Pions and tensor force in heavy quark hadrons

Atsushi Hosaka

Research Center for Nuclear Physics (RCNP), Osaka University

With S. Ohkoda, Y. Yamaguchi, S. Yasui and AH

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Heavy ***exotic*** baryons and mesons

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1. Introduction

What binds the protons and nucleon?

1934 at Osaka Univ

H. Yukawa

- Finite (long) range

$$\Delta\phi = 0 \quad \Rightarrow \quad (\Delta + m_\pi^2)\phi = 0$$

$$m_\pi \sim \frac{1}{\langle r \rangle} \sim 200\ \mathrm{MeV}$$

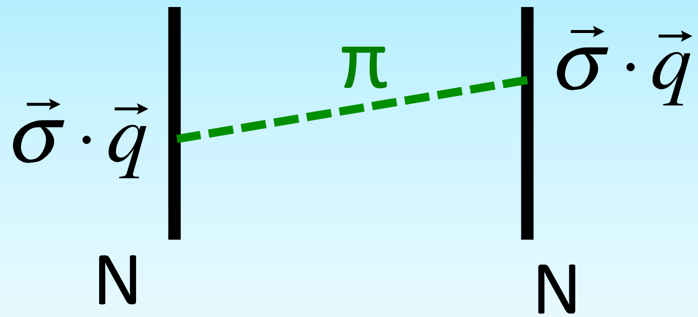
This is light

- Pseudoscalar: $J^P = 0^-$

OPEP

Long range tensor force

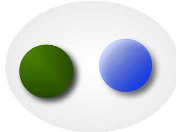
spin and orientation dependent



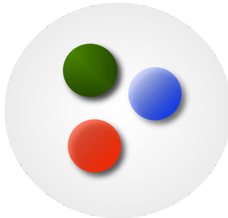
Spontaneous breaking of chiral symmetry

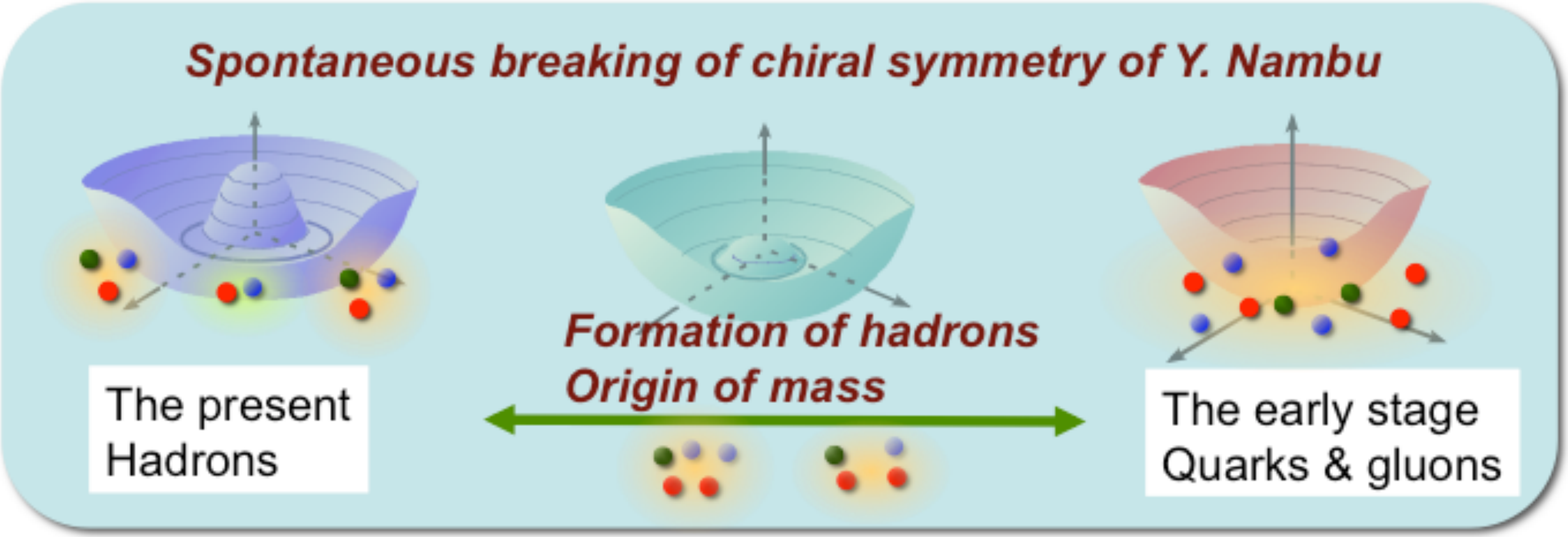
(1) Light bare quarks

=> ***Massive constituent quarks***



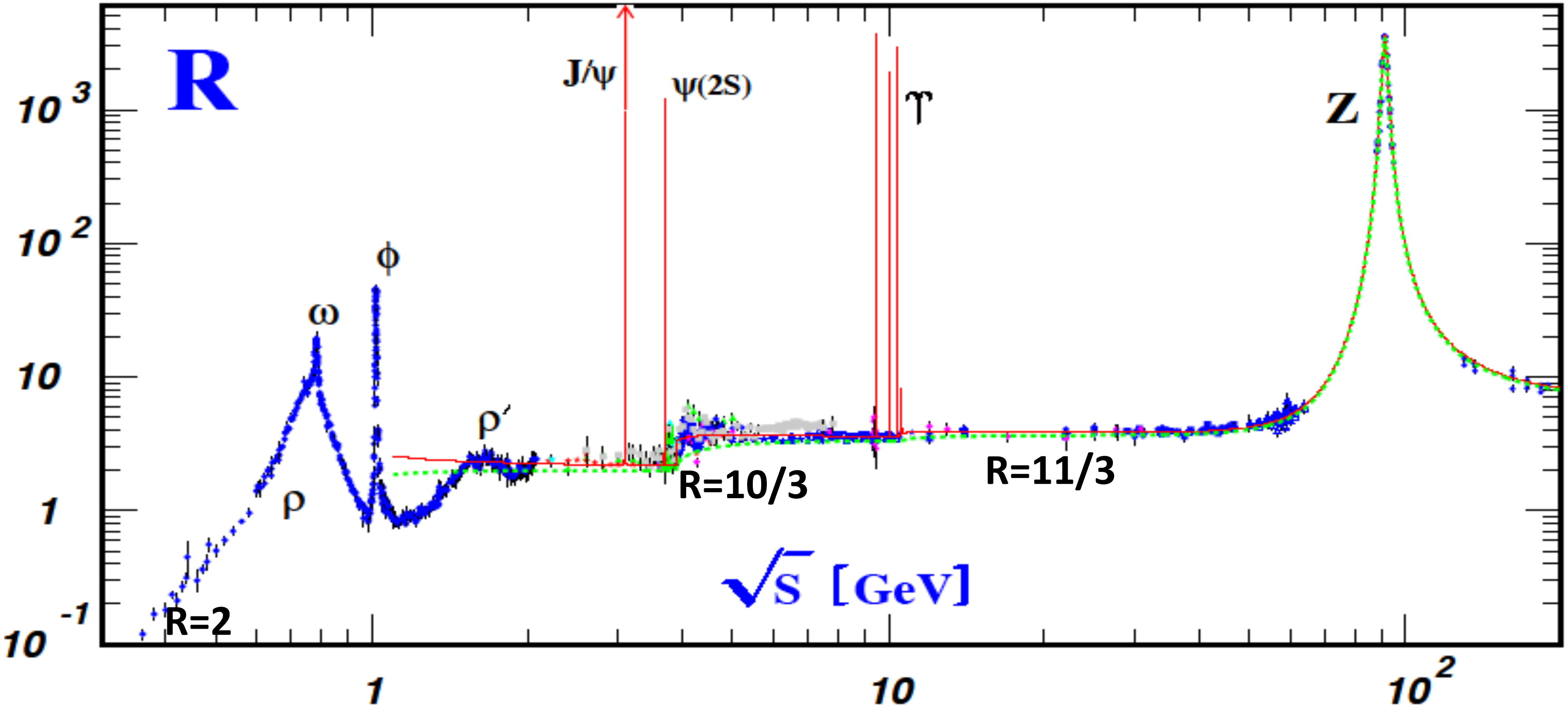
(2) Appearance of the ***massless pion***





