Heavy-quark spin-symmetry partners of Zb(10610) and Zb(10650) molecules

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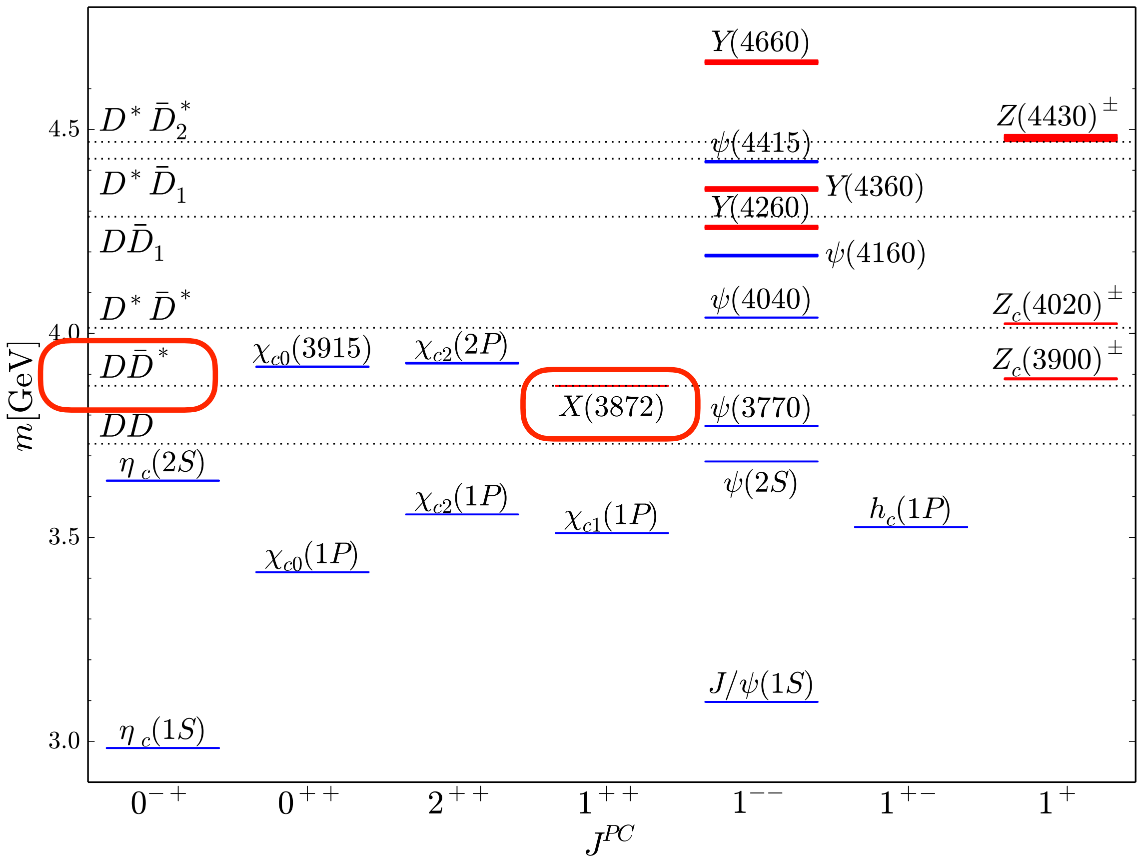
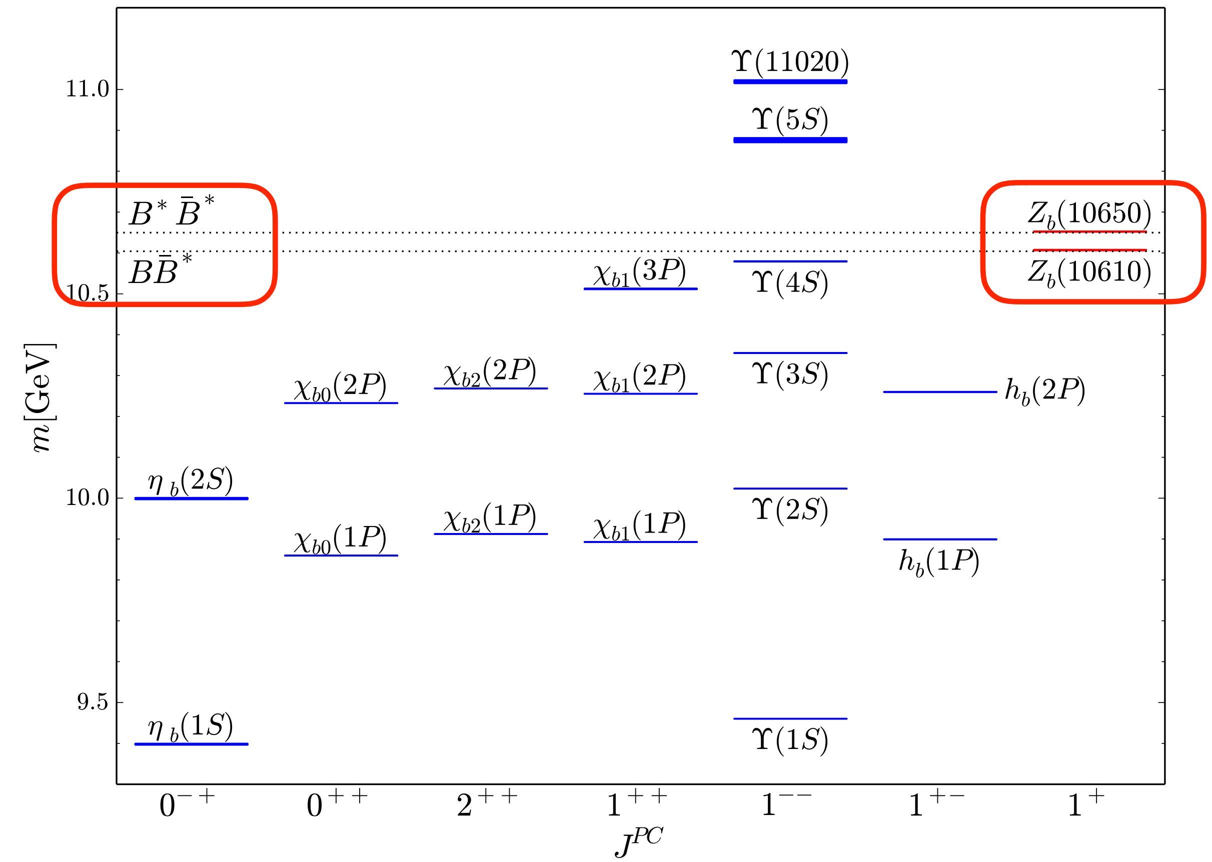
Key Refs: PLB 763, 20 (2016) and arXiv:1704.07332 (JHEP 2017)

