$Z_b(10610)$ and $Z_b(10650)$ and their spin partners from an analysis of experimental line shapes

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in collaboration with

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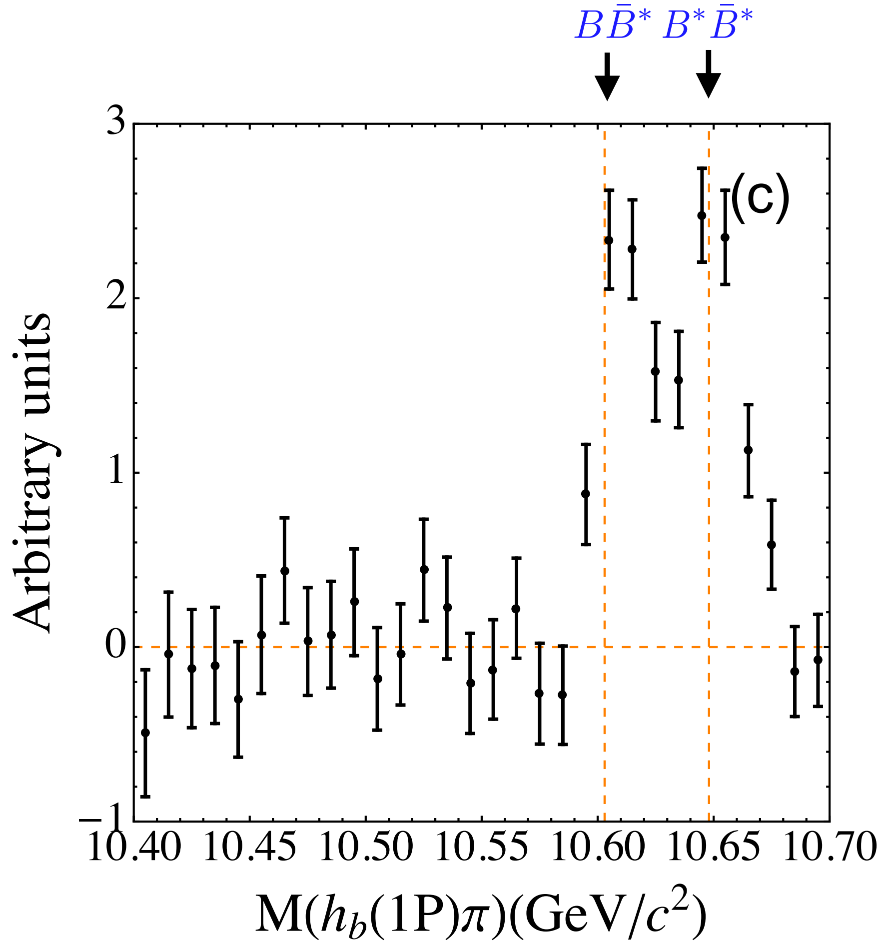
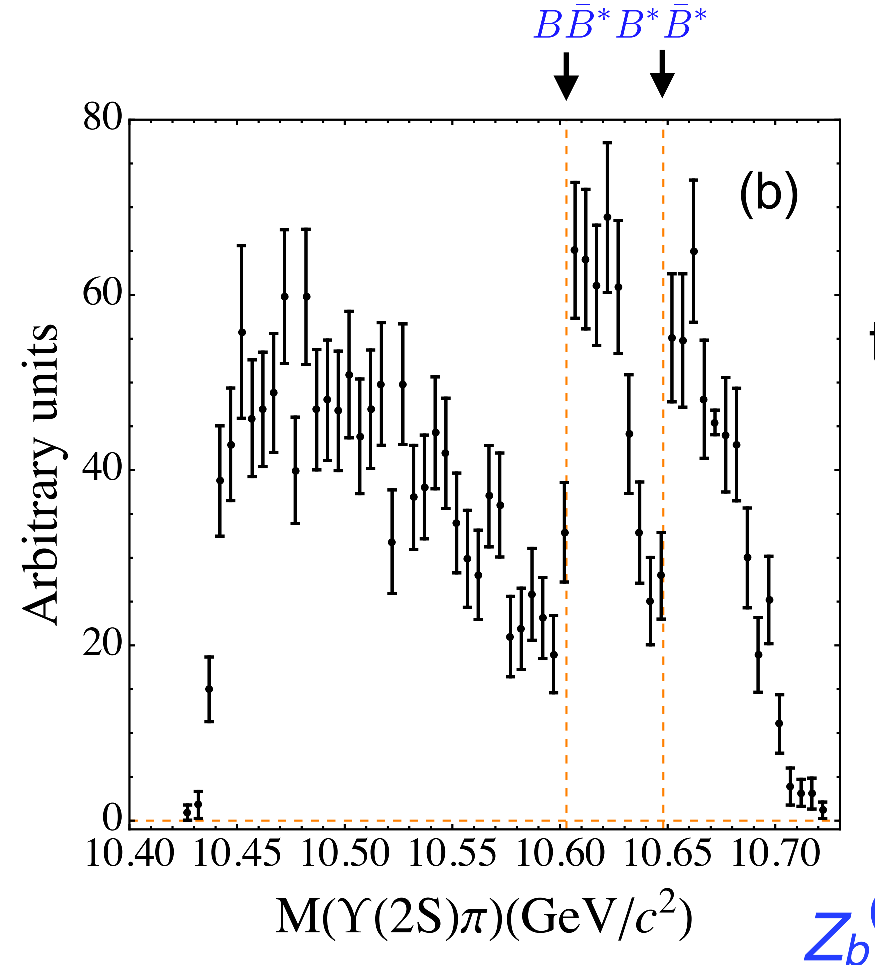
PRD 98, 074023 (2018) and PRD 99, 094013 (2019)

$Z_b(10610)$ and $Z_b(10650)$ from $\Upsilon(10860)$ decays at Belle





Peaks near BB* and B*B* thresholds in various channels:

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

$\pi^\pm h_b(mP),\ \pi^\pm \Upsilon(nS)$

Charged modes $\Longrightarrow$ $Z_b^{(\prime)}$ must be made of ≥4 quarks

- PDG: $M_{Z_b} = 10607.2 \pm 2.0$ MeV, $\Gamma_{Z_b} = 18.4 \pm 2.4$ MeV
  $M_{Z_b'} = 10652.2 \pm 1.5$ MeV, $\Gamma_{Z_b'} = 11.5 \pm 2.2$ MeV

Bondar et al. PRL108, 122001(2012)
Garmash et al.PRL116, 212001(2016)
PRD91, 072003 (2015)

- dominant decays to open flavour channels

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

  Heavy quark spin flip — No spin flip

$\Longrightarrow$ a strong hint for a large molecular component in $Z_b(10610)/Z_b(10650)$

Bondar et al. PRD 84, 054010 (2011)

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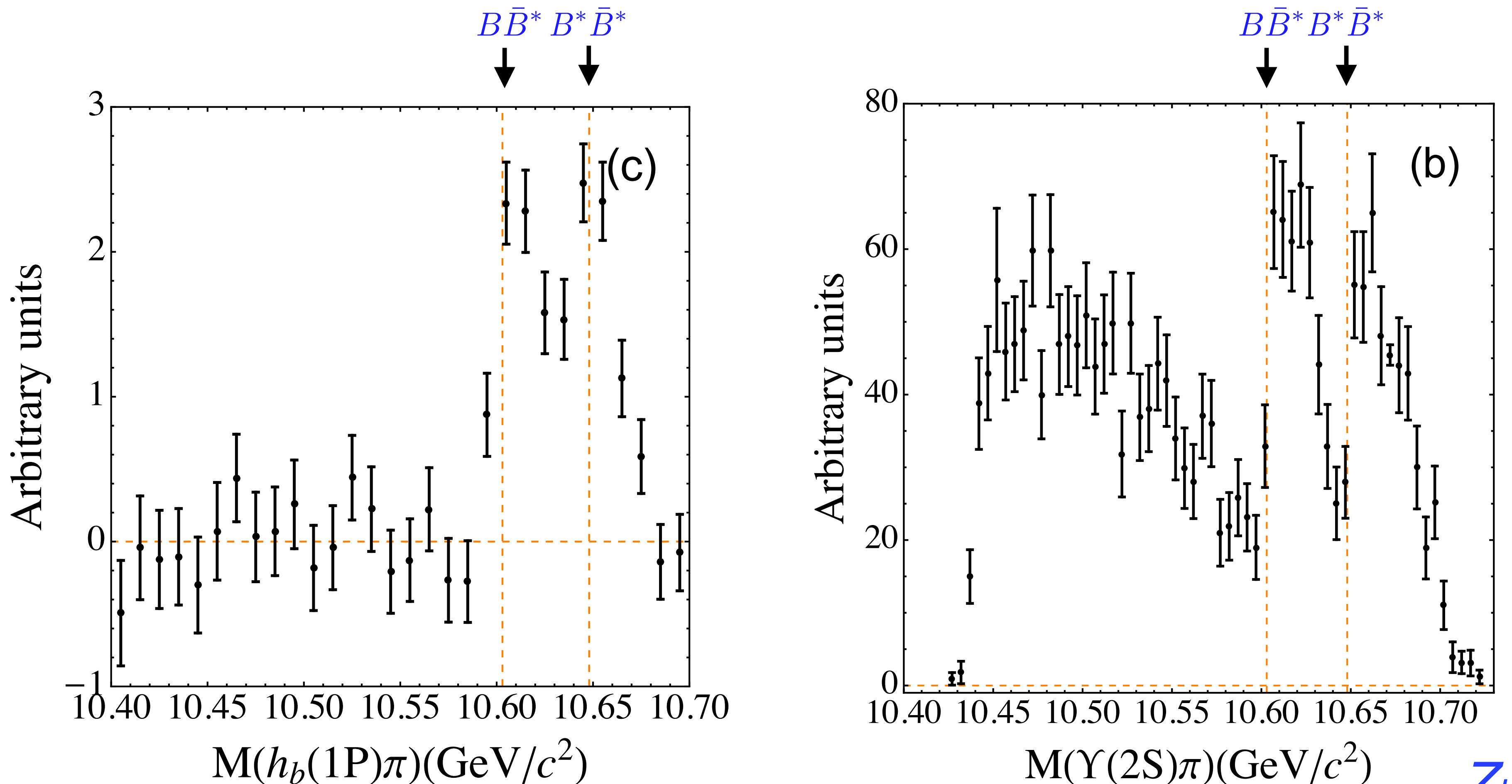