Problems in hadron physics

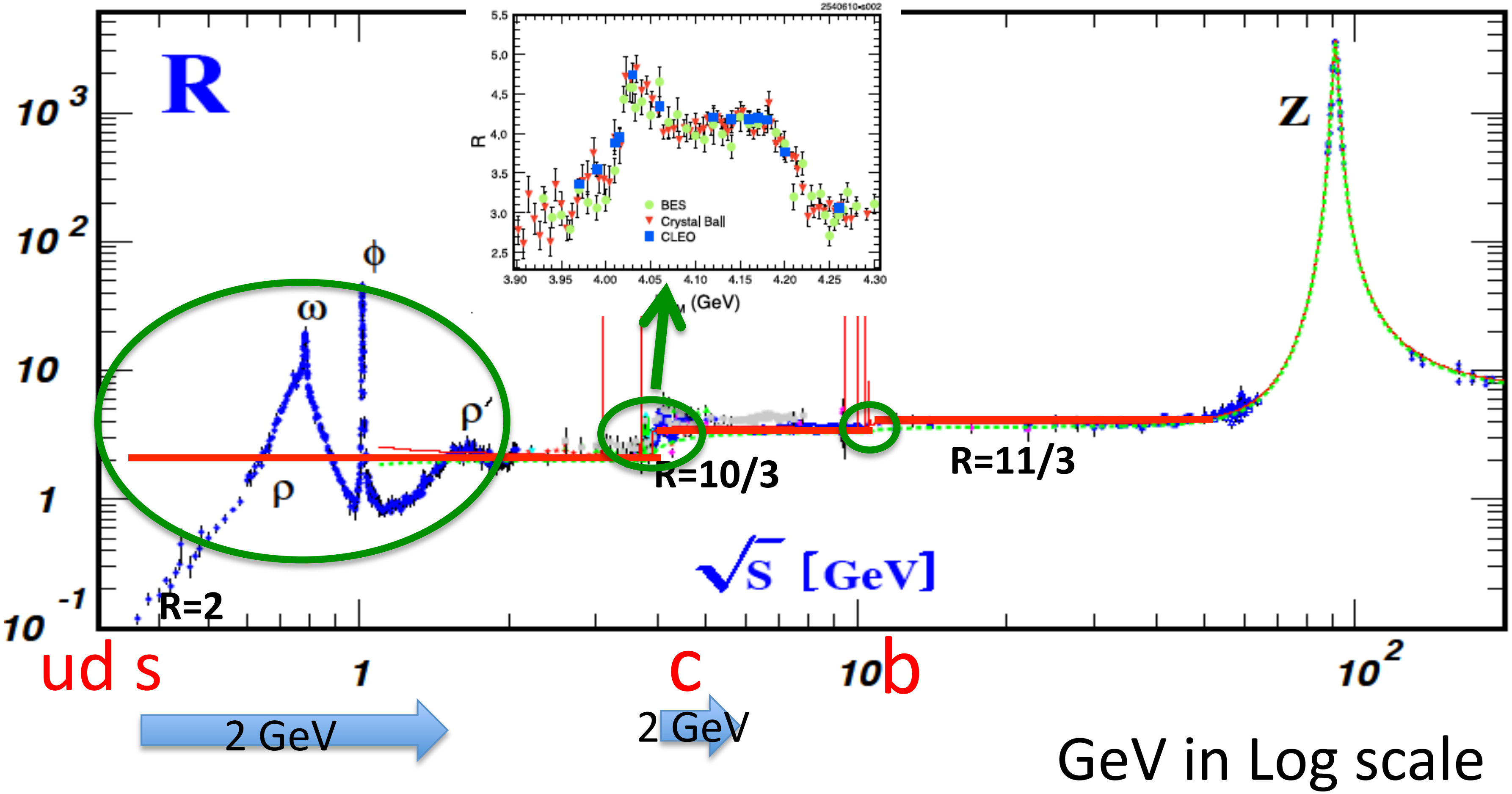
$$R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s).$$



