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Heavy-quark spin-symmetry partners of hadronic molecules

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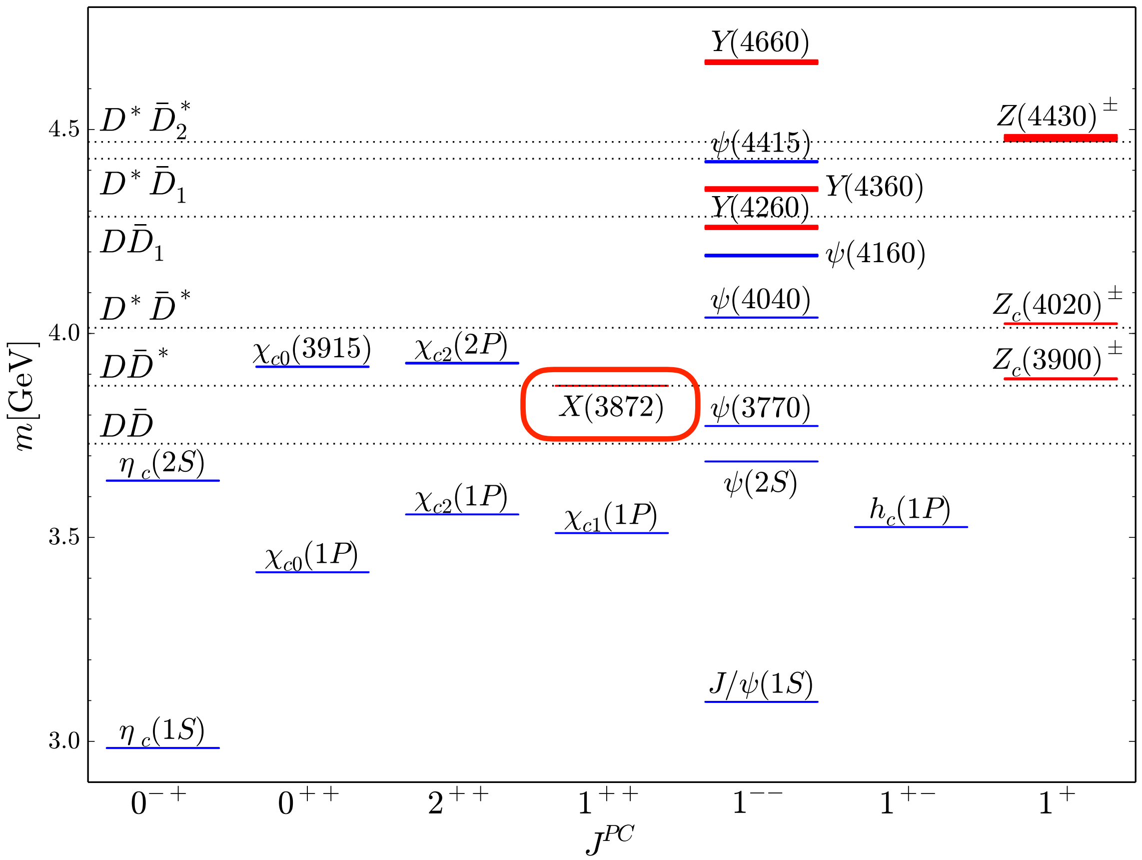
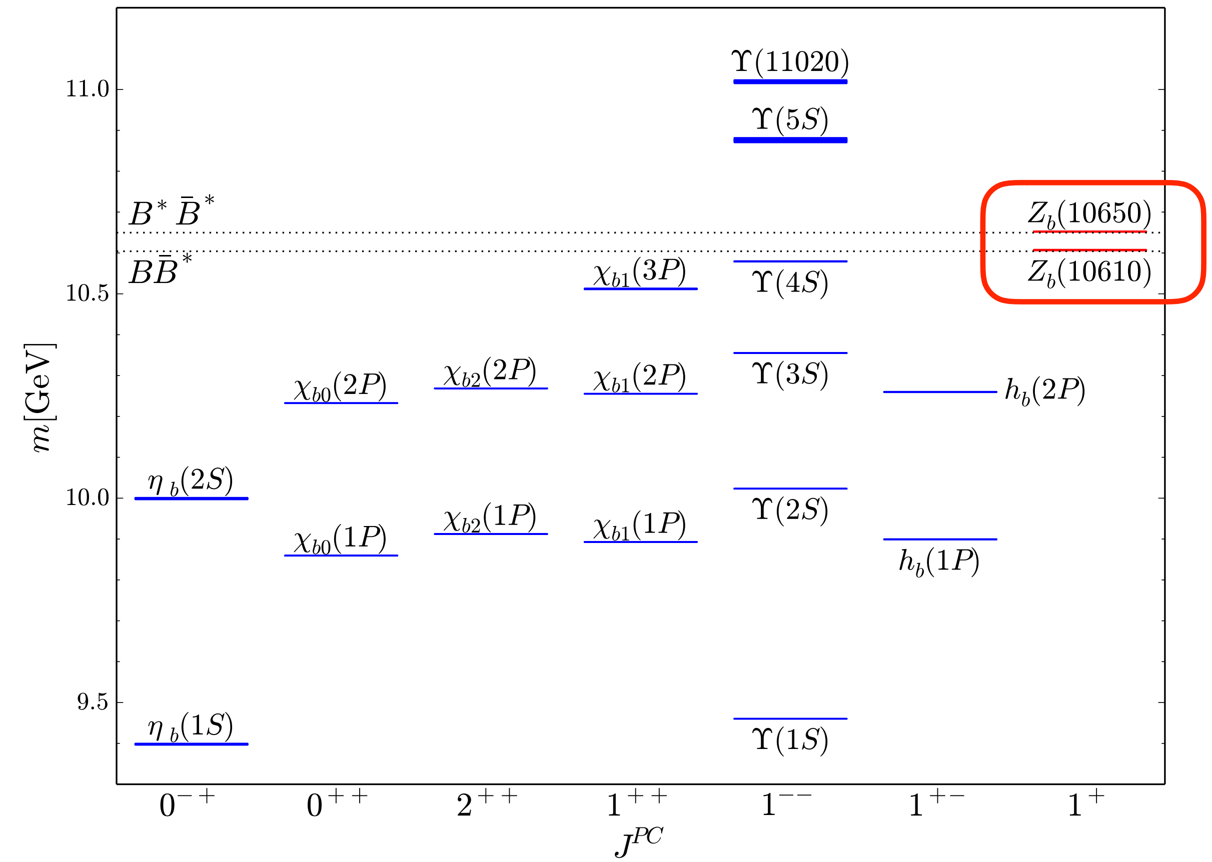
Key Refs: PLB 763, 20 (2016)

