Spin partners of heavy meson molecules

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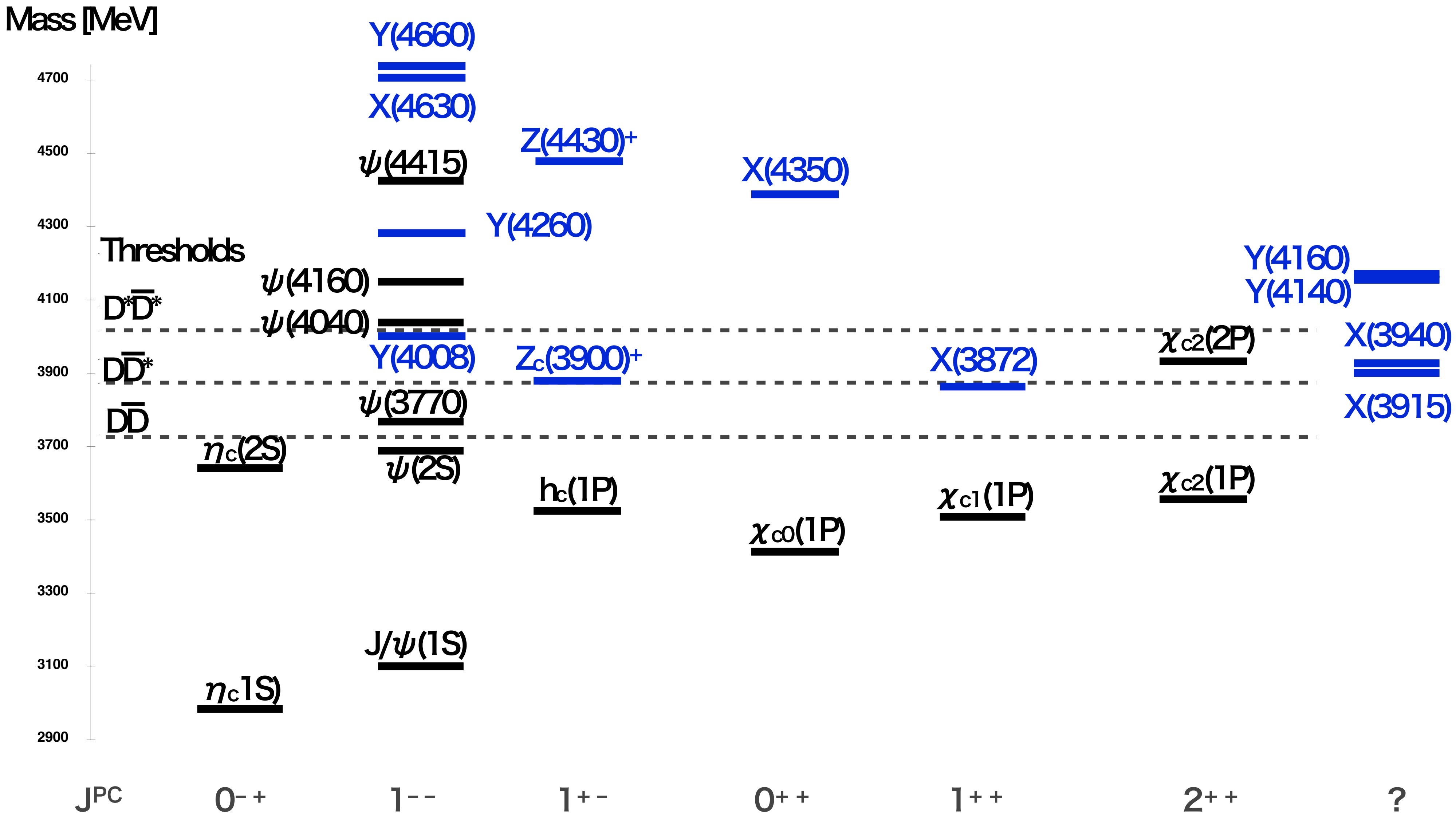
HHIQCD, 3/2/2015

Outline

- Introduction—Z_b and $B^{(*)}\bar{B}^{(*)}$ molecules
- Heavy quark symmetry
- Spin degeneracy in heavy meson molecules
- Spin partners for Z_b
- Summary