GeV in Log scale

Problems in hadron physics

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



Threshold region

2. Heavy Quark Hadrons

u	c	t
d	s	b

Light ~ q

Heavy ~ Q

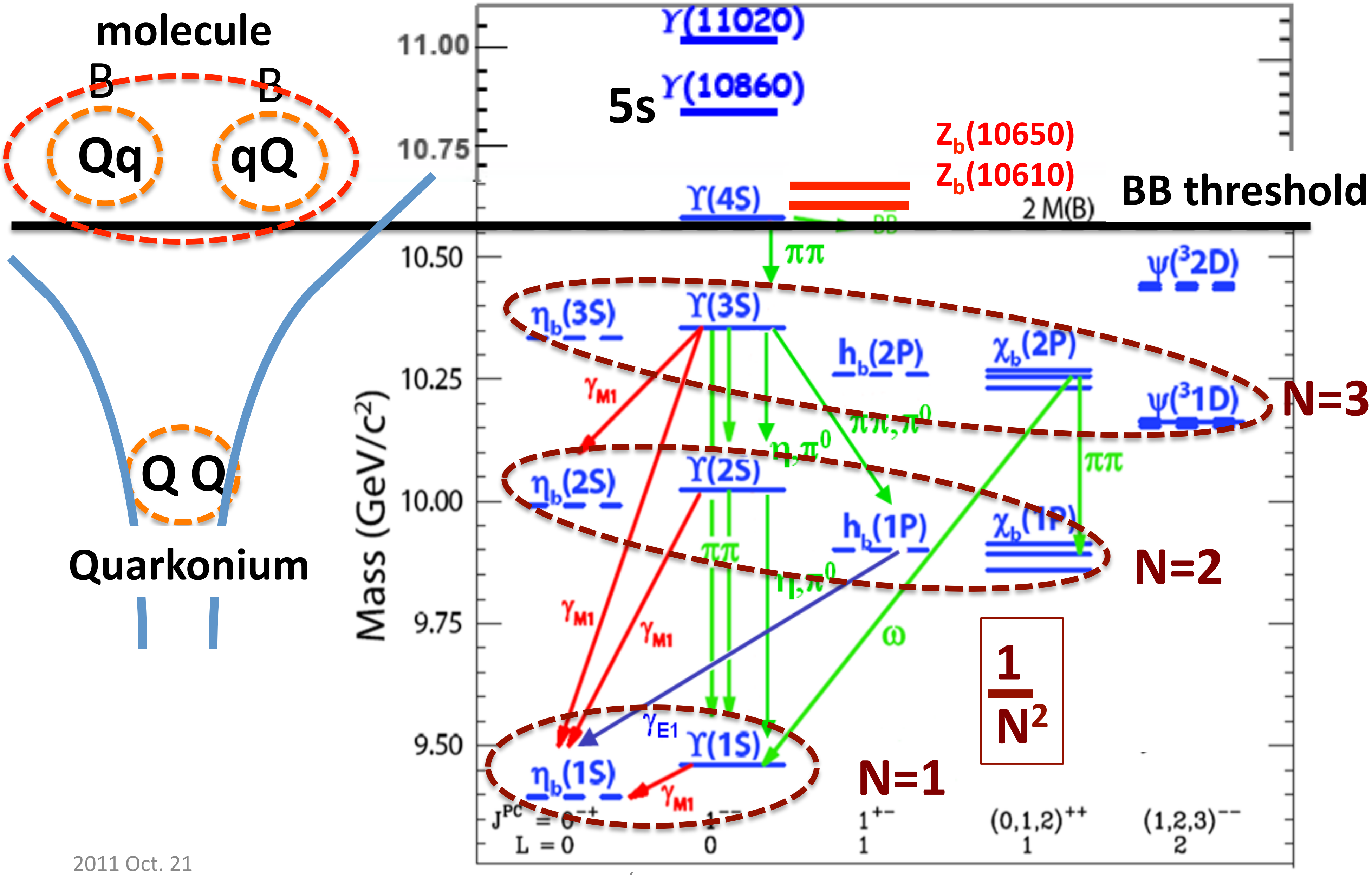
π: ud^{bar}, etc   JP = 0-
ρ: JP = 1-

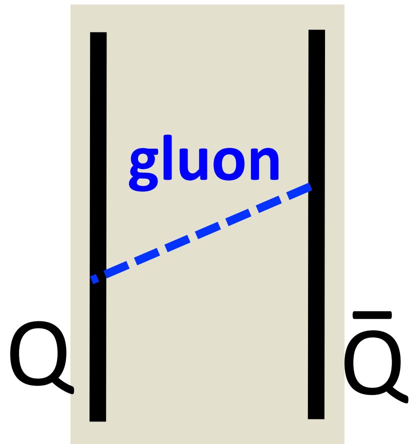
P(0-) and P*(1-)

$\bar{D}$: C^{bar} u, etc   JP = 0-
$\bar{D}^*$:   JP = 1-

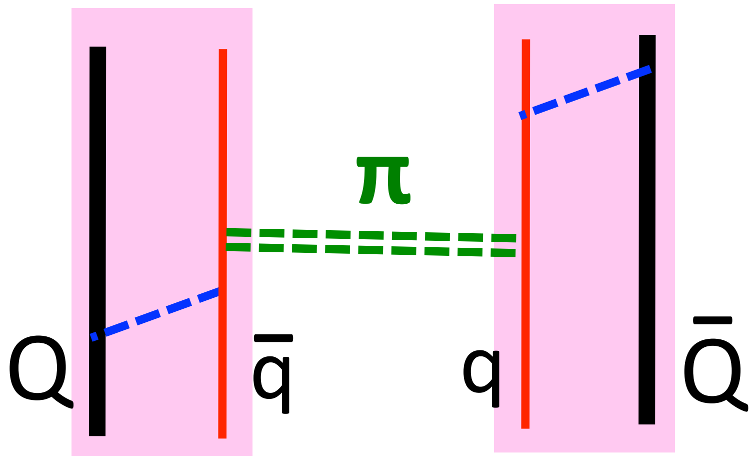
B: B^{bar} u, etc   JP = 0-
B*:   JP = 1-

B quark spectroscopy





As $Q\bar{Q}$ are pulled apart

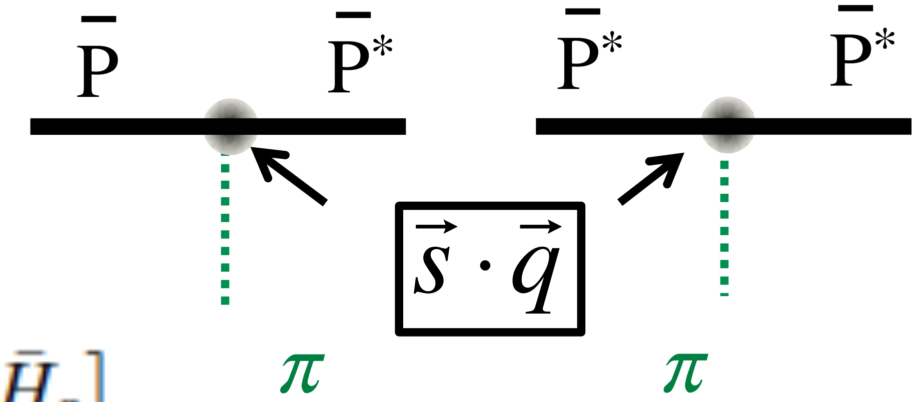


Pions appear where light quarks are

π-Yukawa vertex

πDD, πBB vertex is forbidden
BUT πDD*, πD*D* (πBB*, πB*B*) are allowed

$\bar{\mathrm{P}}$ N interaction



$$\mathcal{L}_{\pi HH} = i g_\pi \mathrm{Tr}\left[H_b \gamma_\mu \gamma_5 A^\mu_{ba} \bar{H}_a\right] ,$$

$$\mathcal{L}_{vHH} = -i\beta \mathrm{Tr}\left[H_b v^\mu (\rho_\mu)_{ba} \bar{H}_a\right] + i\lambda \mathrm{Tr}\left[H_b \sigma^{\mu\nu} F_{\mu\nu}(\rho)_{ba} \bar{H}_a\right]$$

$$H_a \sim q_a \bar{Q} = \frac{1+\not{v}}{2}\left[P^*_{a\,\mu}\gamma^\mu - P_a \gamma_5\right] ,$$

$$\bar{H}_a \sim \gamma_0 (q_a \bar{Q})^\dagger \gamma_0 = \gamma_0 H^\dagger_a \gamma_0$$

