# Implications of spin symmetry for XYZ states

Qian Wang

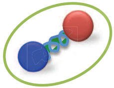
HISKP, Bonn Uni. ⇒ South China Normal University, Guangzhou, China

Hadron 2019


In collaboration with

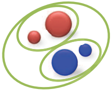
V.V. Baru, E.Epelbaum, A.A. Filin, C. Hanhart, A.V. Nefediev and J.-L. Wynen

# Interpretations



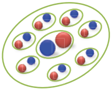
Hybrid

⇒ Compact $Q\bar{Q}$ with excited gluons



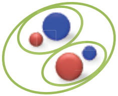
Tetraquark

⇒ Compact object formed from $Qq$ and $\bar{Q}\bar{q}$



Hadro-Quarkonium

⇒ Compact $Q\bar{Q}$ embedded in light quark cloud



Molecule

⇒ Extended object made of $Q\bar{q}$ and $\bar{Q}q$

Size $R \sim 1/\sqrt{E_B}$, with $E_B$ the binding energy

# Properties of hadronic molecule

- ⋆ Probability to find a resonance in continuum $1 - Z$,

  with $Z$ wave-function renormalization constant

  Molecule: $Z \to 0$; Compact: $Z \to 1$

- ⋆ Large effective coupling $g_{\rm eff}$ to continuum

  $\frac{g_{\rm eff}{}^2}{4\pi} = \frac{Z g_0^2}{4\pi} = 4M^2 \frac{\gamma}{\mu} (\underline{1 - Z}), \ \gamma = \sqrt{2\mu E_B}$ Weinberg (1963)

  Exp: $\underline{\mathcal{BR}(Z_b(10610) \to B\bar{B}^* + c.c.) \sim 85.6\%} \to B\bar{B}^*_{\rm candidate}$

- ⋆ Scattering length $a = -2\, \frac{1-Z}{2-Z} \left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right)$

  Effective range $r = -\frac{Z}{1-Z} \left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right)$

- ⋆ The pole counting approach

  poles on k-plane: $k_1 = i\gamma$ , $\quad k_2 = -i\gamma \left(\frac{2-Z}{Z}\right)$

Guo et al. (2018)

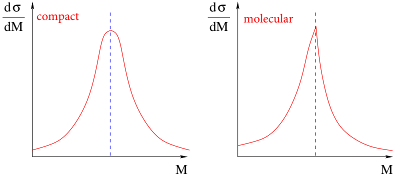
# Properties of hadronic molecule

⋆ Line shapes in inelastic channels

$$T_{\text{in.}}(E) \propto \frac{\sqrt{\Gamma_0}}{E - E_r + ({g_{\text{eff}}}^2/2)(ik+\gamma) + i\Gamma_0/2} \quad \text{with} \quad E = k^2/(2\mu)$$

Symmetric→

$g_{\text{eff}}$ ↓




← Asymmetric

$g_{\text{eff}}$ ↑

⇒ Directly relate to the experimental measurement

⇒ Extract relevant physical quantities, e.g. poles, $g_{\text{eff}}$

⇒ Shed light on the internal nature

Guo et al. (2018)

# Heavy Quark Spin Symmetry (HQSS)

- ⋆ Exotic XYZ states contain a heavy quark (HQ) pair
- ⋆ In the $\Lambda_{QCD}/m_Q \to 0$ limit, spin of HQ decouples

  $\Rightarrow$ Heavy and Light d.o.f conserved individually

  $\Rightarrow$ Test different scenarios — Cleven et al. (2015)

- ⋆ Molecule spin w.f. expanded in terms of $|H \otimes L\rangle$

  $\Rightarrow$ Spin partners related via $\mathcal{C}_L \equiv \langle H \otimes L|\hat{H}_{in}|H \otimes L\rangle$

  $\Rightarrow$ Predictions for the partners using $\mathcal{C}_L$

  Bondar et al. (2011), Voloshin (2011), Mehen and Powell (2011), Guo et al. (2015)

- ⋆ Role of OPE for molecular partners can be non-trivial

  $\Rightarrow$ $p_{\text{typ}} \sim \sqrt{2\mu\delta} \sim 500$ MeV $\geq m_\pi \rightarrow$ Non-perturbative

