Exotic hadrons in the decays of vector bottomonia & Heavy-quark spin-symmetry partners of the bottomonium molecular states at Belle-II

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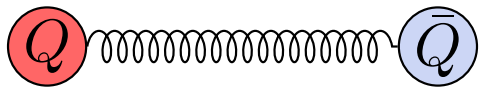
Quark model for charmonium and bottomonium



$$H = 2m_Q + \frac{p^2}{m_Q} + \sigma r - \frac{4\alpha_s}{3r} + C + V_{\text{spin-dep}}$$

Successes:

- Good description of spectrum below open-flavour threshold
- Reasonable description of leptonic, radiative, hadronic widths

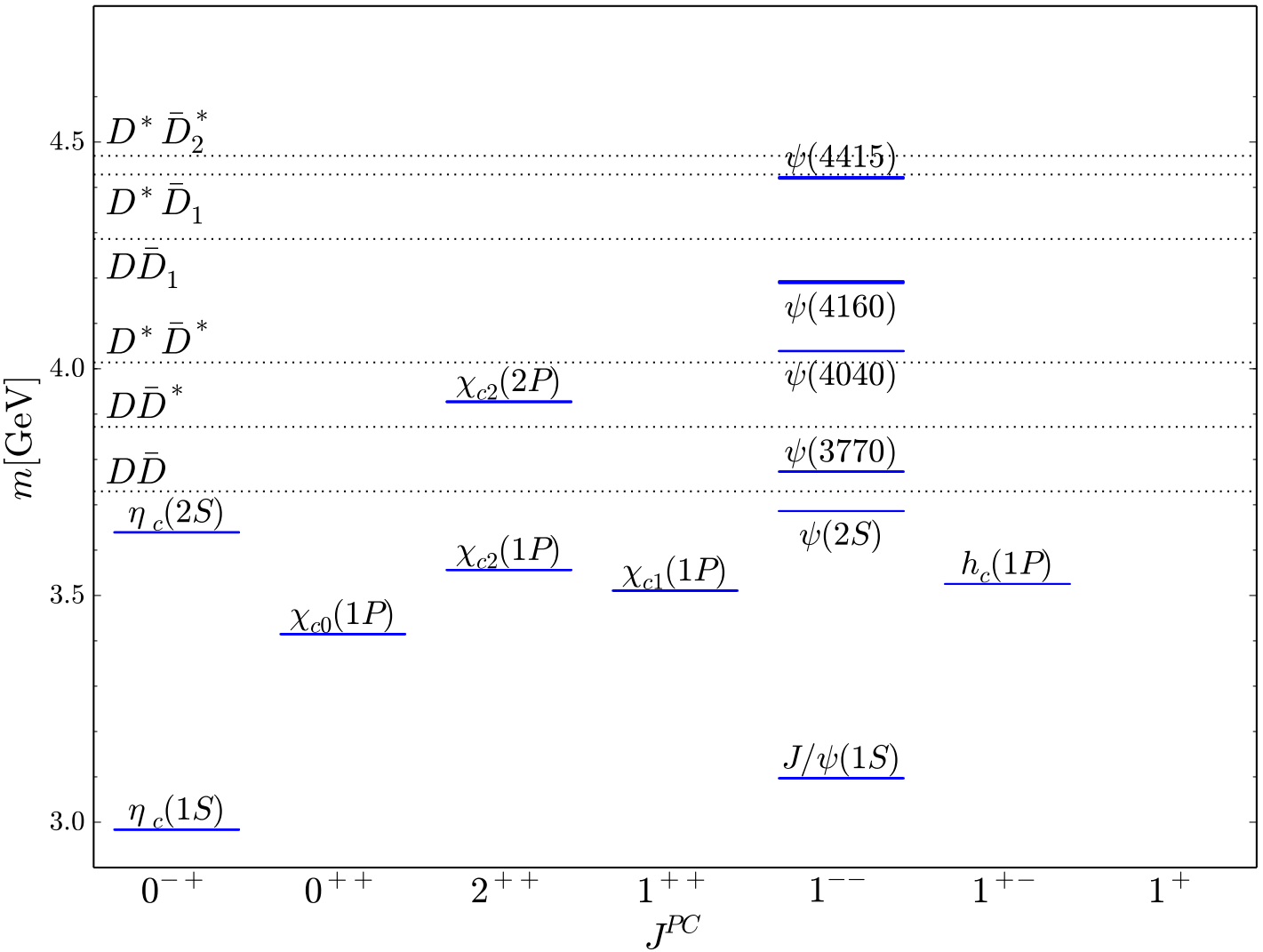
Failure:

- Breakdown for higher quarkonia

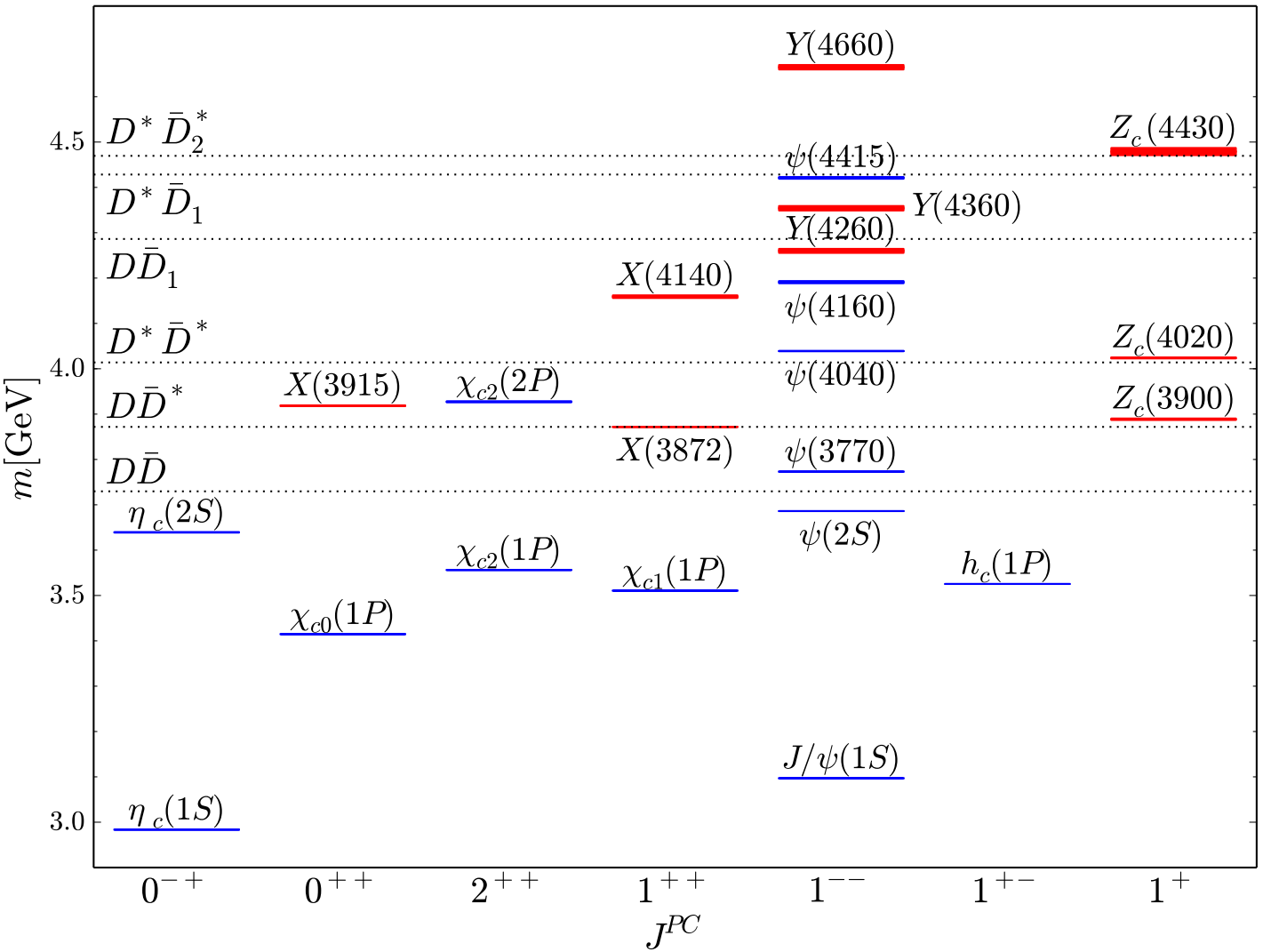
What is missing?

