Exotic molecular states in the decays of vector bottomonia

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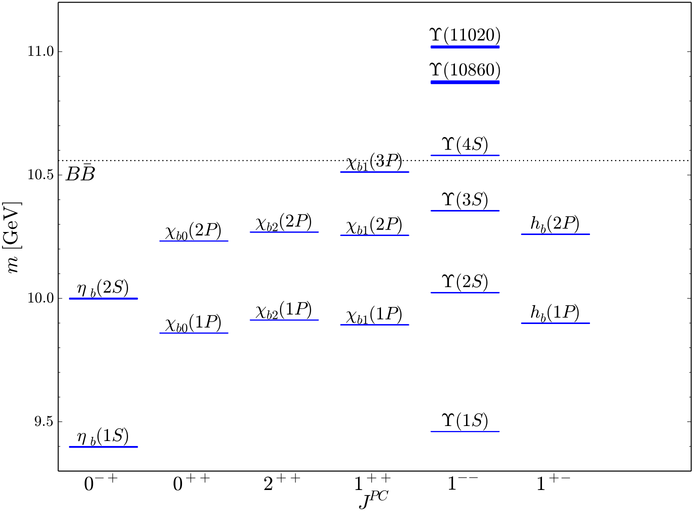
Bottomonium spectrum



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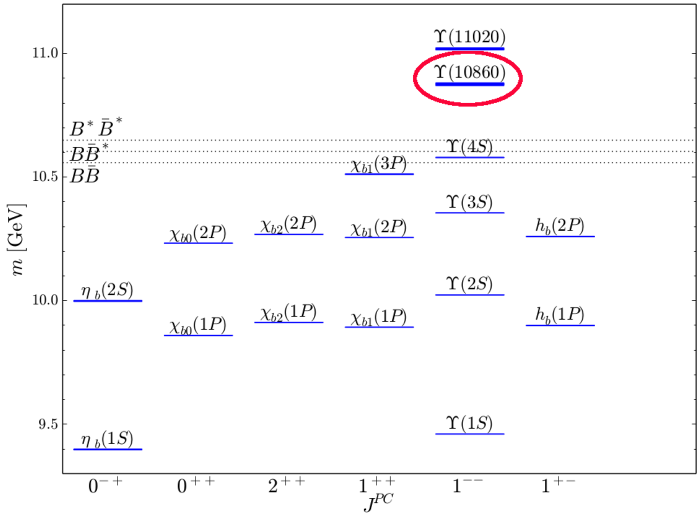
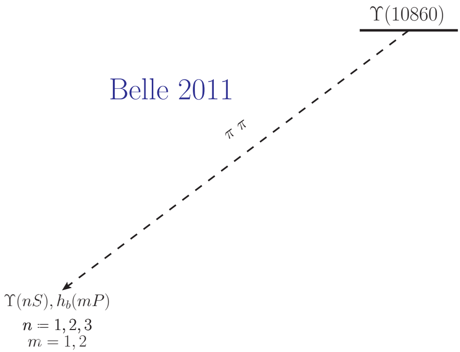


Two-pion decays of $\Upsilon(10860)$



Two-pion decays of $\Upsilon(10860)$

$\Upsilon(10860)$

Belle 2011

$\pi\,\pi$

$\Upsilon(nS), h_b(mP)$

$n = 1, 2, 3$

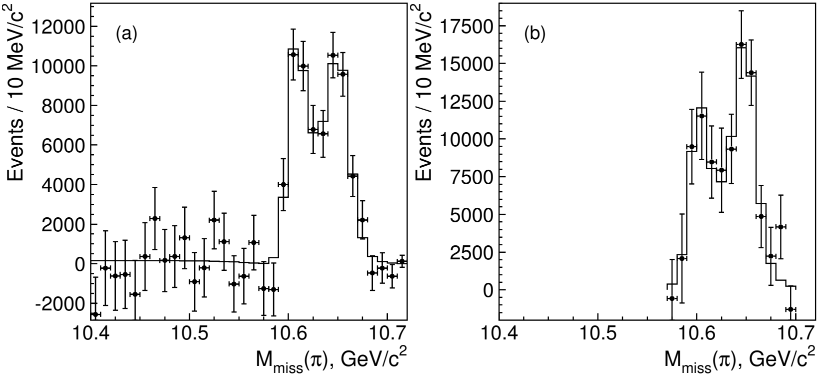
$m = 1, 2$

$$\text{Br}[\Upsilon(10860) \to \pi\pi h_b(mP)] \simeq \text{Br}[\Upsilon(10860) \to \pi\pi\Upsilon(nS)]$$

