Effect of Z_b states on $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ decays

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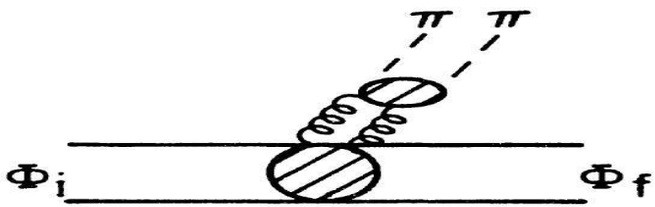
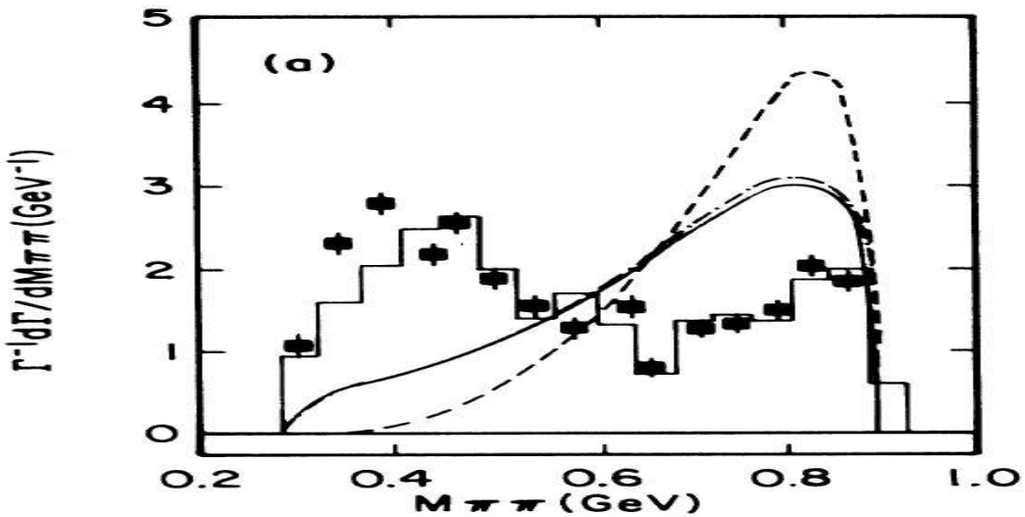
Outline

- Motivation
  - A problem in studying $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ within QCD multipole expansion
  - Solution: Z_b states ?
- Theoretical framework
  - Heavy meson chiral effective theory
  - Dispersion theory, modified Omnés solutions
- Phenomenology discussion
  - Numerical fits
  - Flatté parametrization
- Conclusions

- Typical theoretical method to study $\Upsilon(nS) \to \Upsilon(mS)\pi\pi$:
  QCD multipole expansion + soft-pion theorems



- A well-known anomaly for the $\pi\pi$ mass spectra of $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$
  - Experimental data: two-hump behavior
  - Theoretical prediction : a single peak



Various mechanisms to explain this discrepancy

- coupled-channel effects with open-bottom intermediate states
  [H. J. Lipkin and S. F. Tuan, PRL'1988]

- a hypothetical resonance which couples to $\Upsilon\pi$: $b\bar{b}q\bar{q}$, $I^G(J^P) = 1^+(1^+)$
  [V. V. Anisovich, D. V. Bugg, A. V. Sarantsev and B. S. Zou, PRD'1995]

- the $\pi\pi$ resonance [the $f_0(500)$ or σ meson] or strong $\pi\pi$ final-state interaction
  [G. Bélanger, T. A. DeGrand and P. Moxhay, PRD'1989]