- Constituent gluons
- Effects of light-quarks: loops, thresholds, pions

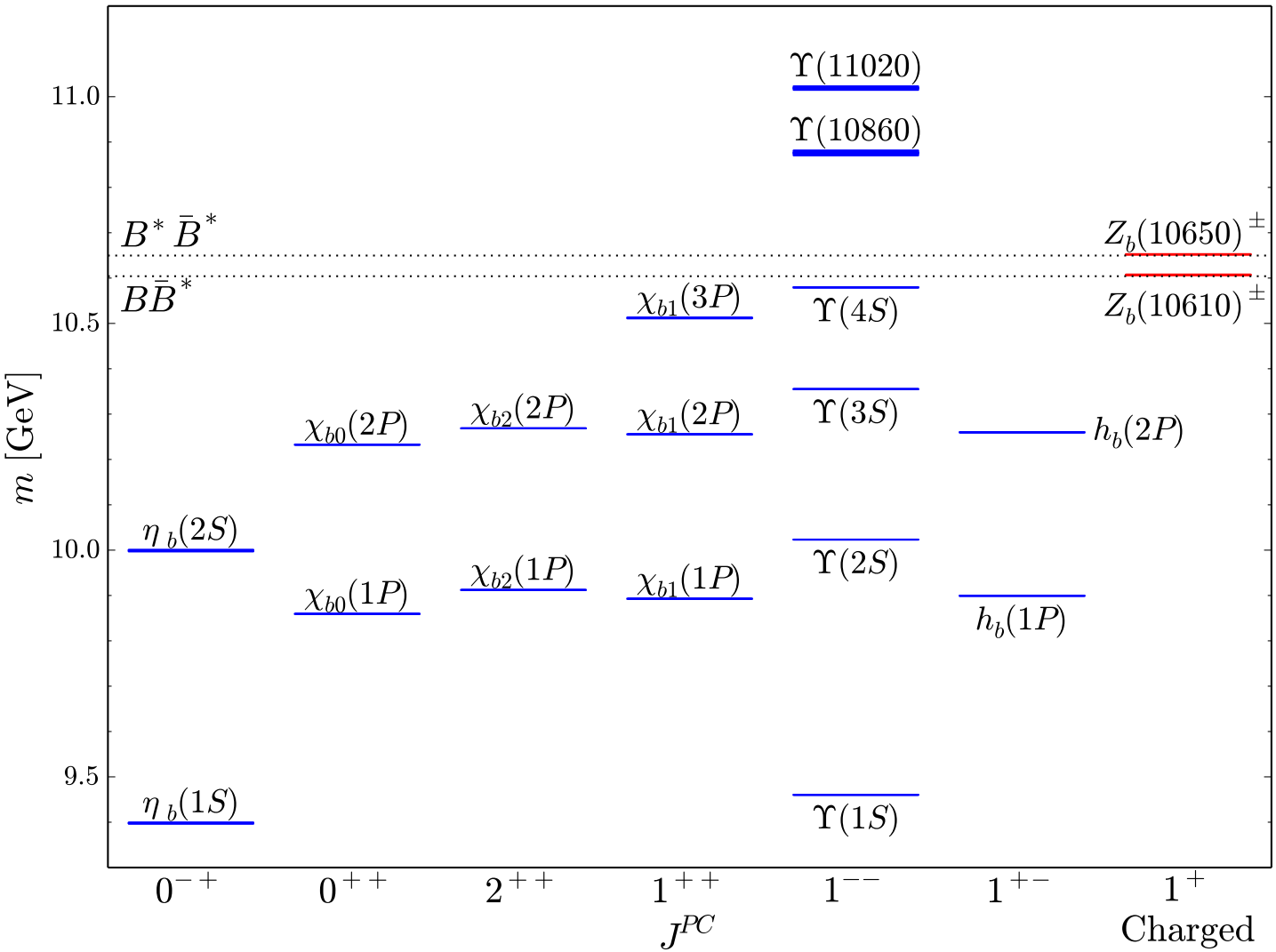
Spectrum of charmonium



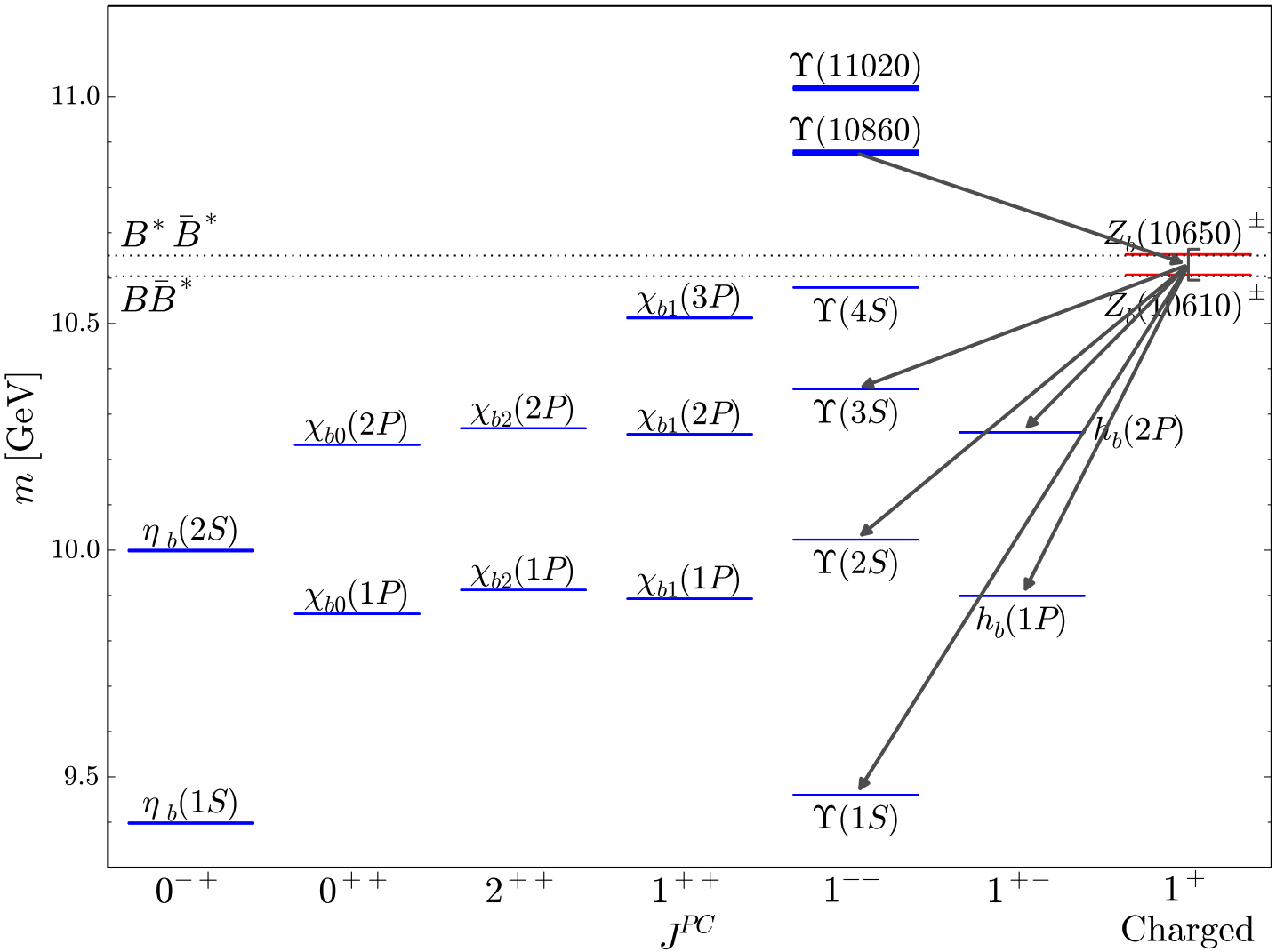
Spectrum of charmonium



Spectrum of bottomonium

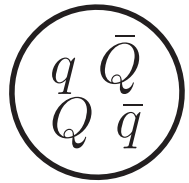


Spectrum of bottomonium



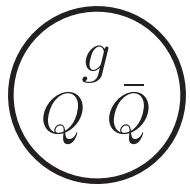
If not $\bar{Q}Q$ then what? Proposals...

- Tetraquark



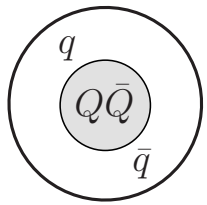
Compact object made of $(Qq)_{\bar{3}}$ and $(\bar{q}\bar{Q})_3$

- Hybrid



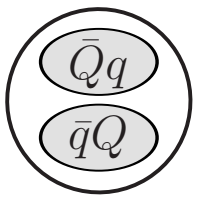
Compact object made of $(Q\bar{Q})_8$ + gluons

- Hadro-Quarkonium



$(Q\bar{Q})_1$ surrounded by light quarks

- Hadronic Molecule



Extended object made of $(\bar{Q}q)_1$ and $(\bar{q}Q)_1$

Hadronic molecule model

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
  $\Longrightarrow$ dynamical problem
- Binding forces
  $\Longrightarrow$ different models
- Free parameters
  $\Longrightarrow$ combined analysis of exp. data in all channels

Heavy-quark spin symmetry

- Exotic XYZ states contain heavy quarks (HQ)
- In the limit $m_Q \to \infty$ $(m_Q \gg \Lambda_{\rm QCD})$ spin of HQ decouples

  $\Longrightarrow$ Heavy Quark Spin Symmetry (HQSS)
- For realistic m_Q's HQSS is approximate but rather accurate symmetry of QCD
- Predictions of HQSS depend crucially on the nature of states under study