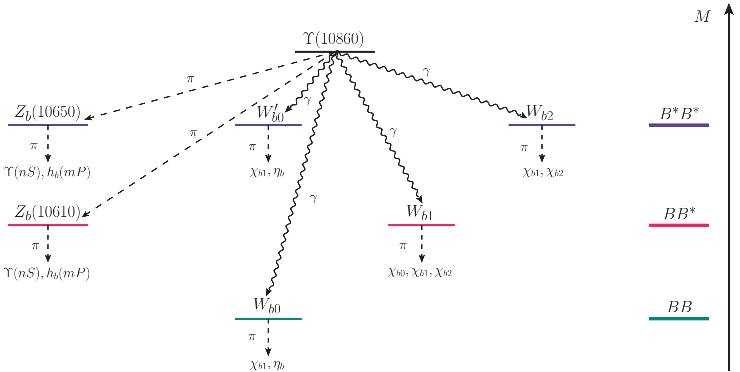
  with $\delta$ the energy gap between the relevant thresholds

  $\Rightarrow$ Tensor force $\rightarrow$ mixture of different partial waves

Baru et al. (2016), (2017)

# Production of $Z_b$ and $W_{bJ}$ in $\Upsilon(5S)$ decays

Baru et al. (2019)




- ⋆ Relevant thresholds
- ⋆ Decay modes

  ⇒ isotriplet

- ⋆ Exp.: $Z_b^{(\prime)}$ @ $B^{(*)}\bar{B}^{(*)}$, $h_b\pi$, $\Upsilon\pi$
- ⋆ $W_{bJ}$ with $J^{PC} = J^{++}$, J=0,1,2

  $\alpha$ suppression vs. huge statistics

# Formalism for line shapes of $\Upsilon(5S) \to Z_b^{(\prime)}\pi \to \alpha\pi$

- ⋆ Input: experimental distributions for

  $\Upsilon(5S) \to Z_b^{(\prime)}\pi \to \alpha\pi$ Belle: Bondar et al. (2012), Garmash et al.(2016)

  with $\alpha = B\bar{B}^*, B^*\bar{B}^*, h_b(1P)\pi,\ h_b(2P)\pi$

  branching fractions for

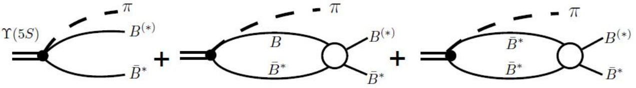
  $B\bar{B}^*, B^*\bar{B}^*, h_b(1P)\pi, h_b(2P)\pi, \Upsilon(1S)\pi, \Upsilon(2S)\pi, \Upsilon(3S)\pi$

- ⋆ Not include $\Upsilon(nS)\pi\pi$ distributions

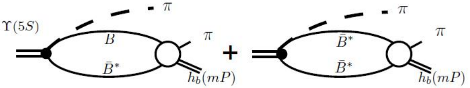
  → multi-dimensional analysis

- ⋆ Production amplitudes by the Zb's poles Baru @ Charm 2018

$U_{\rm el} =$




$U_{\rm inel} =$



# Formalism for line shapes: effective potential for $Z_b$

- ⋆ Production amplitudes $U = P - VGU$

  4 elastic $\alpha = B\bar{B}^*[^3S_1], B\bar{B}^*[^3D_1], B^*\bar{B}^*[^3S_1], B^*\bar{B}^*[^3D_1]$

  5 inelastic $i = h_b(1P)\pi, h_b(2P)\pi, \Upsilon(1S)\pi, \Upsilon(2S)\pi, \Upsilon(3S)\pi$

- ⋆ Neglect the direct interactions between $q\bar{q}$ and $b\bar{b}$

- ⋆ Effective elastic potentials: $V^{\text{eff}}_{\alpha\beta} = V^{\text{CT}}_{\alpha\beta} + V^{\pi}_{\alpha\beta} + V^{\eta}_{\alpha\beta}$

  Contact terms: $V^{\text{CT}}_{\alpha\beta} = v_{\alpha\beta} - \frac{i}{2\pi\sqrt{s}} \sum_j m_{b\bar{b}} m_\pi g_{j\alpha} g_{j\beta} k_j^{2l_j+1}$