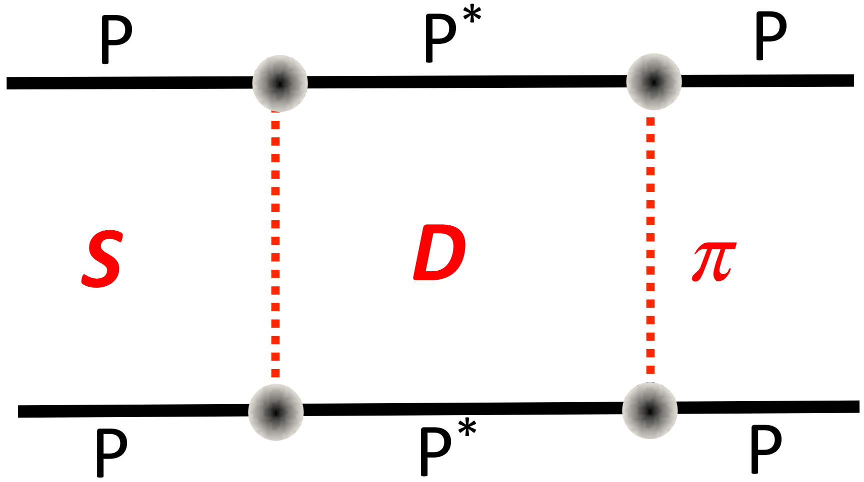
$$A^\mu_{ab} = \frac{1}{2}(\xi^\dagger \partial^\mu \xi - \xi \partial^\mu \xi^\dagger) \simeq \frac{i}{f_\pi} \partial^\mu \hat{\pi}_{ab}$$

Pion dominance

Yamaguchi, Ohkoda,Yasui, Hosaka

Phys.Rev.D84:014032,2011.
e-Print: 1105.0734 [hep-ph]

Tested in DN, BN system

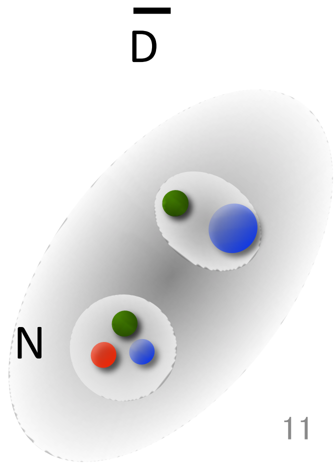


$$m_{K^*} - m_K \sim 400\ MeV$$
$$m_{D^*} - m_D \sim 140\ MeV$$
$$m_{B^*} - m_B \sim 35\ MeV$$

