460)

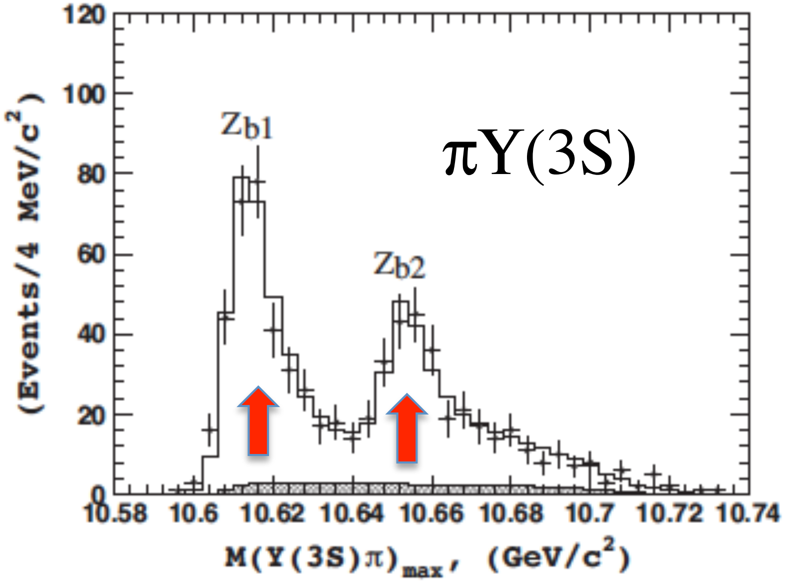
Invariant mass analysis

Three-body decay

Invariant mass of πϒ(nS)







In all cases,
twin peaks are observed!

Characters

- States appear near the thresholds

- Masses of $Z_b(10610)$, $Z_b(10650)$ are similar

- Heavy spin changing processes occur

$\Upsilon(5S) \rightarrow Z_b \rightarrow \Upsilon\pi$ $\upuparrows$ (OK)

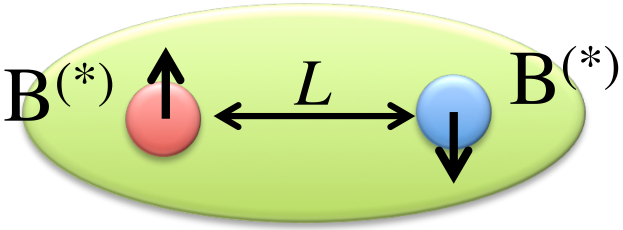
$\upuparrows$ $h_b\pi$ $\uparrow\downarrow$ (No)

Explained by Z_b molecules

$B^{(*)}\overline{B}^{(*)}$ molecules

Ohkoda, Yamaguchi, Yasui, Sudoh and Hodaka
arXiv:1111.2921 [hep-ph], Phys.Rev. D86 (2012) 014004