  (Cleven et al.'2015)
- Quarkonium component of the w.f. (if exists) may impact the predictions

  (Cincioglu et al.'2016)
- HQSS is a tool to relate properties of states with different HQ spin orientation

  $\Longrightarrow$ Spin partners

  (Guo et al.'2009,Bondar et al.'2011,Voloshin et al.'2010,Mehen et al.'2011,Nieves et al.'2012,Guo et al.'2013,Albaladejo et al.'2015, Our works'2016,2017)

$Z_b(10610)$ & $Z_b(10650)$: Experimental status

- Quantum numbers: $J^{PC} = 1^{+-}$, $I = 1$
- Masses and widths:

$$M = 10607.2 \pm 2.0 \text{ MeV} \qquad \Gamma = 18.4 \pm 2.4 \text{ MeV}$$

$$M = 10652.2 \pm 1.5 \text{ MeV} \qquad \Gamma = 11.5 \pm 2.2 \text{ MeV}$$

- Production and decay modes:

$$\begin{aligned}
\Upsilon(10860) &\to \pi Z_b^{(\prime)} \to \pi B^{(*)} \bar{B}^* \\
\Upsilon(10860) &\to \pi Z_b^{(\prime)} \to \pi\pi \Upsilon(nS) \quad n = 1, 2, 3 \\
\Upsilon(10860) &\to \pi Z_b^{(\prime)} \to \pi\pi h_b(mP) \quad m = 1, 2
\end{aligned}$$

- No suppression from heavy quark spin flip

$$\text{BF}(\Upsilon(10860) \to h_b(mP)\pi\pi) \simeq \text{BF}(\Upsilon(10860) \to \Upsilon(nS)\pi\pi)$$

Theoretical approach to $Z_b(10610)$ & $Z_b(10650)$

Molecule Z_b and Z_b' spin w.f.'s are ($B = 0^-_{\bar{b}q}$, $\bar{B} = 0^-_{\bar{q}b}$, $B^* = 1^-_{\bar{b}q}$, $\bar{B}^* = 1^-_{\bar{q}b}$)

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

(Bondar et al.'2011)