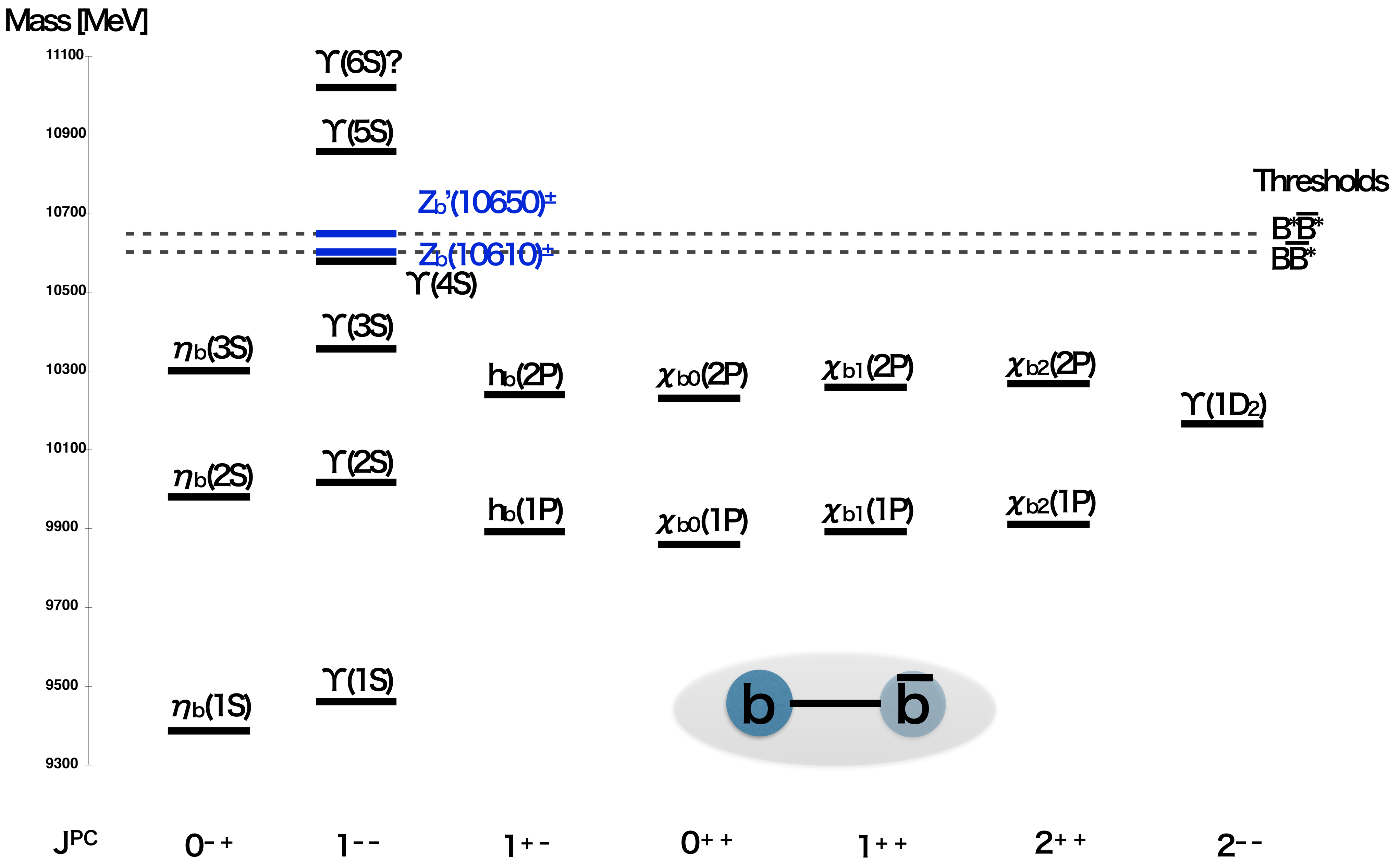
Charmonium

T. Barns, S. Godfrey and S. Swanson
PRD72, 054026 (2005).
N. Brambilla, et al,
Eur. Phys. J. C 71, 1554 (2011).



Bottomonium

Belle group, PRL108, 112001 (2012).



$Z_b(10610)$ and $Z_b(10650)$

Exotic quantum numbers

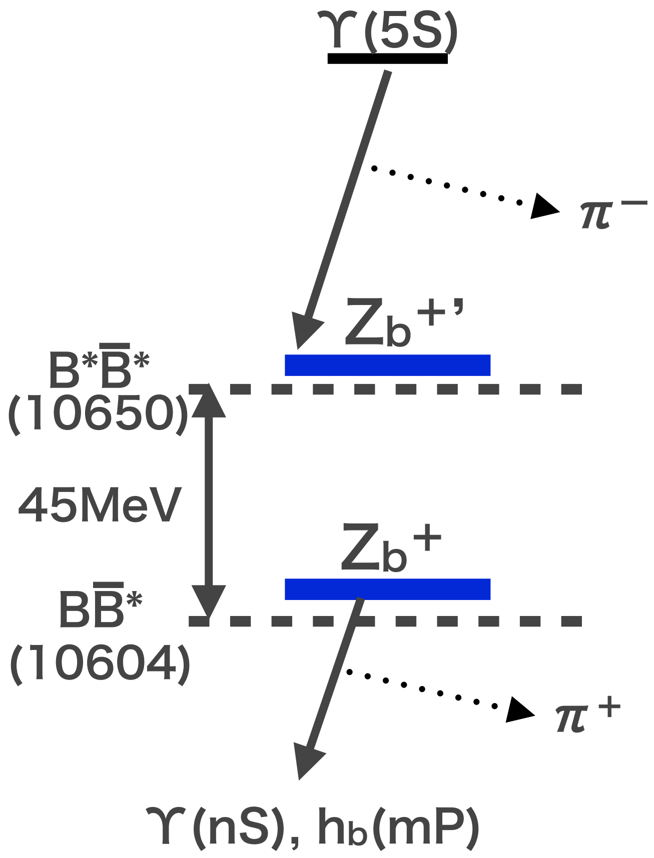
- ✔ $I^G(J^P)=1^+(1^+)$
- ✔ $\Upsilon(5S)\to Z_b^+\pi^-\to\Upsilon(1,2,3S)\pi^+\pi^-$
- ✔ Z_b's are "genuine" exotic states

Exotic masses

- ✔ Z_b's are twin resonances with small mass splitting, ~ 45 MeV
- ✔ Z_b's are very close to the respective thresholds, $B\bar{B}^*$ and $B^*\bar{B}^*$

Exotic decays

- ✔ The decays of $\Upsilon(5S)\to Z_b\pi\to h_b(mP)\pi\pi$ are not suppressed although it needs spin flip



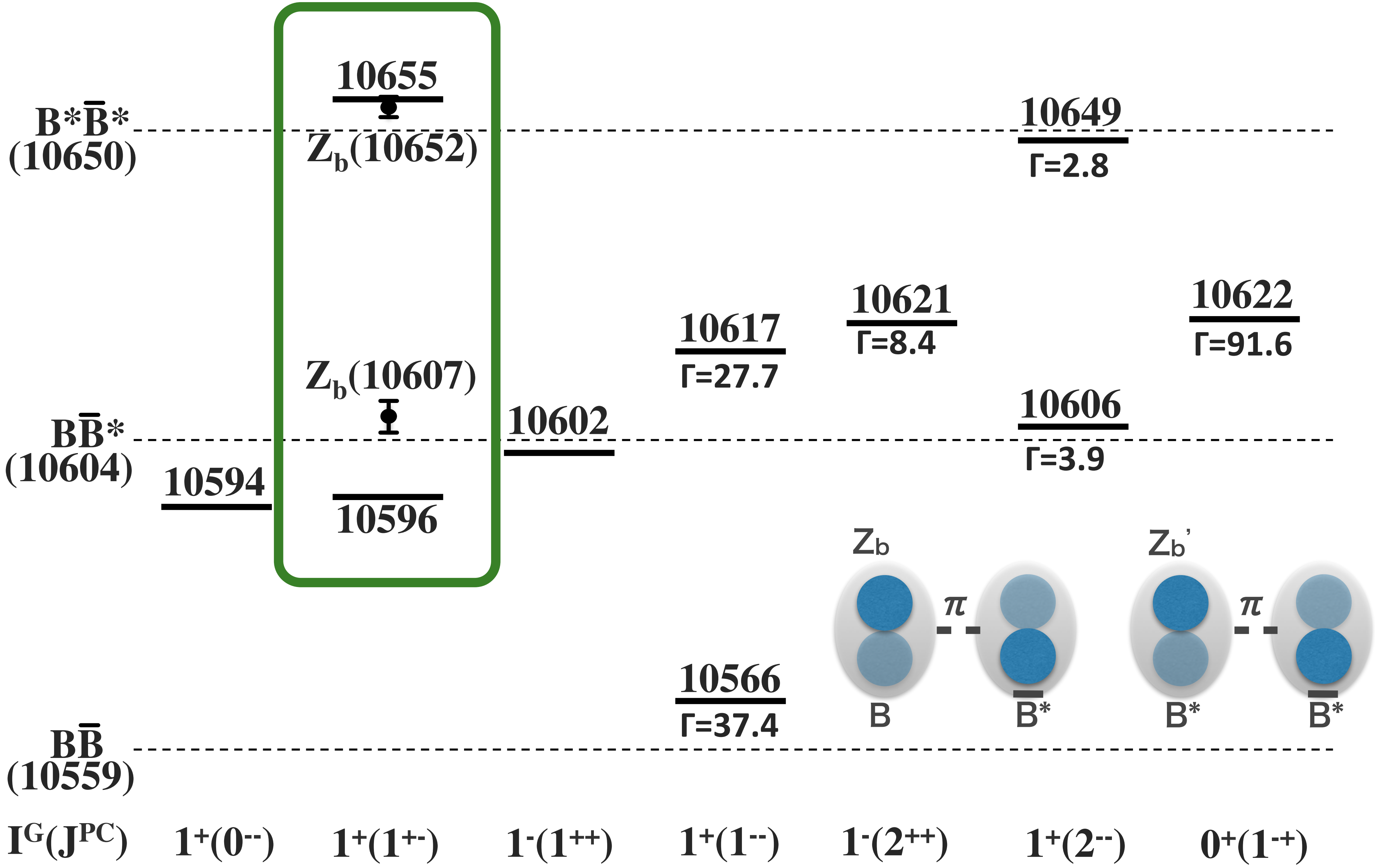
A. Bondar, et al, PRD84 054010 (2011)

S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudoh, and A. Hosaka, Phys. Rev. D86, 014004 (2012)

Z_b are $B^{(*)}\bar{B}^{(*)}$ molecules ?