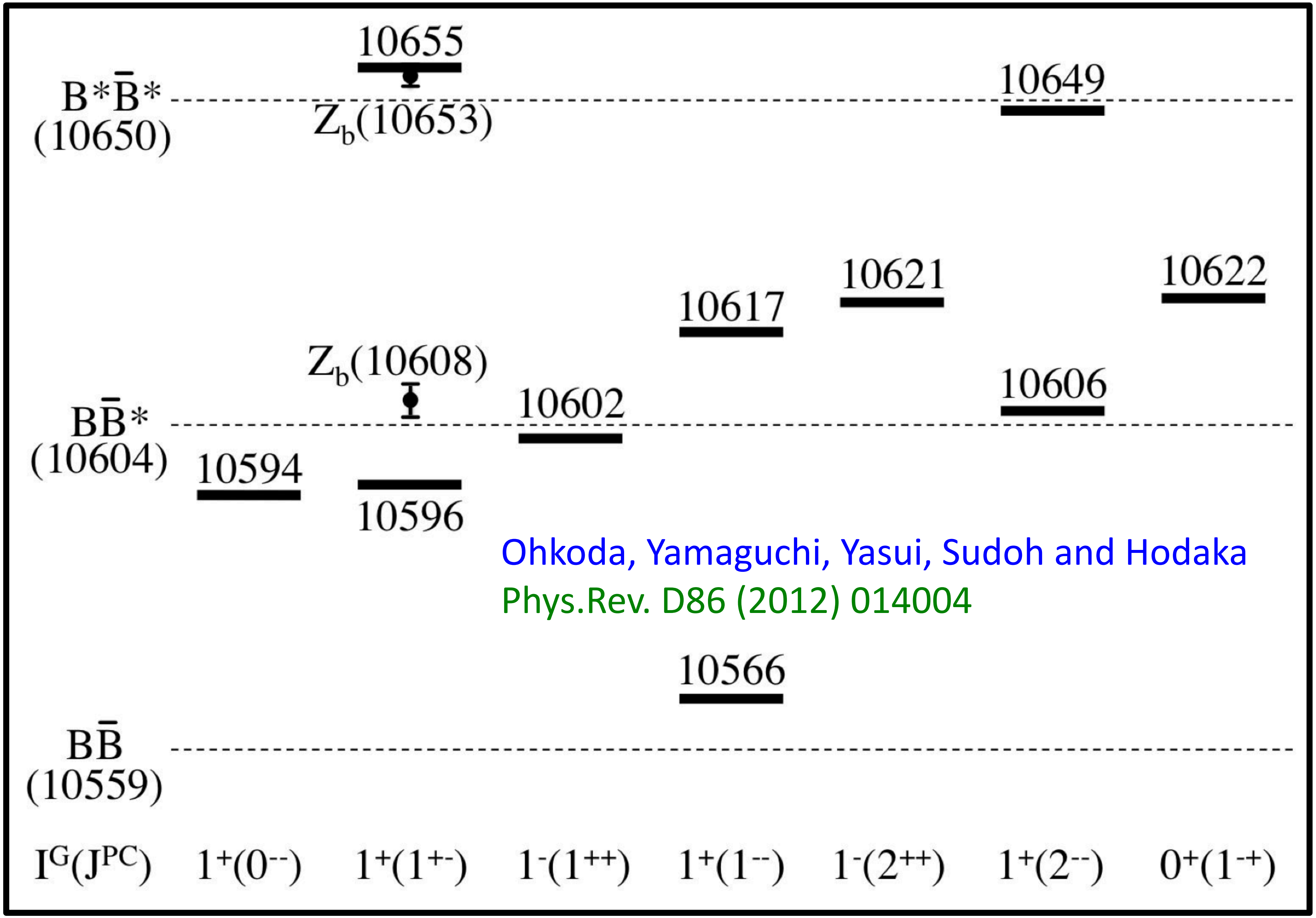
Rich structure due to $B\overline{B}$ (or $Q\overline{Q}q\overline{q}$)