Direct interaction in elastic ($B^{(*)}\bar{B}$) channels includes

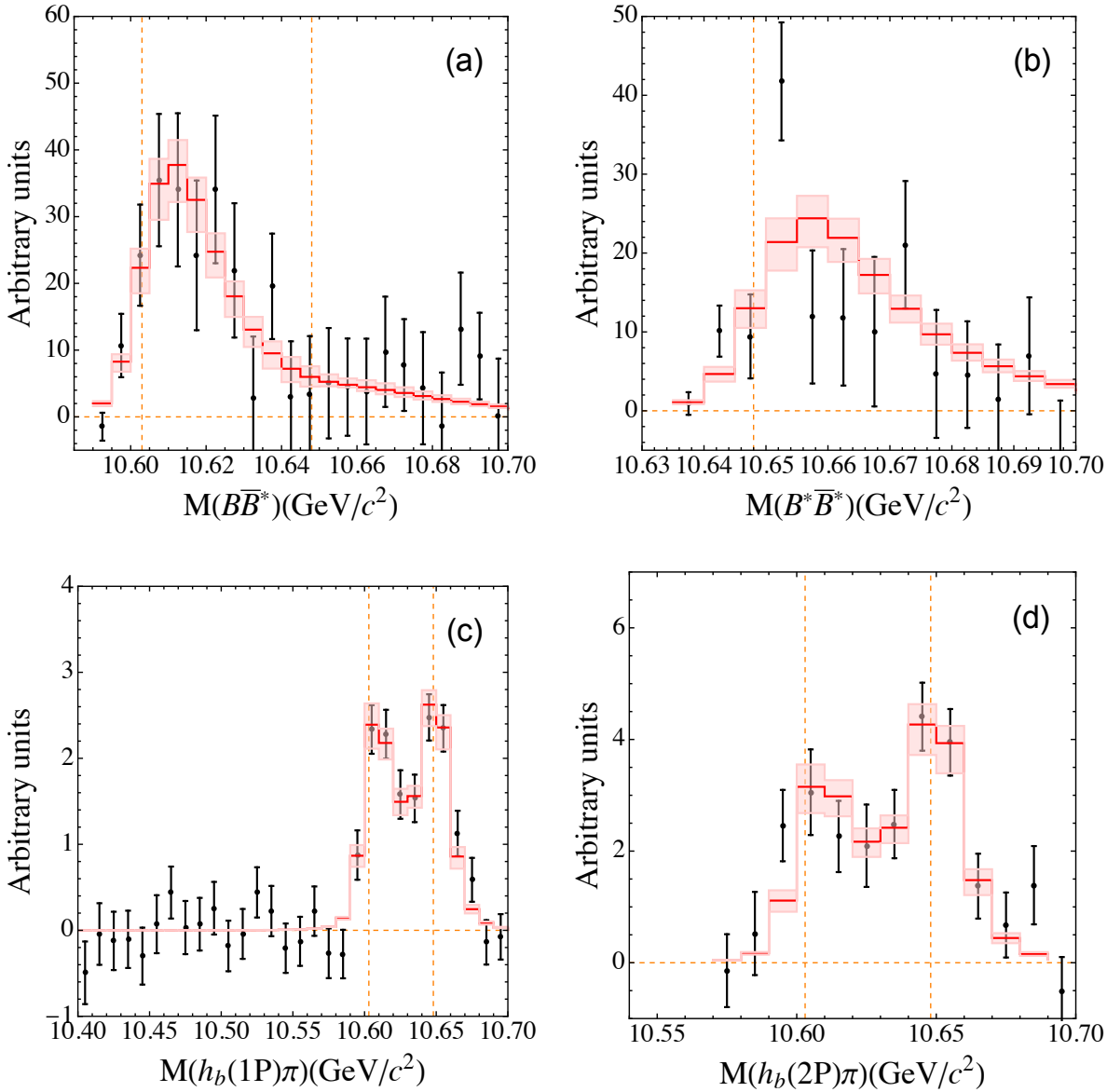
- LO $\mathcal{O}(p^0)$ short-range (contact) potential $\begin{pmatrix} \mathcal{C}_d & \mathcal{C}_f \\ \mathcal{C}_f & \mathcal{C}_d \end{pmatrix}$
- Full (not static, not only central) one-pion exchange
- Full one-η exchange (provides minor effect)
- NLO $\mathcal{O}(p^2)$ contact interaction (to renormalise pions in D waves)

Direct interaction between inelastic ($\pi\Upsilon$, πh_b) channels neglected

Interaction elastic $\Leftrightarrow$ inelastic channels included

HQSS violating parameters included but not required by data

Combined fit for the data



Parameters and poles for Z_b's

- LO ($\mathcal{C}$'s) and NLO ($\mathcal{D}$'s) LECs for elastic $\Leftrightarrow$ elastic interaction

$\mathcal{C}_d$	$\mathcal{C}_f$	$\mathcal{D}_d$	$\mathcal{D}_{SD}$
1.34 ± 0.40	-3.95 ± 0.27	-3.38 ± 0.54	-3.13 ± 0.61

- Coupling constants for elastic $\Leftrightarrow$ inelastic interaction

$g_{\Upsilon(1S)}$	$g_{\Upsilon(2S)}$	$g_{\Upsilon(3S)}$	$g_{h_b(1P)}$	$g_{h_b(2P)}$
0.25 ± 0.06	0.88 ± 0.17	1.15 ± 0.29	1.92 ± 0.22	7.07 ± 0.84

- Branching fractions (Exp *vs* Theor) relative to $B\bar{B}^*\pi$ channel

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

- Extracted poles for Z_b and Z_b'