$B^{(*)}\bar{B}^{(*)}$ molecules with OBEP

S. Ohkoda, Y. Yamaguchi, S. Yasui and A. Hosaka,
Phys.Rev. D86, 014004(2012).



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

We study $B^{(*)}\bar{B}^{(*)}$ molecules with OBEP model

- The $B^{(*)}\bar{B}^{(*)}$ molecules correspond to the mass of Z_b and Z_b'.
- The are many exotic states around the thresholds.
- The predicted molecules will be observed in radiative decays or a pion emission in P-wave from $\Upsilon(5S)$.

In charm region, we do not obtain any $D^{(*)}\bar{D}^{(*)}$ states in I=1.

- It is hard to explain the $Z_c(3900)$ with molecular picture.

Spin degeneracy in heavy meson molecules

Heavy quark symmetry

M. B. Wise,
PRD45, 2188 (1992)

✔The effective Lagrangian for a heavy quark

$$\mathcal{L}_{\rm HQ} = \bar{Q}(i\not{D} - m_{\rm Q})Q \qquad Q_v(x) = e^{im_Q v\cdot x}\frac{1+\not{v}}{2}Q(x)$$

$\downarrow$ 1/mQ expansion

$$\mathcal{L}_{\rm HQET} = \underbrace{\boxed{\bar{Q}_v v\cdot iDQ_v}}_{\text{LO}} + \bar{Q}_v\frac{(iD_\perp)^2}{2m_Q}Q_v - \underbrace{\boxed{c(\mu)g_s\bar{Q}_v\frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_Q}Q_v}}_{\text{Spin-spin int.}} + \mathcal{O}(1/m_Q^2)$$

◎Heavy quark flavor symmetry

◎Heavy quark spin symmetry

—— The heavy quark spins are conserved in mQ -> ∞.

Heavy quark spin symmetry

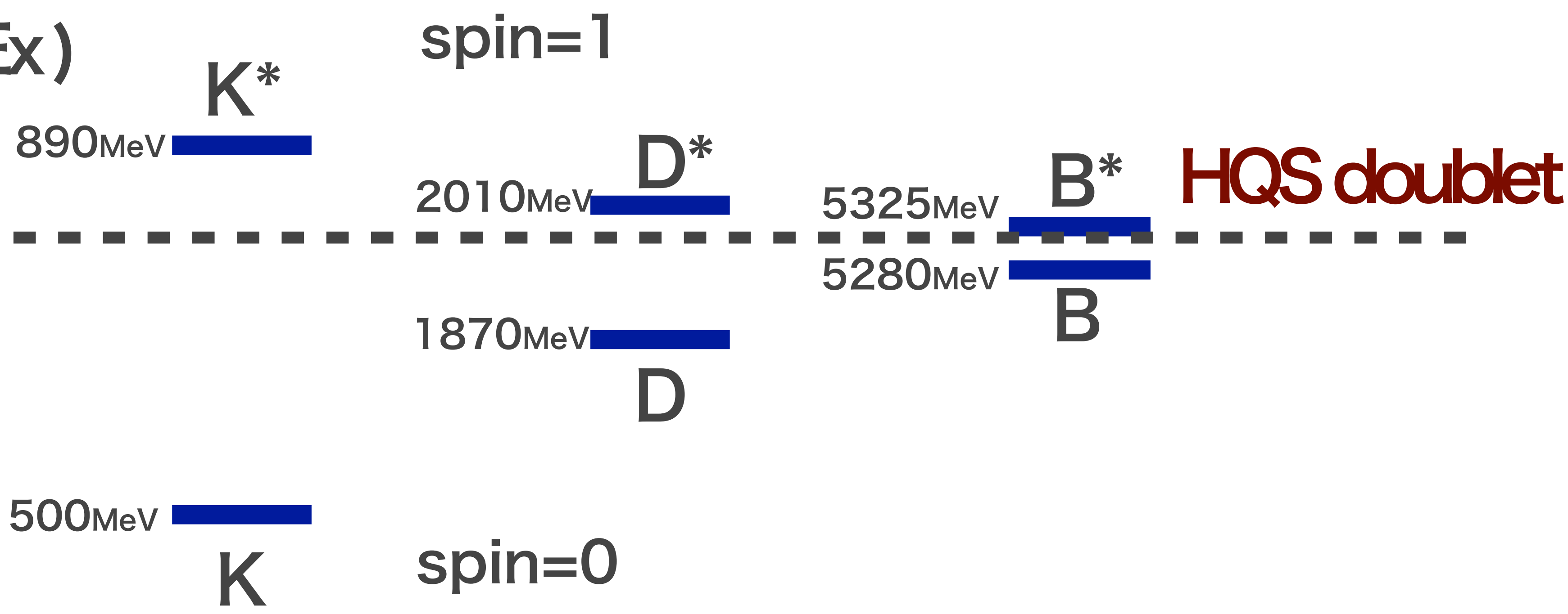
- **light spin** $S_l = J - S_H$

  —— We can classify the heavy hadrons with the spin structures $(S_H \otimes S_l)_J$.