Heavy quark spin flip — No spin flip

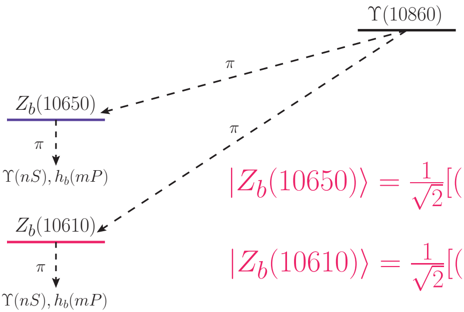
Huge HQSS violation?!

Near-threshold states in πh_b channels (Belle 2012)



Data consistent with two structures at $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds

Decays of $\Upsilon(10860)$

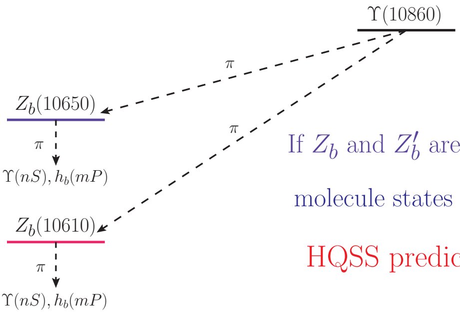


$$|Z_b(10650)\rangle = \frac{1}{\sqrt{2}}[(0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}) - (1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q})]$$

$$|Z_b(10610)\rangle = \frac{1}{\sqrt{2}}[(0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}) + (1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q})]$$

Bondar et al. 2011

Spin partners W_{bJ} $(J = 0, 1, 2)$



If Z_b and Z_b' are near-threshold

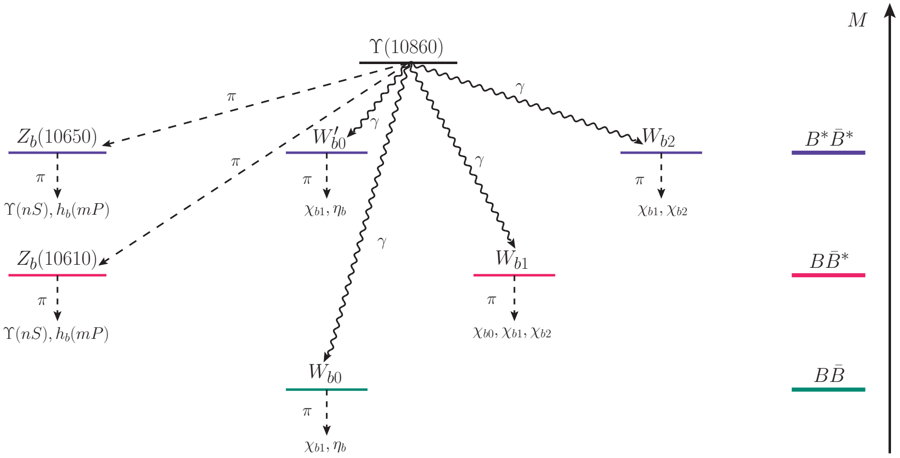
molecule states with $J^{PC} = 1^{+-}$

HQSS predicts existence of

Additional molecular states with $J^{PC} = J^{++}$ $(J = 0, 1, 2)$

(Bondar et al. 2011, Voloshin 2011)