  HQSS: divergence absorbed by the CTs

  ⇒ $g_{i1}/g_{i3} = 1$ for $i = 1, 2$; $-1$ for $i = 3, 4, 5$

  ⇒ Production amplitudes: $g_{\Upsilon(5S)1}/g_{\Upsilon(5S)3} = -1$

  ⇒ CTs: $\mathcal{O}(1)$-$\mathcal{C}_d, \mathcal{C}_l$, $\mathcal{O}(p^2)$-$\mathcal{D}_d, \mathcal{D}_l, \mathcal{D}_{SD}$

  HQSS violation: require more parameters

(The data do not require such parameters!) Wang et al.(2018), Baru et al.(2019)

# Fit scheme

- ⋆ Parameters in the fit

  2 elastic S-S wave contact terms at LO

  3 elastic contact terms at NLO: 1 S-D waves, 2 S-S waves

  5 inelastic-elastic constants

  In total: 10 vs. 5*4=20 parameters in BW parametrization

- ⋆ Fit schemes

  Scheme I: pure S-wave momentum-independent CTs

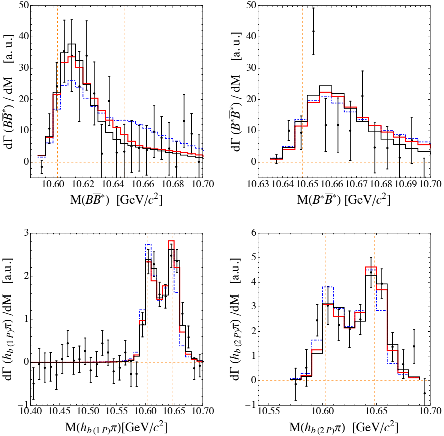
  Scheme II: plus full OPE and $\mathcal{O}(p^2)$ S-D CT

  Scheme III: plus OEE and $\mathcal{O}(p^2)$ S-S at NLO

Wang et al.(2018), Baru et al.(2019)

# The line shapes of $Z_b$s

Blue, red and black curves for I (1.29), II (0.95), III (0.83)



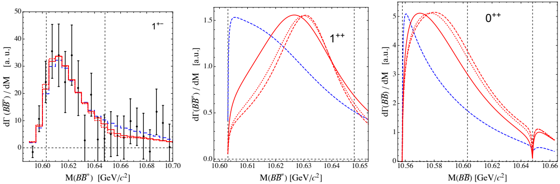

Belle (2012)(2016)

- ⋆ Scheme I agrees with the parameterization Guo et al.(2016)
- ⋆ Scheme I+OPE+HQSS violation does not work
  - ⇒ $\mathcal{O}(p^2)$ $\mathcal{D}_{SD}$ to LO
  - ⇒ cancel the S-D OPE
  - ⇒ Scheme II
- ⋆ small effect from $\mathcal{D}_{d/l}$ and OEE ⇒ Scheme III
  - ⇒ but ren. group invariant

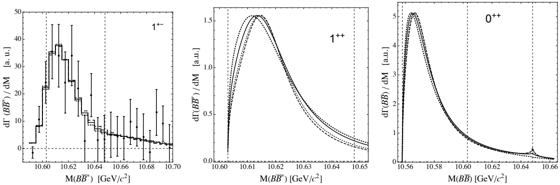
Wang et al.(2018), Baru et al.(2019)

# Renormalization group invariance

Scheme II: blue dashed, red solid, red dotted and red dashed curves for $\Lambda = 0.8$ GeV, 1.0 GeV, 1.2 GeV, 1.3 GeV




Scheme III: thick black dotted, black solid, black dotted and black dahsed curves for $\Lambda = 0.8$ GeV, 1.0 GeV, 1.2 GeV, 1.3 GeV

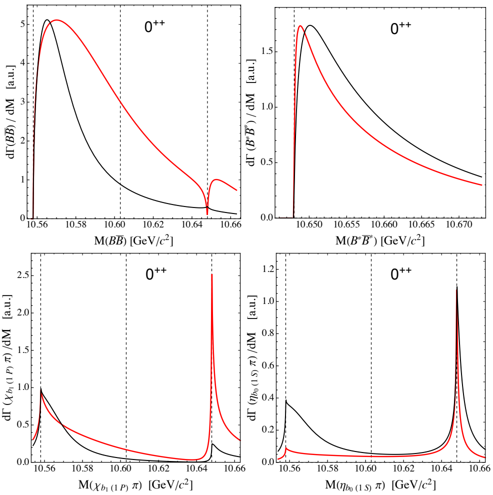



$\Rightarrow$ Scheme III is ren. group invariant

Baru et al.(2019)