Heavy quark symmetry
Degeneracy
SD mixing

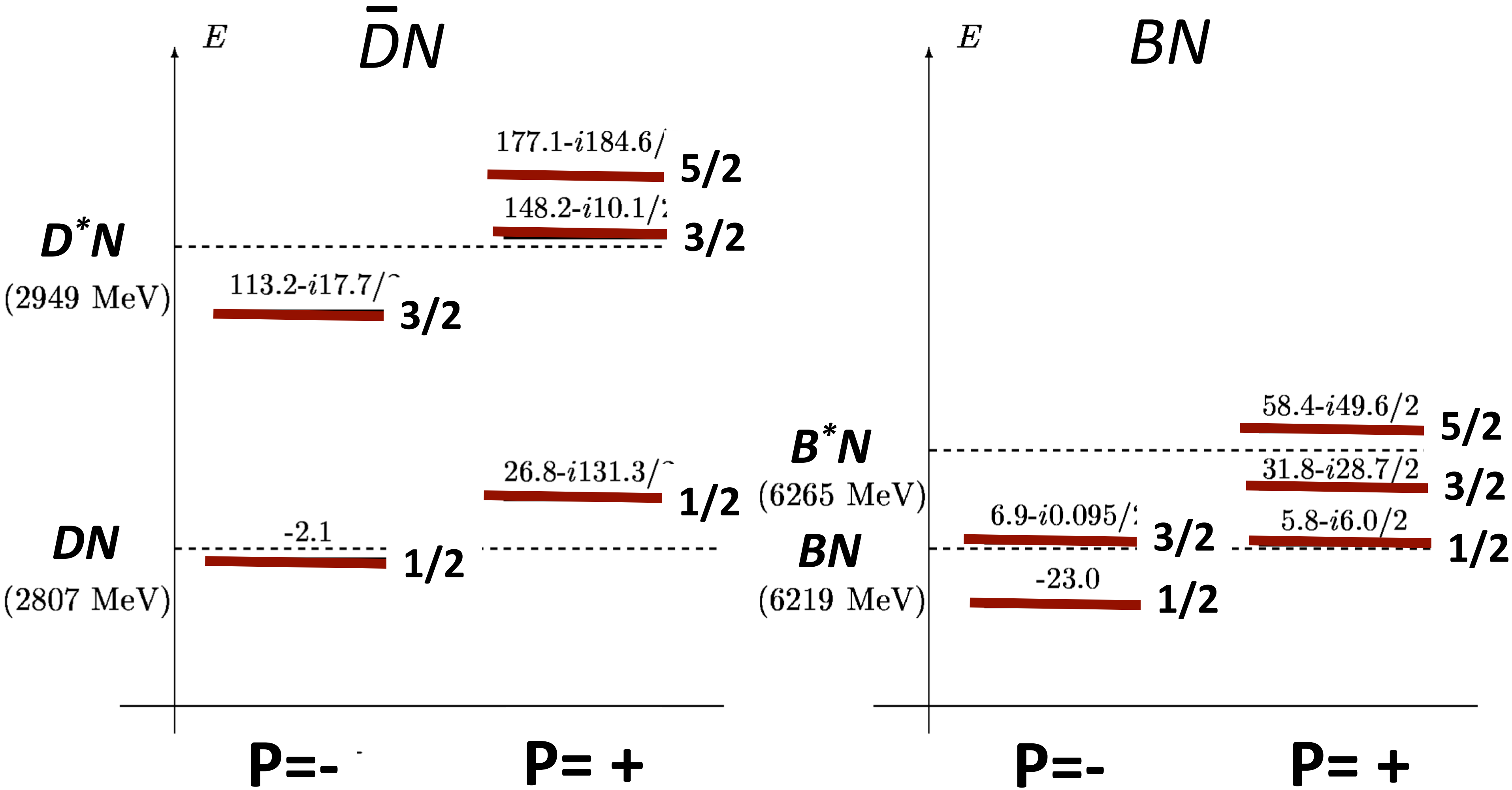
Bound states: $I, J^P = 0, 1/2^-$

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



Exotic $P^{(*)}N$ molecules

Yamaguchi-Ohkoda-Yasui-Hosaka
In preparation



Exotic $P^{(*)}N$ molecules

- **Pion** exchange potential **dominates**

- **Tensor force** causes **SD mixing**
  for heavy Q systems => Strong attraction

- These features are **for $m_Q \gtrsim m_c$**

Z_b resonance at Belle KEK

Exotic hadrons (mesons)

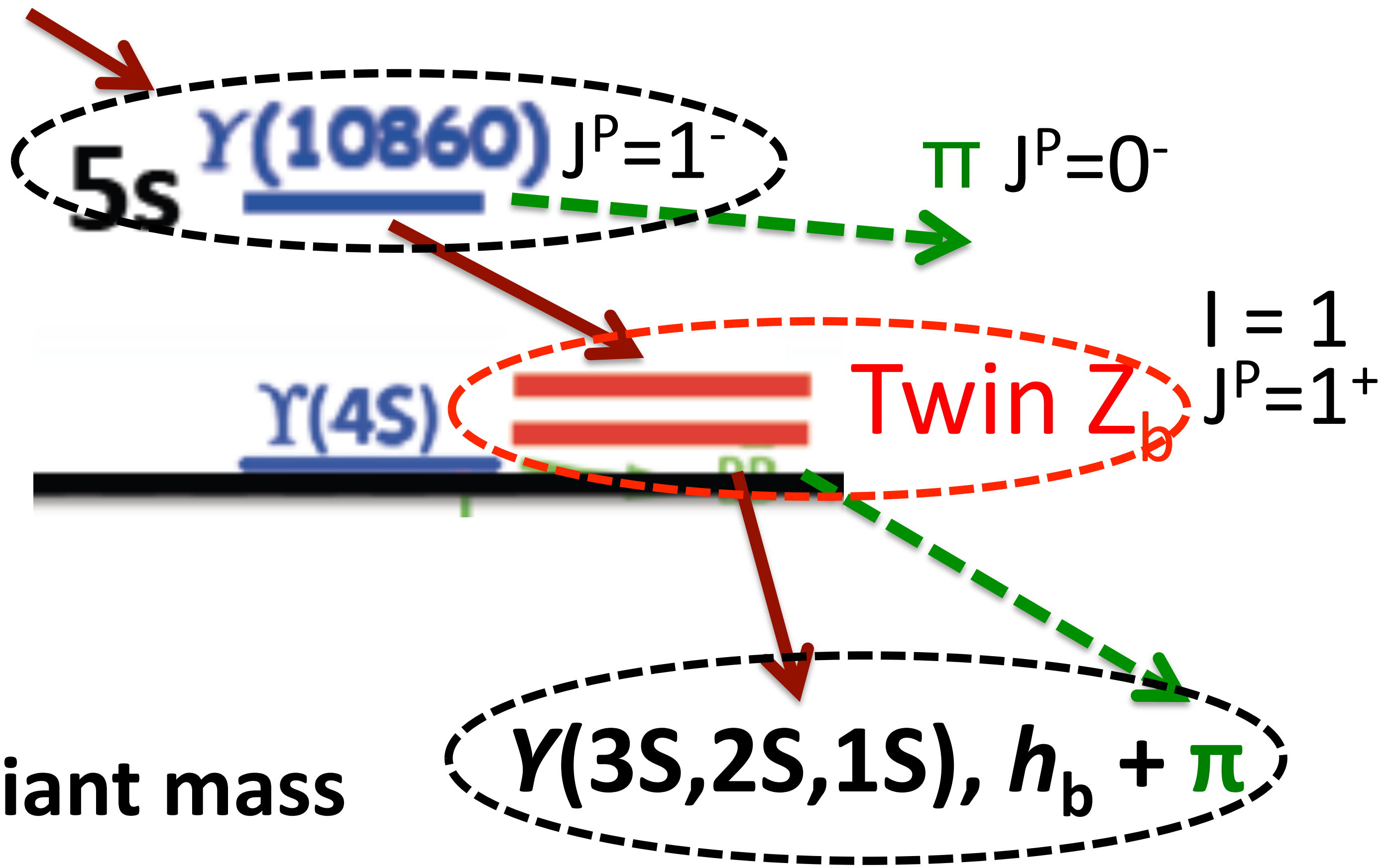
State	Mass (MeV)	Width (MeV)	Decay	Production
Ys(2175)	2175±8	58±26	ff_0	ISR
X(3872)	3871.84±0.33	<0.95	J/ypp, J/yg	B decay
X(3872)	3872.8 +0.7/-0.6	3.9 +2.8/-1.8	$D^{*0}D^0$	B decay
Z(3940)	3929±5	29±10	DD	gg
X(3940)	3942±9	37±17	DD*	Double-charm
Y(3940)	3942±17	87±34	J/yw	B decay
Y(4008)	4008 +82/-49	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

Twin

Belle's discovery, $Z_b(10610, 10650)$

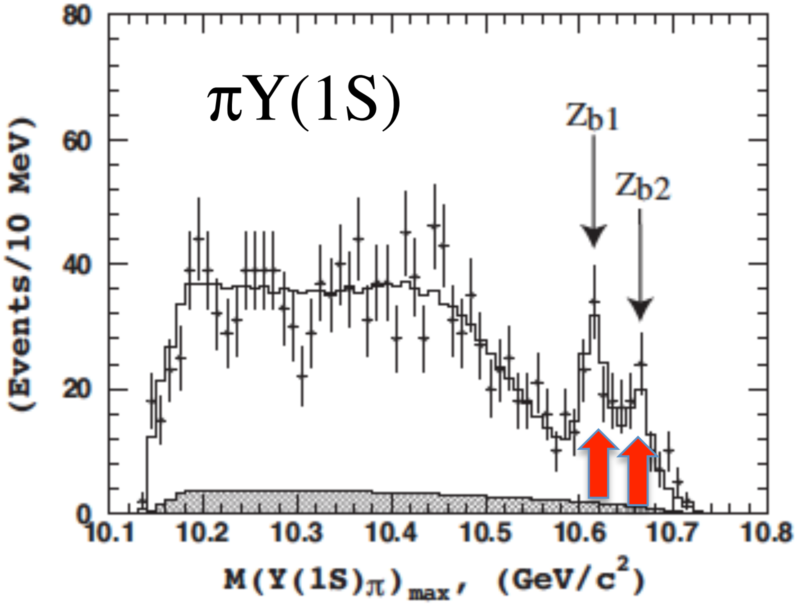
arXiv:1105.4583v1 [hep-ex] $I^G(J^P) = 1^+(1^+)$

