Decays of Z_b resonance as hadronic molecules

S. Ohkoda[A]
Y. Yamaguchi[A], S. Yasui[B] and A. Hosaka[A]
[A]Research Center for Nuclear Physics (RCNP)
[B]KEK theory center

J-PARC研究会 at 東海, 9/12/2013

Outline

- Introduction
  - $Z_b(10610)$ and $Z_b(10650)$
- The relation of spin structures and decay properties of Z_b
- Decays of $Z_b \to \Upsilon(nS)\pi$ as hadronic molecules
- Summary

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

Decay process

- ✓ $\Upsilon(5S) \to Z_b \pi \to \Upsilon(nS)\ \pi\pi$
- ✓ $\Upsilon(5S) \to Z_b \pi \to h_b(mP)\ \pi\pi$
- ✓ $\Upsilon(5S) \to Z_b \pi \to B^*\bar{B}^{(*)}\ \pi\pi$

✳ n=1,2,3 m=1,2

Mass and width

✓ $Z_b(10610)$: Z_b

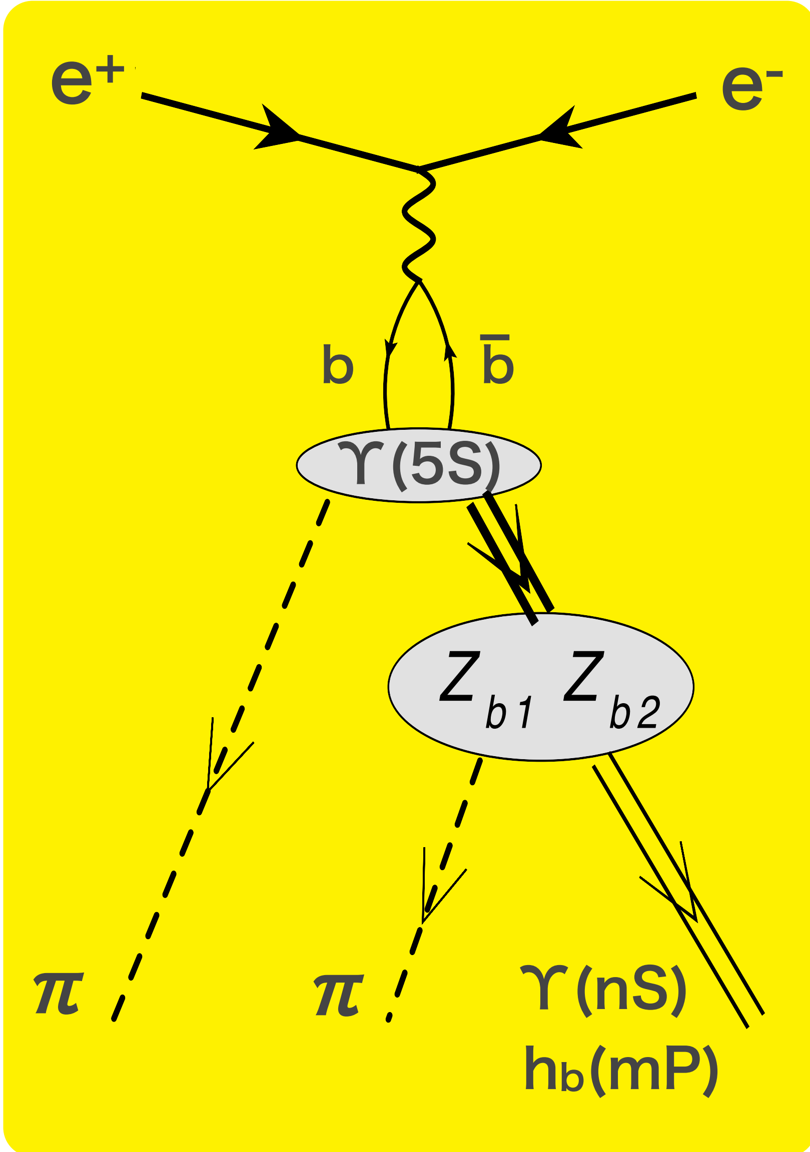
$M = 10607.4 \pm 2.0$ MeV ~$B\bar{B}^*$

$\Gamma = 18.3 \pm 2.4$ MeV

✓ $Z_b(10650)$: Z_b'

$M = 10652.2 \pm 1.5$ MeV ~$B^*\bar{B}^*$

$\Gamma = 11.5 \pm 2.2$ MeV



Belle group, PRL108, 112001 (2012).

