Heavy-quark spin-symmetry partners of hadronic molecules

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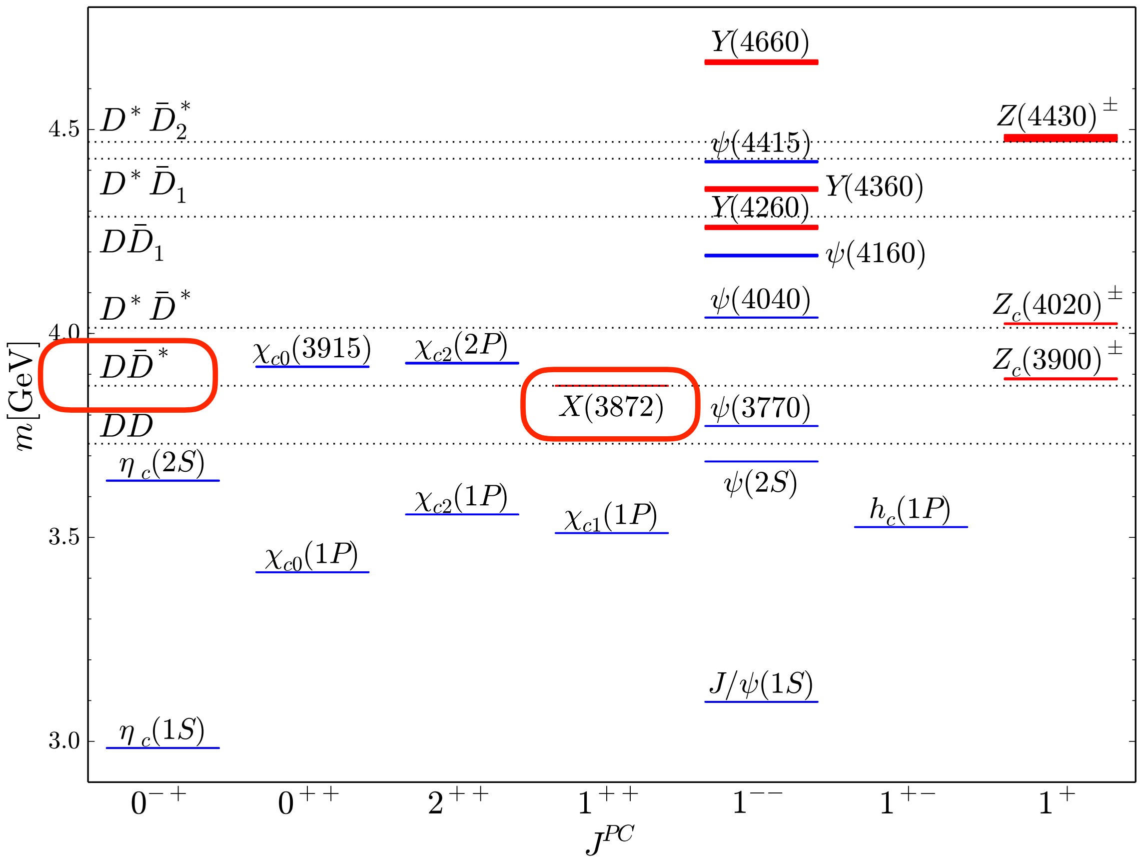
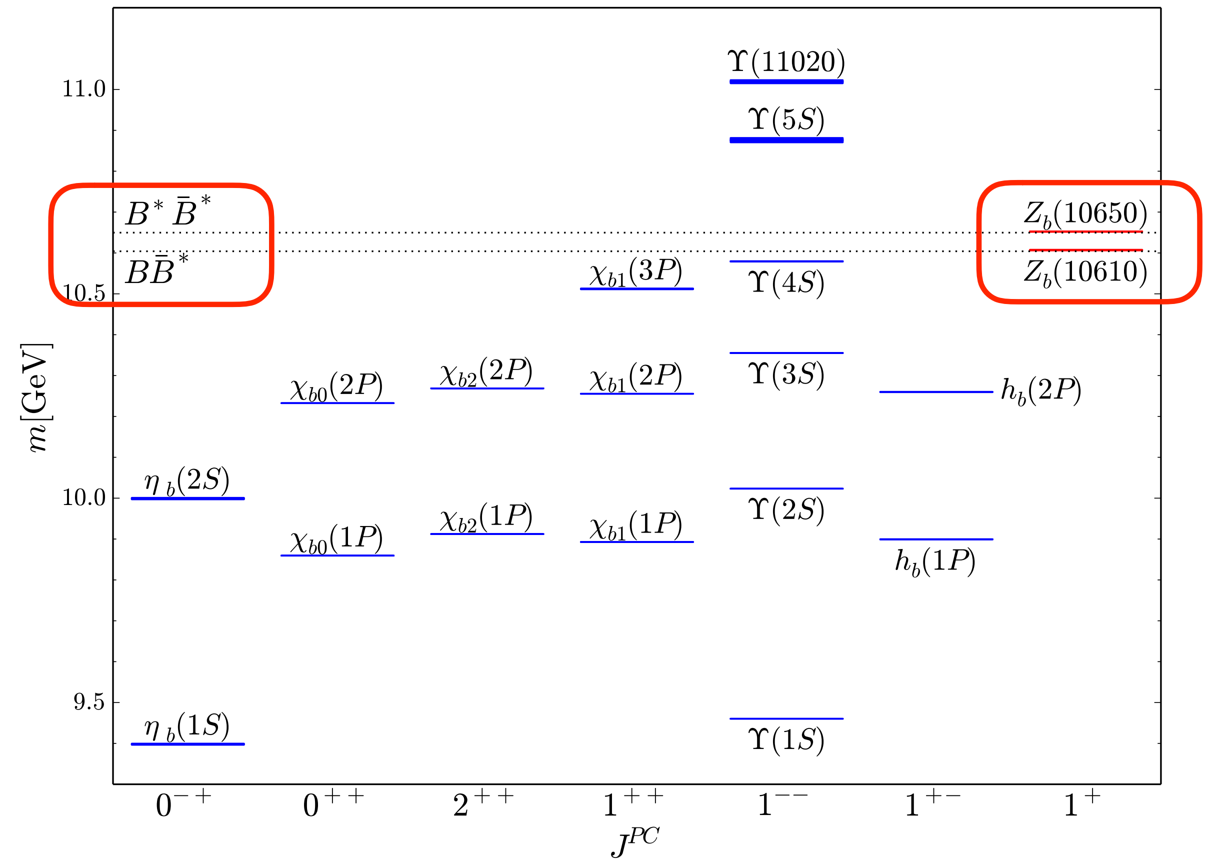
Key Refs: PLB 763, 20 (2016) and JHEP 1706, 158 (2017)