Introduction

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





Enigmatic examples:

☛ X(3872) is an isoscalar $J^{PC} = 1^{++}$ state residing near the $D\bar{D}^*$ threshold

☛ Zb(10610) and Zb(10650) are isovector $J^{PC} = 1^{+-}$ states very close to $B\bar{B}^*$ and $B^*\bar{B}^*$ decay predominantly to the open flavour channels   Belle (2011-2016)

$\Longrightarrow$ Different interpretations, most natural — hadronic molecules   (talk by Christoph Hanhart)

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 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

HQSS for hadronic molecules

- Spin partners of the Zb+(10610) and Zb+(10650): Bondar et al. (2011), Voloshin (2011), Mehen and Powell (2011)

  $J^{PC} = J^{++}$ states W_{bJ} with $J = 0, 1, 2$

- 2^{++} partner of the X(3872) as a shallow bound state in the $D^*\bar{D}^*$ system

  Nieves and Valderrama (2012), Guo et al. (2013)

☛ The width of the 2^{++} state using an EFT with perturbative pions: from a few Mev to about a dozen MeV Albaladejo et al. (2015)

<u>This Talk:</u>

- Revisit *HQSS* predictions for the isoscalar partners of the X(3872) and isovector partners of the Zb's

- Explore the role of coupled-channel dynamics

- Explore the role of pions and HQSS breaking effects

Molecular partners: contact theory

- Basis states **J^{PC}** made of a Pseudoscalar (P) and a Vector (V)

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

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

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

- S-wave derivativeless contact interactions respecting HQSS

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

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

$$V_{\rm LO}^{(1++)} = V_{\rm LO}^{(2++)} \equiv C$$

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

☛ two LECs at LO C and C'

☛ $V_{\rm LO}^{(1++)}$ and $V_{\rm LO}^{(2++)}$ are the same!

☛ C and C' – different for isoscalar and isovectors

☛ In the strict HQSS $\quad \delta = m_* - m \ll E_{\rm Bound} \ll m$

$\Longrightarrow$ two decoupled sets of partner states

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

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

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

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

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

Leading-order relations between the binding momenta of the partner states:

$$\gamma_{1^{+-}} = \gamma'_{1^{+-}}, \quad \gamma_{1^{++}} = \gamma_{2^{++}}, \quad \gamma_{0^{++}} = \frac{\gamma_{1^{+-}} + \gamma_{1^{++}}}{2}, \quad \gamma'_{0^{++}} = \frac{3\gamma_{1^{+-}} - \gamma_{1^{++}}}{2}$$

☛ δ is integrated out at this order

What about further corrections?

Contact theory with HQSS breaking

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

$$\gamma_{2++} = \left(1 - \frac{\delta}{2\bar{m}}\right)\gamma_{1++} + \frac{\delta\,\Lambda}{\pi\bar{m}} + O\left(\frac{\delta^2\Lambda}{\bar{m}^2}, \frac{\gamma_{1++}^2}{\Lambda}\right)$$

$$\gamma'_{1+-} = \left(1 - \frac{\delta}{2\bar{m}}\right)\gamma_{1+-} + \frac{\delta\,\Lambda}{\pi\bar{m}} - \frac{(\gamma_{1+-} - \gamma_{1++})^2}{\sqrt{\bar{m}\delta}} + i\,\frac{(\gamma_{1+-} - \gamma_{1++})^2}{\sqrt{\bar{m}\delta}} + \dots$$

☛ Correction at *O(δ)* is cutoff dependent ⇒ HQSS breaking contact term is needed

⇒ But small impact on the location of the states

☛ γ'_{1+-} acquires an *Im* part due to coupled-channels $D^*\bar{D}^* \to D\bar{D}^* \to D^*\bar{D}^*$, $B^*\bar{B}^* \to B\bar{B}^* \to B^*\bar{B}^*$

We will see that when pions are included the role of both HQSS breaking and coupled-channel dynamics is significantly enhanced!