Properties of Z_b

Exotic quantum numbers

✓ $I^G(J^P)=1^+(1^+)$

✓ Z_b is the "genuine" exotic state

Exotic twin resonances

✓ The masses of Z_b's are very close to the respective thresholds of $B\bar{B}^*$ and $B^*\bar{B}^*$

Exotic decays

✓ The decay of $\Upsilon(5S) \to Z_b\pi \to h_b(mP)\pi\pi$ is not suppressed although it needs spin flip

Z_b is a candidate of $B^*\bar{B}^{(*)}$ molecule !

Branching fractions of $Z_b^{(')}$

Channel	$\mathscr{B}$ of $Z_b(10610)$, %	$\mathscr{B}$ of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	2.15 ± 0.56	14.8 ± 6.22
$B^+B^{*0} + B^0B^{*+}$	86.0 ± 3.6	–
$B^{*+}B^{*0}$	–	73.4 ± 7.0

✓ Open flavor channels are dominant

✓ $h_b\pi$ decays are not suppressed

✓ The decay ratios seems not to be reflected on the difference of phase space

Relations of spin structures and decay properties of Z_b

S. Ohkoda, Y. Yamaguchi, S. Yasui and A. Hosaka,
Phys.Rev. D86, 117502 (2012).

Light spin complex

✓ In the heavy quark limit, new conserved quantity appear —— light spin complex

$$S_l = J - S_H$$

S_l : Light spin complex
J : Total angular momentum
S_H : Heavy quark spin

✓ We can write the wave function of heavy hadrons as the direct product of $S_H \otimes S_l$

		J^{PC}		$S_H \otimes S_l$		$b\bar{b}(^{2S+1}L_J)$
Υ	:	1^{--}	:	$1_H \otimes 0_l$	:	$b\bar{b}(^3S_1)$
h_b	:	1^{+-}	:	$0_H \otimes 1_l$	:	$b\bar{b}(^1P_1)$
χ_{bJ}	:	1^{++}	:	$(1_H \otimes 1_l)_J$	:	$b\bar{b}(^3P_J)$

Spin structure of meson pairs

✓ The spin structure of heavy meson pairs is derived with spin recoupling formula.

$$
\begin{aligned}
B^*\bar{B}^*({}^3S_1) \quad &: \quad \left[[b\bar{q}]^1, [\bar{b}q]^1\right]^1 \\
&= \sum_{H,l} \hat{1}\hat{1}\hat{H}\hat{l} \begin{Bmatrix} 1/2 & 1/2 & 1 \\ 1/2 & 1/2 & 1 \\ H & l & 1 \end{Bmatrix} \left[[b\bar{b}]^H, [\bar{q}q]^l\right]^1 \\
&= \frac{1}{\sqrt{2}}(0_H^- \otimes 1_l^-) + \frac{1}{\sqrt{2}}(1_H^- \otimes 0_l^-)
\end{aligned}
$$

✓ Now consider the heavy meson pairs for $J^{PC}=1^{--}$

$$
\mathrm{B\bar{B}}({}^1P_1),\ \frac{1}{\sqrt{2}}(\mathrm{B\bar{B}^*} + \mathrm{B^*\bar{B}})({}^3P_1),
$$

$$
\mathrm{B^*\bar{B}^*}({}^1P_1),\ \mathrm{B^*\bar{B}^*}({}^5P_1),\ \mathrm{B^*\bar{B}^*}({}^5F_1)
$$

Spin structure of meson pairs

$$B\bar{B}: \frac{1}{2\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} + \frac{1}{2}\psi_{01};$$

$$\frac{B^*\bar{B} - \bar{B}^*B}{\sqrt{2}}: \frac{1}{\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12};$$

$$(B^*\bar{B}^*)_{S=0}: -\frac{1}{6}\psi_{10} - \frac{1}{2\sqrt{3}}\psi_{11} - \frac{\sqrt{5}}{6}\psi_{12} + \frac{\sqrt{3}}{2}\psi_{01};$$

$$(B^*\bar{B}^*)_{S=2}: \frac{\sqrt{5}}{3}\psi_{10} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{11} + \frac{1}{6}\psi_{12}.$$

$$\psi_{ab} = a_H \otimes b_l$$

$$\Upsilon = 1_H \otimes 0_l$$

✓ Spin structures imply the decay ratio of $\Upsilon \to B^{(*)}\bar{B}^{(*)}$

Decay ratio of $\Upsilon \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$

M.B.Voloshin, PRD85 034024(2012)