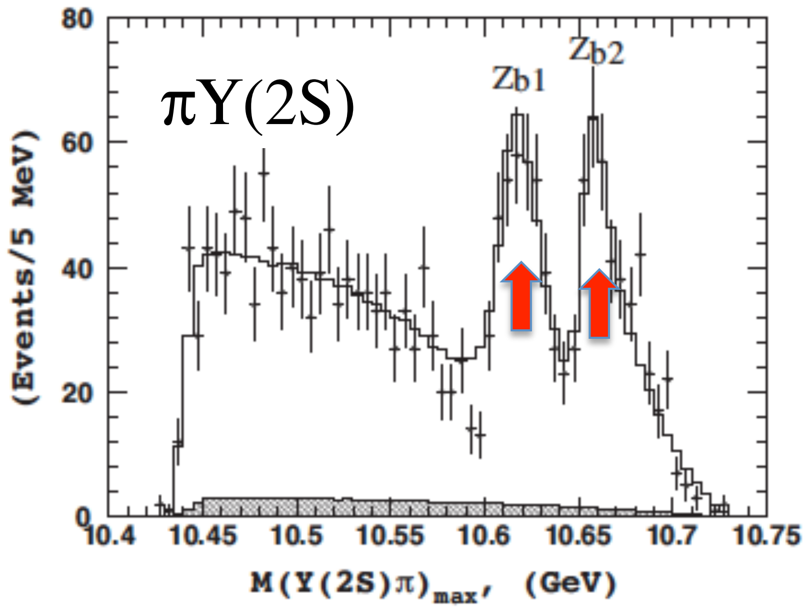
$e^+e^- \to \gamma(5S)$

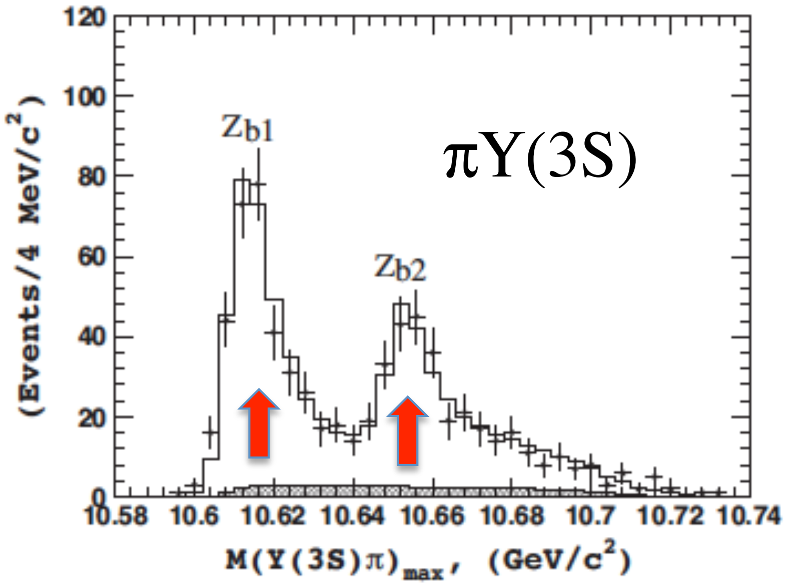


Invariant mass

Invariant mass of πY(nS)





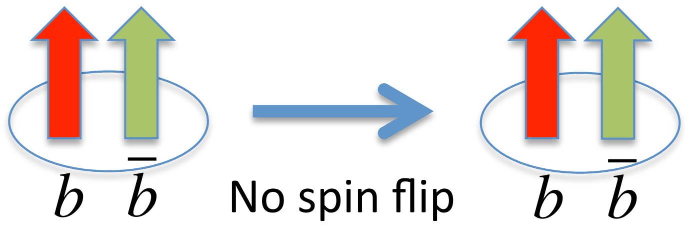


In all cases,
twin peaks are observed!

What are interesting?

Heavy quark limit -> Heavy quark spin is conserved

$\Upsilon(5S) \rightarrow Z_b^+ \pi^- \rightarrow \Upsilon(nS)\ \pi^+\pi^-$



Allowed

$\Upsilon(5S) \rightarrow Z_b^+ \pi^- \rightarrow h_b(kP)\ \pi^+\pi^-$

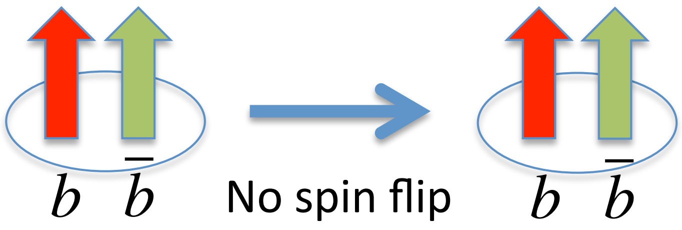
Forbidden

BUT, they occur almost equally

What are interesting?

Heavy quark limit -> Heavy quark spin is conserved

$\Upsilon(5S) \rightarrow Z_b^+ \pi^- \rightarrow \Upsilon(nS)\ \pi^+\pi^-$



Allowed

$\Upsilon(5S) \rightarrow Z_b^+ \pi^- \rightarrow h_b(kP)\ \pi^+\pi^-$

Forbidden

BUT, they occur almost equally

IF molecule

$B^*\bar{B}^*$ $\quad |Z_b'\rangle = \frac{1}{\sqrt{2}}(0^-_H \otimes 1^-_l) - \frac{1}{\sqrt{2}}(1^-_H \otimes 0^-_l),$

$B^*\bar{B} - B\bar{B}^*$ $\quad |Z_b\rangle = \frac{1}{\sqrt{2}}(0^-_H \otimes 1^-_l) + \frac{1}{\sqrt{2}}(1^-_H \otimes 0^-_l),$

$(0^-_H \otimes 1^-_l) \rightarrow h_b\,\pi$ $\qquad (1^-_H \otimes 0^-_l) \rightarrow \Upsilon\,\pi$