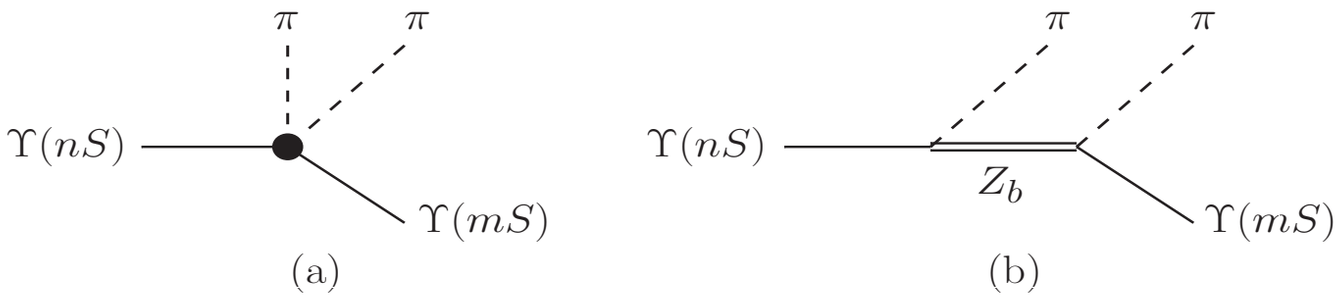
- relativistic corrections
  [M. B. Voloshin, PRD'2006]

In 2011, $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ were observed in the decay processes $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ and $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ $(m = 1, 2)$ by the Belle Collaboration. Their quantum numbers are indeed $I^G(J^P) = 1^+(1^+)$.

Our strategy:

- dispersion theory, based on unitarity, analyticity and crossing symmetry
  $\Rightarrow$ account for the $\pi\pi$ rescattering in a model-independent way
- consider the effects of the measured two Z_bs, which provide a left-hand-cut contribution
- the subtraction constants are obtained by matching the dispersive amplitudes to heavy meson chiral effective theory

- tree-level calculation



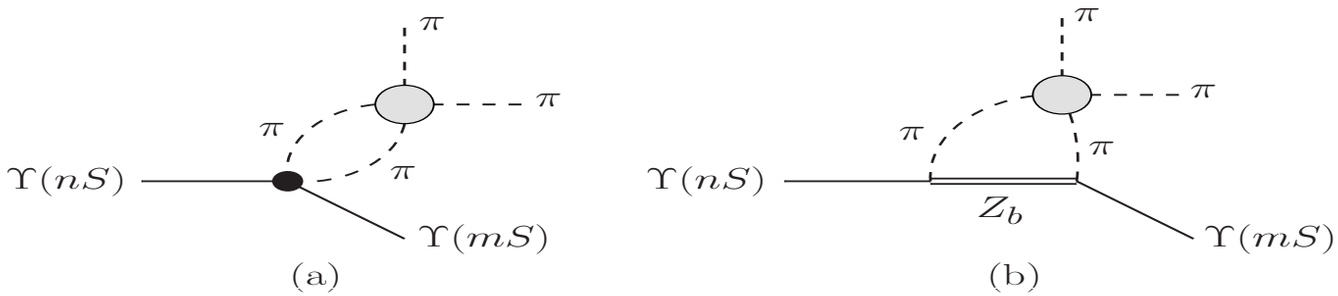
in the heavy-quark limit, the heavy quarks' spin decouples: $J \equiv \Upsilon \cdot \sigma + \eta_b$

$$\mathscr{L}_{\Upsilon\Upsilon'\pi\pi} = \frac{c_1}{2}\langle J^\dagger J'\rangle\langle u_\mu u^\mu\rangle + \frac{c_2}{2}\langle J^\dagger J'\rangle\langle u_\mu u_\nu\rangle v^\mu v^\nu + \text{h.c.} \tag{1}$$

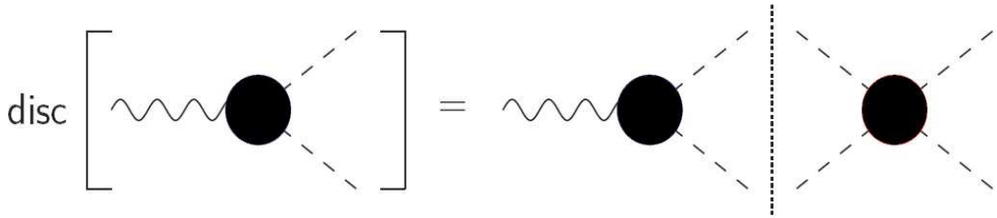
$$\mathscr{L}_{Z_b\Upsilon\pi} = C_Z \Upsilon^i \langle Z^{i\dagger} u_\mu\rangle v^\mu + \text{h.c.} \tag{2}$$

where $v^\mu = (1, \mathbf{0})$: the velocity of the heavy quark.

