Properties of Zb(10610) and Zb(10650) from an analysis of experimental line shapes

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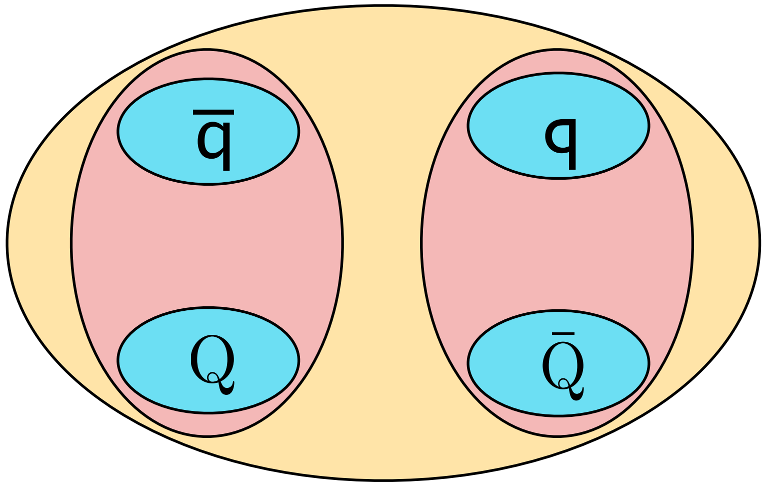
Intro to hadronic molecules

more in a review talk by Alexey Nefediev on Monday

- Plenty of observed *XYZ* states inconsistent with a quark model picture

Hadronic molecules — a special class of exotic states



☛ reside very close to hadronic thresholds and couple to them in S-wave

☛ decay predominantly to open-flavour channels

☛ specific analytic properties: unitarity cut

observable coupling of a state to a hadronic channel

$$\bar{g}_{\rm eff} = \frac{\sqrt{2\mu\epsilon}}{\mu}\lambda^2 + O\left(\frac{\sqrt{2\mu\epsilon}}{\beta}\right) \leq \frac{\sqrt{2\mu\epsilon}}{\mu}$$

— non-analytic in binding energy ϵ

probability of finding a molecular component in the full w.f.

Weinberg 1963-65
our work 2004
…

Natural candidates: X(3872) and Zb(10610)/Zb(10650) Belle (2010-2016)

Heavy-quark spin symmetry (HQSS)

- In the limit $\Lambda_{\rm QCD}/m_Q \to 0$ strong interactions are independent of HQ spin
- Spin decouples $\Longrightarrow$ spin partner states $\Longrightarrow$ test of the nature!

$$\mathcal{H} \propto \frac{\boldsymbol{\sigma}\cdot\boldsymbol{B}}{m_Q}$$

Cleven et al. (2015)

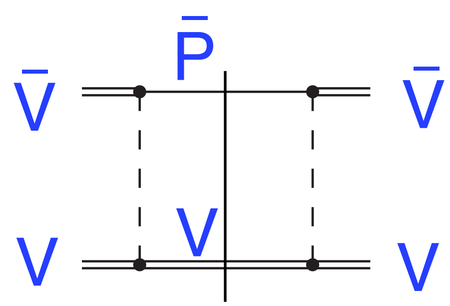
$\Longrightarrow$ plenty of predictions for the partners using contact interactions

Bondar et al. (2011), Voloshin (2011), Mehen and Powell (2011), Guo et al. (2015)

- Role of one-pion exchange (OPE) for the molecular partners can be non-trivial

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

— HQSS violation from the mass splitting δ is enhanced by strong S-D transitions from OPE



$$p_{\rm typ} \simeq \sqrt{2\mu\delta} \approx 500 \text{ MeV} \geq m_\pi$$

$$\delta = m_V - m_P$$

$V = D^*$ and B^*

$P = D$ and B

— Assuming molecules are bound states $\Longrightarrow$ visible shifts of spin partners from thresholds, especially in the c-quark sector

But accurate line shape analyses with the OPE included are needed!

Molecular states from line shape analyses: Goals

- Analyse line shapes in a chiral EFT approach → obeying chiral and HQ symmetries of QCD → manifestly analytic and unitary

The goals:

☛ infer the role of SU(3) GB octet interactions (π and η exchanges) and HQSS violation

☛ extract the molecular state poles directly from line shapes

☛ predict HQSS partner states parameter free

☛ investigate chiral extrapolations of molecular states <—> lattice

Can be applied to various molecule candidates: X(3872), Zc(3900), Zc(4020), …
Zb(10610), Zb(10650) …

This Talk — application to $J^{PC} = 1^{+-}$ $Z_b(10610)$ and $Z_b(10650)$

Formalism for line shapes $\Upsilon(10860) \to \pi Z_b^{(')} \to \pi\alpha$

- Input: experimental distributions for

$$\Upsilon(10860) \to \pi Z_b^{(')} \to \pi\alpha \qquad \alpha = BB^*, \quad B^*B^*, \quad h_b(1P)\pi, \quad h_b(2P)\pi$$

and branching fractions 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. (2016)