Introduction

- Plenty of experimentally observed *XYZ* states do not fit in quark model picture





Enigmatic examples: $J^{PC} = 1^{++}$ X(3872) and 1^{+-} Zb(10610)/Zb(10650) Belle (2010-2016)

- decay predominantly to open-flavour channels
- reside very close to hadronic thresholds $\Longrightarrow$ hadronic molecules (talks by C. Hanhart and M. Karliner)
- strong coupling to nearby open flavour channels in S waves

But very precise measurements are needed to unambiguously disentangle from tetraquarks!

Esposito et al. (2014), Maiani et al.(2005)
(talk by L. Maiani)

Heavy quark spin symmetry

The XYZ states contain heavy quark and antiquark $\Longrightarrow$ employ heavy quark spin symmetry

☛ HQSS implies:

In the limit $\Lambda_{\rm QCD}/m_Q \to 0$ strong interactions are independent of HQ spin

☛ Consequences of HQSS — number of partner states, location and decay properties — are different for different scenarios Cleven et al. (2015)

(talk by Christoph Hanhart)

$\Longrightarrow$ Search for spin partner states $\Longrightarrow$ useful insights into the nature of XYZ states

This Talk: Discuss *HQSS* predictions for the molecular scenario

Molecular partners: contact theory

- Basis states $\mathbf{J^{PC}}$ made of a Pseudoscalar (P) and a Vector (V):

$$0^{++}: \quad \{P\bar{P}(^1S_0), V\bar{V}(^1S_0)\},$$
$$1^{+-}: \quad \{P\bar{V}(^3S_1,-), V\bar{V}(^3S_1)\},$$
$$1^{++}: \quad \{P\bar{V}(^3S_1,+)\},$$
$$2^{++}: \quad \{V\bar{V}(^5S_2)\}.$$

C-parity states: $C = \pm$ $\qquad PV(\pm) = \frac{1}{\sqrt{2}}\left(P\bar{V} \pm V\bar{P}\right)$