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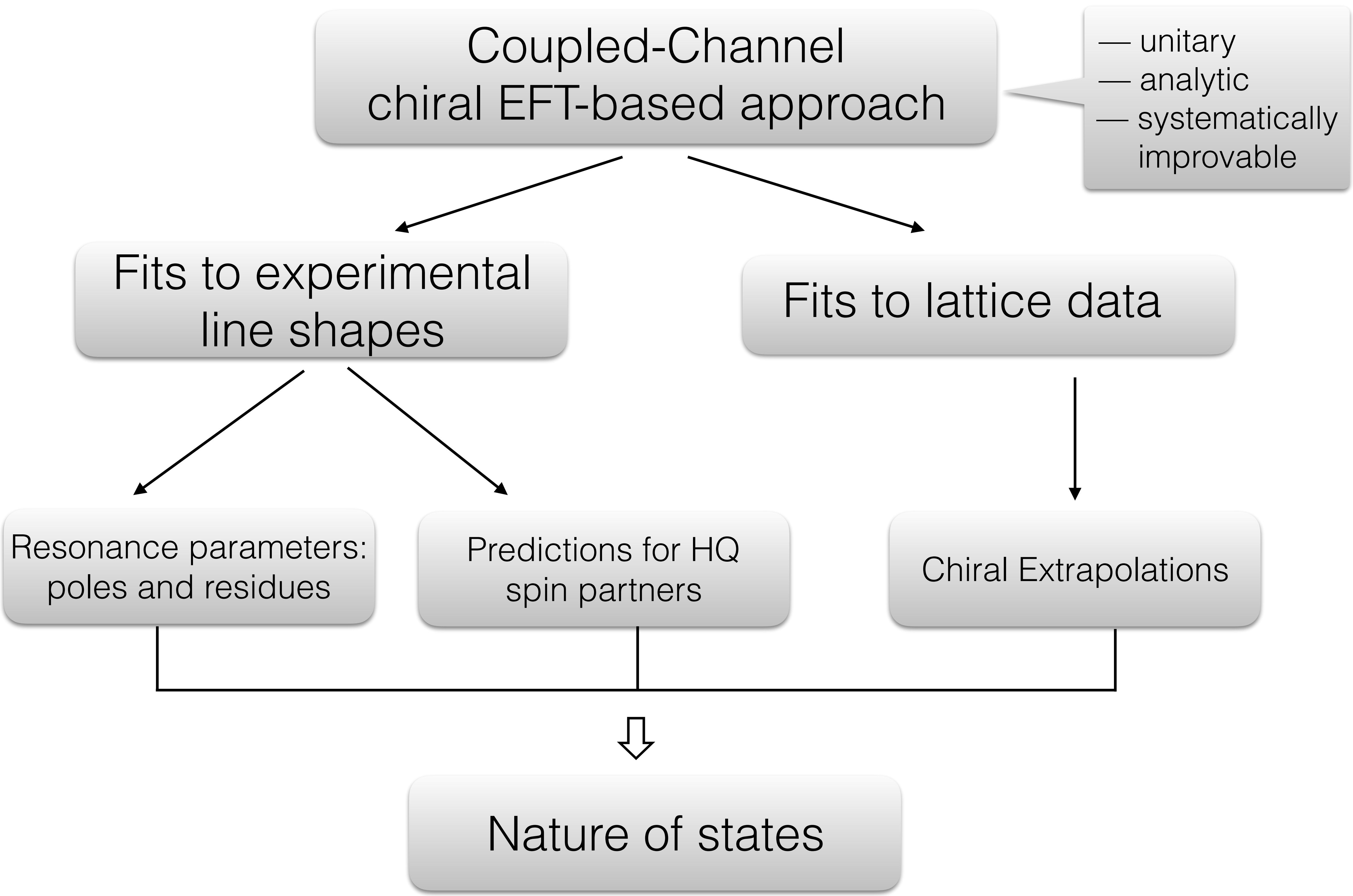
- Exp. analysis is made using a sum of Breit-Wigner amplitudes:
  - — does not account for threshold behavior
  - — naive coherent sum violates unitarity
  - — reaction dependent, no fits of all data simultaneously

How to improve?

Roadmap for analysing near-threshold states



Chiral EFT approach at low energies

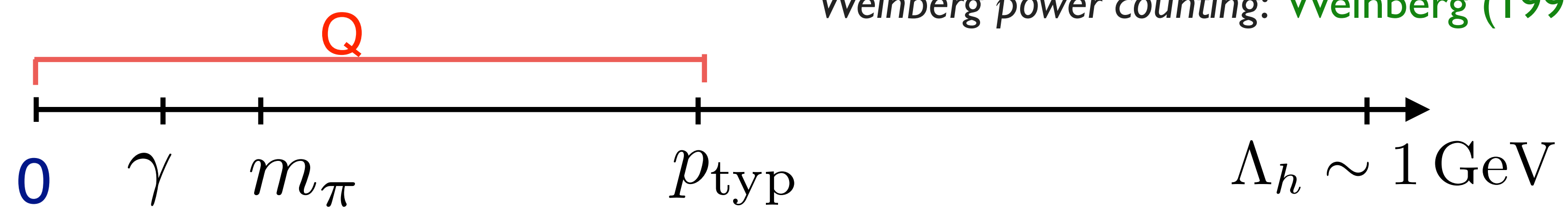
– Very similar to nuclear EFT ⇒ deuteron as proton-neutron bound state, …

review: Epelbaum, Hammer, Meißner

- Elastic $B^{(*)}B^* \to B^{(*)}B^*$ potential is constructed to a given order in Q/Λ_h

Weinberg power counting: Weinberg (1991)

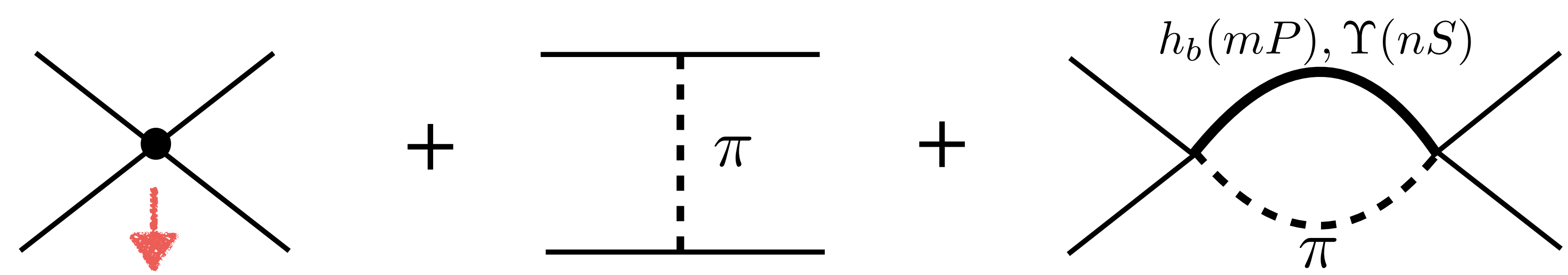
☛ Q is a typical soft scale



$$p_{\rm typ} = \sqrt{m\,\delta} \simeq 500\ \mathrm{MeV}, \qquad \delta = E^{\rm thr}_{B^*B^*} - E^{\rm thr}_{BB^*} = m_* - m \approx 45\ \mathrm{MeV}$$ ~ range of validity

☛ include the mass splitting, residual HQSS violation ~ $\Lambda_{QCD}/m_b \ll 1$

☛ $V^{\rm eff}_{\rm LO}$ = (contact) + (one-pion exchange) + (inelastic loop)



2 S-S wave LECs at O(Q^0)

S-D wave LEC at O(Q^2)