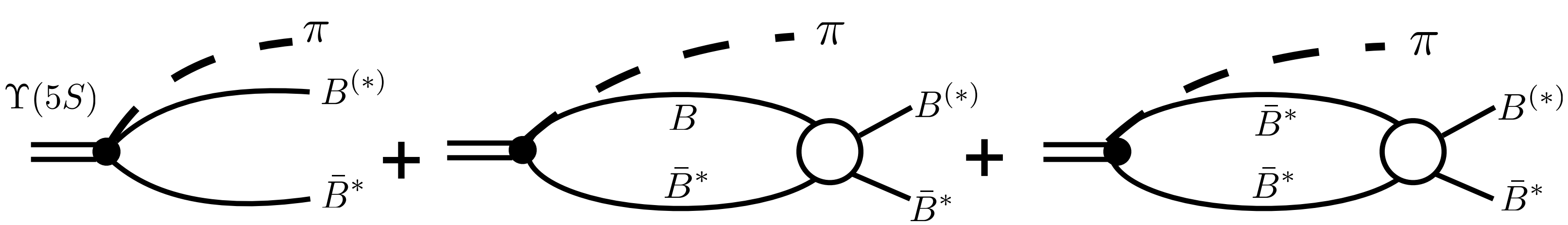
- $\Upsilon(mS)\pi\pi$ distributions not included: involve sizeable $\pi\pi$ FSI

— Recent calculations for $\Upsilon(3S) \to \Upsilon(1S)\pi\pi,\ \Upsilon(4S) \to \Upsilon(1S, 2S)\pi\pi$ but not yet for $\Upsilon(5S) \to \Upsilon(mS)\pi\pi$

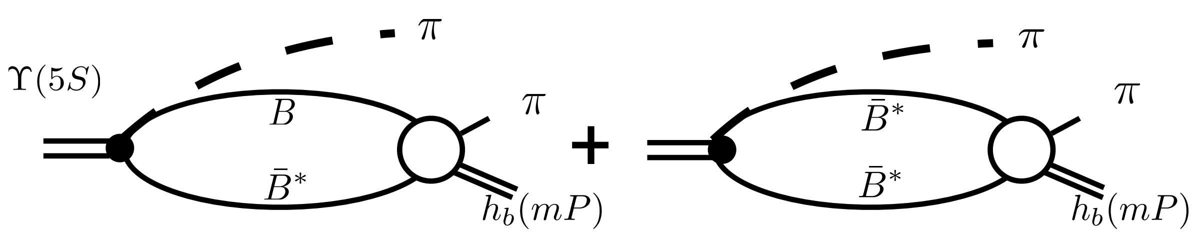
Chen et al. (2016-2017)

Production amplitudes for the events dominated by the Zb's poles:

$U_{\rm el} =$



$U_{\rm inel} =$



☛ Inelastic source $\Upsilon(5S) \to h_b(nP)\pi\pi$ requires flip in the HQ spin $\Longrightarrow$ suppressed by HQSS

Formalism for line shapes: effective potential

- Production amplitudes *U*: from coupled-channel Lippmann-Schwinger Eqs. (LSE)

  2 elastic channels x 2: $\alpha = B\bar{B}^*[^3S_1],\ B\bar{B}^*[^3D_1],\ B^*\bar{B}^*[^3S_1],\ B^*\bar{B}^*[^3D_1]$

  5 inelastic channels: $\alpha = h_b(1P)\pi,\ h_b(2P)\pi,\ \Upsilon(1S)\pi,\ \Upsilon(2S)\pi,\ \Upsilon(3S)\pi$

- Assumption: interaction of light $q\bar{q}$ mesons with heavy quarkonia is suppressed

- Effective elastic potentials: $V^{\text{eff}}_{\alpha\beta}(M,p,p') = V^{\text{CT}}_{\alpha\beta}(M,p,p') + V^{\pi}_{\alpha\beta}(M,p,p') + V^{\eta}_{\alpha\beta}(M,p,p'),$

Contact terms:

$$V^{\text{CT}}_{\alpha\beta} = v_{\alpha\beta} - \underbrace{\frac{i}{2\pi\sqrt{s}}\sum_j m_{H_i} m_{h_i} g_{j\alpha} g_{j\beta} k_j^{2l_j+1}}_{\text{unitarity contribution from inelastic channels}}$$

<u>elastic CT's:</u>

$$v\,(p,p') = \begin{pmatrix} \mathcal{C}_d(1+\epsilon) + \mathcal{D}_d(p^2+p'^2) & \mathcal{D}_{SD}p'^2 & \mathcal{C}_l + \mathcal{D}_l(p^2+p'^2) & \mathcal{D}_{SD}p'^2 \\ \mathcal{D}_{SD}p^2 & 0 & \mathcal{D}_{SD}p^2 & 0 \\ \mathcal{C}_l + \mathcal{D}_l(p^2+p'^2) & \mathcal{D}_{SD}p'^2 & \mathcal{C}_d(1-\epsilon) + \mathcal{D}_d(p^2+p'^2) & \mathcal{D}_{SD}p'^2 \\ \mathcal{D}_{SD}p^2 & 0 & \mathcal{D}_{SD}p^2 & 0 \end{pmatrix}.$$