$[S, L]^J$

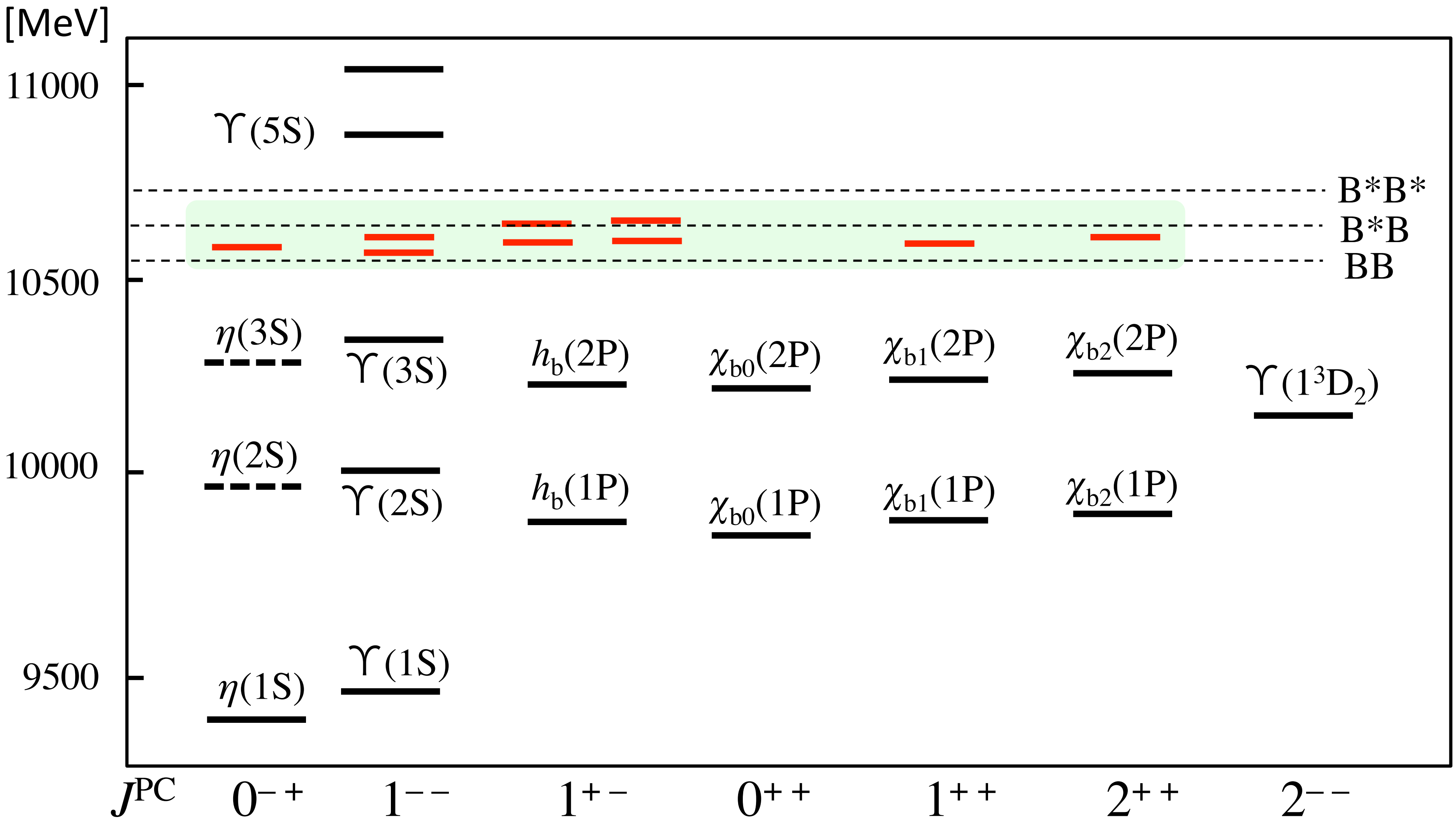
Orbital L \ spin	$B\overline{B}$ $S = 0$	$B\overline{B}^*$ $S = 1$	$B^*\overline{B}^*$ $S = 0, 1, 2$
$L = 0$	0^-	1^-	$0^-, 1^-, 2^-$
$L = 1$	1^+	$0^+, 1^+, 2^+$	$0^+, 1^+, 2^+, 3^+$
….		….	