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 and couple to them in S-wave

$\Longrightarrow$ large molecule component!

But very precise measurements and sophisticated line shape analyses are needed to unambiguously disentangle from tetraquarks! Esposito et al. (2014)

Heavy-quark spin symmetry

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

☛ Heavy-quark spin symmetry (HQSS):

- In the limit $\Lambda_{\rm QCD}/m_Q \to 0$ strong interactions are independent of HQ spin
- Approximate but quite accurate symmetry of QCD

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

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

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

Impact of the charmonium component in the mixed interpretation Cincioglu et al. (2016)

Molecular partners: S-wave short-range interactions

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

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

$P = D$ or B , $V = D^*$ or 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, +)\}\,, \\
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- 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

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

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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
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- ☛ $V_{\rm LO}^{(1++)}$ and $V_{\rm LO}^{(2++)}$ are the same!
- ☛ *C* and *C′* –different for isoscalars and isovectors

- 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

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

Hidalgo-Duque et al. (2013)
our work (2016)

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 $O(\delta)$ and $O\left(\frac{\gamma^2}{\sqrt{m\delta}}\right) \simeq O\left(\sqrt{\frac{E_{\rm bound}}{\delta}}\gamma\right)$ our work (2016)

☛ States 1^{+-} and 0^{++} acquire finite widths due to coupled channels: $D^*\bar{D}^* \to D\bar{D}^* \to D^*\bar{D}^*$, $B^*\bar{B}^* \to B\bar{B}^* \to B^*\bar{B}^*$

☛ 2^{++} tensor state is uncoupled in the contact problem $\Longrightarrow$ no width

Contact + one-pion exchange (OPE) interactions

- Extended basis states:

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

$$
\begin{aligned}
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\end{aligned}
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- coupled-channel dynamics is very important: inconsistent omission $\Longrightarrow$ strongly cutoff dependent results

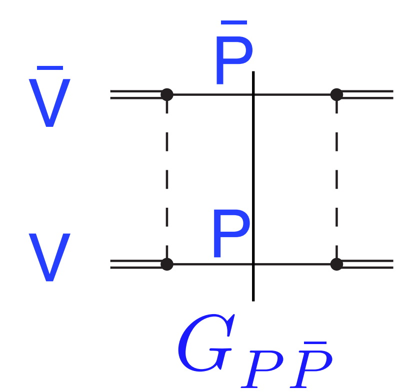
our work (2016)

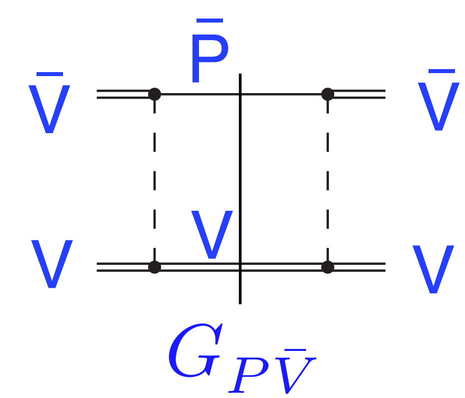
- Pions enhance HQSS violation due to V-P mass splitting

$P = D$ and B $\qquad$ $V = D^*$ 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 have non-trivial impact on the observables due to relatively large momentum scales involved

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

Chiral EFT based approach for hadronic molecules

Our works: PLB 763, 20 (2016), JHEP 1706, 158 (2017)

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

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

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

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

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

☛ Potential: contact operators (2 parameters) + π and η-meson $\Rightarrow$ input is needed!

input in c-quark sector: 1^{++} X(3872) $\Rightarrow$ output : 2^{++} partner state X_{c2}

To predict other partners of the X(3872) one more experimental input is needed! X(3915)?

input in b-quark sector: 1^{+-} Zb(10610)/Zb(10650) $\Rightarrow$ output: W_{b0} (0^{++}), W'_{b0} (0^{++}), W_{b1} (1^{++}) and W_{b2} (2^{++})

Some technical details

- Pionic Lagrangian: $\mathcal{L} = \frac{g_b}{2f_\pi}\left(\mathbf{B}^{*\dagger}\cdot\nabla\pi^a\tau^a\,\mathrm{B} + \mathrm{B}^\dagger\tau^a\nabla\pi^a\cdot\mathbf{B}^* + i[\mathbf{B}^{*\dagger}\times\mathbf{B}^*]\cdot\nabla\pi^a\tau^a\right)$

  with $g_b = g_c \approx 0.57$ from $D^* \to D\pi$ width and HQSS

- Exemplary potential:

$$V_{B\bar{B}^*\to B^*\bar{B}}(\mathbf{p},\mathbf{p}') = -\frac{2g_b^2}{(4\pi f_\pi)^2}\tau_1\cdot\tau_2^c\;(\epsilon_1\cdot\mathbf{q})(\epsilon_{\mathbf{2}}'^{\,*}\cdot\mathbf{q})\left(\frac{1}{D_{BB\pi}(\mathbf{p},\mathbf{p}')}+\frac{1}{D_{B^*B^*\pi}(\mathbf{p},\mathbf{p}')}\right)$$