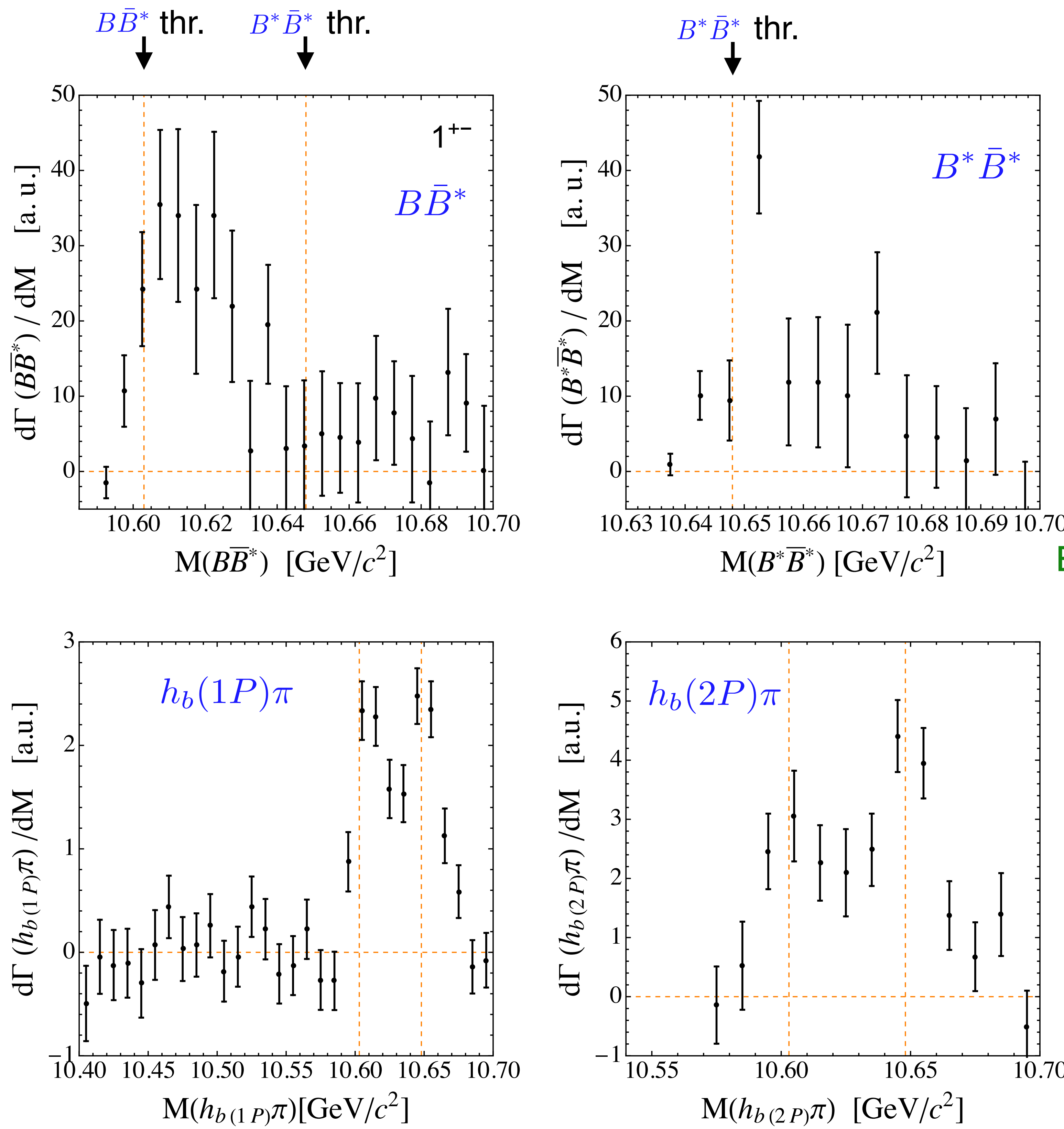
Long range: OPE

Imaginary part from inelastic channels

- Amplitudes: non-perturbative solutions of coupled-channel integral equations

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

Input and fitting procedure



- Input: experimental distributions for

$$\Upsilon(10860) \to \pi Z_b^{(')} \to \pi\alpha$$

and branching fractions (BF's) for

$$\alpha = B\bar{B}^*,\ B^*\bar{B}^*,\ h_b(1P)\pi,\ h_b(2P)\pi,\ \Upsilon(1S)\pi,\ \Upsilon(2S)\pi,\ \Upsilon(3S)\pi$$

Belle: Bondar et al. (2012), Garmash et al. (2015-2016)

- Parameters of the fits:

LO: 2 S-to-S + 1 S-to-D elastic CT's

+ 5 elastic-inelastic constants

↳ largely constrained by BF's

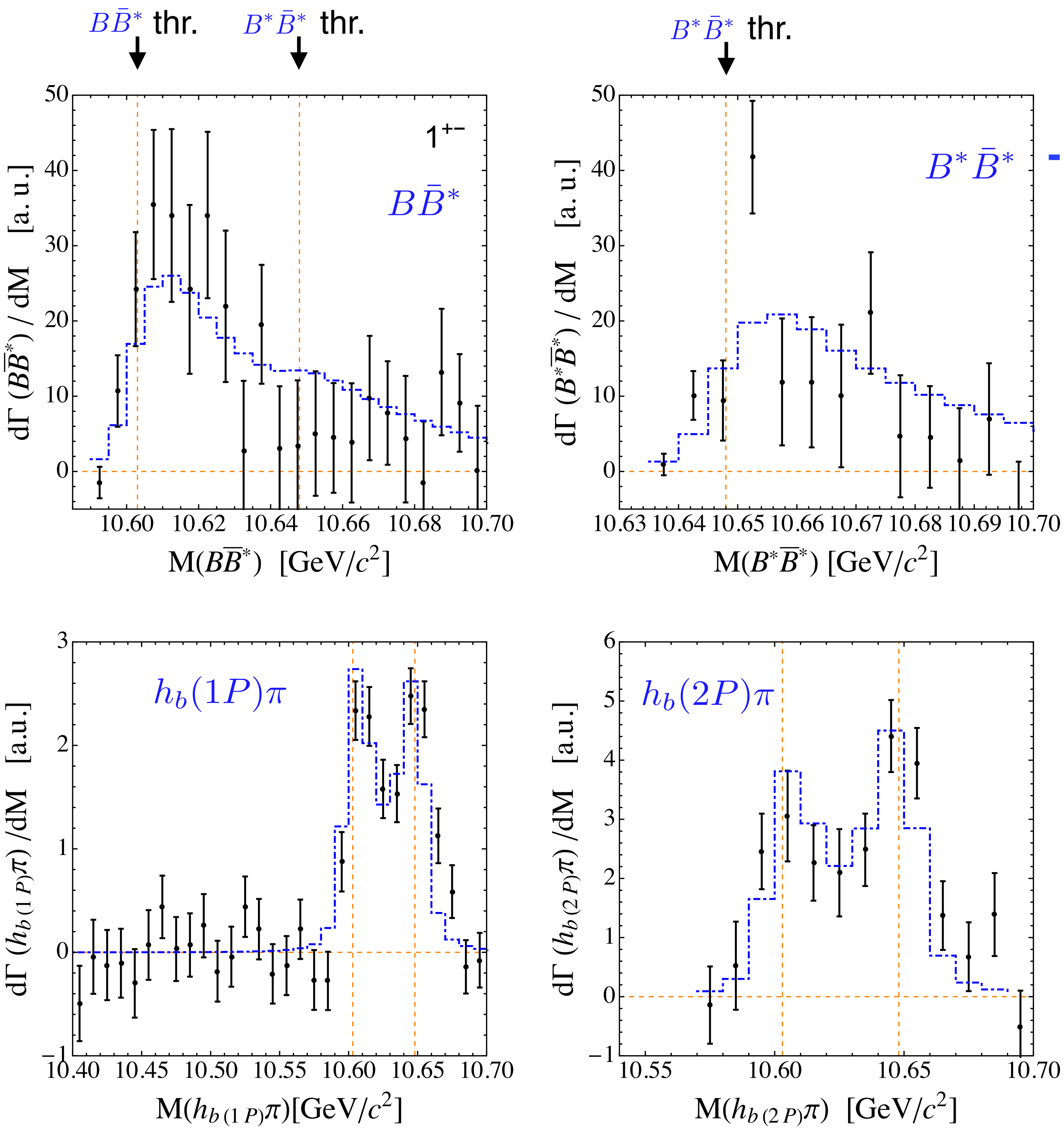
NLO: 2 S-to-S CT's

OPE (as well as all one-pseudoscalar exchange) potentials are parameter free!

Results: pionless theory at LO

PRD 98, 074023 (2018)