✓ The decay ratio of $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}$ is given as

$$\begin{array}{ccccc} \Gamma(\Upsilon(5S) \to B\bar{B}) & : & \Gamma(\Upsilon(5S) \to B^*\bar{B} + c.c.) & : & \Gamma(\Upsilon(5S) \to B^*\bar{B}^*) \\ 1 & : & 4 & : & 7 \end{array}$$

✓ The available data gives the ratio of the decay widths

EXP)

$$\begin{array}{ccccc} \Gamma(\Upsilon(5S) \to B\bar{B}) & : & \Gamma(\Upsilon(5S) \to B^*\bar{B} + c.c.) & : & \Gamma(\Upsilon(5S) \to B^*\bar{B}^*) \\ 1 & : & 2.5 & : & 7 \end{array}.$$

The spin structure of Z_b

✓ The spin structures of Z_b's are given as

	$S_H \otimes S_l$	Component
Z_b	: $\frac{1}{\sqrt{2}}(0^-_H \otimes 1^-_l) + \frac{1}{\sqrt{2}}(1^-_H \otimes 0^-_l)$:	$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})(^3S_1)$
Z_b'	: $\frac{1}{\sqrt{2}}(0^-_H \otimes 1^-_l) - \frac{1}{\sqrt{2}}(1^-_H \otimes 0^-_l)$:	$B^*\bar{B}^*(^3S_1)$

✓ Z_b is a mixture state of 0_H and 1_H

✓ $(0_H \otimes 1_l)$ decays to $h_b\pi$, $\eta_b\gamma$, ...

✓ $(1_H \otimes 0_l)$ decays to $\Upsilon\pi$, $\chi_{bJ}\gamma$, ...

$Z_b \rightarrow \chi_{bJ}\, \gamma$

✓ $\chi_{b0} + \gamma$ (P-wave)

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

✓ $\chi_{b1} + \gamma$ (P-wave)

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

✓ $\chi_{b2} + \gamma$ (P-wave)

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

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

✓ This ratio is testable with experiment

Decays of $Z_b \to \Upsilon(nS)\pi$ as hadronic molecules

S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudoh, and A. Hosaka,
in preparation.

Branching fractions of $Z_b^{(\prime)}$

Channel	$\mathscr{B}$ of $Z_b(10610)$, %	$\mathscr{B}$ of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	2.15 ± 0.56	14.8 ± 6.22
$B^+B^{*0} + B^0B^{*+}$	86.0 ± 3.6	–
$B^{*+}B^{*0}$	–	73.4 ± 7.0

↓~×10

↓~×0.5

✓ The decay ratios seems not to be reflected on the difference of phase space.

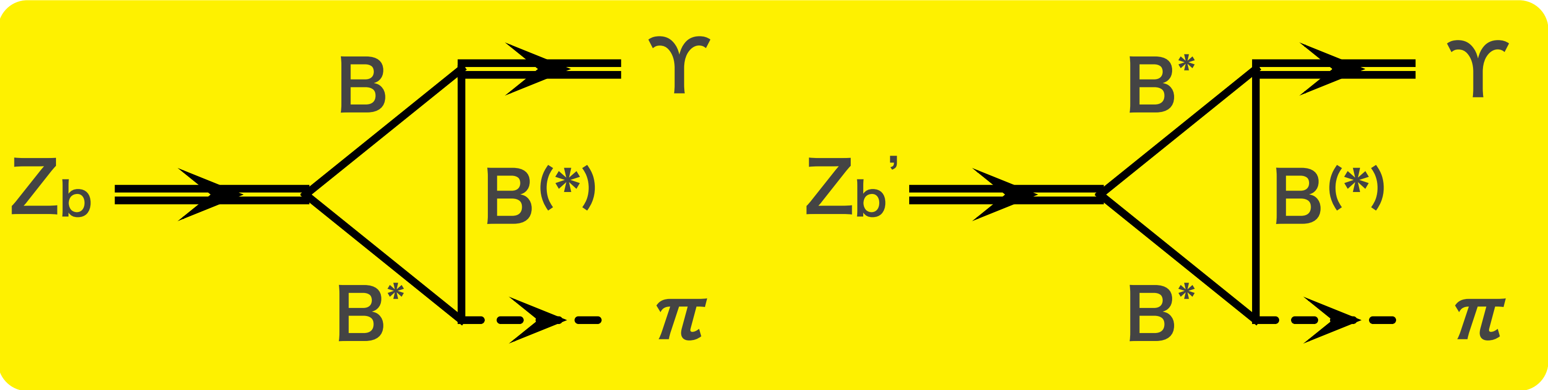
$$\vec{q}_{\Upsilon(2S)}/\vec{q}_{\Upsilon(1S)} \sim 0.55 \qquad \vec{q}_{\Upsilon(3S)}/\vec{q}_{\Upsilon(2S)} \sim 0.42$$