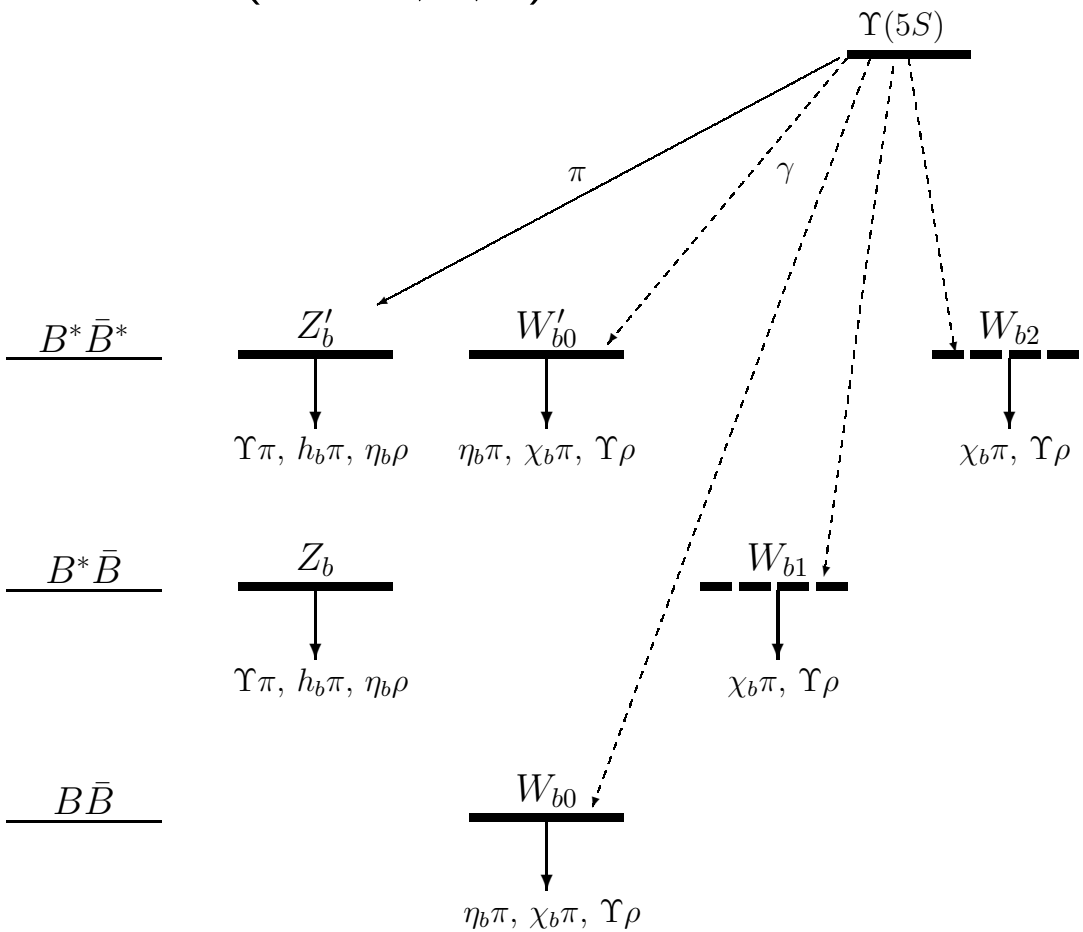
Sign(Im$[k_{\text{inel}}]$)	E_{Z_b}(MeV)	$E_{Z_b'}$(MeV)
$-$	$(-1.7 \pm 1.2) - i(2.6 \pm 0.5)$	$(2.9 \pm 2.3) - i(6.2 \pm 1.8)$
$+$	$(-1.7 \pm 1.2) + i(2.6 \pm 0.5)$	$(0.8 \pm 0.4) + i(3.3 \pm 1.3)$

Results and conclusions for Z_b's

- Description of data is nearly perfect ($\chi^2/\text{d.o.f} = 0.83$)
- Parameters extracted from fit comply with natural hierarchy of scales
- Data are compatible with HQSS
- Effect from pion exchange is important
- Data not compatible with $B\bar{B}^* \leftrightarrow B^*\bar{B}^*$ transitions mediated by π's
- NLO short-range interaction is promoted to LO to tame OPE
- Poles for both Z_b's are extracted from the amplitude:
  - $Z_b(10610)$ is shallow virtual state near $B\bar{B}^*$ threshold
  - $Z_b(10650)$ is above-threshold resonance near $B^*\bar{B}^*$ threshold

Spin partners W_{bJ}

Prediction of Heavy Quark Spin Symmetry: J^{++} spin partner molecular states W_{bJ} $(J = 0, 1, 2)$ should exist



(Bondar et al.'2011,Voloshin'2011)

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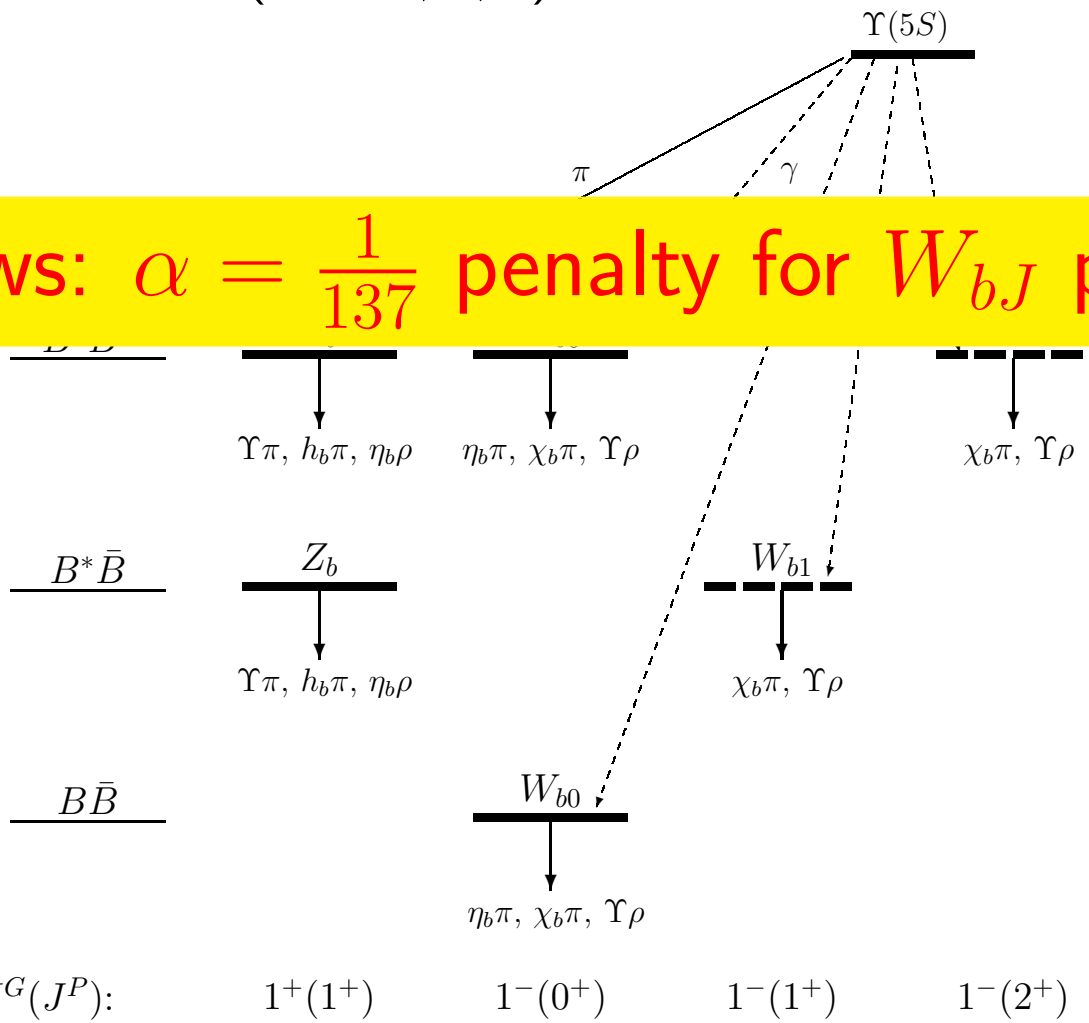

Bad news: $\alpha = \frac{1}{137}$ penalty for W_{bJ} production

(Bondar et al.'2011,Voloshin'2011)