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☛ 3-body propagators with NR heavy mesons and relativistic pions

$$D_{BB\pi}(\mathbf{p},\mathbf{p}') = 2E_\pi(\mathbf{q})\left(m + m + \frac{\mathbf{p}^2}{2m} + \frac{\mathbf{p}'^2}{2m} + E_\pi(\mathbf{q}) - \sqrt{s}\right) \qquad E_\pi(\mathbf{q}) = \sqrt{\mathbf{q}^2 + m_\pi^2}$$

$$D_{B^*B^*\pi}(\mathbf{p},\mathbf{p}') = 2E_\pi(\mathbf{q})\left(m_* + m_* + \frac{\mathbf{p}^2}{2m_*} + \frac{\mathbf{p}'^2}{2m_*} + E_\pi(\mathbf{q}) - \sqrt{s}\right)$$

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- Scattering amplitude from coupled-channel integral Eqs:

$$a_{ij}^{(JPC)}(p,p') = V_{ij}^{(JPC)}(p,p') - \sum_n \int dk\,k^2 V_{in}^{(JPC)}(p,k)G_n(k)a_{nj}^{(JPC)}(k,p')$$

☛ $V_{ij}^{(JPC)}(p,p')$ stands for the partial wave projected π + η-meson exchanges +contact terms

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☛ For D-mesons: $D_{DD\pi}(\mathbf{p},\mathbf{p}')$ and $G_n(k)$ contain 3-body cuts

Sign of the OPE potential

$$V^C_{B\bar{B}^*\to B^*\bar{B}}(\mathbf{p},\mathbf{p}') = -C\frac{2g_b^2}{(4\pi f_\pi)^2}\tau_1\cdot\tau_2^c\;(\epsilon_1\cdot\mathbf{q})(\epsilon_{\mathbf{2}}'^{\,*}\cdot\mathbf{q})\left(\frac{1}{D_{BB\pi}(\mathbf{p},\mathbf{p}')}+\frac{1}{D_{B^*B^*\pi}(\mathbf{p},\mathbf{p}')}\right)$$

- Isospin coefficient: $\tau_1\cdot\tau_2^c = 3-2I(I+1) = \begin{cases} 3 & I=0 \\ -1 & I=1 \end{cases}$ — different signs
- sign also depends on C-parity: C = ±

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

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$\Longrightarrow$ central (S-wave) OPE is attractive for the X(3872) and Z_b's