Predictions: Low-lying states, $L \leq 2$

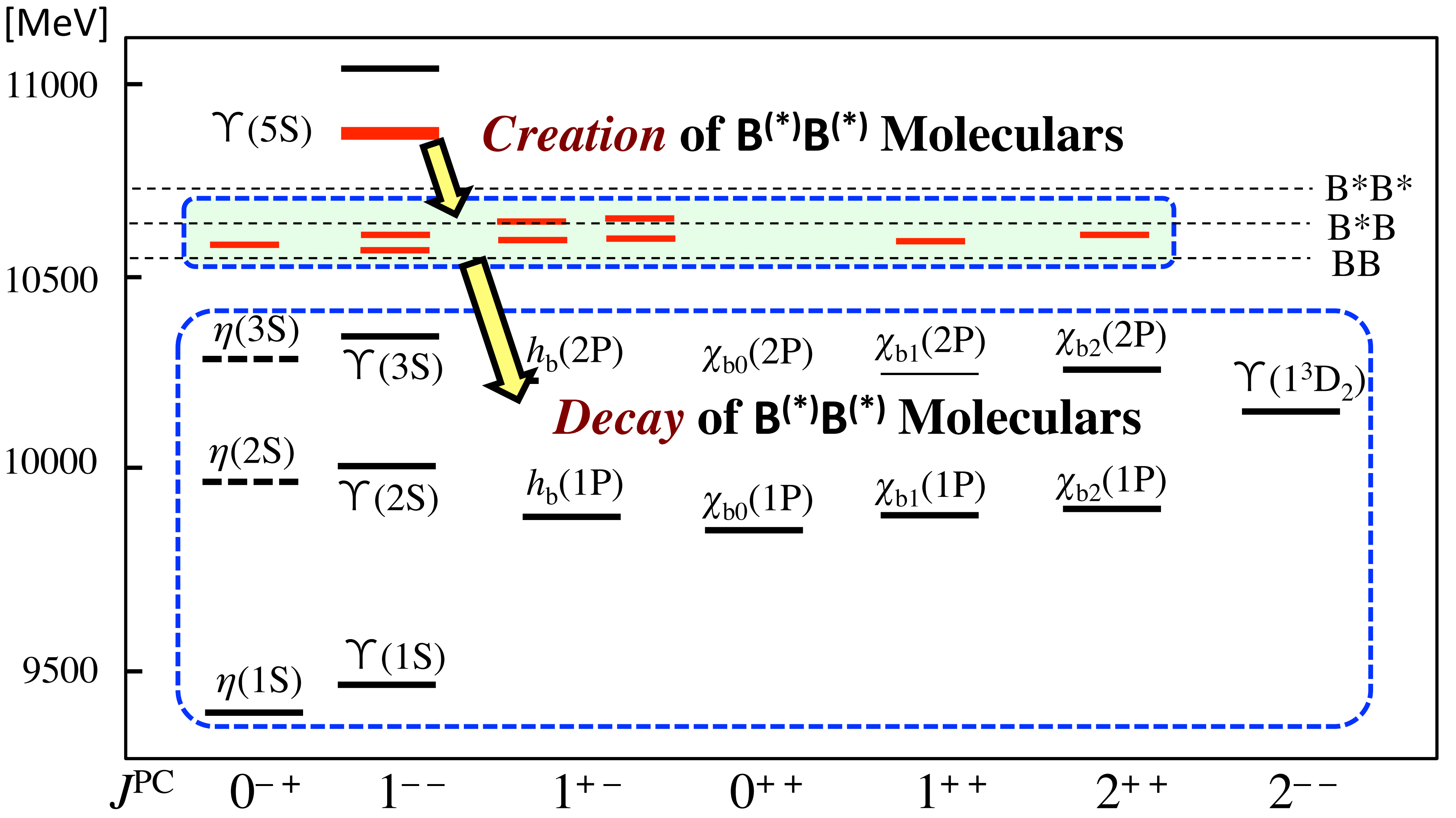


Ohkoda, Yamaguchi, Yasui, Sudoh and Hodaka
Phys.Rev. D86 (2012) 014004

Bottomonia and molecules near the threshols



Transitions and selection rules



HQ selection rules

Ohkoda-Yamaguchi-Yasui-Hosak, arXiv:1210.3170, To appear in PRD

$$J_{tot} = J_H + j_l$$

Heavy-light Recoupling: $[\underline{[\overset{B}{J_{H1}\, j_{l1}}][\overset{B}{J_{H2}\, j_{l2}}]}]^{J_{tot}} \rightarrow [\underline{[J_{H1}\, J_{H2}]}\underline{[j_{l1}\, j_{l2}]}]^{J_{tot}}$