$\chi^2 \equiv \frac{\chi^2}{\text{dof.}}$

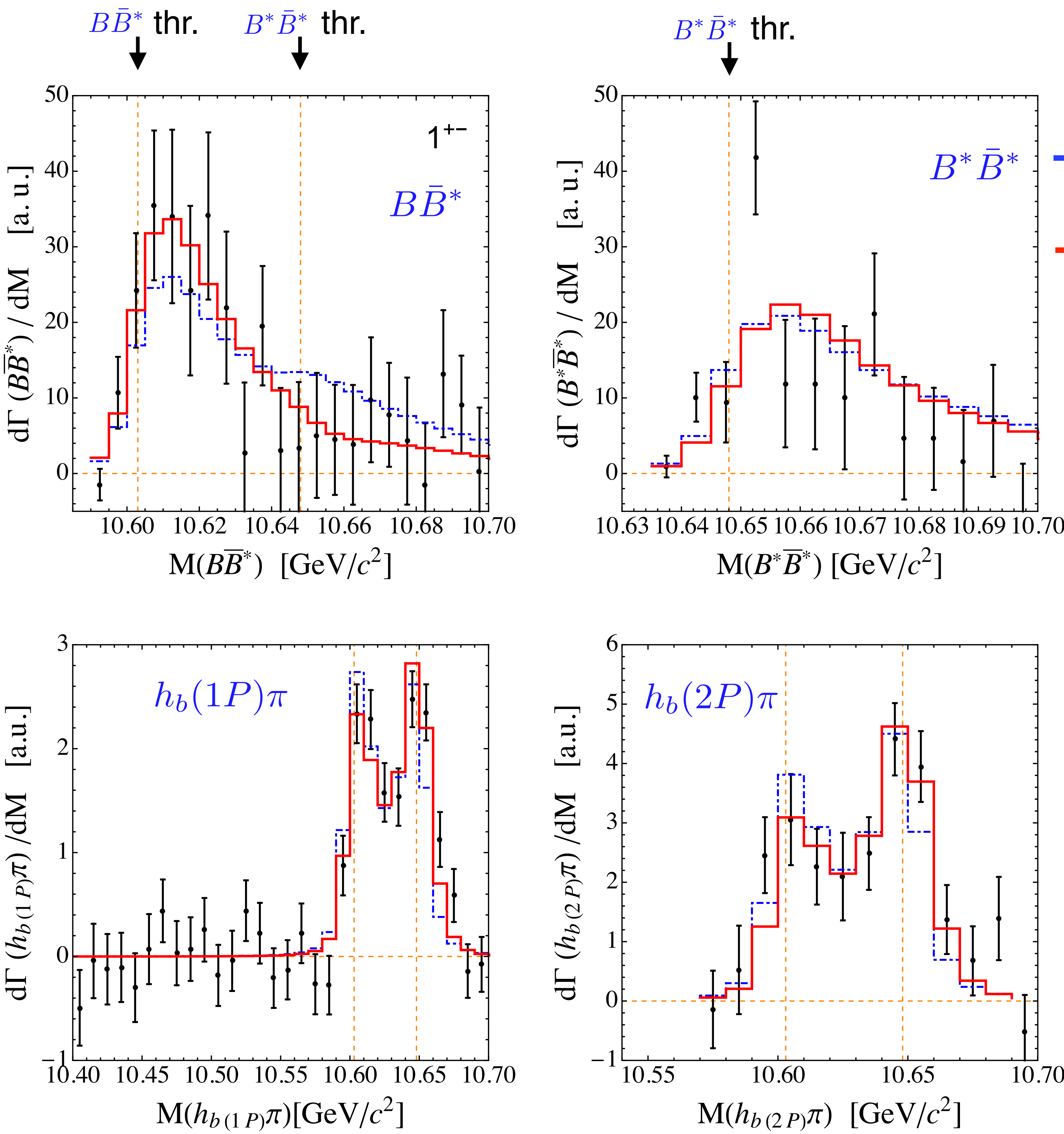


πless: LO CT's χ^2=1.29

— HQSS is preserved in the potentials

— consistent with the parameterisation by Guo et al. PRD 93, 074031 (2016)

Results: LO contact terms (CT's) + OPE PRD 98, 074023 (2018)



$\chi^2 \equiv \frac{\chi^2}{\text{dof.}}$

πless: LO CT's χ^2=1.29

πful 1: LO CT's + OPE χ^2=0.95

- S-wave central OPE is weak

- S-wave-to-D-wave tensor forces from OPE are important
  our work: JHEP 1706, 158 (2017)

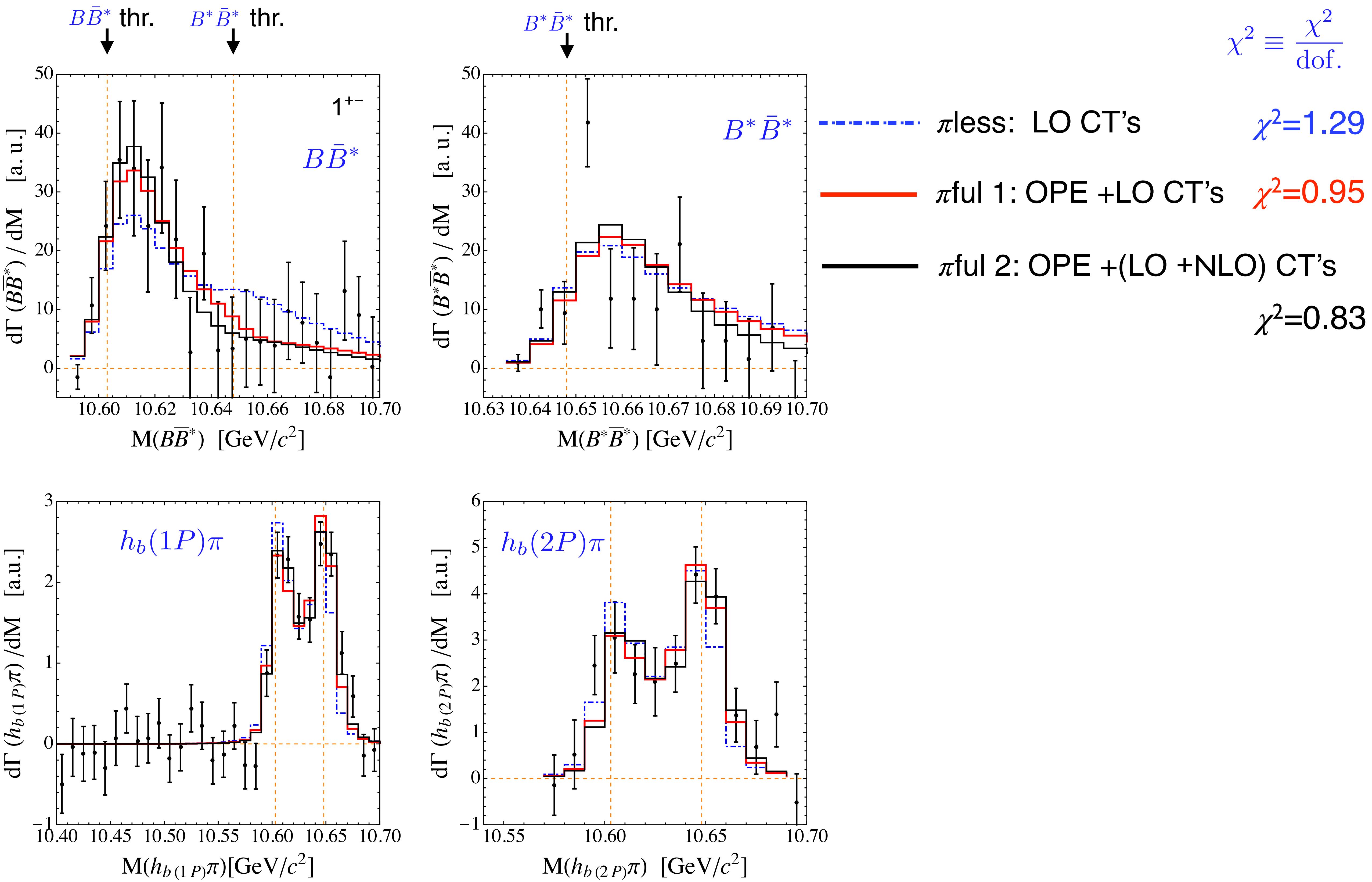
- Cutoff independence requires S-wave-to-D-wave contact term to appear together with OPE

see also our work: PRD 91 034002 (2015)

Residual effect from OPE results in a quantitative improvement of the fit

Results: LO CT's + OPE + NLO CT's

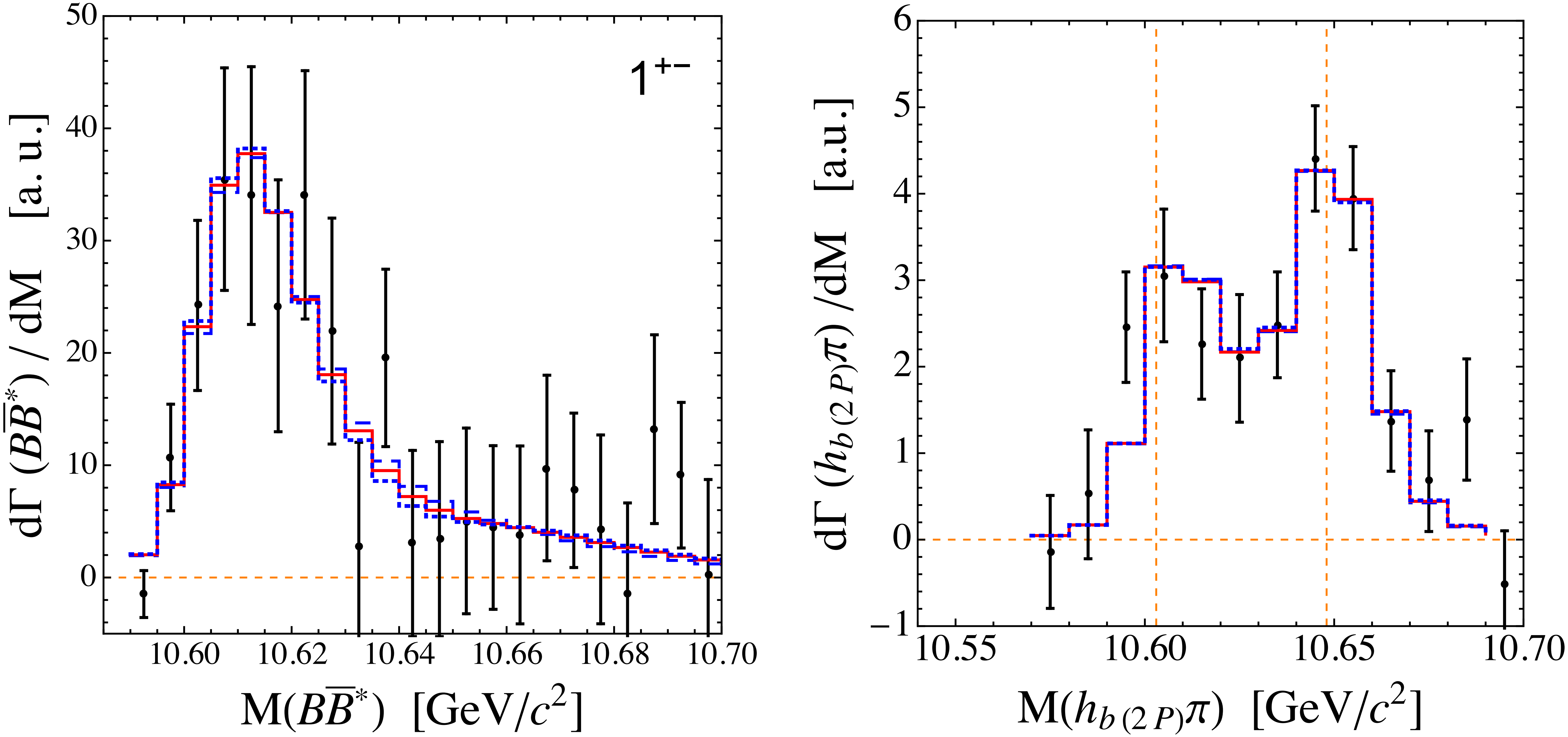
PRD 98, 074023 (2018)