- pion-pion final-state interactions



- elastic unitarity



$$\frac{1}{2i}\text{disc}\, F_l(s) = \text{Im}\, F_l(s) = F_l(s) \sin \delta_l^I(s) e^{-i\delta_l^I(s)} \,. \tag{3}$$

Watson's theorem: phase of $F_l(s)$ is just $\delta_l^I(s)$, the elastic $\pi\pi$ phase shift

- traditional solution to this homogeneous integral equation [Omnès, Nuovo Cim'1958]

$$F_l(s) = P_n(s)\Omega_l^I(s)\,, \qquad \Omega_l^I(s) = \exp\left\{\frac{s}{\pi}\int_{4m_\pi^2}^{\infty} \frac{dx}{x}\frac{\delta_l^I(x)}{x-s}\right\}. \tag{4}$$

$P_n(s)$: polynomial; $\Omega_l^I(s)$: Omnès function

- inhomogeneous Omnès problem [A. V. Anisovich and H. Leutwyler,, PLB'1996]

$$\mathrm{Im}\, M_l(s) = \left[M_l(s) + \hat{M}_l(s)\right] \sin\delta_l^I(s) e^{-i\delta_l^I(s)} \,. \tag{5}$$

$$M_l(s) = \Omega_l^I(s)\left\{P_l^{n-1}(s) + \frac{s^n}{\pi}\int_{4m_\pi^2}^{\infty} \frac{dx}{x^n}\frac{\hat{M}_l(x)\sin\delta_l^I(x)}{|\Omega_l^I(x)|(x-s)}\right\}, \tag{6}$$

  - $\hat{M}_l(s)$: inhomogeneities, represent left-hand-cut contributions, here approximated by partial-wave projection of Z_b exchange only
  - $P_l^{n-1}(s)$: subtraction polynomial determined by matching to heavy meson chiral effective theory
  - $\delta_l^I(x)$: $\pi\pi$ phase shift as input, isospin I=0, S-wave and D-wave

- to calculate the $\pi\pi$ invariant mass spectrum and helicity angular distribution

$$\frac{d\Gamma}{d\sqrt{s}\, d\cos\theta} = \frac{\sqrt{s}\,\sigma_\pi|\mathbf{q}|}{128\pi^3 m_{\Upsilon(nS)}^2}\left|M_0(s) + \hat{M}_0(s) + (M_2(s) + \hat{M}_2(s))P_2(\cos\theta)\right|^2 , \tag{7}$$

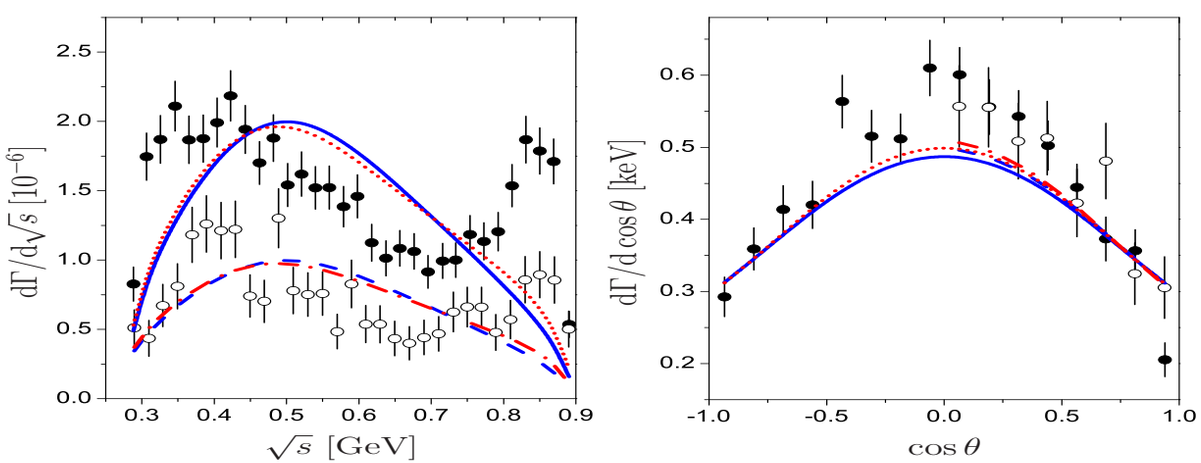
- naive extraction of the $Z_{bi}\Upsilon(nS)\pi$ coupling strengths.