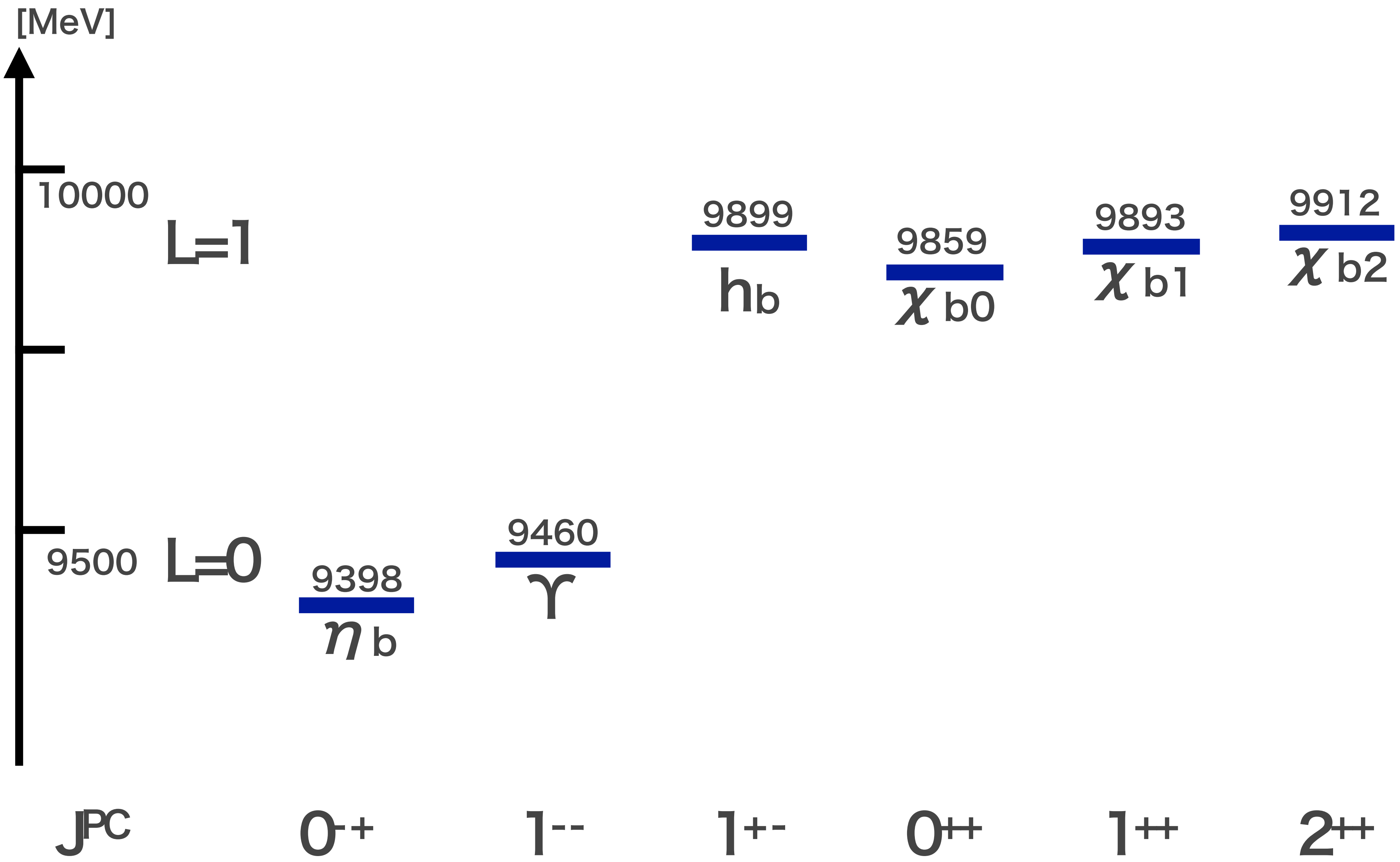
- **Spin degeneracy**

  —— Masses of the spin partners are degenerate.

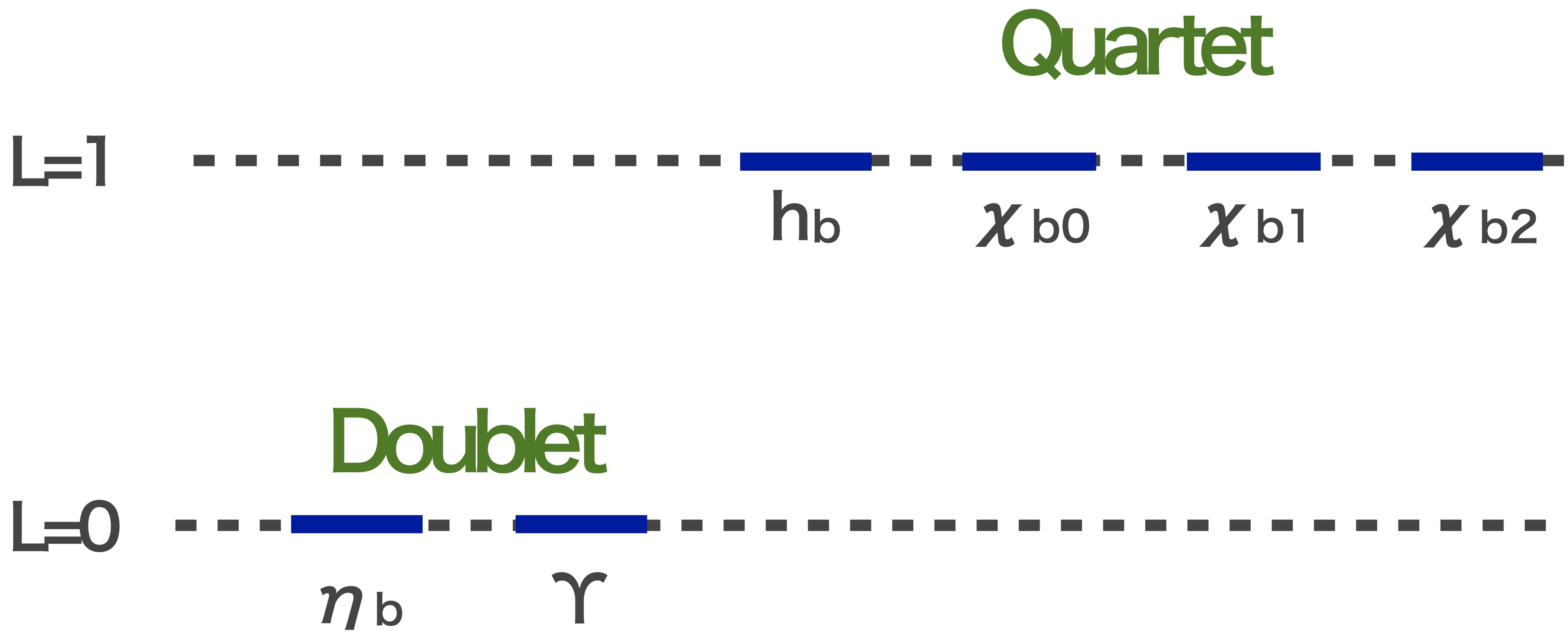
▶ Ex)



Spin partners of heavy quarkonium



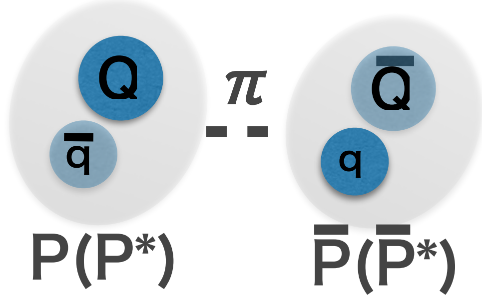
Spin partners of heavy quarkonium



J^{PC}	0^{-+}	1^{--}	1^{+-}	0^{++}	1^{++}	2^{++}
$(S_H \otimes S_l)_J$	$(0_H \otimes 0_l)_0$	$(1_H \otimes 0_l)_1$	$(0_H \otimes 1_l)_1$	$(1_H \otimes 1_l)_{0,1,2}$		

Purpose

◎Why do we study $P^{(*)}\bar{P}^{(*)}$ in the HQ limit?



✔Spin degeneracy may occur in the heavy meson molecules, but how do they arise? Doublet or quartet?