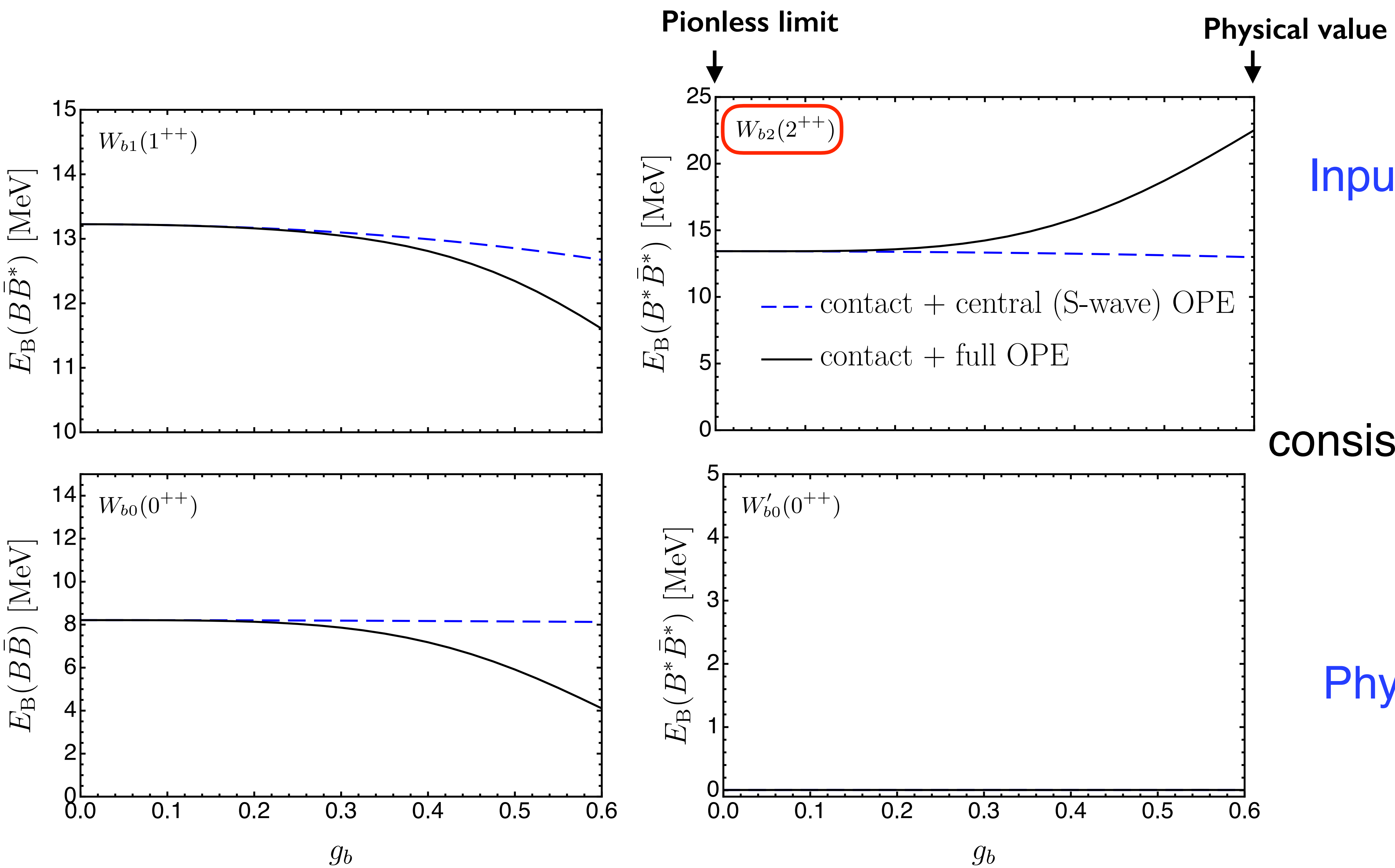
$\Longrightarrow$ Naively, repulsive OPE should reduce the binding energies of the Z_b's partner states

But too naive:

- tensor forces (off diagonal S-D transitions) bring additional attraction!
- when OPE is added LECs must be refitted to reproduce the exp.input

$\Longrightarrow$ effect of OPE is nontrivial

Z_b's partner states BE (E_B) vs pion coupling constant g_B



Input for binding energies:

$E_B(Z_b) = 5$ MeV

$E_B(Z_b') = 1$ MeV

consistent with data by Belle

Cleven et al. (2011)

Physical value of g_B:

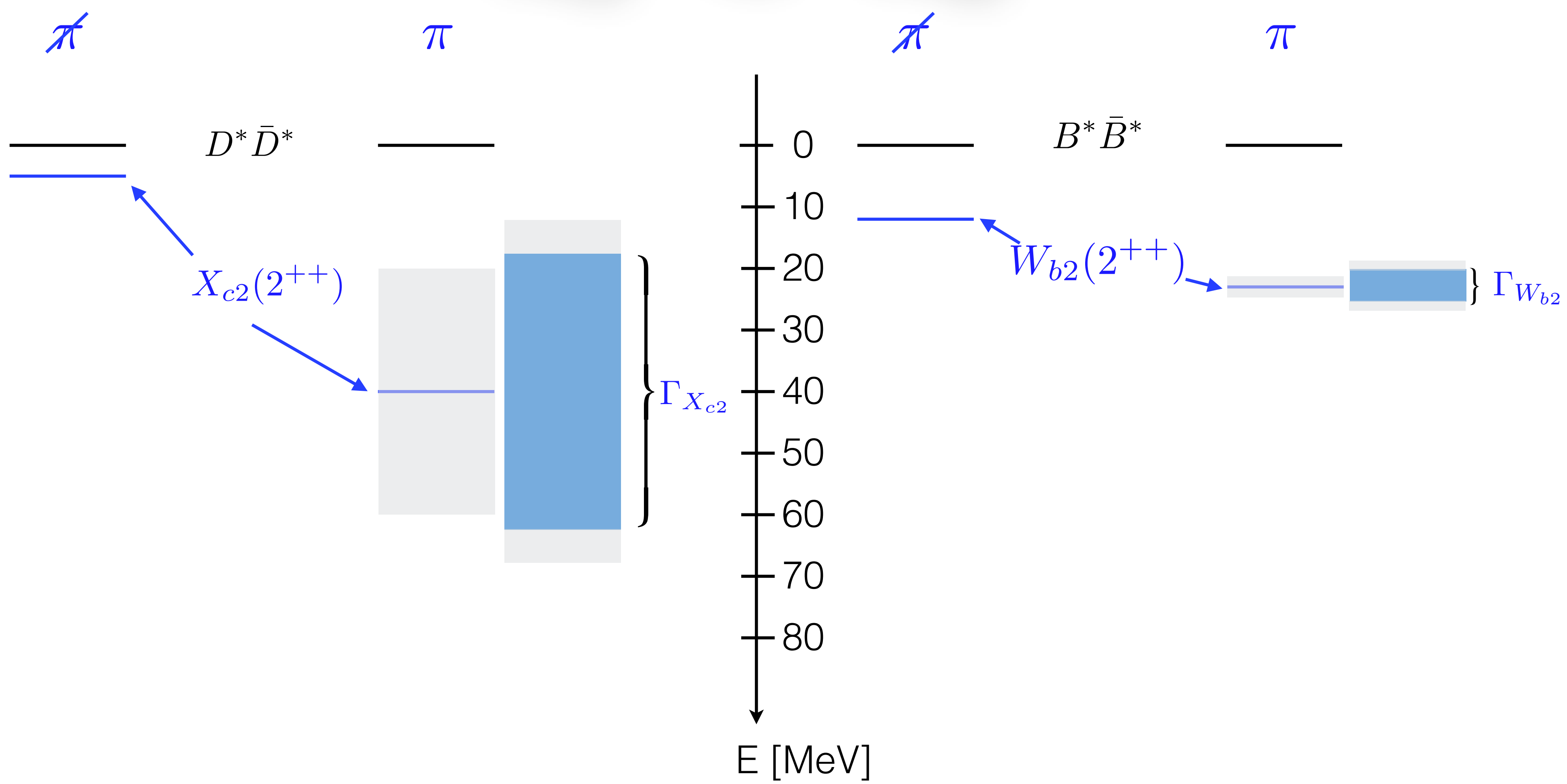
$g_B = g_C = 0.57$

☛ For each g_B — refit the contact terms to reproduce 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