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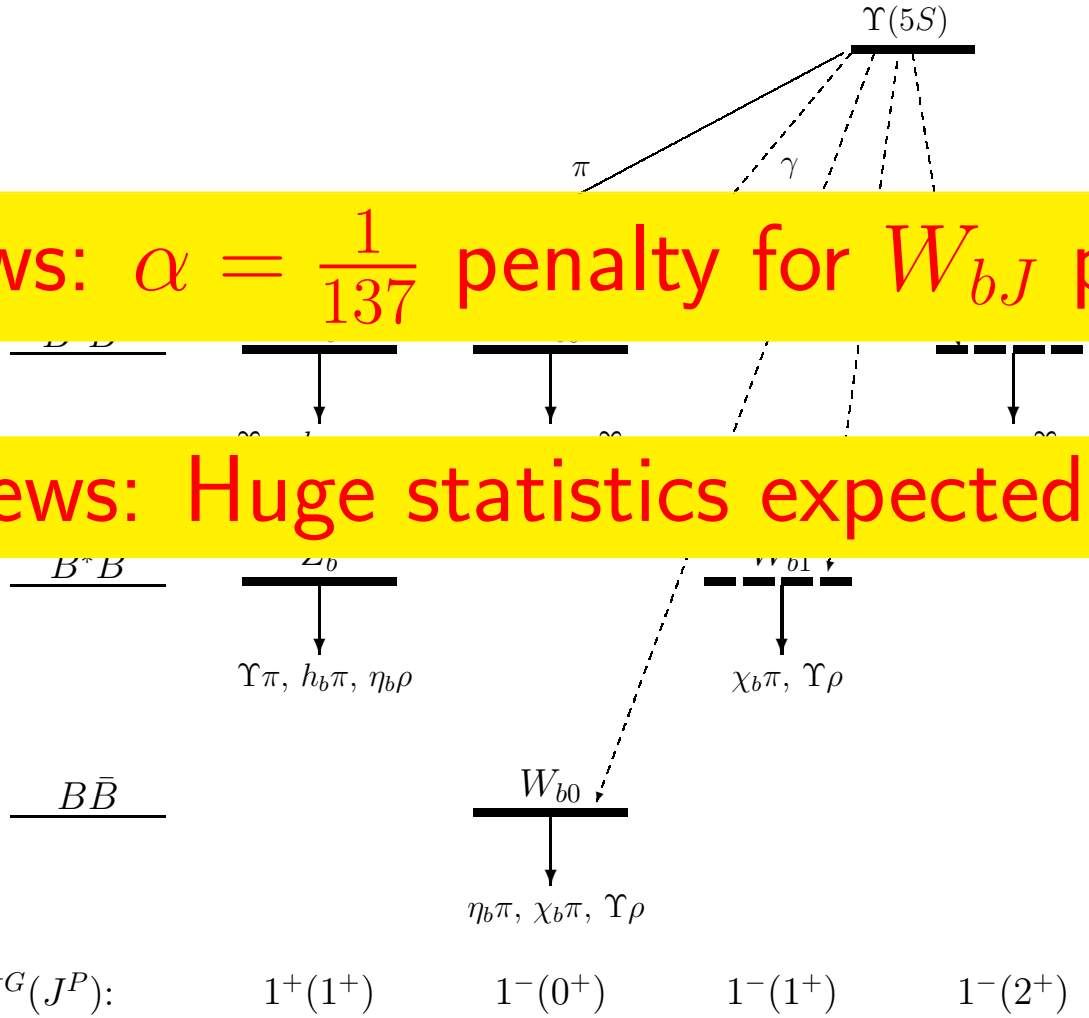

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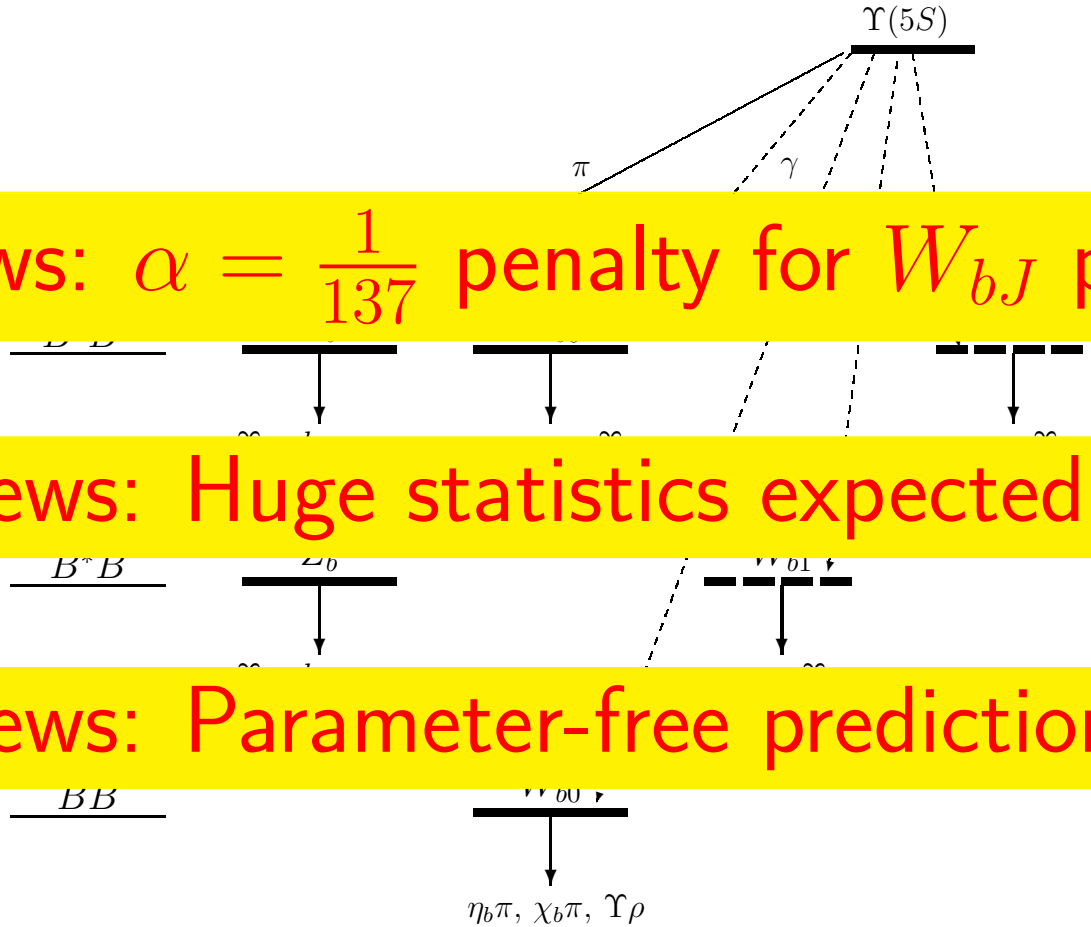