✔This study clarify the $1/m_Q$ effects in charm/bottom region.

This study

✔We focus on $I^G(J^P)=1^+(1^+)$, which corresponds to Z_b channel

✔What are the spin partners for Z_b?

OPEP model

✔Hamiltonian

S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudoh, and A. Hosaka, Phys. Rev. D86, 014004 (2012)

1+(1+-): $\frac{1}{\sqrt{2}}\left(\mathrm{P}\bar{\mathrm{P}}^{*}-\mathrm{P}^{*}\bar{\mathrm{P}}\right)({}^{3}S_{1}),\ \frac{1}{\sqrt{2}}\left(\mathrm{P}\bar{\mathrm{P}}^{*}-\mathrm{P}^{*}\bar{\mathrm{P}}\right)({}^{3}D_{1}),\ \mathrm{P}^{*}\bar{\mathrm{P}}^{*}({}^{3}S_{1}),\ \mathrm{P}^{*}\bar{\mathrm{P}}^{*}({}^{3}D_{1})$

$$H_{1^{+-}} = \begin{pmatrix} K_0 + C_I & -\sqrt{2}T_I & -2C_I & -\sqrt{2}T_I \\ -\sqrt{2}T_I & K_2 + C_I + T_I & -\sqrt{2}T_I & -2C_I + T_I \\ -2C_I & -\sqrt{2}T_I & K_0 + C_I & -\sqrt{2}T_I \\ -\sqrt{2}T_I & -2C_I + T_I & -\sqrt{2}T_I & K_2 + C_I + T_I \end{pmatrix}$$

K_0 : kinetic term

C : Center force

T : Tensor force

1-(1++): $\frac{1}{\sqrt{2}}\left(\mathrm{P}\bar{\mathrm{P}}^{*}+\mathrm{P}^{*}\bar{\mathrm{P}}\right)({}^{3}S_{1}),\ \frac{1}{\sqrt{2}}\left(\mathrm{P}\bar{\mathrm{P}}^{*}+\mathrm{P}^{*}\bar{\mathrm{P}}\right)({}^{3}D_{1}),\ \mathrm{P}^{*}\bar{\mathrm{P}}^{*}({}^{5}D_{1})$

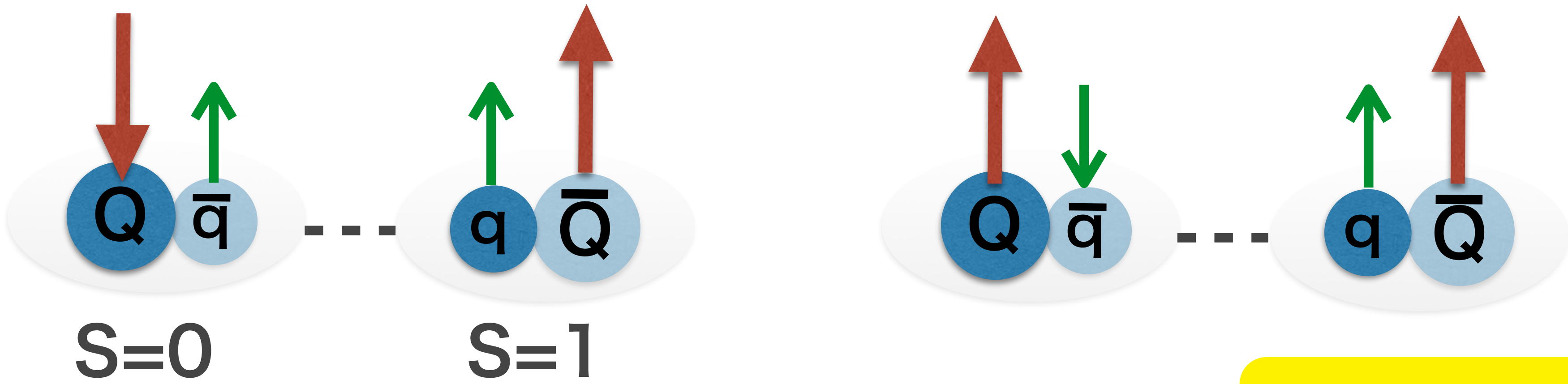
$$H_{1^{++}} = \begin{pmatrix} K_0 - C_I & \sqrt{2}T_I & -\sqrt{6}T_I \\ \sqrt{2}T_I & K_2 - C_I - T_I & -\sqrt{3}T_I \\ -\sqrt{6}T_I & -\sqrt{3}T_I & K_2 - C_I + T_I \end{pmatrix}$$

Spin structures

$S_l = S_{q\bar{q}} + L \ (\neq 0^{+-}, 1^{-+}, 2^{+-}, J<2)$

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

$$|\tfrac{1}{\sqrt{2}}(P\bar{P}^* - P^*\bar{P})(^3S_1)\rangle = \frac{1}{\sqrt{2}}|0_H \otimes 1_l\rangle_1 + \frac{1}{\sqrt{2}}|1_H \otimes 0_l\rangle_1$$



$$\begin{pmatrix} |\frac{1}{\sqrt{2}}(P\bar{P}^* - P^*\bar{P})(^3S_1)\rangle \\ |\frac{1}{\sqrt{2}}(P\bar{P}^* - P^*\bar{P})(^3D_1)\rangle \\ |P^*\bar{P}^*(^3S_1)\rangle \\ |P^*\bar{P}^*(^3D_1)\rangle \end{pmatrix} = U_{1^{+-}} \begin{pmatrix} |0_H, 1_q, 0_L, 1_l; 1\rangle \\ |0_H, 1_q, 2_L, 1_l; 1\rangle \\ |1_H, 0_q, 0_L, 0_l; 1\rangle \\ |1_H, 0_q, 2_L, 2_l; 1\rangle \end{pmatrix}$$

$(S_H \otimes S_l)_J$

$(0_H \otimes 1_l)_1$

$(1_H \otimes 0_l)_1$

$(1_H \otimes 2_l)_1$

OPEP model in HQ limit

S. Ohkoda, Y. Yamaguchi, S. Yasui,
K. Sudoh, and A. Hosaka,
Phys. Rev. D86, 014004 (2012)

$H^{HQ}_{J^{PC}}$: Hamiltonian in HQ basis

$$
\begin{aligned}
H^{HQ}_{1+-} &= U^{-1}_{1+-} H_{1+-} U_{1+-} \\
&= \left(\begin{array}{cc|c|c}
K_0 - C & -2\sqrt{2}T & 0 & 0 \\
-2\sqrt{2}T & K_2 - C + 2T & 0 & 0 \\
\hline
0 & 0 & K_0 + 3C & 0 \\
\hline
0 & 0 & 0 & K_2 + 3C
\end{array}\right)
\begin{array}{l}
(0_H \otimes 1_l)_1 \\
\\
(1_H \otimes 0_l)_1 \\
(1_H \otimes 2_l)_1
\end{array} \\
&= \left(\begin{array}{c|c|c}
H^{(0,1)}_{1+-} & 0 & 0 \\
\hline
0 & H^{(1,0)}_{1+-} & 0 \\
\hline
0 & 0 & H^{(1,2)}_{1+-}
\end{array}\right)
\end{aligned}
$$