$P = D \text{ or } B\,, \qquad V = D^* \text{ or } B^*$

- Consequences of HQSS for S-wave contact interactions

Grinstein et al. (1992),
AlFiky et al. (2006),
Nieves and Valderrama (2012)

  - only two parameters at LO: LECs *C* and *C′*
  - $V_{\rm LO}^{(1++)}$ and $V_{\rm LO}^{(2++)}$ are the same!
  - *C* and *C′* –different for isoscalars and isovectors

$$V_{\rm LO}^{(0++)} = \frac{1}{4}\begin{pmatrix} 3\,C + C' & -\sqrt{3}(C - C') \\ -\sqrt{3}(C - C') & C + 3\,C' \end{pmatrix},$$
$$V_{\rm LO}^{(1+-)} = \frac{1}{2}\begin{pmatrix} C + C' & C - C' \\ C - C' & C + C' \end{pmatrix},$$
$$V_{\rm LO}^{(1++)} = V_{\rm LO}^{(2++)} \equiv C$$

- strict HQSS limit: *V-P* mass splitting much smaller than all other scales

$$\delta = m_* - m \ll E_{\rm Bound} \ll m$$

$\Longrightarrow$ solutions of coupled-channel problem: two decoupled sets of partner states

$$E_{1++}^{(0)} = E_{2++}^{(0)} = E_{1+-}^{(0)} = E_{0++}^{(0)} \quad \text{and} \quad E_{0++}^{(0)'} = E_{1+-}^{(0)'}$$

our work (2016)

our finding is in line with Hidalgo-Duque et al. (2013)

Contact theory with HQSS breaking

- Bondar et al. (2011), Voloshin (2011), Mehen and Powell (2011) propose a different expansion to account for HQSS breaking

$E_{\rm Bound} \ll \delta \ll m$ with

$\delta \simeq 140$ MeV $\delta/m \simeq 7\%$ in the c-sector

$\delta \simeq 45$ MeV $\delta/m \simeq 1\%$ in the b-sector

- Leading effect — the states reside near their thresholds: $P\bar{P}, \; P\bar{V}$ and $V\bar{V}$

For example: $M_{2^{++}} = M_{1^{++}} + \delta$

- Next-to-leading terms *O(δ)* and $O\left(\frac{\gamma^2}{\sqrt{m\delta}}\right) \simeq O\left(\sqrt{\frac{E_{\rm bound}}{\delta}}\gamma\right)$

our work (2016)

$D^*\bar{D}^* \to D\bar{D}^* \to D^*\bar{D}^*$

$B^*\bar{B}^* \to B\bar{B}^* \to B^*\bar{B}^*$

☛ Binding energies of 1^{+-} and 0^{++} states acquire an *Im* part due to coupled-channels

☛ 2^{++} tensor state is uncoupled $\Longrightarrow$ has no *Im* part in the contact problem

Contact + one-pion exchange (OPE) interactions

- Extended basis states:

☛ Coupled-channel transitions in S, D and even G-waves

$$0^{++}: \quad \{P\bar{P}(^1S_0), V\bar{V}(^1S_0), V\bar{V}(^5D_0)\},$$
$$1^{+-}: \quad \{P\bar{V}(^3S_1,-), P\bar{V}(^3D_1,-), V\bar{V}(^3S_1), V\bar{V}(^3D_1)\},$$
$$1^{++}: \quad \{P\bar{V}(^3S_1,+), P\bar{V}(^3D_1,+), V\bar{V}(^5D_1)\},$$
$$2^{++}: \quad \{P\bar{P}(^1D_2), P\bar{V}(^3D_2), V\bar{V}(^5S_2), V\bar{V}(^1D_2), V\bar{V}(^5D_2), V\bar{V}(^5G_2)\}$$