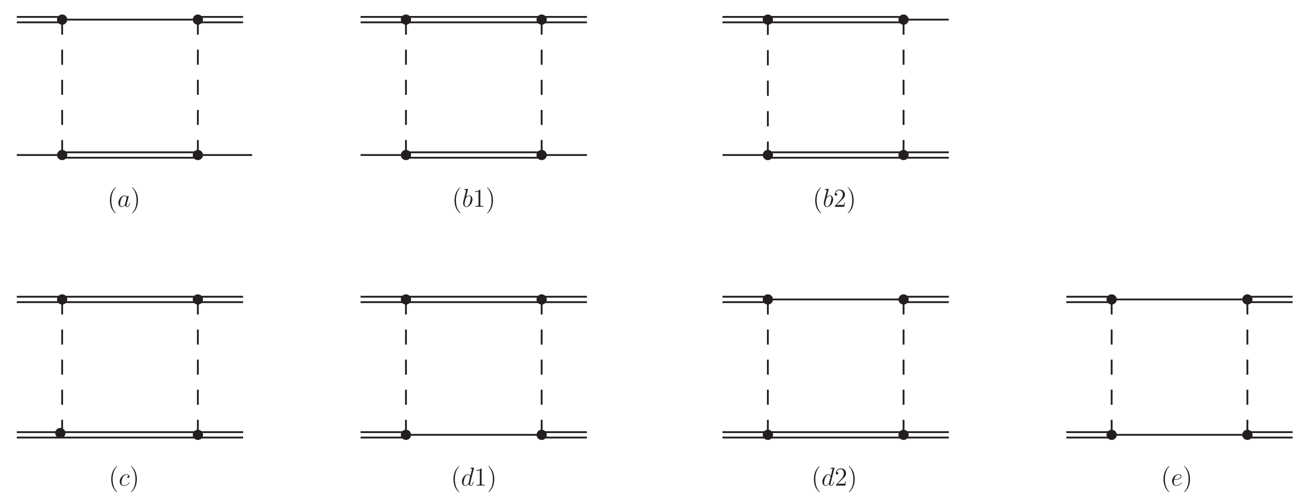
Strict HQSS limit in the presence of pions

- New transitions due to OPE $\Longrightarrow$ more coupled channels

For example, at one loop:

$D\bar{D}^*$

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



- Extended basis states:

$$
\begin{aligned}
0^{++}: &\quad \{D\bar{D}(^1S_0), D^*\bar{D}^*(^1S_0), D^*\bar{D}^*(^5D_0)\},\\
1^{+-}: &\quad \{D\bar{D}^*(^3S_1,-), D\bar{D}^*(^3D_1,-), D^*\bar{D}^*(^3S_1), D^*\bar{D}^*(^3D_1)\},\\
1^{++}: &\quad \{D\bar{D}^*(^3S_1,+), D\bar{D}^*(^3D_1,+), D^*\bar{D}^*(^5D_1)\},\\
2^{++}: &\quad \{D\bar{D}(^1D_2), D\bar{D}^*(^3D_2), D^*\bar{D}^*(^5S_2), D^*\bar{D}^*(^1D_2), D^*\bar{D}^*(^5D_2), D^*\bar{D}^*(^5G_2)\}
\end{aligned}
$$

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

- EFT at LO — contact terms + static OPE — does not depend on the heavy-quark mass

$\Longrightarrow$ two decoupled sets of partner states

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

- But HQSS predictions hold only if all particle coupled channels are included!

Neglecting $D^*\bar{D}^* \to D\bar{D} \to D^*\bar{D}^*$, $D^*\bar{D}^* \to D\bar{D}^* \to D^*\bar{D}^*$ transitions as done by Nieves, Valderrama (2012) $\Longrightarrow$

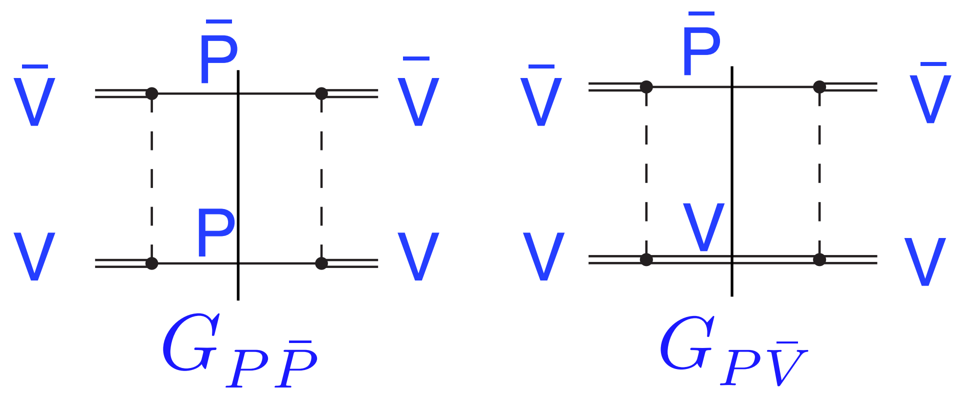
$\Longrightarrow$ severe violation of HQSS

Contact + OPE interactions: including HQSS breaking

- Switch on V–P mass splitting $\Longrightarrow$ 2^{++} $V\bar{V}$ states acquire finite widths

Example of transitions which cause the Imaginary part of the amplitudes:

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



- *Relevant momentum scales* stem from coupled-channels induced by OPE tensor forces