Effect from two NLO CT's is subleading, as expected in EFT

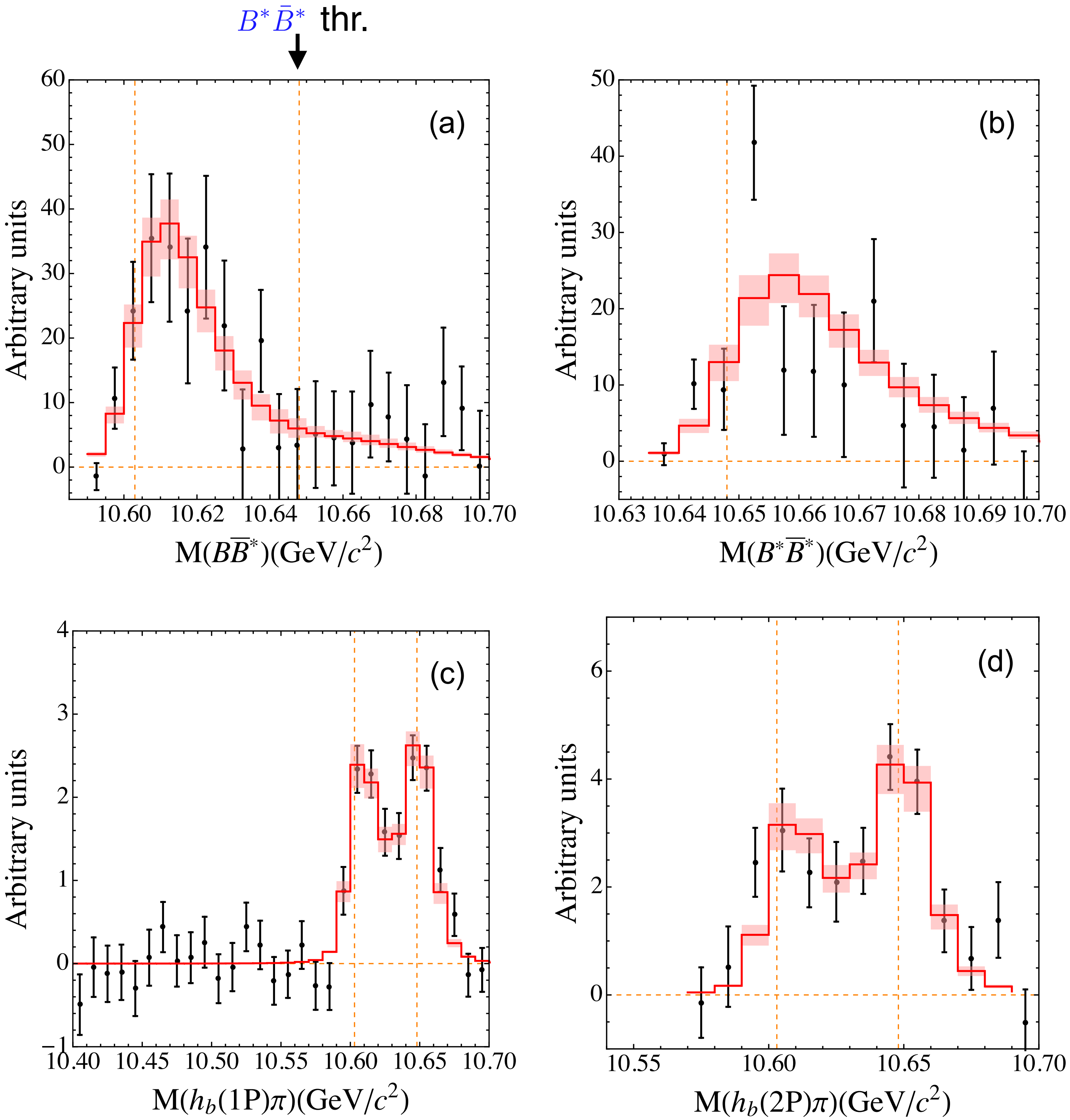
Independence of the regulator

we use sharp cutoff $\Lambda \in$ [0.8 GeV, 1.3 GeV]



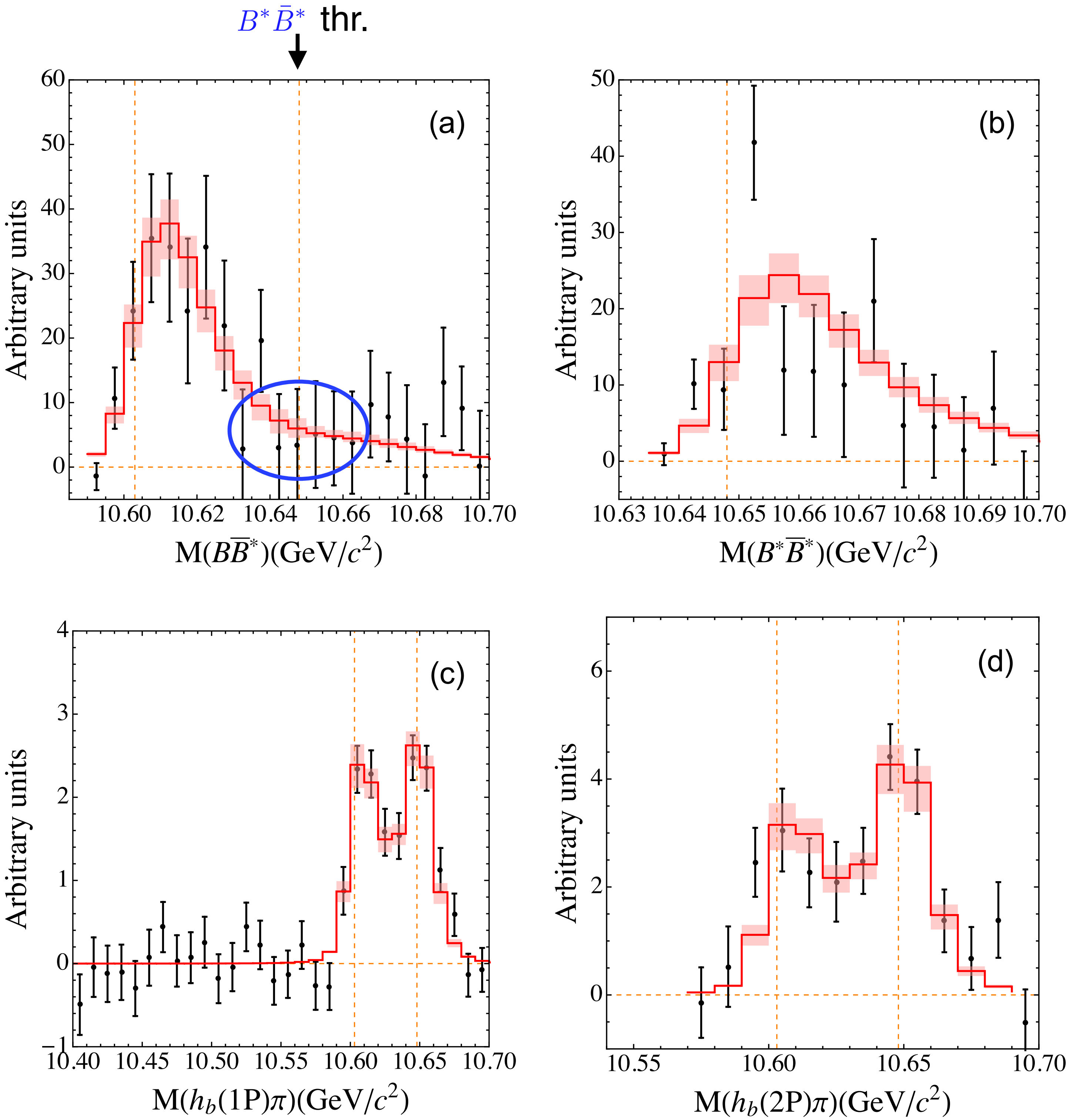
Residual cutoff dependence is small and expected to be removed by higher-order CT's

Final remarks



- All LECs are extracted from the best fit including 1σ errors
- Visible effect from OPE
- Natural suppression of higher-order terms
- Data are consistent with HQSS