$B^{(*)}B^{(*)}$ classification (I = 1)

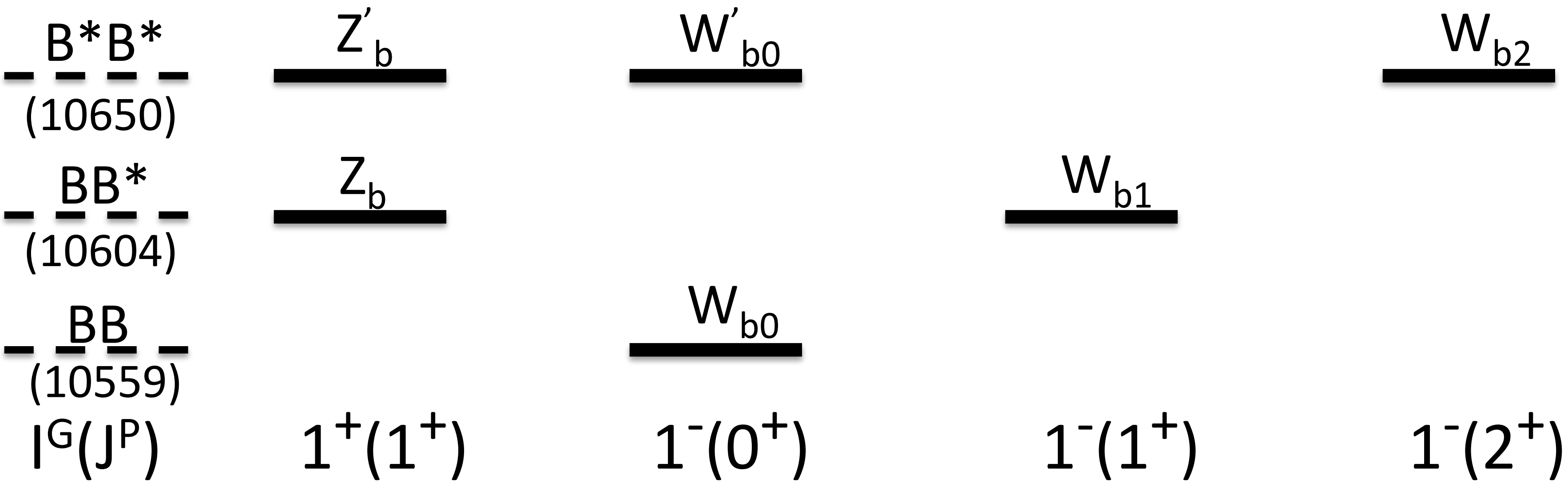
J^{PC}	components	exoticness	
		$I=0$	$I=1$
0^{++}	$\mathrm{B\bar{B}}(^1S_0)$, $\mathrm{B^*\bar{B}^*}(^1S_0)$, $\mathrm{B^*\bar{B}^*}(^5D_0)$	χ_{b0}	$\surd$
1^{+-}	$\frac{1}{\sqrt{2}}\left(\mathrm{B\bar{B}^*}-\mathrm{B^*\bar{B}}\right)(^3S_1)$, $\frac{1}{\sqrt{2}}\left(\mathrm{B\bar{B}^*}-\mathrm{B^*\bar{B}}\right)(^3D_1)$, $\mathrm{B^*\bar{B}^*}(^3S_1)$, $\mathrm{B^*\bar{B}^*}(^3D_1)$	$\mathrm{h_b}$	Z_b
1^{++}	$\frac{1}{\sqrt{2}}\left(\mathrm{B\bar{B}^*}+\mathrm{B^*\bar{B}}\right)(^3S_1)$, $\frac{1}{\sqrt{2}}\left(\mathrm{B\bar{B}^*}+\mathrm{B^*\bar{B}}\right)(^3D_1)$, $\mathrm{B^*\bar{B}^*}(^5D_1)$	χ_{b1}	$\surd$
2^{++}	$\mathrm{B\bar{B}}(^1D_2)$, $\frac{1}{\sqrt{2}}\left(\mathrm{B\bar{B}^*}+\mathrm{B^*\bar{B}}\right)(^3D_2)$, $\mathrm{B^*\bar{B}^*}(^1D_2)$, $\mathrm{B^*\bar{B}^*}(^5S_2)$, $\mathrm{B^*\bar{B}^*}(^5D_2)$, $\mathrm{B^*\bar{B}^*}(^5G_2)$	χ_{b2}	$\surd$

$B^{(*)}B^{(*)}$ classification (I = 1)