→ Diagonalized Hamiltonian : $H^{(S_Q, S_l)}_{J^{PC}}$

$$
\begin{aligned}
H^{HQ}_{1++} &= \left(\begin{array}{cc|c}
K_0 - C & -2\sqrt{2}T & 0 \\
-2\sqrt{2}T & K_2 - C + 2T & 0 \\
\hline
0 & 0 & K_2 - C - 2T
\end{array}\right) \\
&= \left(\begin{array}{c|c}
H^{(1,1)}_{1++} & 0 \\
\hline
0 & H^{(1,2)}_{1++}
\end{array}\right)
\end{aligned}
$$

HQS Quartet

$$H^{(0,1)}_{1+-} = H^{(1,1)}_{0++} = H^{(1,1)}_{1++} = H^{(1,1)}_{2++}$$

Spin partners of $P^{(*)}\bar{P}^{(*)}$ with I=1

Attraction

Hamiltonian	$diag(V)$	multiplets $H^{(S_H,S_l)}_{JPC}$	
$\begin{pmatrix} K_0 - C & -2\sqrt{2}T \\ -2\sqrt{2}T & K_2 - C + 2T \end{pmatrix}$	$-C-2T, -C+4T$	$H^{(0,1)}_{1+-} = H^{(1,1)}_{0++} = H^{(1,1)}_{1++} = H^{(1,1)}_{2++}$	S-D
$K_1 - C - 2T$	$-C-2T$	$H^{(0,1)}_{1--} = H^{(1,1)}_{0-+} = H^{(1,1)}_{1-+} = H^{(1,1)}_{2-+}$	P
$\begin{pmatrix} K_1 - C + \frac{2}{5}T & -\frac{6\sqrt{6}}{5}T \\ -\frac{6\sqrt{6}}{5}T & K_3 - C + \frac{8}{5}T \end{pmatrix}$	$-C-2T, -C+4T$	$H^{(0,2)}_{2-+} = H^{(1,2)}_{1--} = H^{(1,2)}_{2--} = H^{(1,2)}_{3--}$	P-F
$K_2 - C - 2T$	$-C-2T$	$H^{(0,2)}_{2+-} = H^{(1,2)}_{1++} = H^{(1,2)}_{2++} = H^{(1,2)}_{3++}$	D
$\begin{pmatrix} K_2 - C + \frac{4}{7}T & -\frac{12\sqrt{3}}{7}T \\ -\frac{12\sqrt{3}}{7}T & K_4 - C + \frac{10}{7}T \end{pmatrix}$	$-C-2T, -C+4T$	$H^{(0,3)}_{3+-} = H^{(1,3)}_{2++} = H^{(1,3)}_{3++} = H^{(1,3)}_{4++}$	D-G
$K_3 - C - 2T$	$-C-2T$	$H^{(0,3)}_{3-+} = H^{(1,3)}_{2--} = H^{(1,3)}_{3--} = H^{(1,3)}_{4--}$	F

Repulsion

$K_0 + 3C$	$3C$	$H^{(0,0)}_{0++} = H^{(1,0)}_{1+-}$
$K_1 + 3C$	$3C$	$H^{(0,1)}_{1--} = H^{(1,1)}_{0-+} = H^{(1,1)}_{1-+} = H^{(1,1)}_{2-+}$
$K_2 + 3C$	$3C$	$H^{(0,2)}_{2++} = H^{(1,2)}_{1+-} = H^{(1,2)}_{2+-} = H^{(1,2)}_{3+-}$
$K_3 + 3C$	$3C$	$H^{(0,3)}_{3--} = H^{(1,3)}_{2-+} = H^{(1,3)}_{3-+} = H^{(1,3)}_{4-+}$
$K_1 - C + 4T$	$-C+4T$	$H^{(0,0)}_{0-+} = H^{(1,0)}_{1--}$

Spin partners of $P^{(*)}\bar{P}^{(*)}$ with I=0

	Hamiltonian	$diag(V)$	multiplets $H^{(S_H,S_l)}_{J^{PC}}$	attraction	
$h_b(nP)$-$\chi_b(nP)$	$\begin{pmatrix} K_0+3C & 6\sqrt{2}T \\ 6\sqrt{2}T & K_2+3C-6T \end{pmatrix}$	$3C+6T, 3C-12T$	$H^{(0,1)}_{1+-} = H^{(1,1)}_{0++} = H^{(1,1)}_{1++} = H^{(1,1)}_{2++}$	$\surd\surd$	Strong attraction
$\eta_b(nD)$-$\Upsilon_b(nD)$	$\begin{pmatrix} K_1+3C-\frac{6}{5}T & \frac{18\sqrt{6}}{5}T \\ \frac{18\sqrt{6}}{5}T & K_3+3C-\frac{24}{5}T \end{pmatrix}$	$3C+6T, 3C-12T$	$H^{(0,2)}_{2-+} = H^{(1,2)}_{1--} = H^{(1,2)}_{2--} = H^{(1,2)}_{3--}$	$\surd\surd$	
$h_b(nF)$-$\chi_b(nF)$	$\begin{pmatrix} K_2+3C-\frac{12}{7}T & \frac{36\sqrt{3}}{7}T \\ \frac{36\sqrt{3}}{7}T & K_4+3C-\frac{30}{7}T \end{pmatrix}$	$3C+6T, 3C-12T$	$H^{(0,3)}_{3+-} = H^{(1,3)}_{2++} = H^{(1,3)}_{3++} = H^{(1,3)}_{4++}$	$\surd\surd$	
$\eta_b(nS)$-$\Upsilon_b(nS)$	$K_1+3C-12T$	$3C-12T$	$H^{(0,0)}_{0-+} = H^{(1,0)}_{1--}$	$\surd\surd$	
	K_0-9C	$-9C$	$H^{(0,0)}_{0++} = H^{(1,0)}_{1+-}$	$\surd$	weak attraction
	K_1-9C	$-9C$	$H^{(0,1)}_{1--} = H^{(1,1)}_{0-+} = H^{(1,1)}_{1-+} = H^{(1,1)}_{2-+}$	$\surd$	
	K_2-9C	$-9C$	$H^{(0,2)}_{2++} = H^{(1,2)}_{1+-} = H^{(1,2)}_{2+-} = H^{(1,2)}_{3+-}$	$\surd$	
	K_3-9C	$-9C$	$H^{(0,3)}_{3--} = H^{(1,3)}_{2-+} = H^{(1,3)}_{3-+} = H^{(1,3)}_{4-+}$	$\surd$	
	$K_1+3C+6T$	$3C+6T$	$H^{(0,1)}_{1-+} = H^{(1,1)}_{0--} = H^{(1,1)}_{1--} = H^{(1,1)}_{2--}$		repulsion
	$K_2+3C+6T$	$3C+6T$	$H^{(0,2)}_{2+-} = H^{(1,2)}_{1++} = H^{(1,2)}_{2++} = H^{(1,2)}_{3++}$		
	$K_3+3C+6T$	$3C+6T$	$H^{(0,3)}_{3-+} = H^{(1,3)}_{2--} = H^{(1,3)}_{3--} = H^{(1,3)}_{4--}$		

- ✔ Doublets only appear in I=0.
- ✔ Quarkonia can only couple to $P^{(*)}\bar{P}^{(*)}$ states where the strong attraction force exists.