$Z_b(10650)$ $\quad B^*\bar{B}^*(^3S_1) \quad : \quad \underline{\left[[b\bar{q}]^1, [\bar{b}q]^1\right]}^1$

$$= \sum_{H,l} \hat{1}\hat{1}\hat{H}\hat{l} \begin{Bmatrix} 1/2 & 1/2 & 1 \\ 1/2 & 1/2 & 1 \\ H & l & 1 \end{Bmatrix} \left[[b\bar{b}]^H, [\bar{q}q]^l\right]^1$$

$$= \frac{1}{\sqrt{2}}(\underline{0_H^-} \otimes \underline{1_l^-}) + \frac{1}{\sqrt{2}}(\underline{1_H^-} \otimes \underline{0_l^-})$$

$Z_b(10610)$ $\quad \frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})(^3S_1) : \frac{1}{\sqrt{2}}(\underline{0_H^-} \otimes \underline{1_l^-}) - \frac{1}{\sqrt{2}}(\underline{1_H^-} \otimes \underline{0_l^-})$

Example: $Z_b^0 \rightarrow \chi_{bJ}\,\gamma$

Heavy-light recoupling

M1 $\chi_{b0}\,\gamma\,(1^+)$ $$(1_H \otimes 1_l)|_{J=0} \otimes (0_H \otimes 1_l)$$
$$= \frac{1}{3}\underline{(1_H \otimes 0_l)} - \frac{1}{\sqrt{3}}(1_H \otimes 1_l)|_{J=1} + \frac{\sqrt{5}}{3}(1_H \otimes 2_l)|_{J=1}$$

……

M1 $\chi_{b1}\,\gamma\,(1^+)$ $$\sim -\frac{1}{\sqrt{3}}\underline{(1_H \otimes 0_l)} + \frac{1}{2}(1_H \otimes 1_l)|_{J=1} + \frac{15}{6}(1_H \otimes 2_l)|_{J=1}$$

E2 $\chi_{b1}\,\gamma\,(2^+)$ $$\sim -\frac{1}{2}(1_H \otimes 1_l)|_{J=1} + \frac{\sqrt{3}}{2}(1_H \otimes 2_l)|_{J=1}$$

……

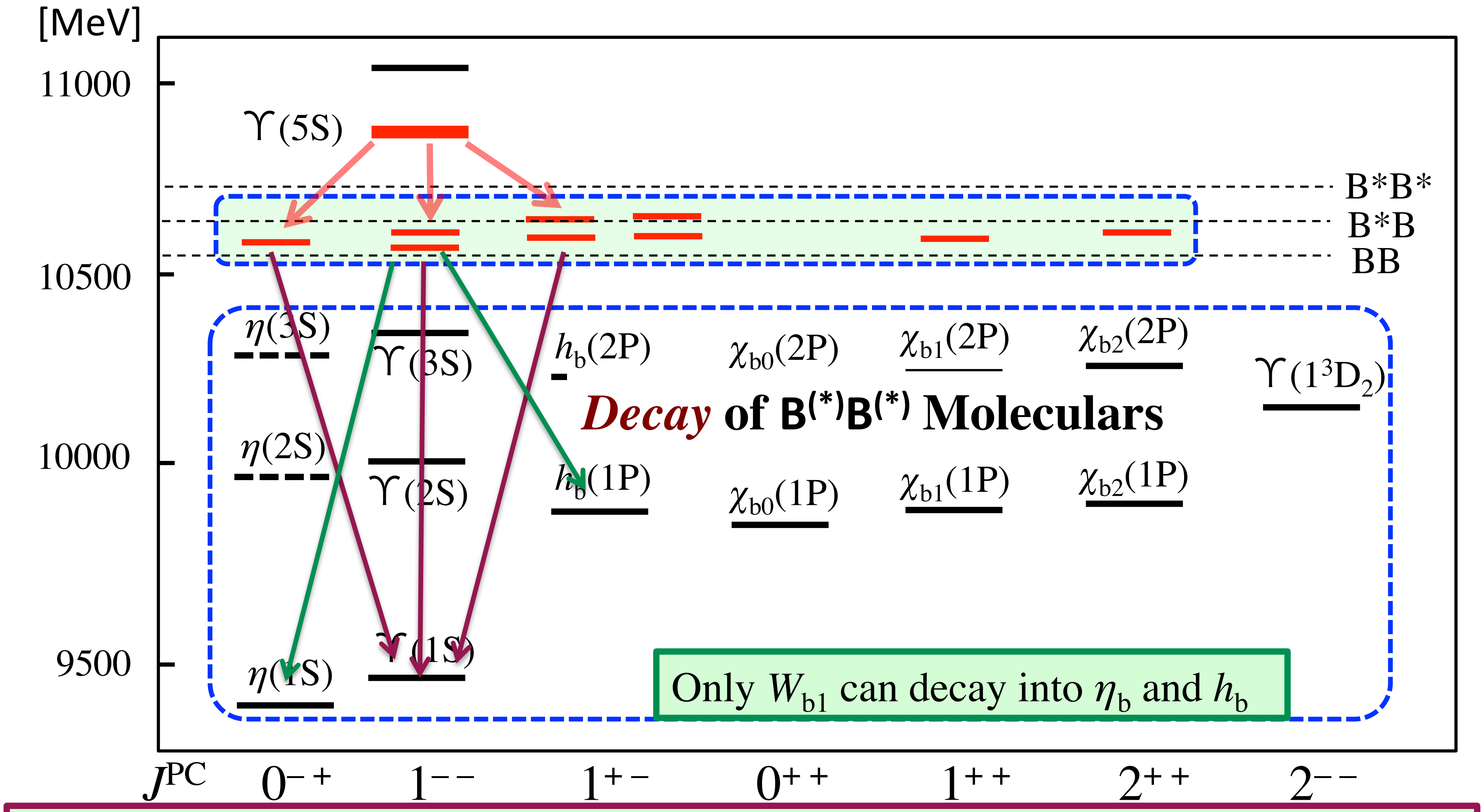
M1 $\chi_{b2}\,\gamma\,(1^+)$ $$\sim \frac{\sqrt{5}}{3}\underline{(1_H \otimes 0_l)} + \frac{\sqrt{15}}{6}(1_H \otimes 1_l)|_{J=1} + \frac{1}{6}(1_H \otimes 2_l)|_{J=1}$$