Final remarks



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— Visible effect from OPE

— Natural suppression of higher-order terms

— Data are consistent with HQSS

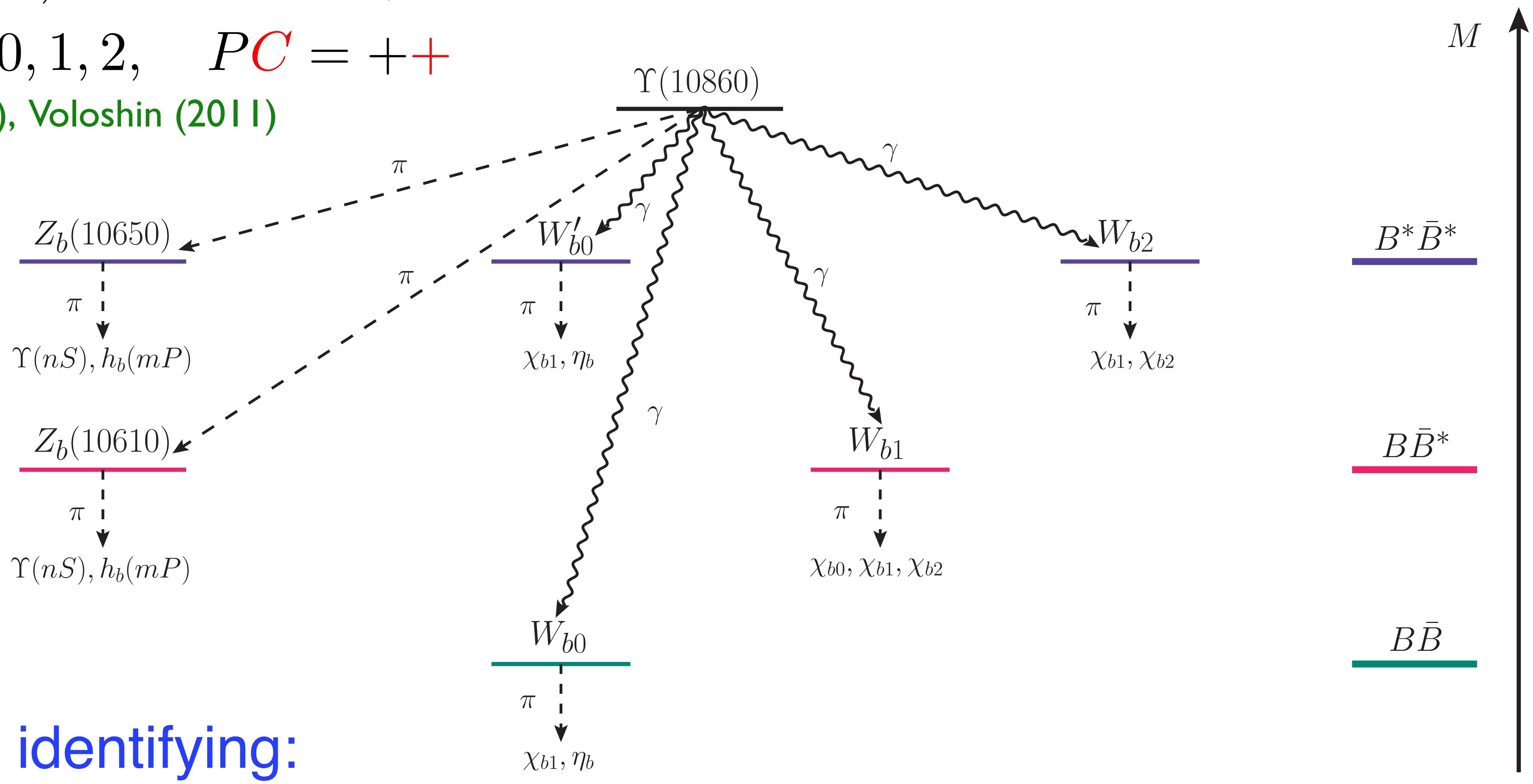
— Data: no pronounced coupled-channel structure around B*B* threshold.

Why?

Applications: spin partners of $Z_b(10610)/Z_b(10650)$

$$Z_b^{(\prime)}: \quad J=1, \quad PC=+-$$
$$W_{bJ}: \quad J=0,1,2, \quad PC=++$$

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



Difficulties in identifying:

$\Upsilon(10860) \to \gamma W_{bJ} \to$ final state — α=1/137 penalty

$\Upsilon(10860) \to \pi\pi W_{b0} \to$ final state — very limited phase space

$\Upsilon(10860) \not\to \pi\pi W_{b1},\ \pi\pi W'_{b0},\ \pi\pi W_{b2}$ — not possible

$\Upsilon(11020) \to \pi\pi W_{bJ} \to$ final state — very limited phase space

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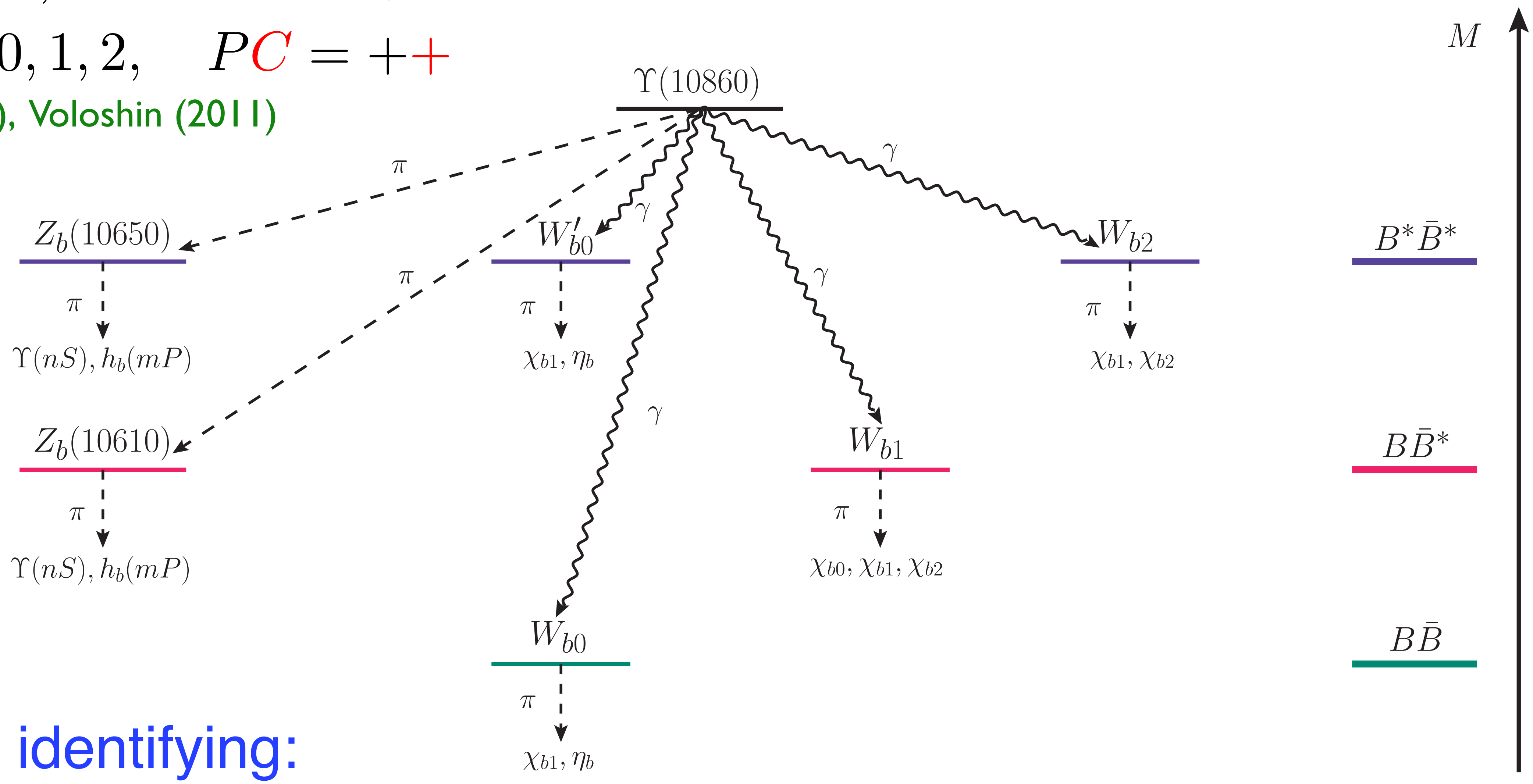