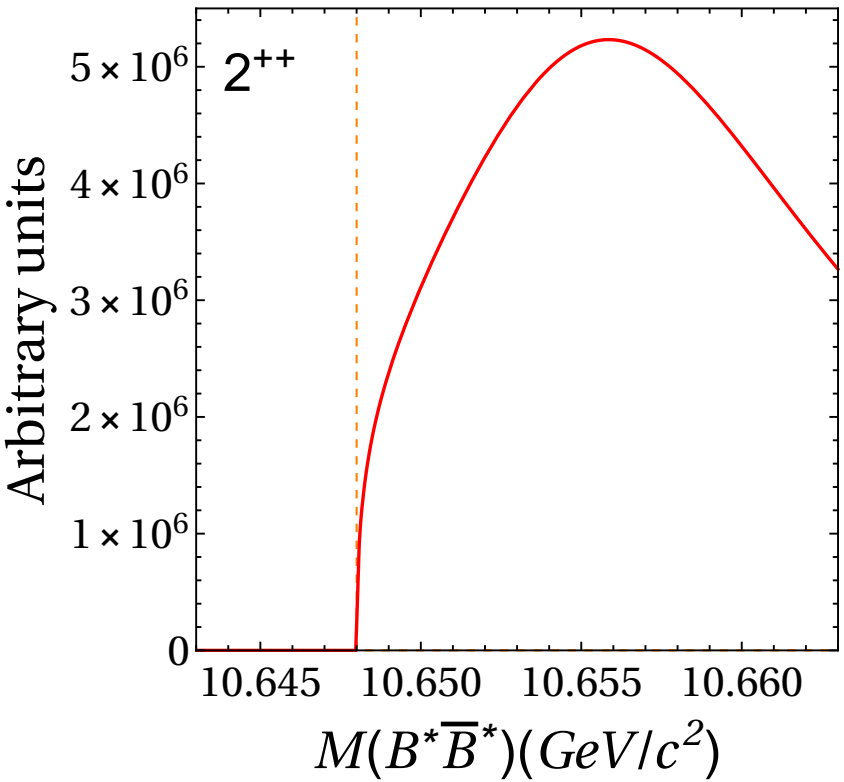
Bad news: $\alpha = \frac{1}{137}$ penalty for W_{bJ} production

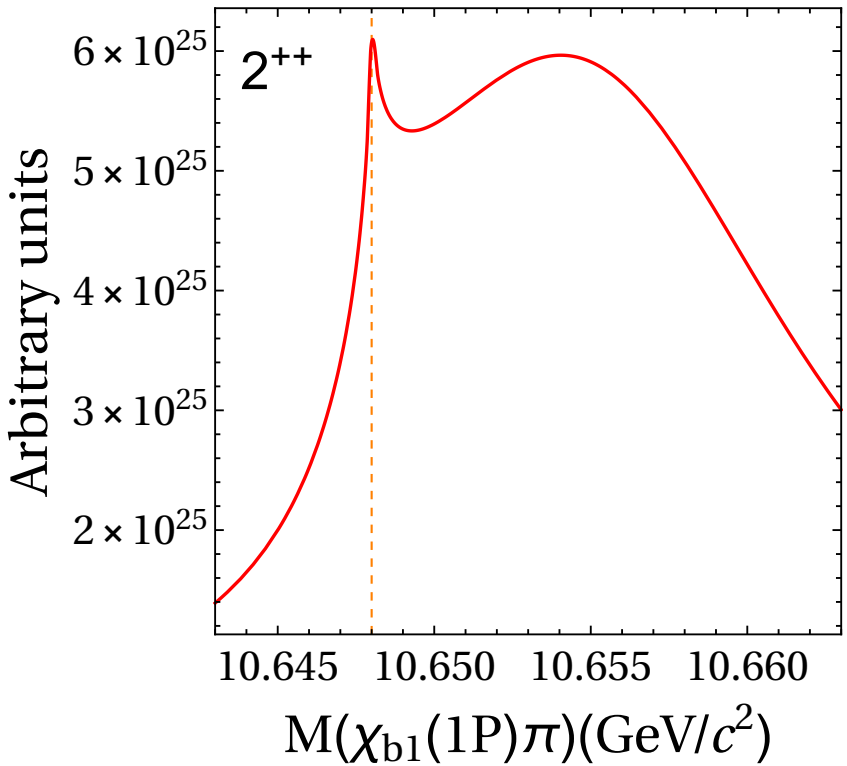
Good news: Huge statistics expected at Belle-II

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

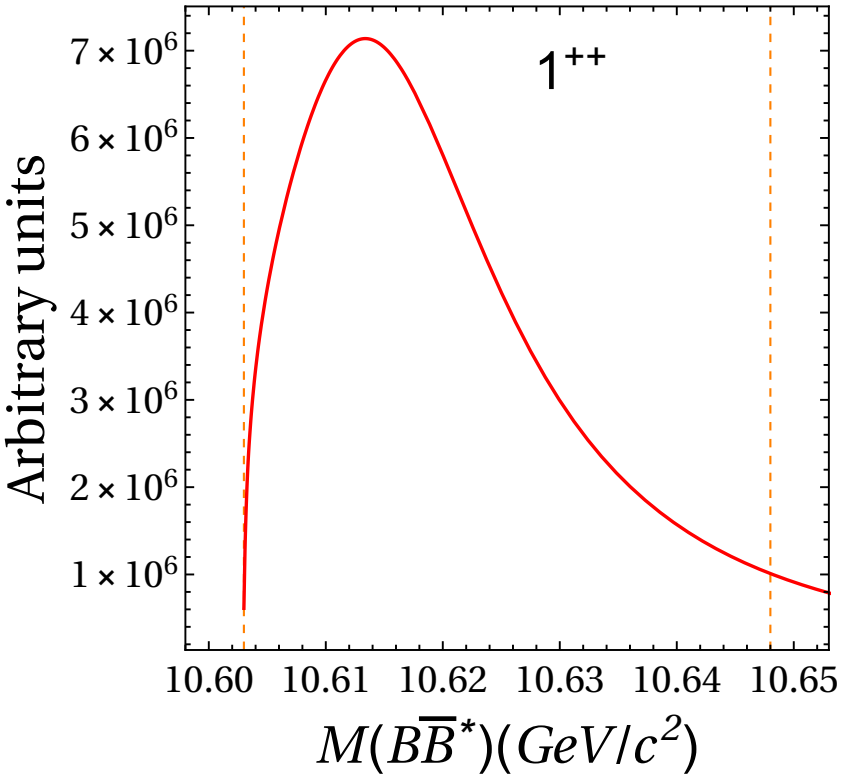
(Bondar et al.'2011,Voloshin'2011)