Diagrams for $Z_b^{(\prime)+} \to \Upsilon(nS)\pi^+$

✓ Assuming that $Z_b^{(\prime)}$ is hadronic molecule.

$$|Z_b\rangle = \frac{1}{\sqrt{2}}|B\bar{B}^* - B^*\bar{B}\rangle \, ,$$
$$|Z_b'\rangle = |B^*\bar{B}^*\rangle \, .$$

✓ Feynman diagrams are described with hadronic loops



Effective Lagrangians

✓ Lagrangians for $ZB\bar{B}^*$ and $ZB^*\bar{B}^*$

✓ Couplings are determined by $Z_b \to B\bar{B}^*$ and $Z_b \to B^*\bar{B}^*$

$$\mathcal{L}_{ZBB^*} = g_{ZBB^*} M_z Z^\mu (B\bar{B}^*_\mu + B^*_\mu \bar{B}) ,$$

$$\mathcal{L}_{Z'B^*B^*} = g_{Z'B^*B^*} \epsilon^{\mu\nu\alpha\beta} \partial_\mu Z'_\nu B^*_\alpha \bar{B}^*_\beta ,$$

✓ Lagrangian for pion and B(B*) meson

✓ Coupling g is determined by $D^* \to D\pi$

$$\mathcal{L}_I = ig\,\mathrm{Tr}[H_b \gamma_\mu \gamma_5 A^\mu_{ba} H_a] \quad g = 0.59$$

$$H_a = \left(\frac{1+\not{v}}{2}\right)[M^\mu_a \gamma_\mu - M_a \gamma_5]$$

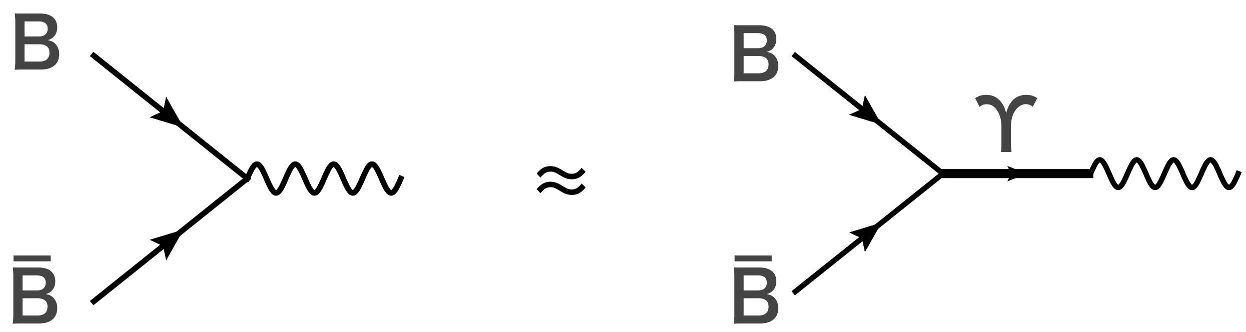
Couplings of Υ and B(B*)