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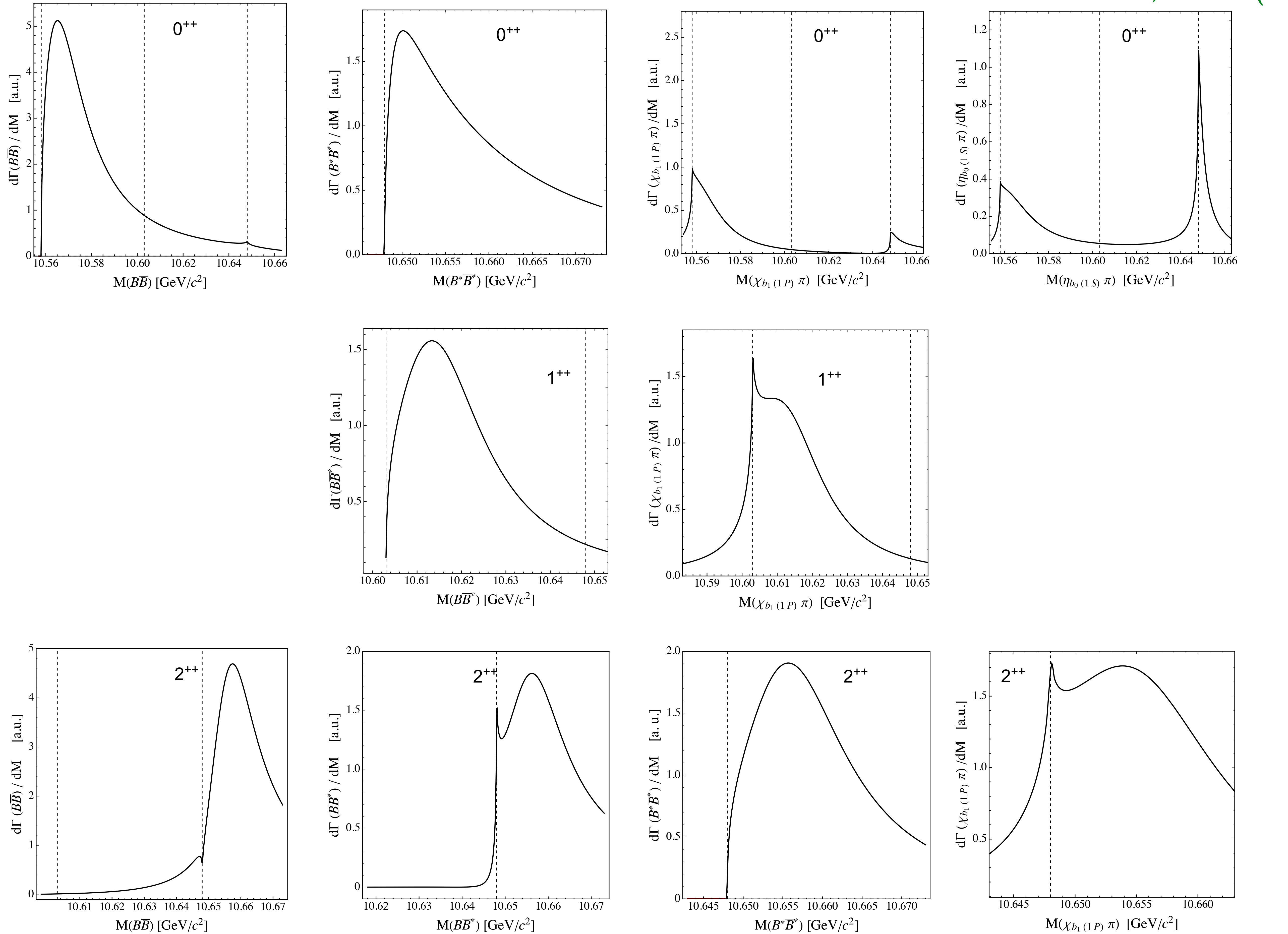
Good news: large statistics by BELLE II!

Line shapes for spin partners in $\Upsilon(10860) \to \gamma W_{bJ} \to$ final state

PRD 99, 094013 (2019)



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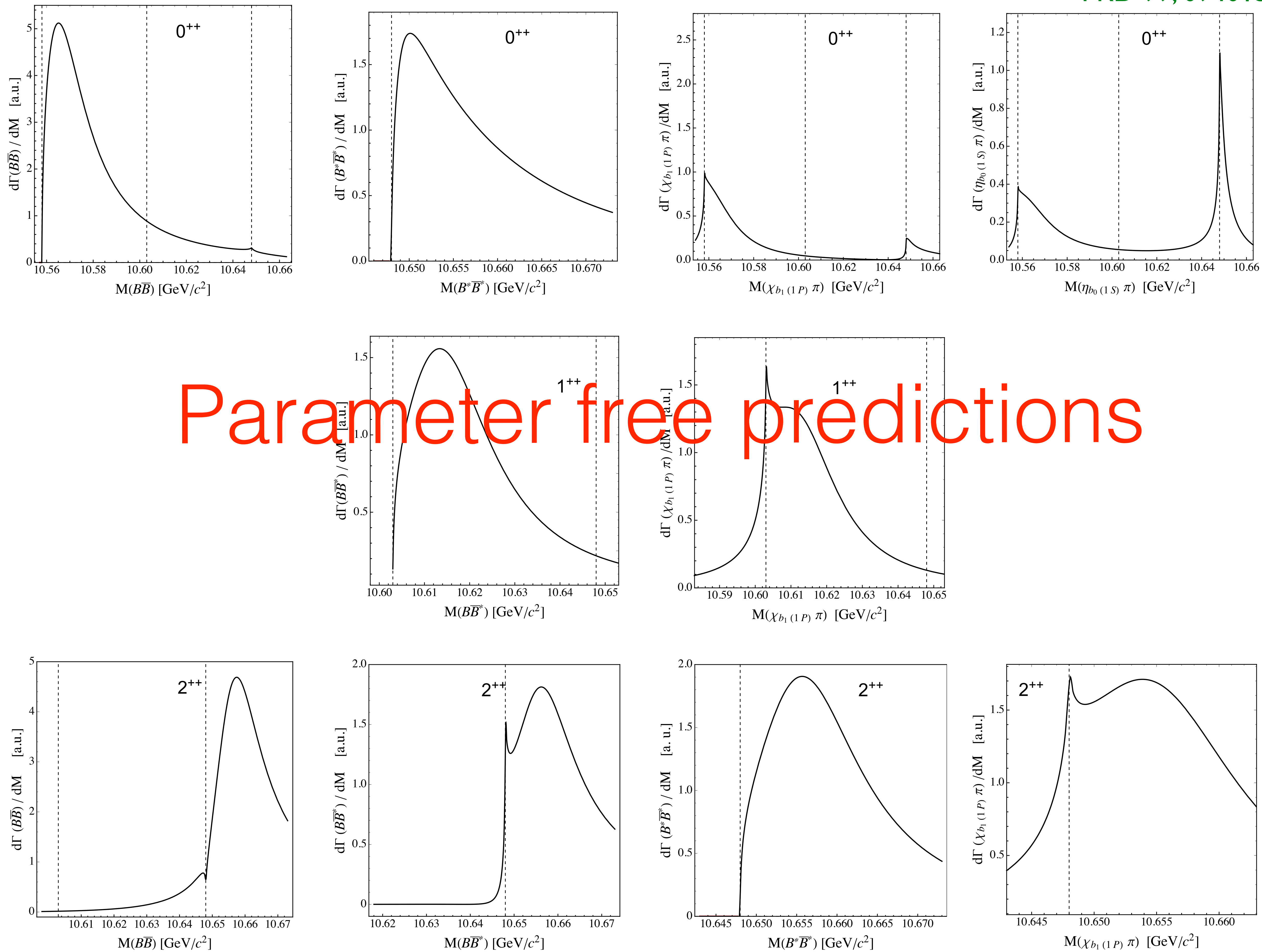
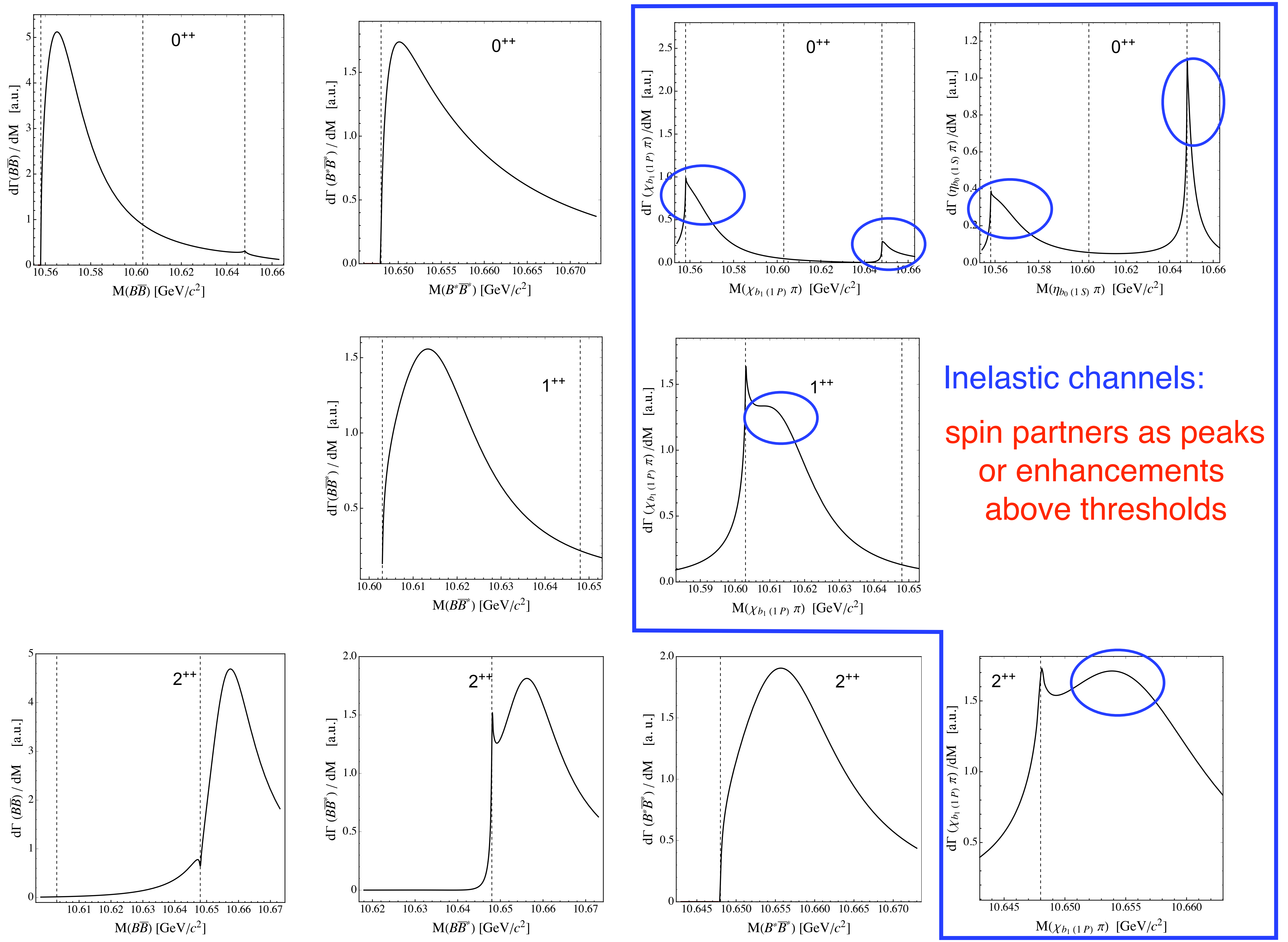
PRD 99, 094013 (2019)