W_{bJ}'s in radiative decays of $\Upsilon(10860)$



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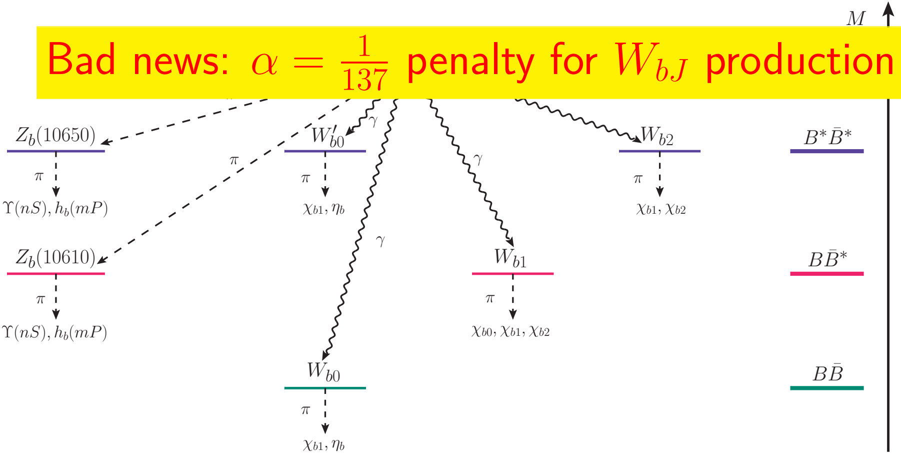

Bad news: $\alpha = \frac{1}{137}$ penalty for W_{bJ} production

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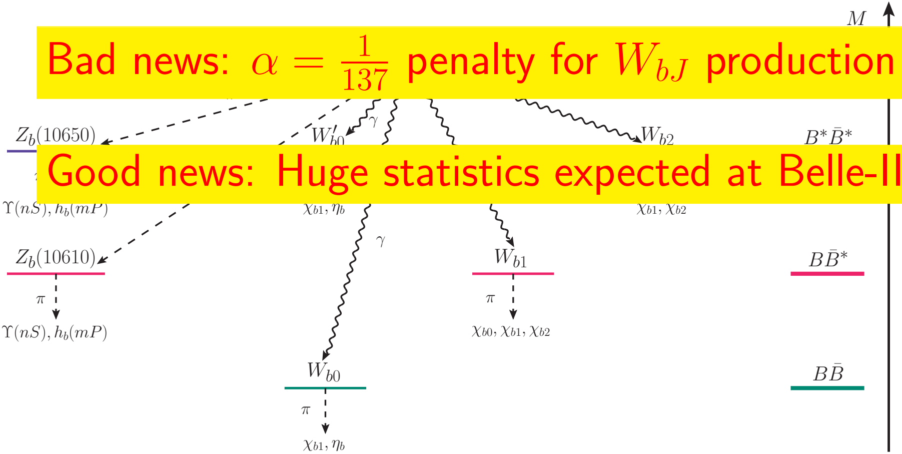
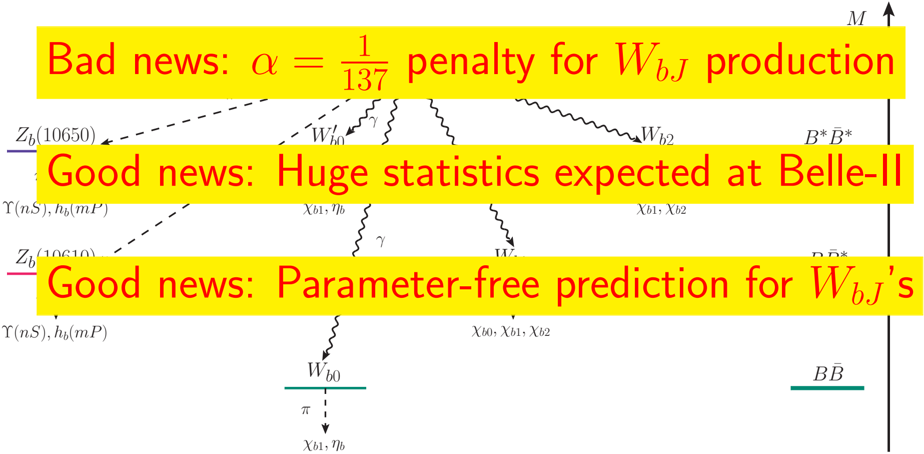
Good news: Huge statistics expected at Belle-II