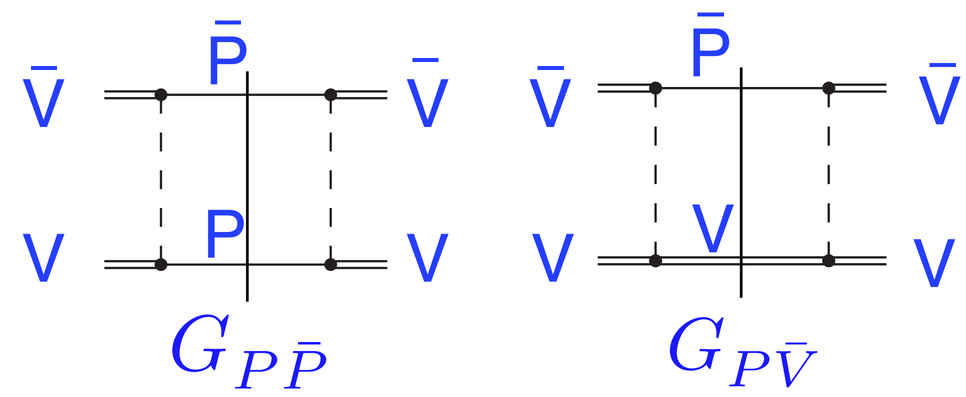
- coupled-channel dynamics is very important: inconsistent omission (as done by Nieves, Valderrama (2012)) $\Longrightarrow$ strongly cutoff dependent results — our work (2016)

- Pions enhance HQSS violation due to V-P mass splitting

$P = D$ and B $\quad$ $V = D^*$ and B^*

$P\bar{P}$ and $P\bar{V}$ intermediate states can go on shell

$\Longrightarrow$ also 2^{++} $V\bar{V}$ states acquire finite widths



- pionic (S-D) tensor forces play dominant role due to relatively large momentum scales

$\Longrightarrow$ Non-perturbative pion dynamics is to be important

Chiral EFT based approach for hadronic molecules

Our works: PLB 763, 20 (2016), arXiv:1704.07332 (JHEP 2017)

- A systematic approach for studying various molecular candidates with special emphasis on:

☛ pionic dof, coupled-channel dynamics, HQSS and the pattern of its breaking

☛ three-body effects ($P\bar{P}\pi$) and the $\boldsymbol{\eta}$-meson from SU(3) GB octet are included also

- nonperturbative solutions of the LS integral Eqs. for various $J^{PC} = 1^{++}, 2^{++}, 0^{++}$ and 1^{+-}

☛ Potential: contact operators (2 parameters) + OPE ⇒ input is needed!

☛ leading HQSS violation is included via the *V-P* mass splitting

- Can be applied to study very different aspects of light quark dynamics:

☛ identification of the long-distance modes in the resonance w.f. — Our works (2010)

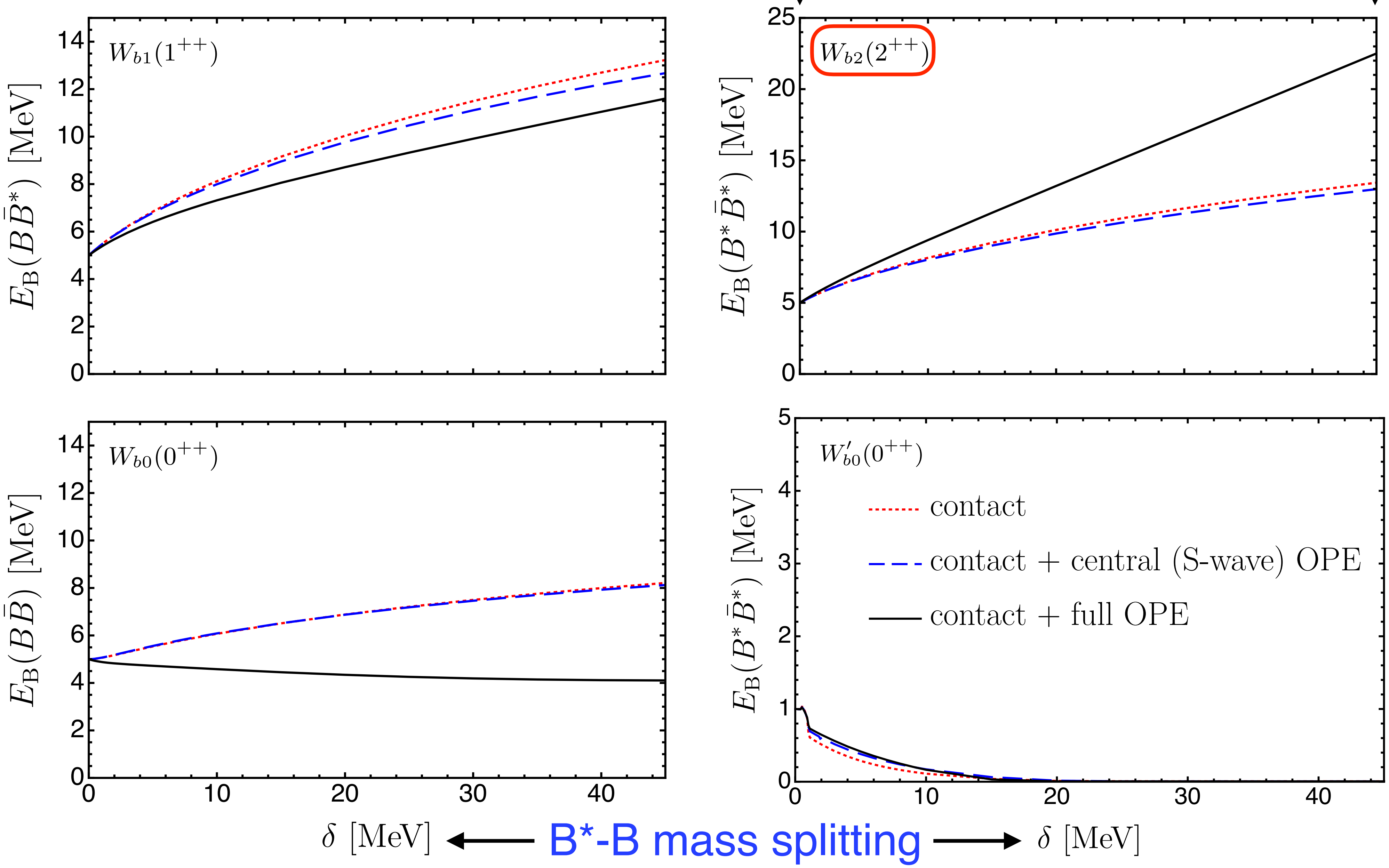
☛ implications of HQSS: 1^{++} X(3872), 1^{+-} Zb(10610)/Zb(10650), … — This Talk!