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

2++ tensor partners: X_{c2} vs W_{b2}



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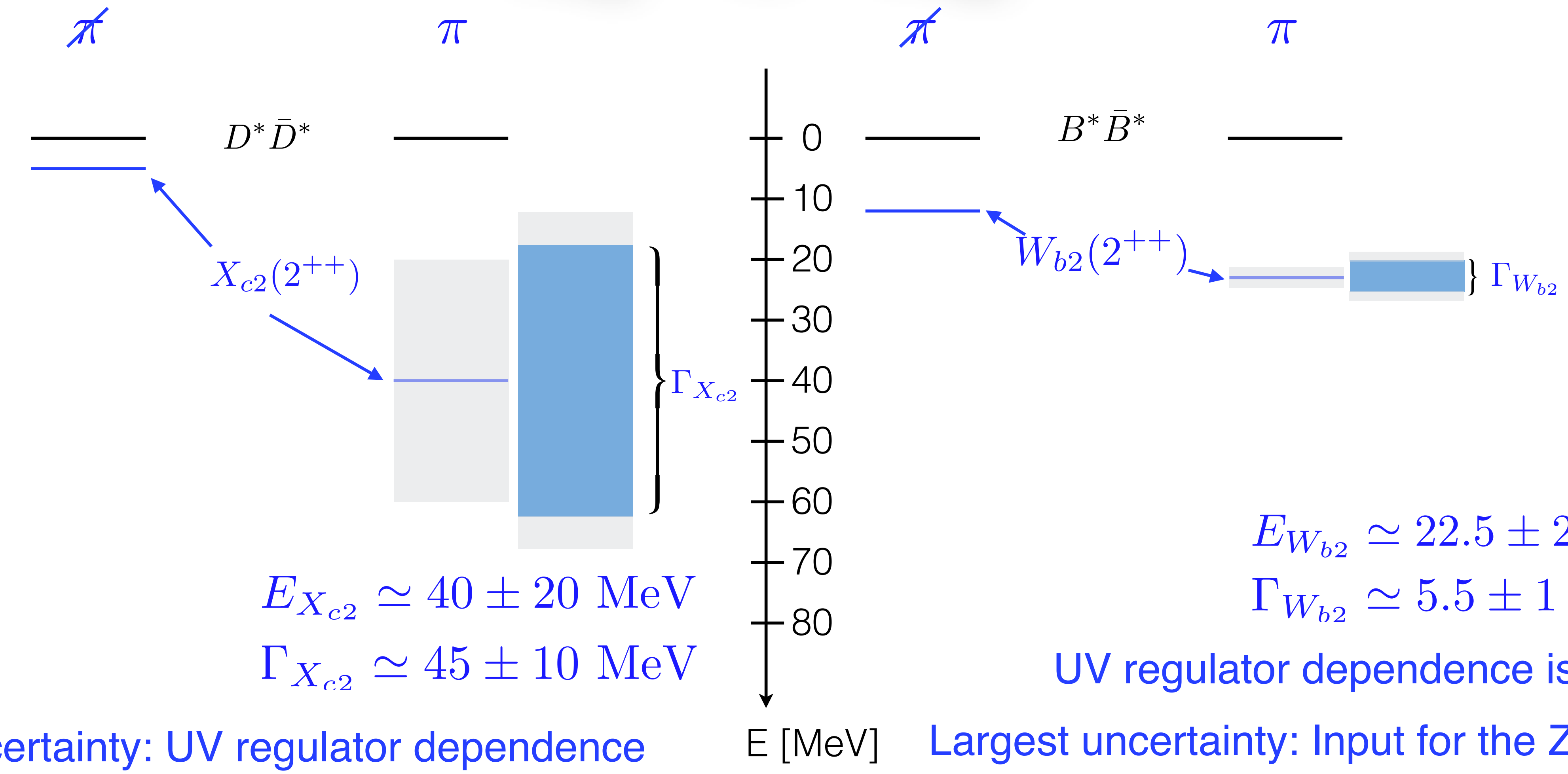

$E_{X_{c2}} \simeq 40 \pm 20$ MeV

$\Gamma_{X_{c2}} \simeq 45 \pm 10$ MeV

Largest uncertainty: UV regulator dependence

$E_{W_{b2}} \simeq 22.5 \pm 2$ MeV

$\Gamma_{W_{b2}} \simeq 5.5 \pm 1$ MeV

UV regulator dependence is very mild

Largest uncertainty: Input for the Z_b's masses (not shown)