W_{bJ}'s in radiative decays of $\Upsilon(10860)$



Bad news: $\alpha = \frac{1}{137}$ penalty for W_{bJ} production

Good news: Huge statistics expected at Belle-II

Good news: Parameter-free prediction for W_{bJ}'s

Hadronic molecules

Molecule = large probability to observe resonance in hadron-hadron channel

- Proximity of open-flavour thresholds
  $\Longrightarrow$ large admixture of meson-meson component
- Bound state/virtual state/above-threshold resonance/CC pole
  $\Longrightarrow$ dynamical problem
- Binding forces origins
  $\Longrightarrow$ different models
- Free parameters fixing
  $\Longrightarrow$ combined analysis of exp. data in all channels

Building common EFT for Z_b's and W_{bJ}'s

- HQSS in potential $\Longrightarrow$ parameter $\Lambda_{\rm QCD}/m_b \ll 1$
- Typical scale generated by coupled-channel dynamics

$$p_{\rm typ} = \sqrt{m_B\delta} \simeq 500 \text{ MeV} \qquad \delta = m_{B^*} - m_B \approx 45 \text{ MeV}$$

is soft scale (hard scale $\Lambda \simeq 1$ GeV) $\Longrightarrow$ parameter $p_{\rm typ}/\Lambda \lesssim 1$

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Then

- Pionic dynamics (no additional parameters!) is to be treated explicitly
- D waves from OPE are important
- Convergence of EFT has to be a special concern
  - S-to-D $\mathcal{O}(p^2)$ CT is promoted from NLO to LO
    $\Longrightarrow$ improved renormalisability
  - S-to-S $\mathcal{O}(p^2)$ CT is included explicitly
    $\Longrightarrow$ almost complete NLO [up to (small?) long-range two-pion exchange]

Coupled-channel problem

Elastic potential:

$$V_{\text{el-el}} = V_{\text{CT}}(\text{to order } O(p^0))$$

Coupled channels:

$$1^{+-} : B\bar{B}^*({}^3S_1, -), B^*\bar{B}^*({}^3S_1)$$
$$0^{++} : B\bar{B}({}^1S_0), B^*\bar{B}^*({}^1S_0)$$
$$1^{++} : B\bar{B}^*({}^3S_1, +)$$
$$2^{++} : B^*\bar{B}^*({}^5S_2)$$

Coupled-channel problem

Elastic potential:

$$V_{\text{el-el}} = V_{\text{CT}}(\text{to order } O(p^2)) + V_\pi$$

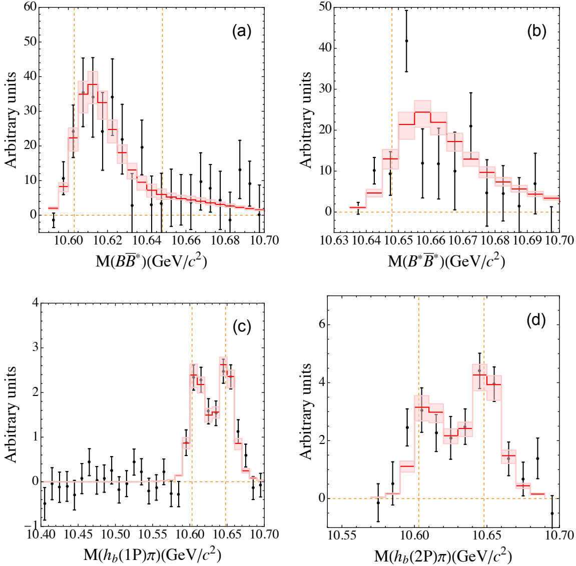
Coupled channels:

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

Lippmann-Schwinger equation ($V^{\text{eff}} = V_{\text{el-el}} + \sum_{\text{inel}} V_{\text{el-inel-el}}$):

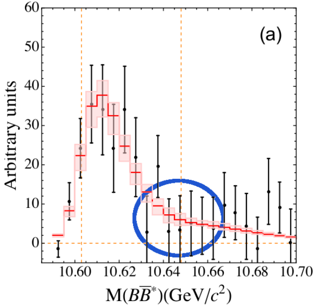
$$T_{\alpha\beta}(M,\boldsymbol{p},\boldsymbol{p}') = V^{\text{eff}}_{\alpha\beta}(\boldsymbol{p},\boldsymbol{p}') - \sum_\gamma \int \frac{d^3q}{(2\pi)^3} V^{\text{eff}}_{\alpha\gamma}(\boldsymbol{p},\boldsymbol{q}) G_\gamma(M,\boldsymbol{q}) T_{\gamma\beta}(M,\boldsymbol{q},\boldsymbol{p}')$$