$D\bar{D}$ and $B\bar{B}$: $\quad q_1 = \sqrt{2\delta\bar{m}} \approx 700$ MeV $\quad$ from $\quad G_{P\bar{P}} = \dfrac{1}{(k^2/2\mu - 2\delta - E - i0)}$

$D\bar{D}^*$ and $B\bar{B}^*$: $\quad q_2 = \sqrt{\delta\bar{m}} \approx 500$ MeV $\quad$ from $\quad G_{P\bar{V}} = \dfrac{1}{k^2/2\mu_* - \delta - E - i0}$

$\Longrightarrow$ D-wave coupled-channel transitions are not suppressed relative to S-wave ones

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

Applications

1) HQSS partners of the X(3872)

- ☛ the X(3872) can be used as input to fix the contact term C
- ☛ the 2++ partner X_{2++} can be predicted
- ☛ no other evident molecular candidates are experimentally observed yet

$\Longrightarrow$ no input to fix C' $\Longrightarrow$ solid predictions for other partner states are not possible yet

2) HQSS partners of the Zb(10610) and Zb(10650) to appear very soon in arXiv (2017)

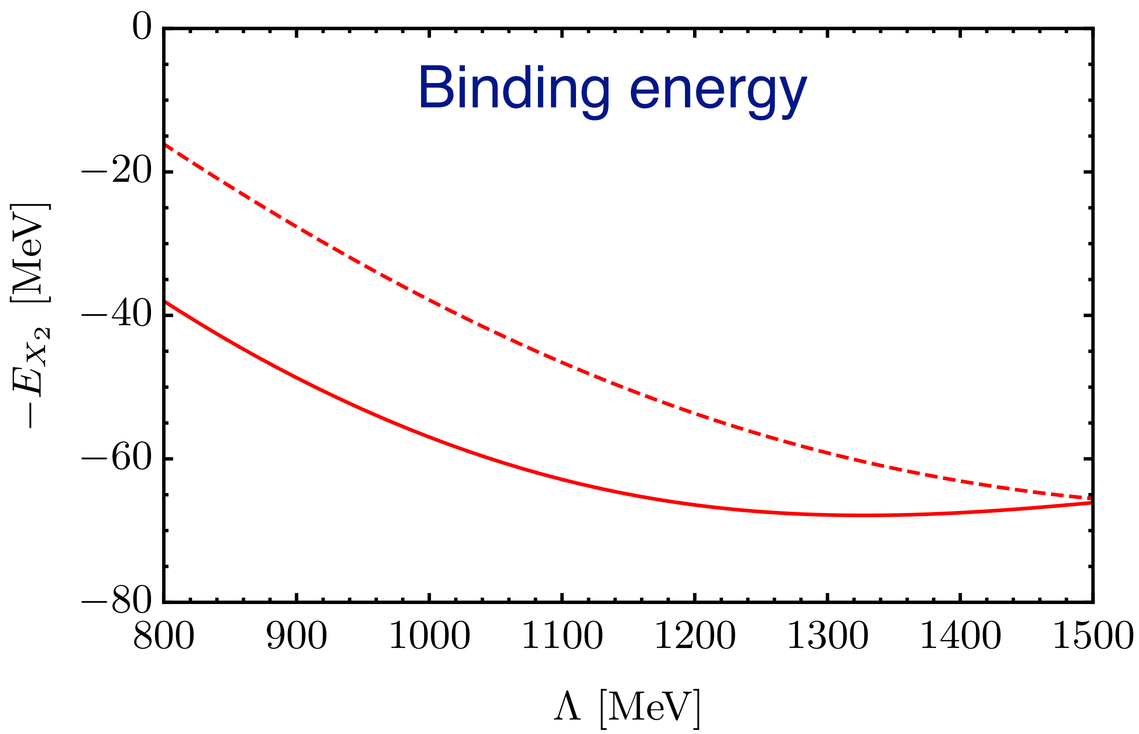
- ☛ assuming that the Zb states are bound, fix both C and C'
- ☛ solve the coupled-channel integral equations for the contact + OPE potential

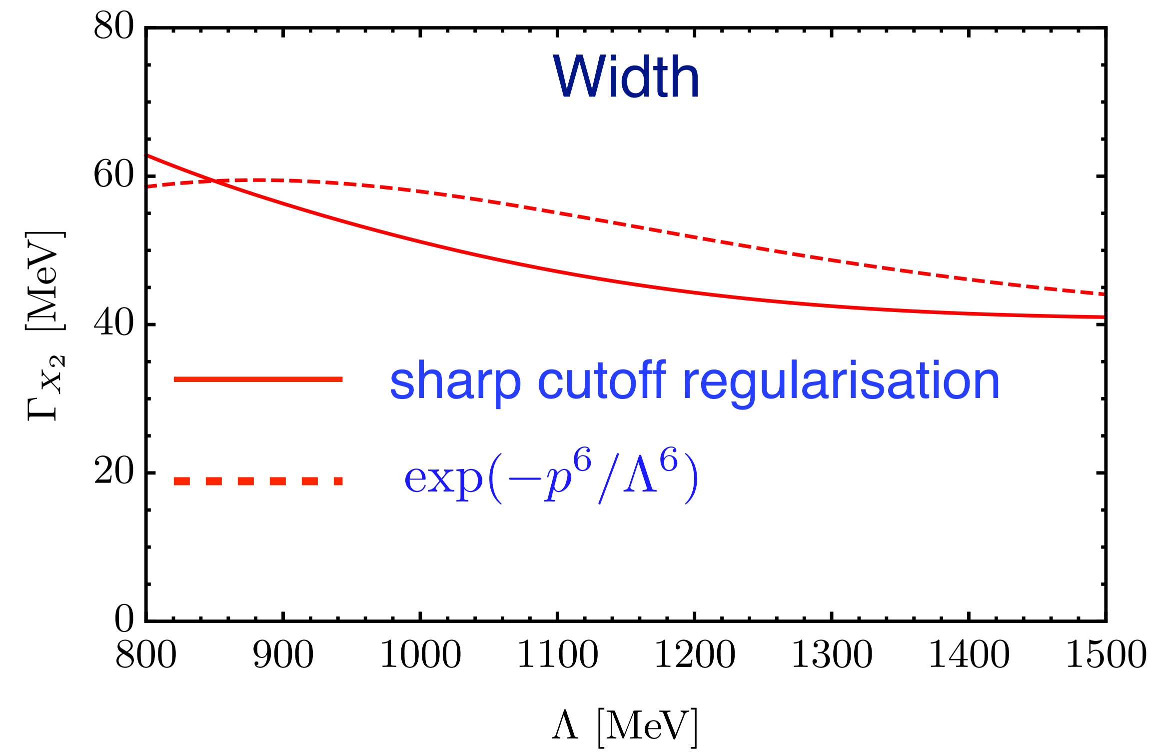
$\Longrightarrow$ predict the other partner states