TABLE : List of branching fractions for the $Z_b^+(10610)$ and $Z_b^+(10650)$ decays.

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	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
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

Belle[arXiv:1209.6450], using Breit–Wigner forms for Z_b line shapes.

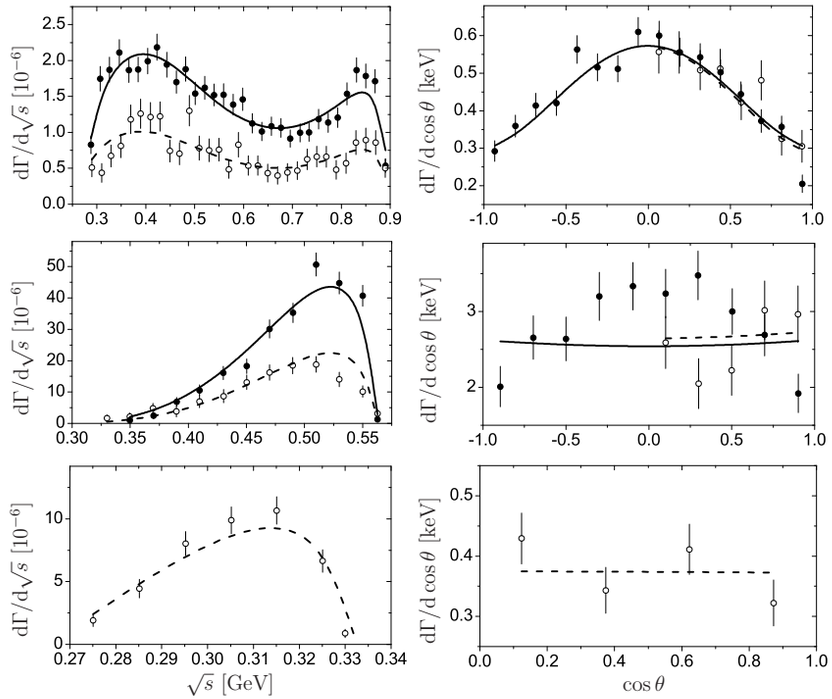
$|C^{naive}_{31,1}| = (0.014 \pm 0.004)$, $\quad |C^{naive}_{31,2}| = (0.004 \pm 0.001)$, $C_{nm,i} \equiv C_{Z_{bi}\Upsilon(nS)\pi} C_{Z_{bi}\Upsilon(mS)\pi}$



$\Upsilon(3S) \to \Upsilon(1S)\pi\pi$
fit $\pi\pi$ mass spectra and angle distribution
blue: without the Z_bs
red: using naive values of $Z_{bi}\Upsilon(nS)\pi$ couplings

- fit with the $Z_{bi}\Upsilon(nS)\pi$ coupling strengths as free parameters

the Z_{b1} and Z_{b2} are strongly correlated in the fit, therefore, we use only one Z_b state.



CLEO [PRD'2007]

from top to bottom:

$\Upsilon(3S) \to \Upsilon(1S)\pi\pi$,

$\Upsilon(2S) \to \Upsilon(1S)\pi\pi$,

$\Upsilon(3S) \to \Upsilon(2S)\pi\pi$.

	$\Upsilon(3S) \to \Upsilon(1S)\pi\pi$	$\Upsilon(2S) \to \Upsilon(1S)\pi\pi$	$\Upsilon(3S) \to \Upsilon(2S)\pi^0\pi^0$
c_1	-0.025 ± 0.001	0.09 ± 0.05	-0.6 ± 0.1
c_2	0.026 ± 0.001	0.04 ± 0.08	0.2 ± 0.3
$C_{nm,1}$	0.145 ± 0.006	1.3 ± 1.4	3.7 ± 2.6
$\frac{\chi^2}{\text{d.o.f}}$	$\frac{108.18}{87-3} = 1.29$	$\frac{101.68}{40-3} = 2.75$	$\frac{12.18}{11-3} = 1.52$