Combined fit to the data for Z_b's



Results and conclusions for Z_b's

- Description of data is nearly perfect (χ^2/d.o.f $= 0.83$)
- Parameters (LEC's and couplings) are extracted directly from data
- Data are compatible with HQSS
- Effect from (long range) pion exchange is visible
- $B\bar{B}^*$-$B^*\bar{B}^*$ transitions:
  - Enhanced by pions
  - Not supported by data (surprise!)
  - Tamed by S-to-D contact terms



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Apply the same EFT to W_{bJ}'s

- $B\bar{B}^*$-$B^*\bar{B}^*$ transitions:
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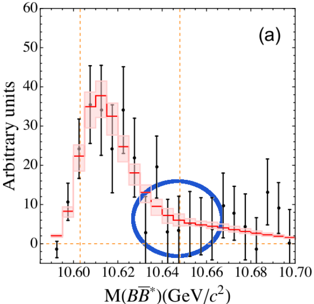
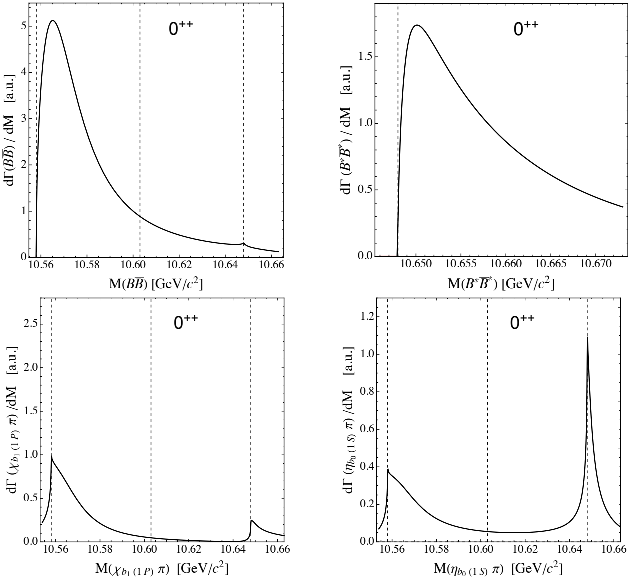
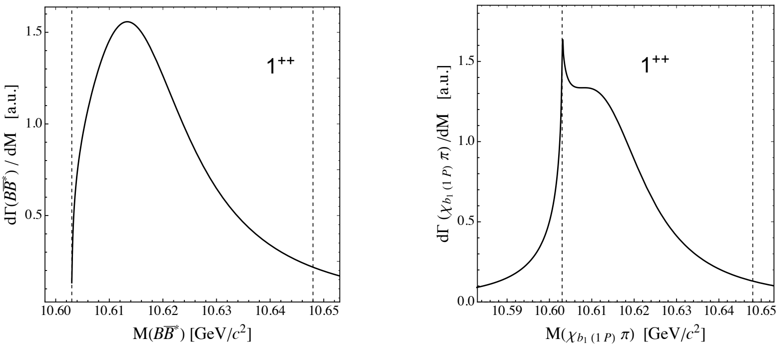


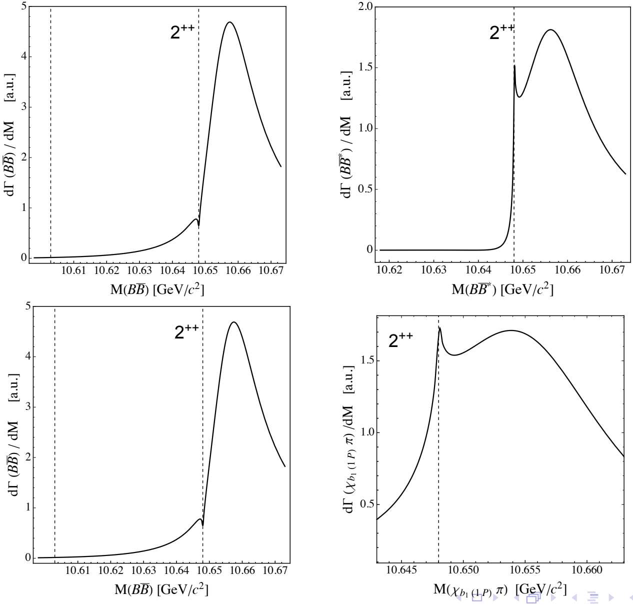
Predicted line shapes for W_{b0}



Predicted line shapes for W_{b1}



Predicted line shapes for W_{b2}



Predicted relations between partial decay widths

Predicted partial branching fractions (not considered channels neglected):