2^{++} Partner of the X(3872)

our work (2016)

- Attraction generated by tensor part of the OPE in combination with HQSS breaking yield





Relatively Λ independent due to unitarity

☛ Significant shift of $E_{X_{2++}}$ from $D^*\bar{D}^*$ threshold and large width $\Gamma_{X_{2++}} \simeq 50 \pm 10$ MeV

much larger than in the perturbative study
Albaladejo et al. (2015)

☛ Cutoff variation $\Longrightarrow$ rough estimate of a higher-order HQSS breaking contact term at *O(δ)*

Cutoff dependence at smaller cutoffs is due to bad separation of soft and hard scales

Open Questions and Theory To-Do List

- Relatively small separation of scales may call the convergence of the EFT into question

  ☛ include explicitly the members of SU(3) pseudoscalar octet as well as vector mesons

- Investigate the role of three-body effects in the OPE potential

  For the role of three-body dynamics for the X(3872) see Fleming et al. (2007), our works (2010-2015), Jansen et al. (2015), Guo et al. (2014)

  ☛ Since the main contribution to the width of the 2^{++} $D^*\bar{D}^*$ state stems from coupled channels, three-body effects are not expected to change the picture qualitatively

  ☛ Bring additional Imaginary parts from the right-hand cut

  ☛ Bring additional HQSS corrections due to D, D* energies

- Estimate HQSS violating contact terms more reliably

- Explore the role of the $c\bar{c}$ component in the wave function of the X(3872)

  Cincioglu et al. (2016)

Remark on the X(3915)

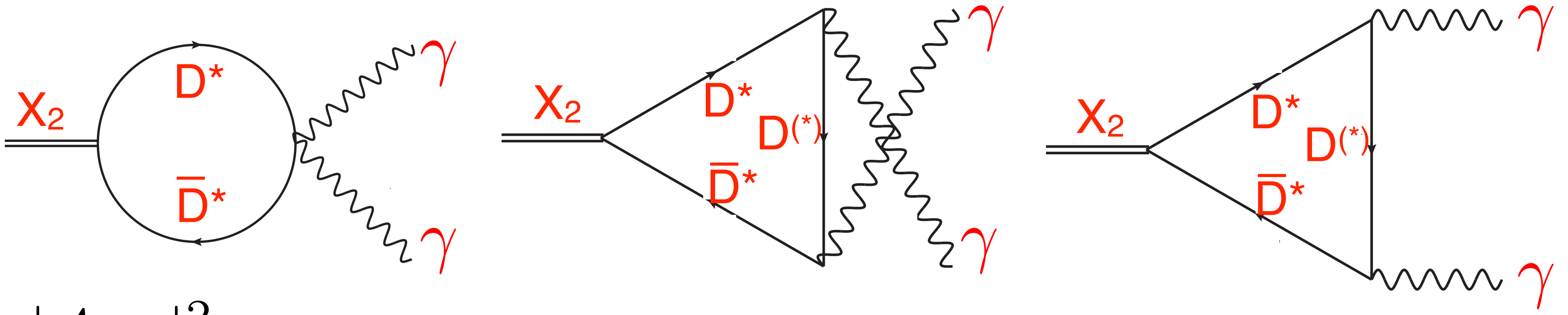
- X(3915) is seen by Belle (2010) in $\gamma\gamma \to \omega J/\Psi$ $\Longrightarrow$ $J^{PC} = 0^{++}$ or 2^{++}
- Babar (2012): angular distributions in $\gamma\gamma \to \omega J/\Psi$ favour 0^{++} if helicity-2 dominance is assumed for the tensor state like in conventional charmonia

- Zhou et al. (PRL 2015): ☛ X(3915) could be an exotic state and then

☛ Data by BaBar are better described if the X(3915) is a helicity-0 realisation of the 2^{++} state identified with $\chi_{c2}(3930)$

- V.B., Hanhart and Nefediev (2017): arXiv 1703.01230 ☛ assume X(3915) is a 2^{++} spin partner of X(3872)