Parameter free predictions

Line shapes for spin partners in $\Upsilon(10860) \to \gamma W_{bJ} \to$ final state



Pole positions and residues

PRD 99, 094013 (2019)

J^{PC}	State	Threshold	E_B w.r.t. threshold, [MeV]	Residue at pole
1^{+-}	Z_b	BB^*	$(-2.3 \pm 0.5) - i(1.1 \pm 0.1)$	$(-1.2 \pm 0.2) + i(0.3 \pm 0.2)$
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}	BB	$(2.3 \pm 4.2) - i(16.0 \pm 2.6)$	$(1.7 \pm 0.6) - i(1.7 \pm 0.5)$
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}	$B^*\bar{B}^*$	$(7.4 \pm 2.8) - i(9.9 \pm 2.2)$	$(0.7 \pm 0.1) - i(0.3 \pm 0.1)$

- Criterion of relevance for poles: shortest path to the physical region

- Classification of poles: quasi-bound state, virtual states, resonances
  - ☛ quasi-bound state affects line shapes below threshold
  - ☛ virtual state ⇒ enhanced threshold cusp in inelastic line shapes
  - ☛ resonance ⇒ peak or enhancement in inelastic line shapes above threshold

Conclusion from our EFT analysis: All Z_b's and W_{bJ}'s are resonances

(without pions ⇒ virtual states)

Partial decay widths

Predicted ratios of the decay widths for a given J

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

⇒ largest fractions to nearby elastic channels

Predicted ratios of the elastic decay widths for different J

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

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

⇒ 1^{++} and 2^{++} elastic channels have the largest elastic widths

Summary and Perspectives

- Line shapes in *c* and *b*-sectors can be systematically analysed within an EFT approach consistent with chiral and heavy quark symmetries, analyticity and unitarity

- A combined analysis of the line shapes $\Upsilon(10860) \to \pi Z_b^{(\prime)} \to \pi\alpha$ with $\frac{\chi^2}{\text{dof.}} \lesssim 1$

  $\alpha = B\bar{B}^*,\ B^*\bar{B}^*,\ h_b(1P)\pi,\ h_b(2P)\pi$

$\Longrightarrow$ poles and residues of $Z_b^{(\prime)}$ are extracted

- Employing HQSS line shapes for spin partners of $Z_b^{(\prime)}$ states and their poles are predicted parameter free $\Longrightarrow$ W_{bJ} can be searched for at Belle II

- Effects from pion cloud have visible impact on the observables $\Longrightarrow$

  poles of $Z_b^{(\prime)}$ and W_{bJ}'s are above threshold resonances (vs virtual states w/o pions)

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Ongoing :

☛ Inclusion of S-wave $\pi\pi$ FSI $\Longrightarrow$ access to data on $\Upsilon(5S) \to \Upsilon(mS)\pi\pi$

☛ Include pion loop contributions at NLO (no new params.) $\Longrightarrow$ check convergence, reduce errors

☛ Application to the charm sector: yes!
But no reliable predictions employing *flavour* symmetry for heavy-heavy molecules is possible!
VB, Epelbaum, Gegelia, Hanhart, Meißner, Nefediev Eur. Phys. J. C79 (2019)

Backup

Extracting the poles

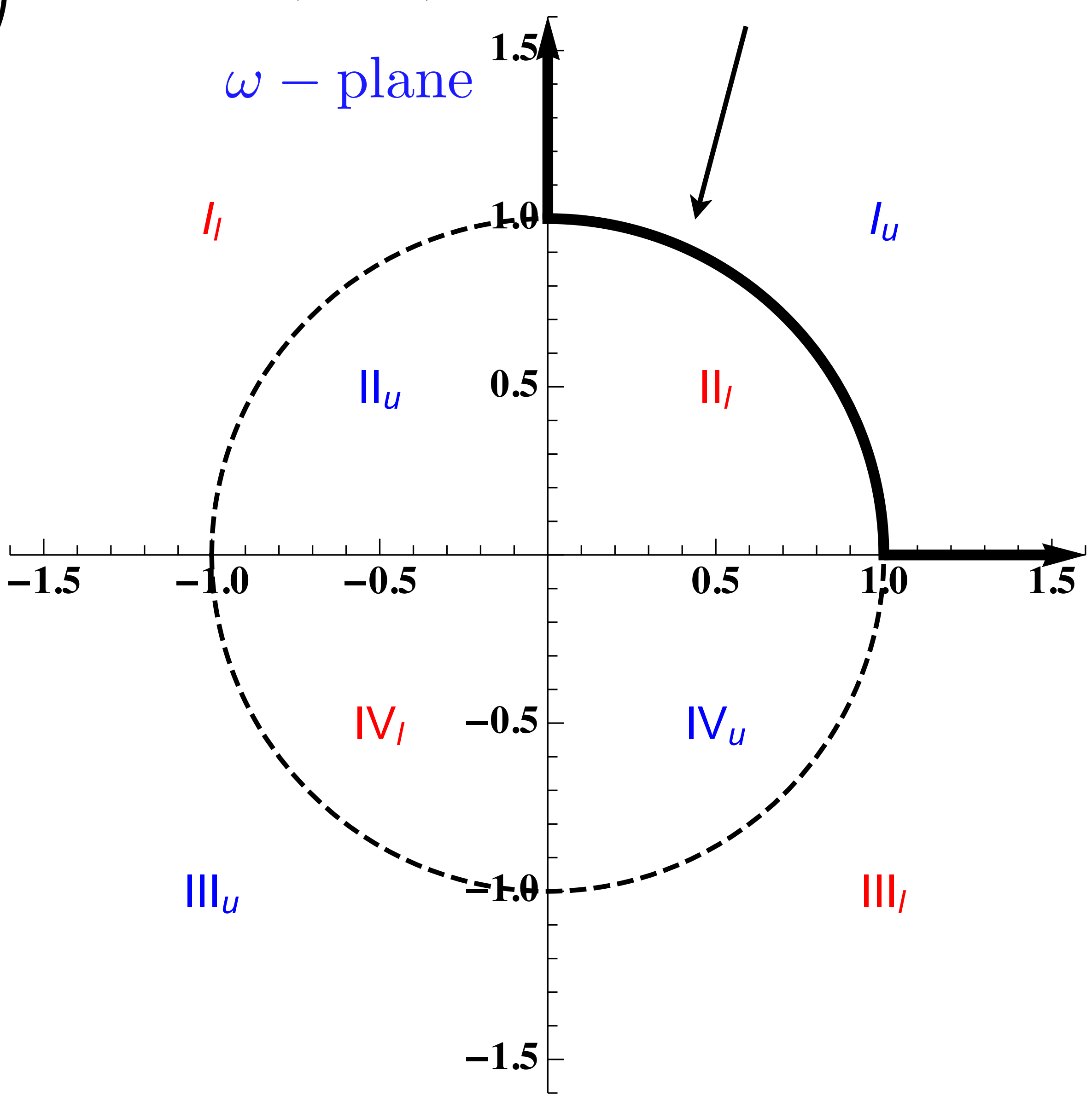
- W/O inelastic channels two-channel problem: BB* and B*B*

Conformal mapping of 4 RS surface to a single sheet surface in omega-plane:

$$k_1 = \sqrt{\frac{\mu_1 \delta}{2}} \left(\omega + \frac{1}{\omega} \right), \qquad k_2 = \sqrt{\frac{\mu_2 \delta}{2}} \left(\omega - \frac{1}{\omega} \right)$$

$$\delta = m_{B^*} - m_B$$

Kato (1965)



Definition of Riemann Sheets (RS):

$$\begin{aligned}
\text{RS-I}: &\quad \text{Im } k_1 > 0, \quad \text{Im } k_2 > 0, \\
\text{RS-II}: &\quad \text{Im } k_1 < 0, \quad \text{Im } k_2 > 0, \\
\text{RS-III}: &\quad \text{Im } k_1 < 0, \quad \text{Im } k_2 < 0, \\
\text{RS-IV}: &\quad \text{Im } k_1 > 0, \quad \text{Im } k_2 < 0.
\end{aligned}$$

Energy relative to the BB* threshold:

$$E = \frac{k_1^2}{2\mu_1} = \frac{k_2^2}{2\mu_2} + \delta = \frac{\delta}{4} \left(\omega^2 + \frac{1}{\omega^2} + 2 \right)$$

- Only the poles close to the physical region are relevant

Contact + one-pion exchange (OPE) interactions

- Extended basis states:

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

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

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

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

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

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