P. Colangelo, et al,
PRD64 054023 (2004)

$$\mathcal{L}_2 = \frac{g_2}{2} \mathrm{Tr}[R^{(Q_1Q_2)} H_{2a} \overleftrightarrow{\not\partial} H_{1a}] + \mathrm{H.c.} + (Q_1 \leftrightarrow Q_2)$$

$$R^{(Q_1Q_2)} = \left(\frac{1+\not v}{2}\right)[L^\mu \gamma_\mu - L\gamma_5]\left(\frac{1-\not v}{2}\right)$$

✓ Vector meson dominance determines the couplings



$$< 0|b\gamma^\mu \bar{b}|\Upsilon >= f_\Upsilon \epsilon^\mu$$

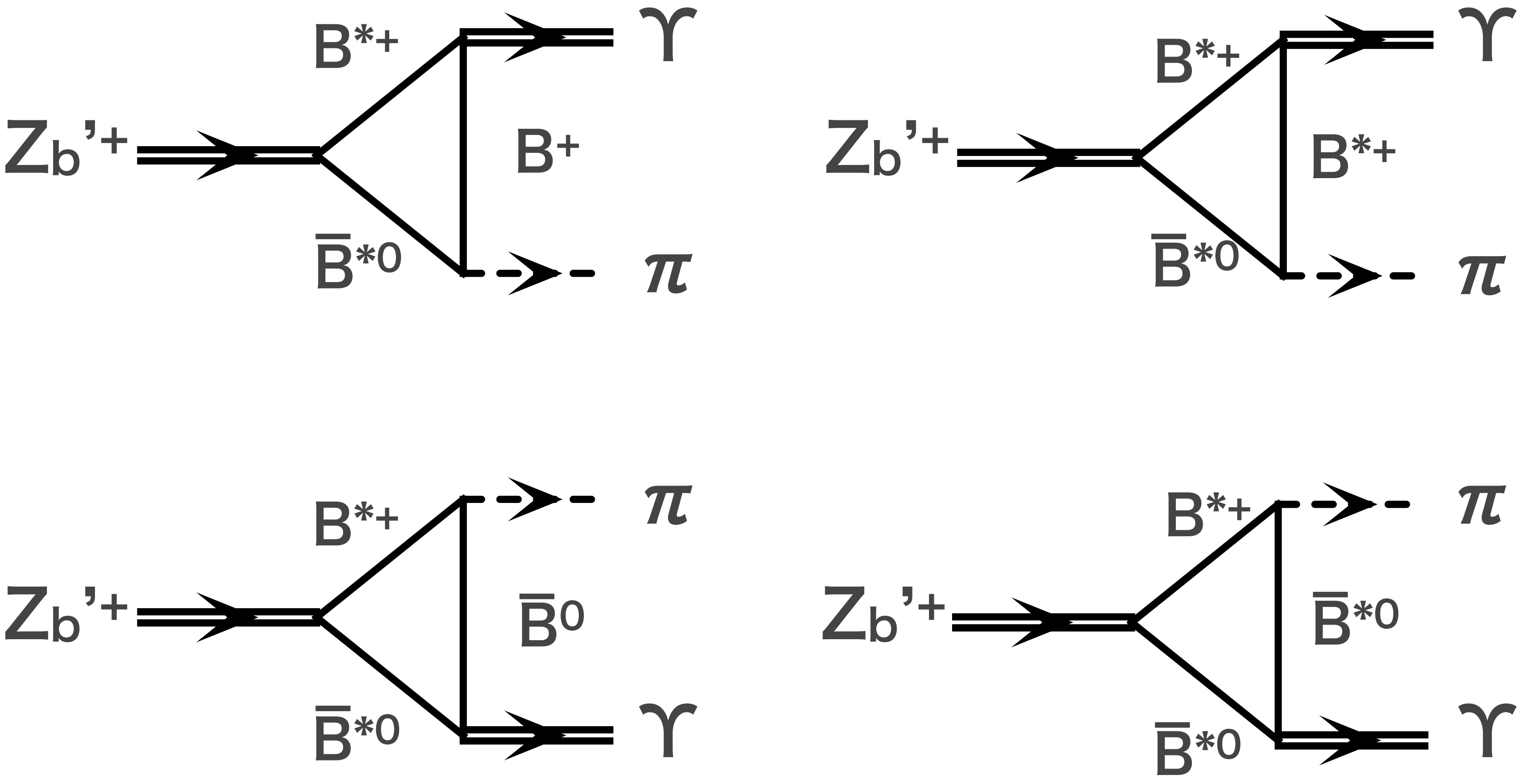
$$g_{BB\Upsilon(nS)} = \frac{m_{\Upsilon(nS)}}{f_{\Upsilon(nS)}}$$