E2 $\chi_{b2}\,\gamma\,(2^+)$ $$\sim \frac{\sqrt{3}}{2}(1_H \otimes 1_l)|_{J=1} + \frac{1}{2}(1_H \otimes 2_l)|_{J=2}$$

$$\begin{array}{ccccc} \Gamma(Z_b^0 \to \chi_{b0}\gamma) & : & \Gamma(Z_b^0 \to \chi_{b1}\gamma) & : & \Gamma(Z_b^0 \to \chi_{b2}\gamma) \\ 1 & : & 3 & : & 5 \end{array}$$

$$f(W_{b0}^{--}\pi) \quad : \quad f(W_{b1}'^{--}\pi) \quad : \quad f(W_{b1}^{--}\pi) \quad : \quad f(W_{b2}'^{--}\pi) \quad : \quad f(W_{b2}^{--}\pi)$$

$$2 \quad : \quad 9 \quad : \quad 4.5 \quad : \quad 9 \quad : \quad 12$$



Decay **of $B^{(*)}B^{(*)}$ Moleculars**

Only W_{b1} can decay into η_b and h_b

$$\Gamma(W_{b0}^{--} \to \Upsilon\pi) \quad : \quad \Gamma(W_{b1}'^{--} \to \Upsilon\pi) \quad : \quad \Gamma(W_{b1}^{--} \to \Upsilon\pi) \quad : \quad \Gamma(W_{b2}'^{--} \to \Upsilon\pi) \quad : \quad \Gamma(W_{b2}^{--} \to \Upsilon\pi)$$

$$4 \quad : \quad 1 \quad : \quad 1 \quad : \quad 3 \quad : \quad 1$$

Summary

- In the heavy quark region we have seem many unusual states
- Some (many) of them are candidates of hadronic molecules
  Chiral dynamics through the pion and heavy quark symmetry
- Where are other excitations (gluons and multiquarks other than HM)
- Heavy quarks may probe diquarks
  Manifest in hadron spectroscopy, production-decay properties
  Could explain (non) existence of multiquark hadrons