- Flatté parametrization VS Breit–Wigner parametrization

structure located very close to a strongly coupled threshold
$\Rightarrow$ Flatté parametrization, fulfills unitarity and analyticity
[S. M. Flatté,PLB'1976]

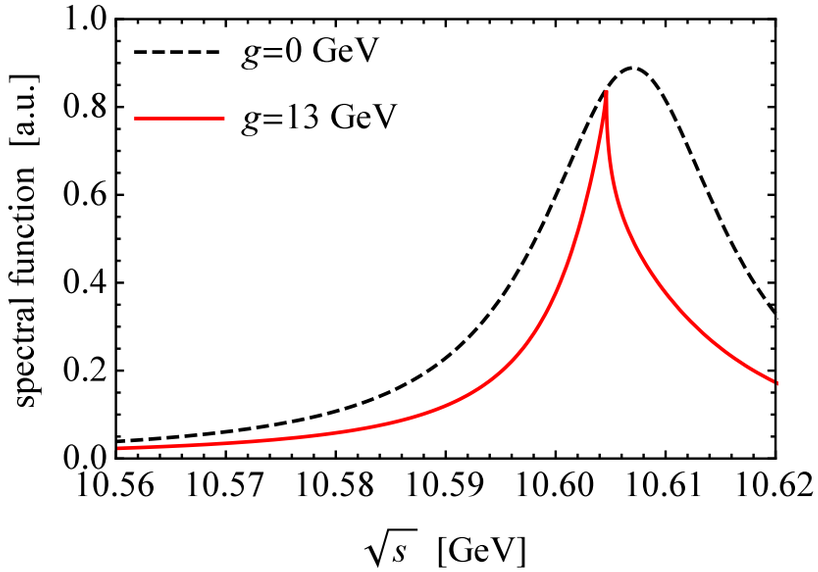
taking $Z_b(10610)$ as an example, $(Br_{B\bar{B}^*} = 86.0 \pm 3.6\%, M_B + M_{\bar{B}^*} = 10605$ MeV)

$\Gamma_{B\bar{B}^*}(s)$: $\frac{g^2}{8\pi m^2_{Z_{b1}}}\left[k\,\theta(\sqrt{s} - m_B - m_{B^*}) + i\,\kappa\,\theta(-\sqrt{s} + m_B + m_{B^*})\right]$,
Γ_1 (constant): the sum of other channels, like $\Upsilon(nS)\pi$, $h_b(mP)\pi$, $\eta_b\rho$, etc.

the Flatté parametrization for the Z_b spectral function is proportional to

$$\frac{1}{\left|s - m^2_{Z_{b1}} + i m_{Z_{b1}}\left[\Gamma_1 + \Gamma_{B\bar{B}^*}(s)\right]\right|^2}, \tag{8}$$

for either $\sqrt{s} > m_B + m_{B^*}$ or $\sqrt{s} < m_B + m_{B^*}$ the denominator becomes larger when g increases



a coupling to $B\bar{B}^*$ makes the Z_b spectral function narrower than Γ_1

$\Rightarrow$ in the Flatté parametrization, Γ_1 should be larger than the nominal width of the structure observed in the invariant mass distributions

Belle[arXiv:1209.6450], Breit–Wigner parametrization

- $\Gamma(Z_b(10610)) = (18.4 \pm 2.4)$ MeV
- summing over all the $\Upsilon(nS)\pi$ and $h_b(mP)\pi$ channels: about 14% in branching fraction or 3 MeV in partial width

$\Rightarrow$ $|C_{Z_{b1}\Upsilon(nS)\pi}|^2$ roughly one order larger than those from naive extraction.

$\Rightarrow$ calls for a detailed study for the data, using the formalism satisfies unitarity and analyticity [see C .Hanhart's talk]

Conclusions

- Dispersion theory can consider pion-pion final-state interaction in a model-independent way

- Z_b states can naturally explain the double-peak $\pi\pi$ mass spectrum in $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ decay

- The larger product of couplings $C_{Z_{b1}\Upsilon(3S)\pi} C_{Z_{b1}\Upsilon(1S)\pi}$ obtained here, is consistent with a rough estimate based on a Flatté parametrization, which is more appropriate for near-threshold states.

Thanks for your patience