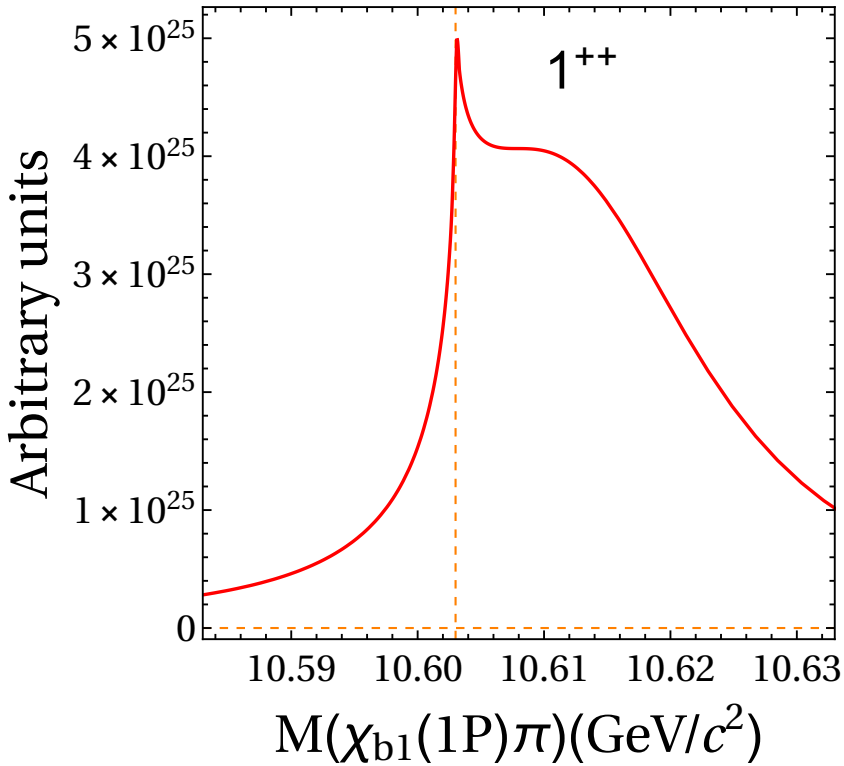
W_{b2} (2^{++}) line shapes (preliminary!)



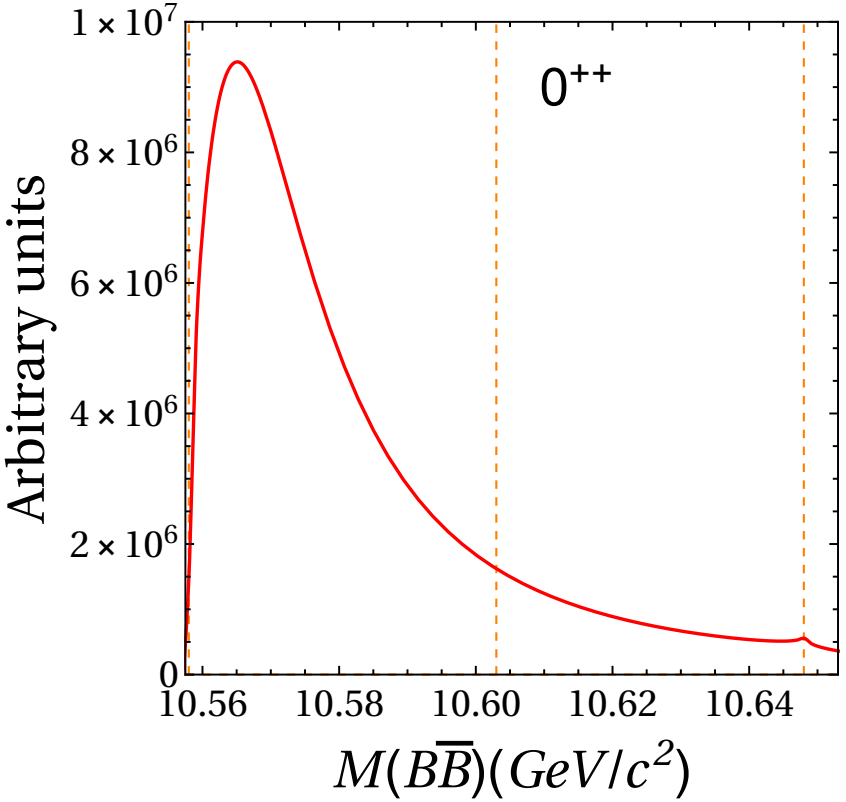


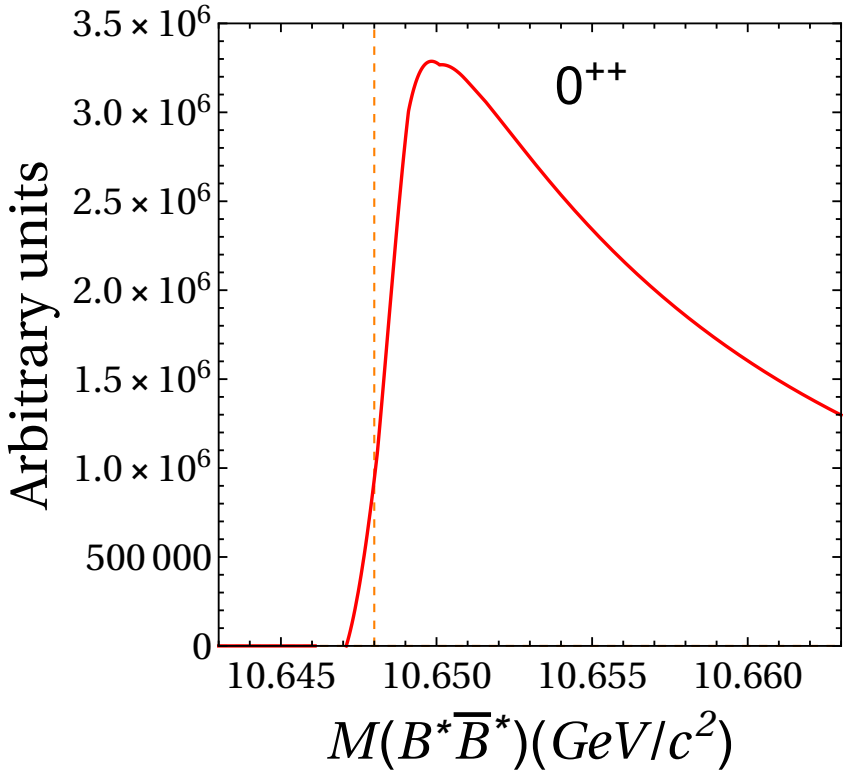
W_{b1} (1^{++}) line shapes (preliminary!)





$W_{b0}^{(\prime)}$ (0^{++}) line shapes (preliminary!)





Conclusions

Phenomenological approach based on molecular picture:

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

Further developments:

- Relation between different heavy-quark sectors
- Proper inclusion of compact components
- Generalisation to $SU(3)$ flavour group for light quarks
- Tests of accuracy of HQSS, especially in the charm sector