M. B. Voloshin,
Phys. Rev. D 84 (2011) 031502
[arXiv:1105.5829 [hep-ph]]

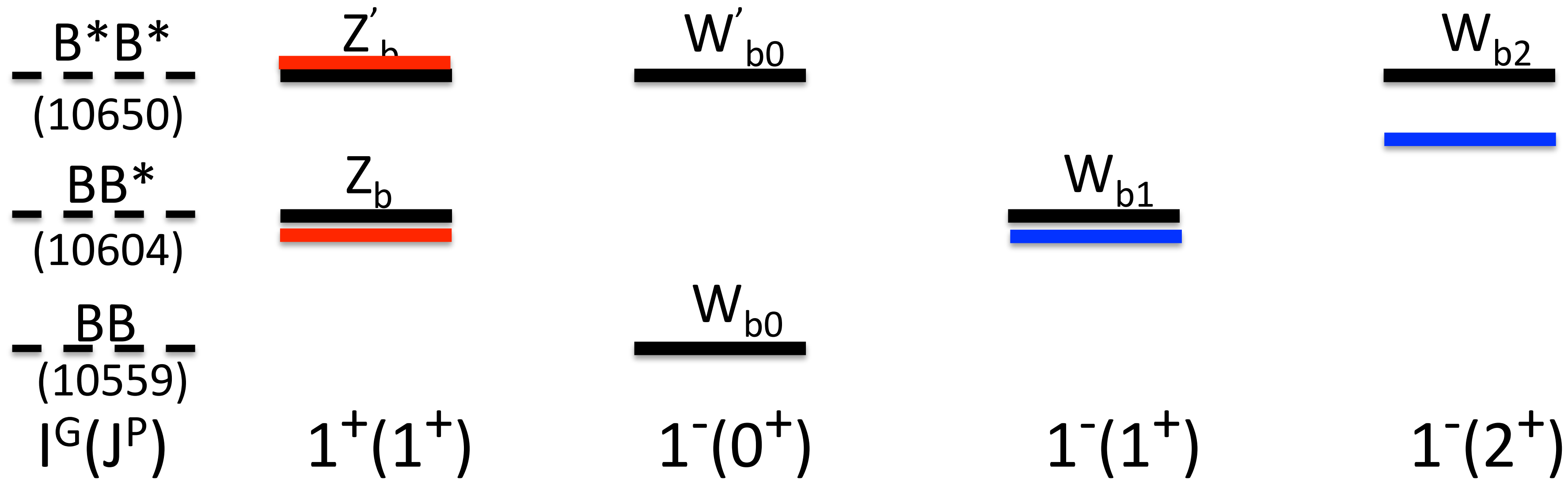
Assuming S wave

J^{PC}	components		
0^{++}	$B\bar{B}(^1S_0)$, $B^*\bar{B}^*(^1S_0)$, $B^*\bar{B}^*($		
1^{+-}	$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})\,(^3S_1)$, $\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})\,(^3D_1)$, $B^*\bar{B}^*(^3S_1)$, $B^*\bar{B}^*(^3D_1)$	h_b	Z_b
1^{++}	$\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})\,(^3S_1)$, $\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})\,(^3D_1)$, $B^*\bar{B}^*(^5D_1)$	χ_{b1}	√
2^{++}	$B\bar{B}(^1D_2)$, $\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})\,(^3D_2)$, $B^*\bar{B}^*(^1D_2)$, $B^*\bar{B}^*(^5S_2)$, $B^*\bar{B}^*(^5D_2)$, $B^*\bar{B}^*(^5G_2)$	χ_{b2}	√



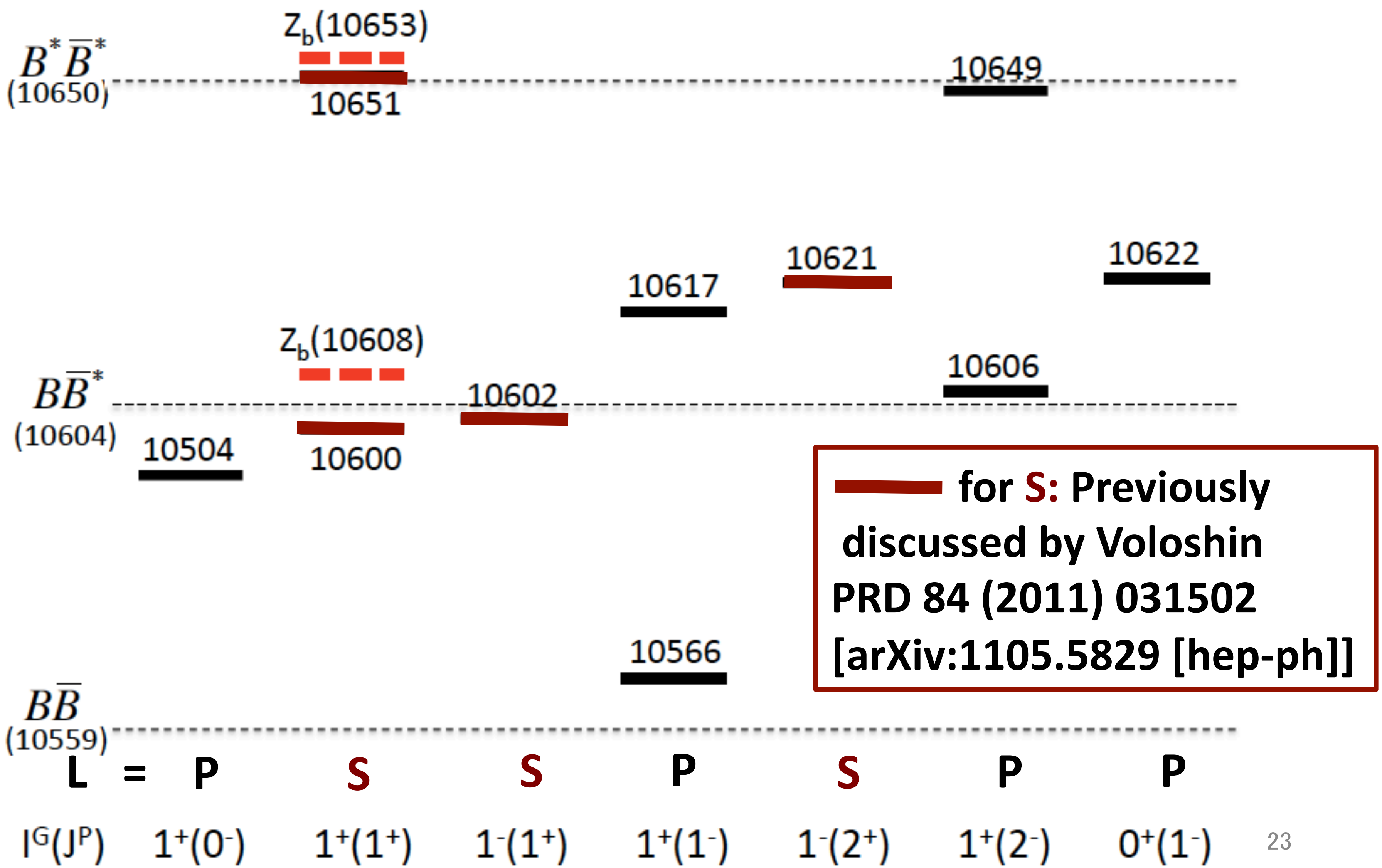
Four states are found

J^{PC}	components	exoticness	
		$I=0$	$I=1$
0^{++}	$B\bar{B}(^1S_0)$, $B^*\bar{B}^*(^1S_0)$, $B^*\bar{B}^*(^5D_0)$	χ_{b0}	$\surd$
1^{+-}	$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})\,(^3S_1)$, $\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})\,(^3D_1)$, $B^*\bar{B}^*(^3S_1)$, $B^*\bar{B}^*(^3D_1)$	h_b	Z_b
1^{++}	$\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})\,(^3S_1)$, $\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})\,(^3D_1)$, $B^*\bar{B}^*(^5D_1)$	χ_{b1}	$\surd$
2^{++}	$B\bar{B}(^1D_2)$, $\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})\,(^3D_2)$, $B^*\bar{B}^*(^1D_2)$, $B^*\bar{B}^*(^5S_2)$, $B^*\bar{B}^*(^5D_2)$, $B^*\bar{B}^*(^5G_2)$	χ_{b2}	$\surd$



More for I = 0 but with exotic J^{PC}

Ohkoda, Yamaguchi, Yasui and Hosaka, in preparation



Summary

- In the threshold region, **light quarks** appear and the **pion** starts to play.
- Exotic baryons are very likely to exist in the heavy quark region, $\mathbf{m_Q \gtrsim m_C}$, as a hadronic molecule.
- The $\mathbf{Z_b}$ may well be a **BB molecule** bound by the **pion**