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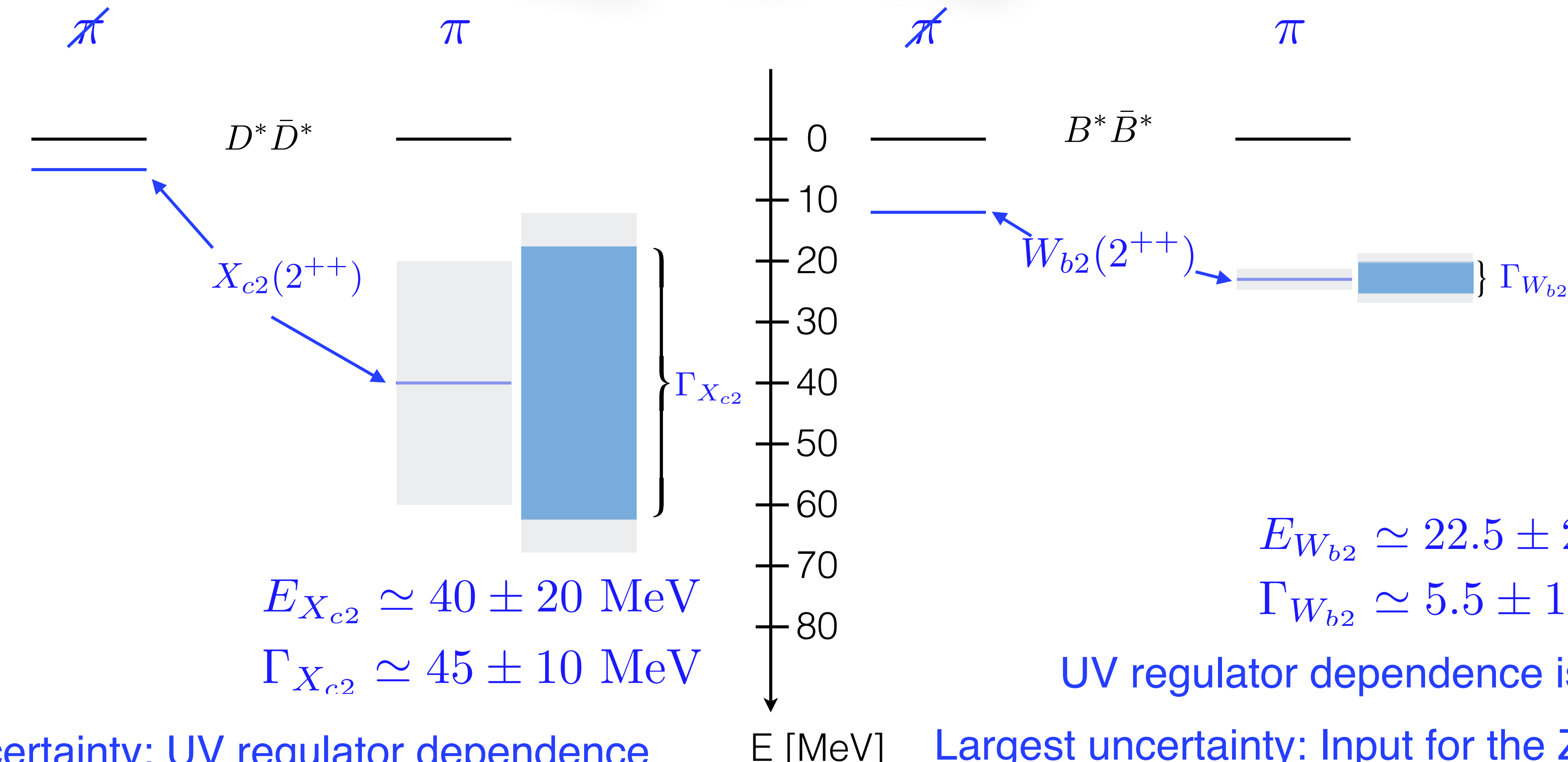

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- Impact of HQSS violation enhanced by nonperturbative pions on the tensor:
  - ☛ stronger in the c-sector than in the b-sector
  - ☛ larger than with perturbative pions

For a perturbative approach see Albaladejo et al. (2015)

- Role of 3-body effects: sizeable in the c-sector (reduce E_B and Γ up to 20%)
  marginal in the b-sector

Summary and conclusions

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

- It can be applied to study various aspects of light quark dynamics in $D^{(*)}D^{(*)}$ and $B^{(*)}B^{(*)}$

- Generalisation to other systems involving $\{D_1, D_2\}$ and $\{B_1, B_2\}$ doublets is straight fwd

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.

☛ Accurate predictions of the Zb partners: relatively weak HQSS breaking, no $b\bar{b}$ admixture

X_{c2++} is significantly shifted from $D^*\bar{D}^*$ threshold and has the width $\Gamma_{X_{c2}} \simeq 45 \pm 10$ MeV

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

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