# Lineshapes of $W_{bJ}$

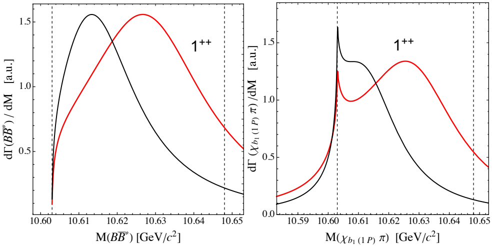
Baru et al.(2019)




- ⋆ Taking $\chi_{b1}(1P)\pi$ and $\eta_b(1S)\pi$ as an example
- ⋆ Red: Scheme II
  Black: Scheme III
- ⋆ Bump above threshold sizeable distortion at thr.
- ⋆ Asymmetric line shapes
- ⋆ Taking $W_{b0}$ as an example
  II: virtual st. below $B\bar{B}_{\rm thr}$
  III: resonance above $B\bar{B}_{\rm thr}$

# Lineshapes of $W_{bJ}$

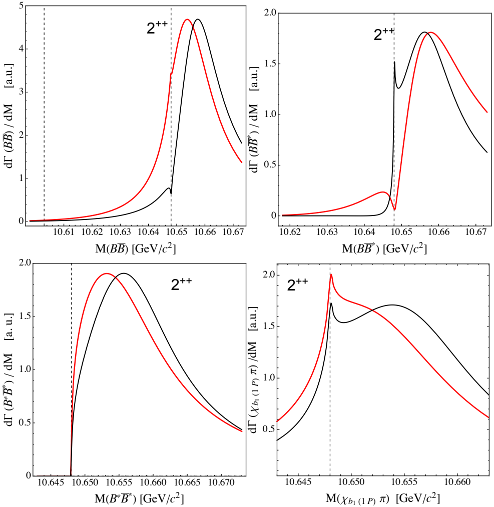
Baru et al.(2019)




- ⋆ Taking $\chi_{b1}(1P)\pi$ and $\eta_b(1S)\pi$ as an example
- ⋆ Red: Scheme II
  Black: Scheme III
- ⋆ Bump above threshold
  sizeable distortion at thr.
- ⋆ Asymmetric line shapes
- ⋆ Taking $W_{b0}$ as an example
  II: virtual st. below $B\bar{B}_{\rm thr}$
  III: resonance above $B\bar{B}_{\rm thr}$

# Lineshapes of $W_{bJ}$

Baru et al.(2019)




- ⋆ Taking $\chi_{b1}(1P)\pi$ and $\eta_b(1S)\pi$ as an example
- ⋆ Red: Scheme II  
  Black: Scheme III
- ⋆ Bump above threshold  
  sizeable distortion at thr.
- ⋆ Asymmetric line shapes
- ⋆ Taking $W_{b0}$ as an example  
  II: virtual st. below $B\bar{B}_{\rm thr}$  
  III: resonance above $B\bar{B}_{\rm thr}$

# Results: branching ratios

Wang et al.(2018), Baru et al.(2019)

⋆ Branching fractions (Exp vs. Theor) relative to $\mathcal{B}(B\bar{B}^*\pi)$

| $B^*\bar{B}^*\pi$ | $\Upsilon(1S)\pi\pi$ | $\Upsilon(2S)\pi\pi$ | $\Upsilon(3S)\pi\pi$ | $h_b(1P)\pi\pi$ | $h_b(2P)\pi\pi$ |
|---|---|---|---|---|---|
| $50 \pm 10$ | $0.6 \pm 0.3$ | $4 \pm 1$ | $2 \pm 1$ | $9 \pm 2$ | $15 \pm 3$ |
| $54.1^{+18.8}_{-18.1}$ | $0.6^{+0.4}_{-0.3}$ | $3.5^{+2.3}_{-1.5}$ | $1.8^{+1.6}_{-1.0}$ | $9.2^{+3.6}_{-2.4}$ | $14.9^{+6.0}_{-4.1}$ |