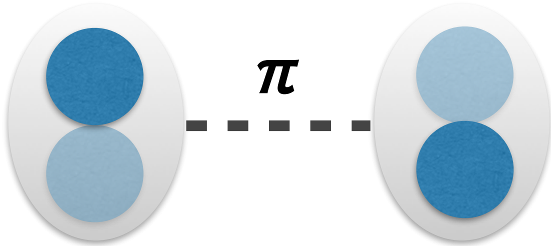
Spin partners of Z_b

$P^{(*)}\bar{P}^{(*)}$ states in HQ limit

$P(P^*)$ $\bar{P}(\bar{P}^*)$

Pion

Extended



$P\bar{P}^*, P^*\bar{P}^*$

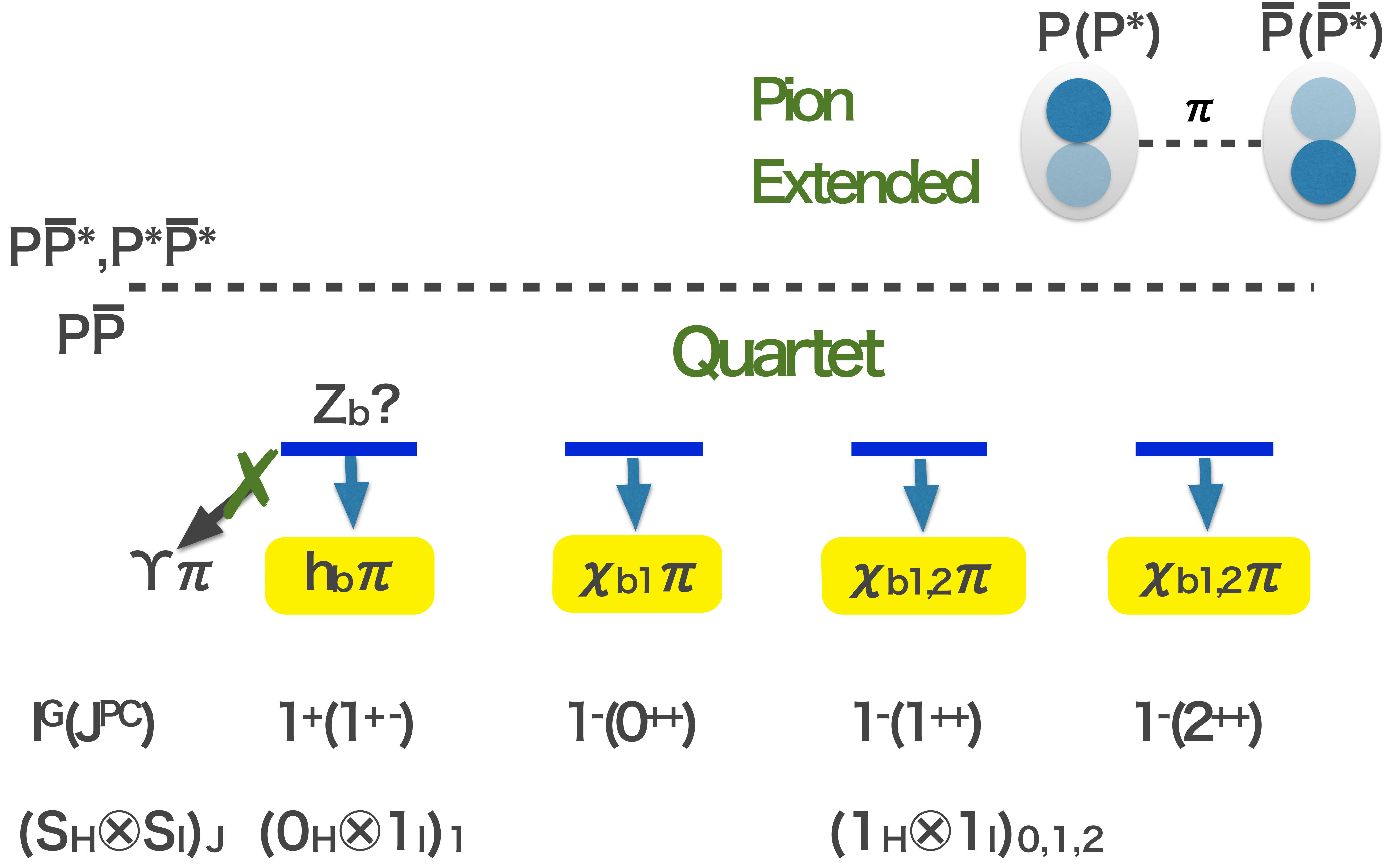
$P\bar{P}$

Quartet

Z_b?

$I^G(J^{PC})$	$1^+(1^{+-})$	$1^-(0^{++})$	$1^-(1^{++})$	$1^-(2^{++})$
$(S_H \otimes S_l)_J$	$(0_H \otimes 1_l)_1$		$(1_H \otimes 1_l)_{0,1,2}$	