J^{PC}	$B\bar{B}$	$B\bar{B}^*$	$B^*\bar{B}^*$	$\chi_{b0}(1P)\pi$	$\chi_{b0}(2P)\pi$	$\chi_{b1}(1P)\pi$	$\chi_{b1}(2P)\pi$	$\chi_{b2}(1P)\pi$	$\chi_{b2}(2P)\pi$	$\eta_{b0}(1S)\pi$	$\eta_{b0}(2S)\pi$
0^{++}	0.73	—	0.14	—	—	0.05	0.06	—	—	0.002	0.01
1^{++}	—	0.76	—	0.03	0.06	0.02	0.04	0.04	0.05	—	—
2^{++}	0.06	0.07	0.54	—	—	0.03	0.06	0.09	0.16	—	—

Predicted ratios of partial widths:

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

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

Pole positions (mirror poles not shown)

J^{PC}	State	Threshold	E_B w.r.t. threshold, [MeV]	Residue at 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}	$B^*\bar{B}^*$	$(7.4 \pm 2.8) - i(9.9 \pm 2.2)$	$(0.7 \pm 0.1) - i(0.3 \pm 0.1)$

- Relevant pole = pole with the shortest path to the physical region
- Riemann sheet is fixed by combination of signs of Im(p) for all channels
- Relevant pole can be bound state, virtual state, resonance
- Virtual state enhances threshold cusp
- Resonance distorts line shape above threshold (hump for nearby pole)

Conclusion: All Z_b's and W_{bJ}'s are resonances

(without pions — virtual states)

Conclusions

EFT approach to near-threshold molecular states:

- Compatible with constraints from unitarity, analiticity, HQSS
- Incorporates all most relevant types of interactions and scales
- Able to explain existing data on $Z_b(10610)$ and $Z_b(10650)$
- Suitable to predict in parameter-free way spin partners W_{bJ}

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Phenomenological approach based on molecular picture:

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Desperately wait for Belle-II data!

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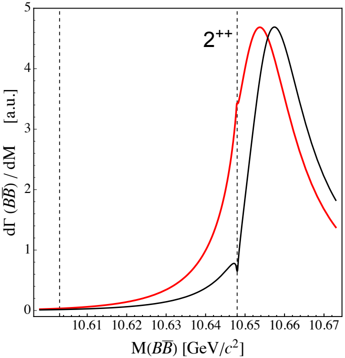
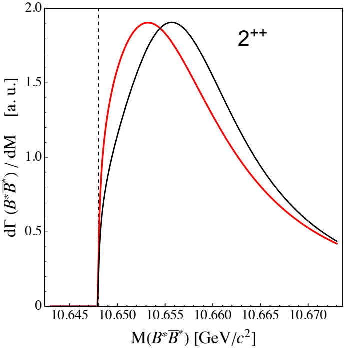
Further theoretical developments needed:

- Complete NLO — to improve theoretical accuracy
- Pion FSI — to improve parameters extraction from data
- Inclusion of w.f. compact component — to treat isoscalar molecules
- Extension to $SU(3)$ flavour group for light quarks — to predict molecules with strange quark
- Tests of accuracy of HQSS (especially in c-sector) — to better control theoretical uncertainties

Theoretical uncertainty estimate





Red curve: complete LO

Black curve: (almost) complete NLO

$$X^{(\nu)}(Q) = \sum_{n=0}^{\nu} \alpha_n \left(\frac{p_{\rm typ}}{\Lambda}\right)^n \underset{\rm NLO\ vs\ LO}{\Longrightarrow} \delta E \simeq E_{\rm typ}\frac{p_{\rm typ}}{\Lambda} \simeq 15\frac{500}{1000} \simeq 7.5\ \text{MeV}$$

Complex ω-plane