☛ evaluate the helicity-0 contribution to the width



☛ Using data extract $R = \dfrac{|A_{\pm 2}|^2}{|A_0|^2} \simeq 11 \gg 1$

☛ X(3915) is either not a spin partner of the X(3872) or a 0^{++} state

☛ But uncertainty is hard to estimate

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

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

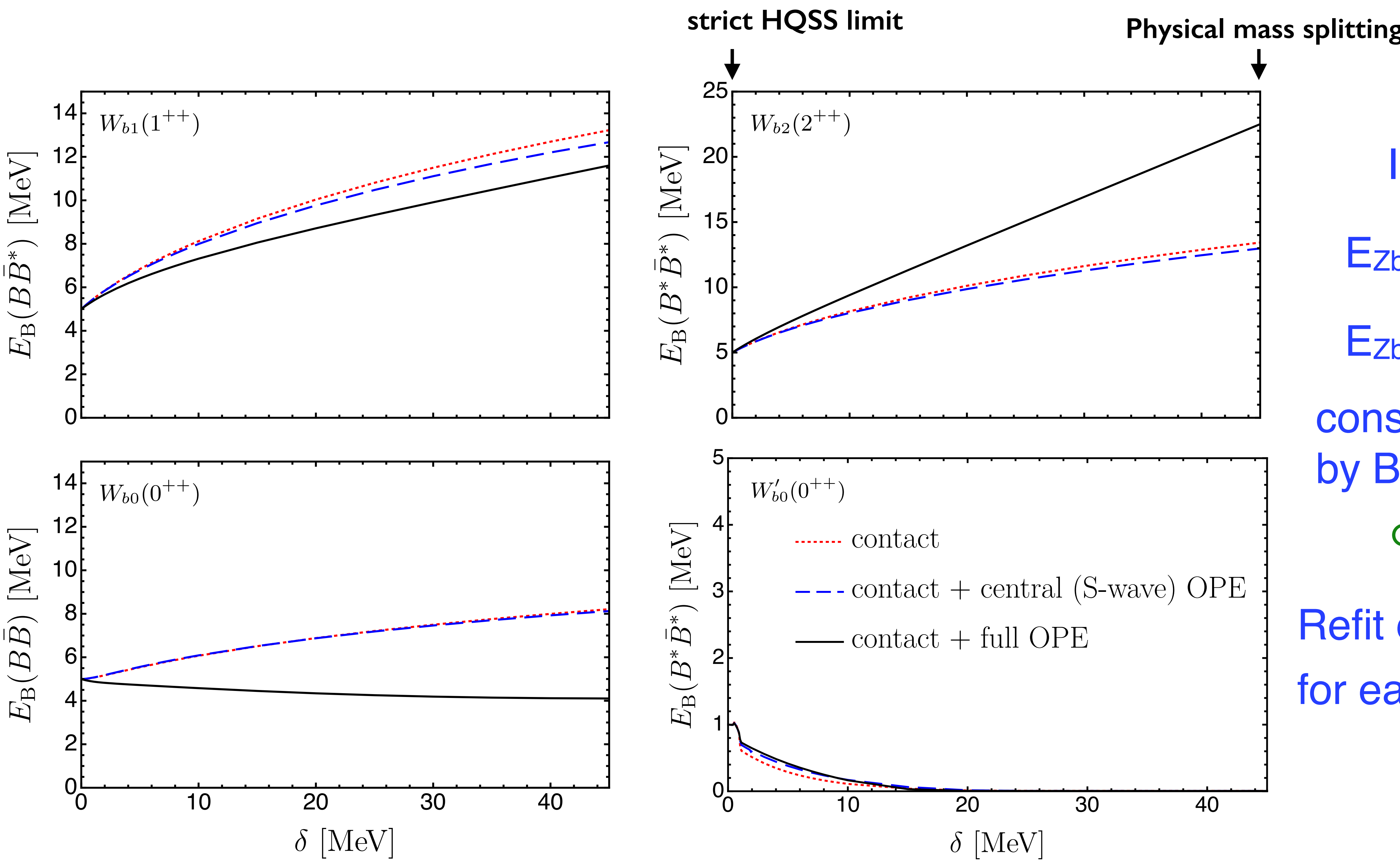
☛ central (S-wave) OPE for isospin-0 0^{++}, 1^{++} and 2^{++} states is attractive for 1^{+-} — repulsive

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

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

⟹ But tensor forces (off diagonal transitions) bring additional attraction!

Evolution of the Z_b's partner states binding energies with δ



Input:

E_{Zb} = 5 MeV

$E_{Zb'}$ = 1 MeV

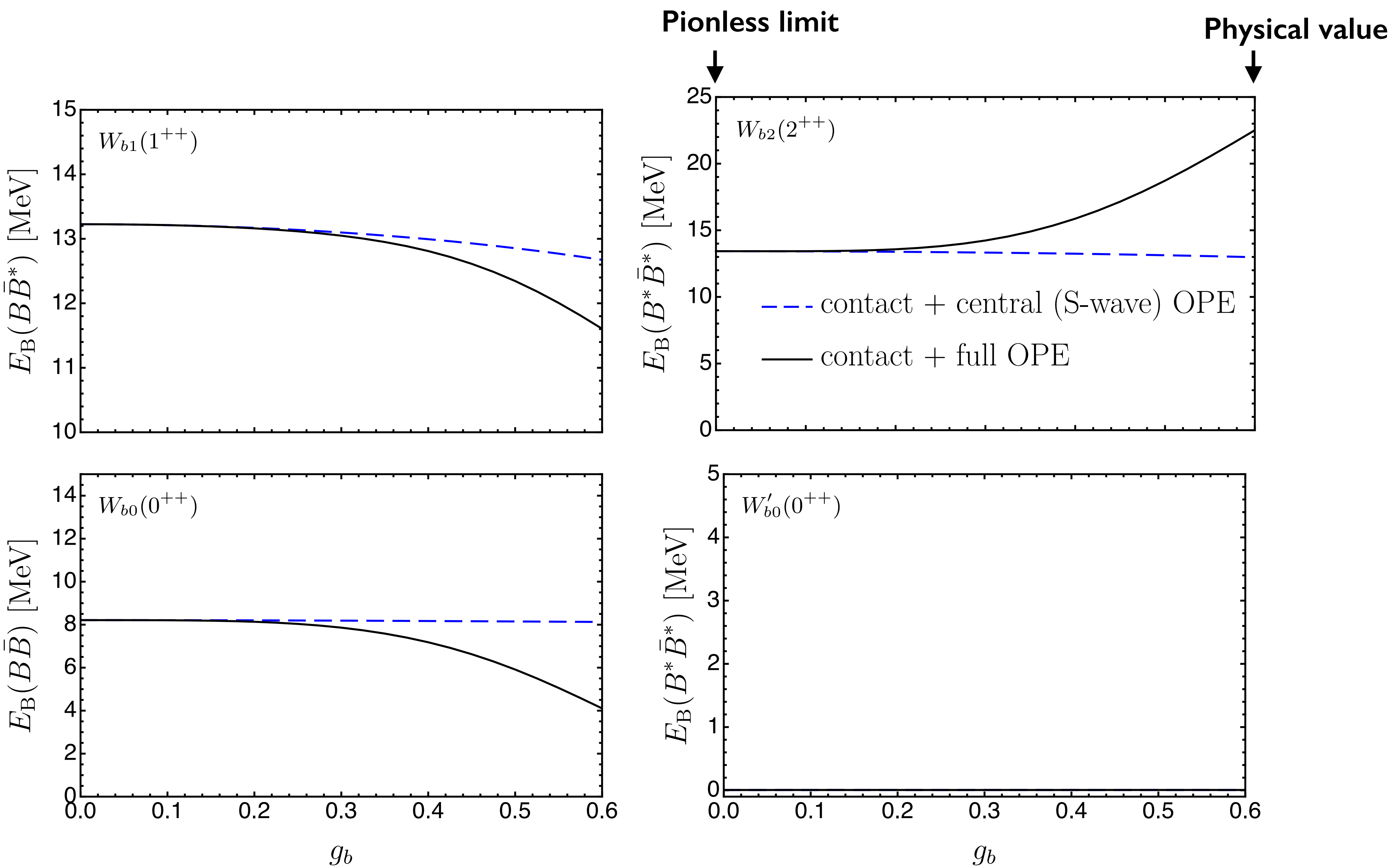
consistent with data by Belle

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
  - ☛ OPE Central (Swave) force is not important

Z_b's partner states vs pion coupling constant g_B



Input:

E_{Zb} = 5 MeV

$E_{Zb'}$ = 1 MeV

consistent with data by Belle

Cleven et al. (2011)

Physical value of g_B from HQSS:

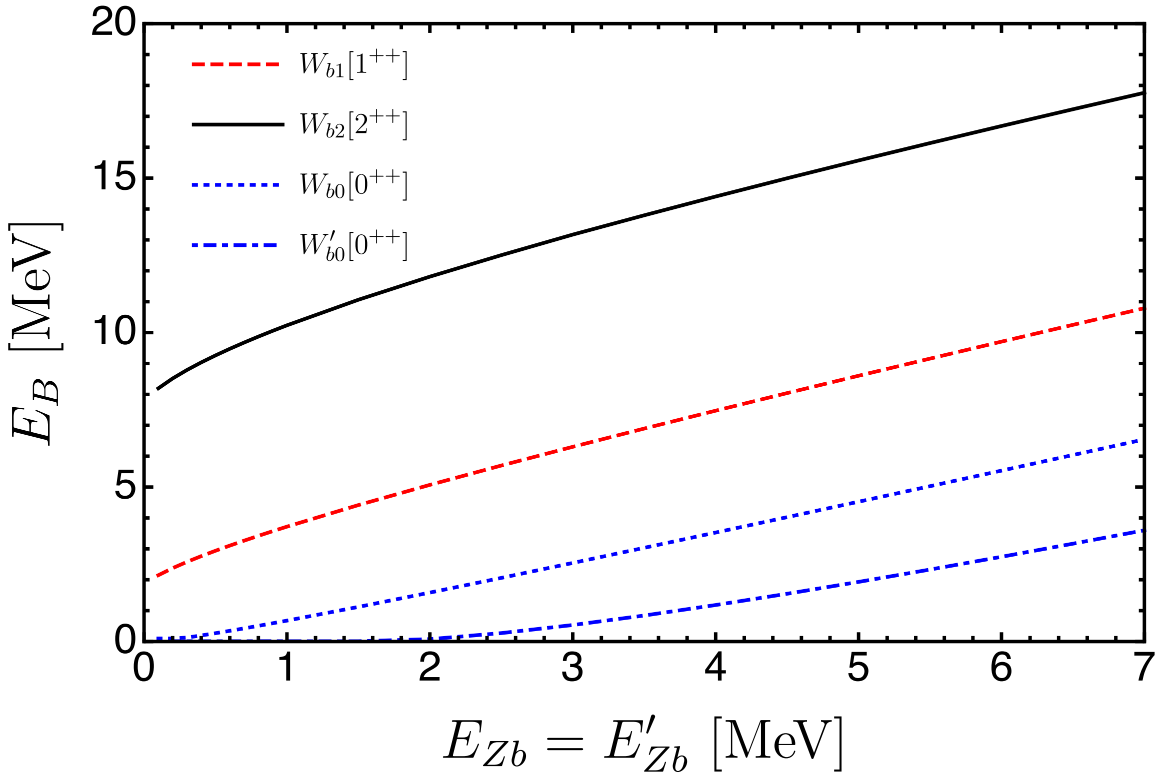
$g_B = g_C = 0.57$

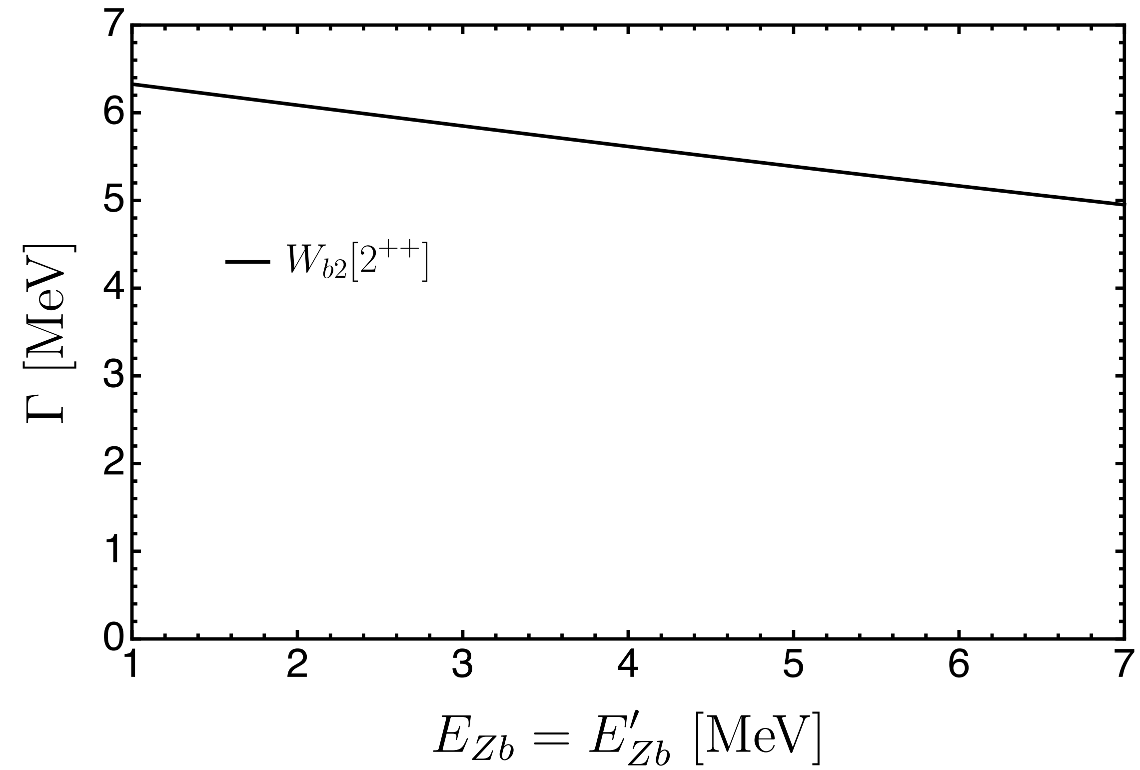
- For each g_B — refit the contact terms to require the input values for the Z_b's
- For $g_B < 0.3$ pions can be absorbed into redefinitions of the contact terms
- OPE Tensor forces: sizeable contributions at the physical value of g_B
- OPE Central (Swave) force —almost no influence on the results

Sensitivity to the input for the Z_b's

- Recent analysis: Z_b's are virtual states with excitation energy 1 MeV below threshold
  Guo et al. (2015)

- Assume that $E_{Zb} = E_{Zb'}$ and vary them from 7 MeV to 0 when they turn to virtual states





- W_{b2} (1++) and especially W_{b2} (2++) remain bound when $E_{Zb} = E_{Zb'}$ turn to be virtual

- The width of the W_{b2} (2++) due to $B\bar{B}$ and $B\bar{B}^*$ transitions generated by OPE is a few MeV

- Mild dependence on the cutoff can not affect these conclusions

Summary

- In the *strict HQSS* limit there are two degenerate multiplets of molecular partner states

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

☛ In the presence of OPE this holds if and only if all particle coupled-channels are included

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

☛ New coupled-channel transitions are generated and enhanced due to HQSS breaking

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

☛ X_{2++} is much more bound than in the pionless case and has the width

$$\Gamma_{X_{2++}} \simeq 50 \pm 10 \text{ MeV}$$

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

?? Some uncertainty in the prediction for the spin partners W_{bJ++} comes from the input for the Zb(10610) and Zb(10650) treated as bound states

Future plans: predictions for the partner states from an analysis of the exp. line shapes