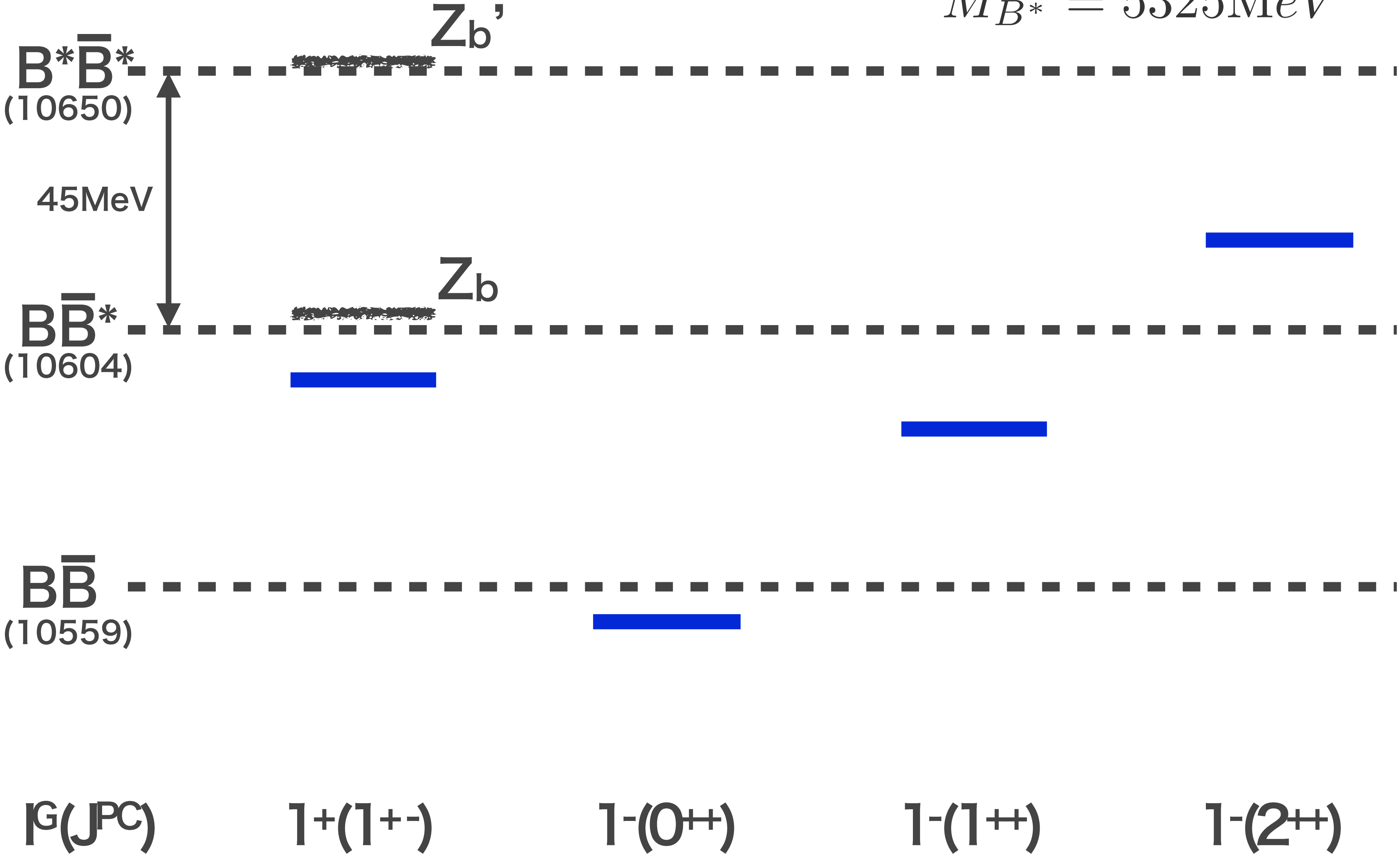
$P^{(*)}\bar{P}^{(*)}$ states in HQ limit



$B^{(*)}\bar{B}^{(*)}$ states with OPEP

S. Ohkoda, Y. Yamaguchi, S. Yasui,
K. Sudoh, and A. Hosaka,
Phys. Rev. D86, 014004 (2012)

$$M_B = 5280\mathrm{MeV}$$
$$M_{B^*} = 5325\mathrm{MeV}$$



$B^{(*)}\bar{B}^{(*)}$ states

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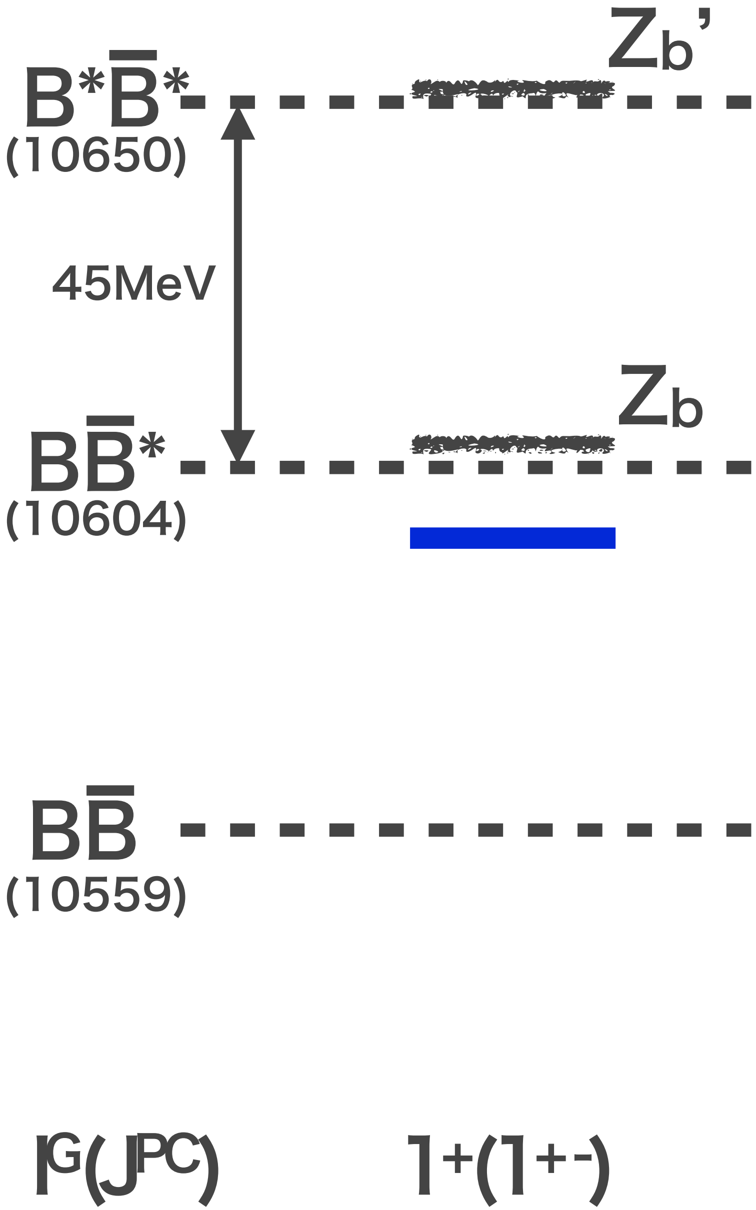

Mixing ratio of each channel

$(S_H \otimes S_l)_J$	$(0_H \otimes 1_l)_1$	$(1_H \otimes 0_l)_1$	$(1_H \otimes 2_l)_1$
$P^{(*)}\bar{P}^{(*)}$	100%	0%	0%
$B^{(*)}\bar{B}^{(*)}$	84%	15%	1%
Decays	$h_b\pi$ $\eta_b\gamma$	$\Upsilon\pi$ $\chi_{bJ}\gamma$	$(\Upsilon\pi)_{\text{D-wave}}$

- HQS is broken in the bottom quark region
- $(1_H \otimes 0_l)_1$ component allows the decays,
  $\Upsilon(5S) \to Z_b^+\pi^- \to \Upsilon(nS)\pi^+\pi^-$
- $$\Gamma(Z_b^0 \to \chi_{b0}\gamma) : \Gamma(Z_b^0 \to \chi_{b1}\gamma) : \Gamma(Z_b^0 \to \chi_{b2}\gamma)$$
  $$1 : 3 : 5$$

Summary

- We investigate the $P^{(*)}\bar{P}^{(*)}$ states in HQ limit.
- The spin degeneracy may be useful to understand the nature of exotic hadrons.
- We find spin partners of Z_b: $H^{(0,1)}_{1+-} = H^{(1,1)}_{0++} = H^{(1,1)}_{1++} = H^{(1,1)}_{2++}$
- Spin partners of Z_b are possible to be observed in future experiments.
- Spin structures give the decay properties.