☛ chiral extrapolations of lattice results — Our works (2013), (2015)

Application: HQSS partners of Zb(10610)/Zb(10650)

Our work: arXiv:1704.07332 (JHEP 2017)

strict HQSS limit ↓ … Physical mass splitting ↓



Input:

E_{Zb} = 5 MeV

$E_{Zb'}$ = 1 MeV

consistent with Belle

Cleven et al. (2011)

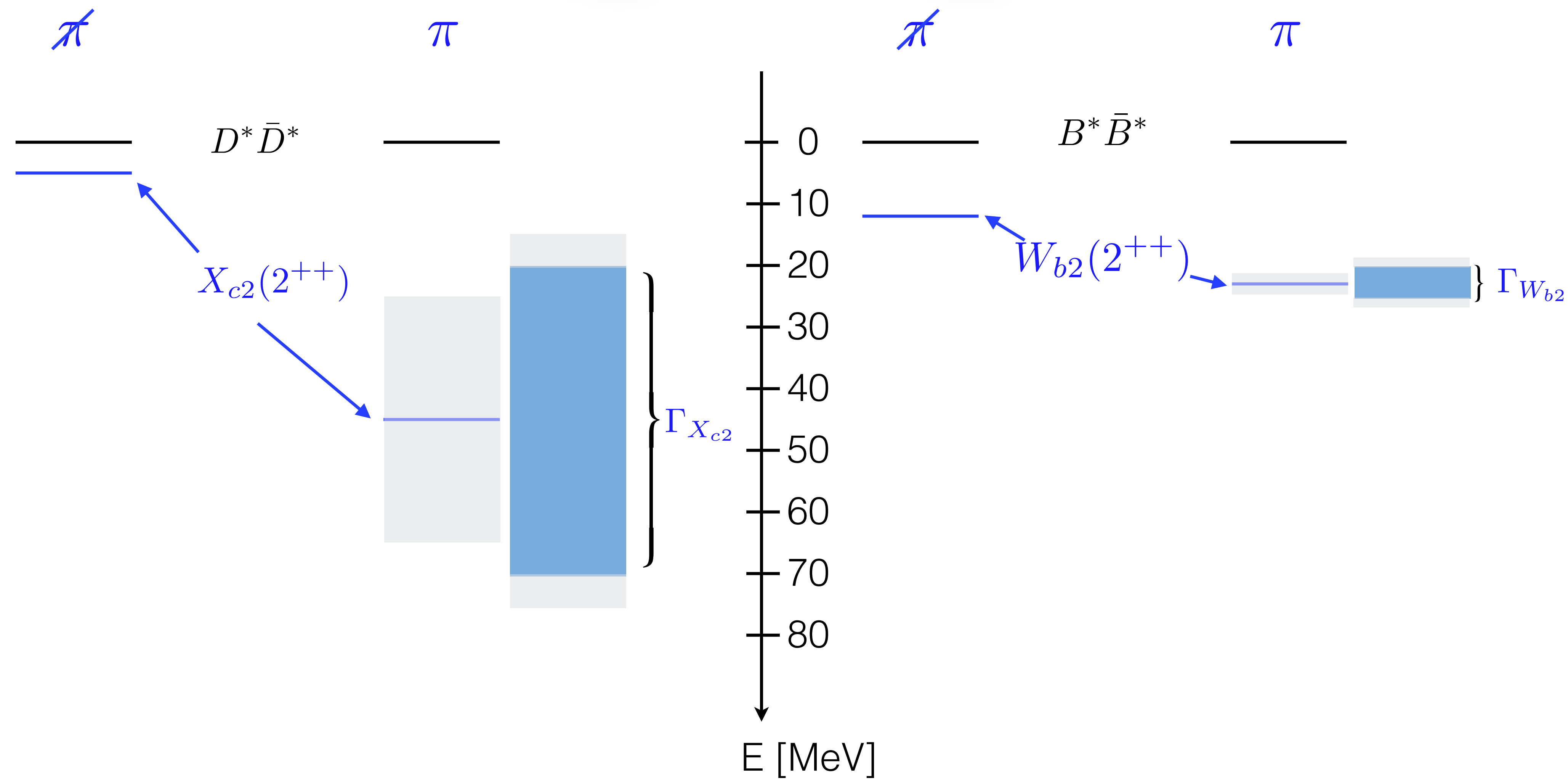
Refit contact terms for each value of δ!