⋆ Predicted branching ratios for $W_{bJ}$s

$\chi_{b1}(1P)\pi$ for instance

| $J^{PC}$ | $B\bar{B}$ | $B\bar{B}^* + c.c.$ | $B^*\bar{B}^*$ | $\chi_{b1}(1P)\pi$ |
|---|---|---|---|---|
| $2^{++}$ | 0.06 | 0.07 | 0.54 | 0.03 |
| $1^{++}$ | – | 0.76 | – | 0.02 |
| $0^{++}$ | 0.73 | – | 0.14 | 0.05 |

⇒ Furthermore

$$\Gamma^{1^{++}}_{B\bar{B}^*(^3S_1)} : \Gamma^{2^{++}}_{B^*\bar{B}^*(^5S_2)} : \Gamma^{0^{++}}_{B\bar{B}(^1S_0)} : \Gamma^{0^{++}}_{B^*\bar{B}^*(^1S_0)} \approx 15 : 12 : 5 : 1$$

$$\Gamma^{2^{++}}_{B\bar{B}(^1D_2)} : \Gamma^{2^{++}}_{B\bar{B}^*(^3D_2)} : \Gamma^{0^{++}}_{B^*\bar{B}^*(^1S_0)} \approx 3 : 3 : 2.$$

→ strong coupling to the nearby elastic channels

→ the largest rates $\Upsilon(5S) \to \gamma W_{b1}(W_{b2}) \to \gamma B^{(*)}\bar{B}^*$ Belle-II

→ the first ratio is consistent with the results in Voloshin (2018)

# Results: pole positions

Pole positions of Scheme III: Baru et al.(2019)

| $J^{PC}$ | State | Threshold | $E_{\text{pole}}$ w.r.t. threshold [MeV] | Residue at $E_{\text{pole}}$ |
|---|---|---|---|---|
| $1^{+-}$ | $Z_b$ | $B\bar{B}^*$ | $(-2.3 \pm 0.5) - i(1.1 \pm 0.1)$ | $(-1.2 \pm 0.2) + i(0.3 \pm 0.2)$ |
| $1^{+-}$ | $Z_b'$ | $B^*\bar{B}^*$ | $(1.8 \pm 2.0) - i(13.6 \pm 3.1)$ | $(1.5 \pm 0.2) - i(0.6 \pm 0.3)$ |
| $0^{++}$ | $W_{b0}$ | $B\bar{B}$ | $(2.3 \pm 4.2) - i(16.0 \pm 2.6)$ | $(1.7 \pm 0.6) - i(1.7 \pm 0.5)$ |
| $0^{++}$ | $W_{b0}'$ | $B^*\bar{B}^*$ | $(-1.3 \pm 0.4) - i(1.7 \pm 0.5)$ | $(-0.9 \pm 0.3) - i(0.3 \pm 0.2)$ |
| $1^{++}$ | $W_{b1}$ | $B\bar{B}^*$ | $(10.2 \pm 2.5) - i(15.3 \pm 3.2)$ | $(1.3 \pm 0.2) - i(0.4 \pm 0.2)$ |
| $2^{++}$ | $W_{b2}$ | $B^*\bar{B}^*$ | $(7.4 \pm 2.8) - i(9.9 \pm 2.2)$ | $(0.7 \pm 0.1) - i(0.3 \pm 0.1)$ |

- ⋆ $Z_b$ and $W_{b0}'$ locate just @ the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds
- ⋆ $Z_b'$ and $W_{b0}$ as bumps
- ⋆ $W_{b1}$ and $W_{b2}$ pronounced peaks above-threshold
- ⋆ Poles with only CTs: virtual states.

  Difference from dynamic pion
- ⋆ Large effective couplings → molecular nature

# Summary

- ⋆ A systematic EFT approach w.r.t chiral and HQ symmetries
- ⋆ Satisfy unitarity and analiticity with inclusion of inelastic and OPE dynamically
- ⋆ Molecular picture describes the existing data of the two $Z_b$s well
  - ⇒ only one near-threshold pole
  - ⇒ large effective couplings
  - ⇒ asymmetric line shapes
- ⋆ Predict the spin partners $W_{bJ}$ in a parameter-free way
- ⋆ Outlook
  - ⇒ Proper inclusion of compact components
  - ⇒ Extension to SU(3) flavor group for light quarks

Thank you very much for your attention!