$$g_{BB\Upsilon(1S)} = 13.2$$

$$g_{BB\Upsilon(2S)} = 20.1$$

$$g_{BB\Upsilon(3S)} = 24.1$$

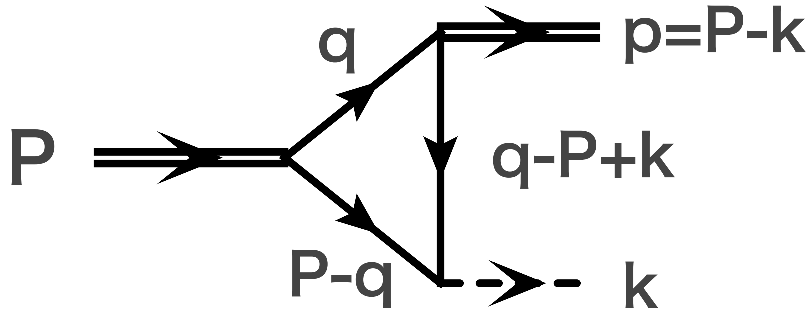
Diagrams for $Z_b'^+ \to \Upsilon(nS)\pi^+$



$$\mathcal{M}_{total} = 2\mathcal{M}^{(B)}_{B^*B^*} + 2\mathcal{M}^{(B^*)}_{B^*B^*}$$

Diagrams for $Z_b'^+ \to \Upsilon(nS)\pi^+$

✓ The explicit transition amplitude is given as follows



$$
\begin{aligned}
i\mathcal{M}^{(\mathrm{B})}_{\mathrm{B^*B^*}} = \; & (i)^3 \int \frac{d^4q}{(2\pi)^4} [ig_{z'}\epsilon_{\mu\nu\alpha\beta}P^{\mu}\epsilon_z^{\nu}\epsilon^{\alpha}_{B^{*+}}\epsilon^{\beta}_{\bar{B}^{*0}}] \\
& \times \; [ig_{B^*B^*\Upsilon(nS)}\epsilon_{\delta\tau\theta\phi}\upsilon^{\delta}\epsilon^{\tau}_{\upsilon}\epsilon^{\alpha}_{B^{*+}}(2q-P+k)^{\phi}][g_{BB^*\pi}(\epsilon_{\bar{B}^{*0}}\cdot k)] \\
& \times \; \frac{1}{(q)^2-m^2_{B^*}} \frac{1}{(P-q)^2-m^2_{B^*}} \frac{1}{(q-P+k)^2-m^2_B} \mathcal{F}(q^2,k^2)
\end{aligned}
$$

✓ We introduce the form factor

$$
\mathcal{F}(q^2,k^2) = \frac{\Lambda_Z^2}{q^2+\Lambda_Z^2}\frac{\Lambda^2}{k^2+\Lambda^2}\frac{\Lambda^2}{k^2+\Lambda^2}
$$

Numerical results

✓ Partial decay widths of $Z_b'(10650)$

	No Cutoff	$\Lambda_Z = 1000\,, \Lambda = 600$	exp
$\Upsilon(1S)\pi^+$	71.3	0.044	0.028
$\Upsilon(2S)\pi^+$	17.6	0.31	0.28
$\Upsilon(3S)\pi^+$	0.86	0.18	0.19

✓ Partial decay widths of $Z_b(10610)$

	No Cutoff	$\Lambda_Z = 1100\,, \Lambda = 600$	exp
$\Upsilon(1S)\pi^+$	95.5	0.081	0.059
$\Upsilon(2S)\pi^+$	19.8	0.51	0.806
$\Upsilon(3S)\pi^+$	0.485	0.14	0.396

✓ The momentum of final states mainly control the results.

✓ The form factor plays significant roll.

Summary

- We study the decay properties of Z_b as hadronic molecules.
- The spin structure of Z_b implies that $Z_b \to h_b \pi$
- Analyzing the spin structure gives useful information of the decay properties.
- We analyze the decays of $Z_b \to \Upsilon \pi$ with the intermediate meson loops and the form factor.