- W_{b2} (0++), W_{b2} (1++) and W_{b2} (2++) remain bound for physical δ, W'_{b2} (0++) turn to be virtual
- W_{b2} (2++) state:
  - ☛ Binding energy exhibits large HQSS violation
  - ☛ OPE Tensor forces: large shift of E_B
  - ☛ Effect of η-meson is opposite to OPE but minor

HQSS implications: X(3872) vs Zb(10610)/Zb(10650)

Our works: PLB 763, 20 (2016), arXiv:1704.07332 (JHEP 2017)

2++ tensor partner X_{c2} vs W_{b2}



Impact of HQSS violation together with nonperturbative pions on the tensor:

- much larger than with perturbative pions
- much stronger in the c-sector than in the b-sector

For perturbative approach see Albaladejo et al. (2015)

Summary

- We propose a systematic approach consistent with chiral and heavy quark symmetries and including all relevant scales to probe various molecular candidates in *c* and *b*-sectors

- Applied in this talk to predict HQSS partners of X(3872) and Zb(10610)/Zb(10650)

☛ HQSS breaking and non-perturbative pions have significant impact on the partner states

☛ The effect from OPE is stronger in the c-quark sector, than in the b-quark one.

X_{c2++} is significantly shifted from D*D* threshold and has the width $\Gamma_{X_{c2++}} \simeq 50 \pm 10\ \mathrm{MeV}$

W_{b2++} is still located around $B^*\bar{B}^*$ threshold and has a few MeV width

$\Rightarrow$ should be detectable in $BB^{(*)}$ and also in $\chi_{b1}\pi$ and $\chi_{b2}\pi$ channels

- To predict other partners of the X(3872) one more experimental input is needed

Could X(3915) be a 0++ molecule — spin partner of X(3872)?

Talk by Alexey Nefediev

Spares

HQSS partners of the Zb(10610) and Zb(10650)

A comment on the sign of the OPE potential in isoscalar and isovector channels:

- Isospin coefficient: $3 - 2\,I\,(I+1) = \begin{cases} 3 & I=0 \\ -1 & I=1 \end{cases}$ — different signs
- sign also depends on C-parity

☛ central (S-wave) OPE for isospin-0 0^{++}, 1^{++} and 2^{++} states is attractive for 1^{+-} — repulsive

☛ central (S-wave) OPE for isospin-1 0^{++}, 1^{++} and 2^{++} states is repulsive for 1^{+-} — attractive

$\Longrightarrow$ Naively, OPE should reduce the binding energies of the partner states W_{b2} (0++), W_{b2} (1++) and W_{b2} (2++)

$\Longrightarrow$ But tensor forces (off diagonal transitions) bring additional attraction!