$\mathcal{C}_d, \mathcal{C}_l - \mathcal{O}(1)$ $\quad$ $\mathcal{D}_d,\ \mathcal{D}_l,\ \mathcal{D}_{SD} - \mathcal{O}(p^2)$ $\quad$ ϵ — HQSS violation

Formalism for line shapes: Fitting procedure

- Input:

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

  — experimental distributions for

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

  — branching fractions for $\alpha = BB^*,\ B^*B^*,\ \ h_b(1P)\pi,\ h_b(2P)\pi,\ \Upsilon(1S)\pi,\ \Upsilon(2S)\pi,\ \Upsilon(3S)\pi$

- Parameters of the fits:

2 elastic S-S waves contact terms at LO

3 elastic contact terms at NLO: 1 S-D waves , 2 S-S waves

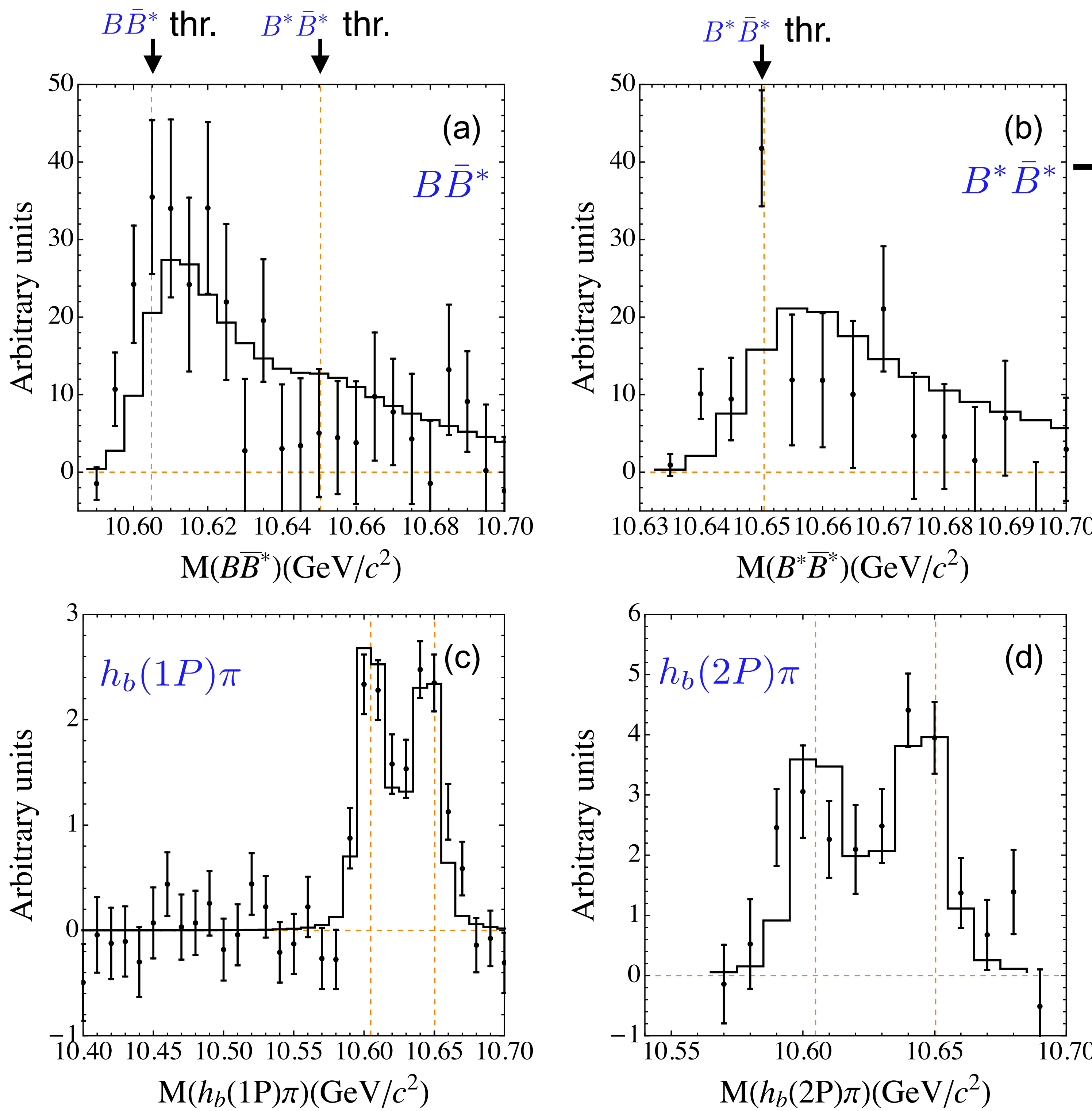
5 inelastic-elastic constants

7 HQSS violation parameters if included : 1 elastic + 6 inelastic

One π and one η-exchange potentials are parameter free!

Results: contact theory (CT) at LO

arXiv: 1805.07453



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

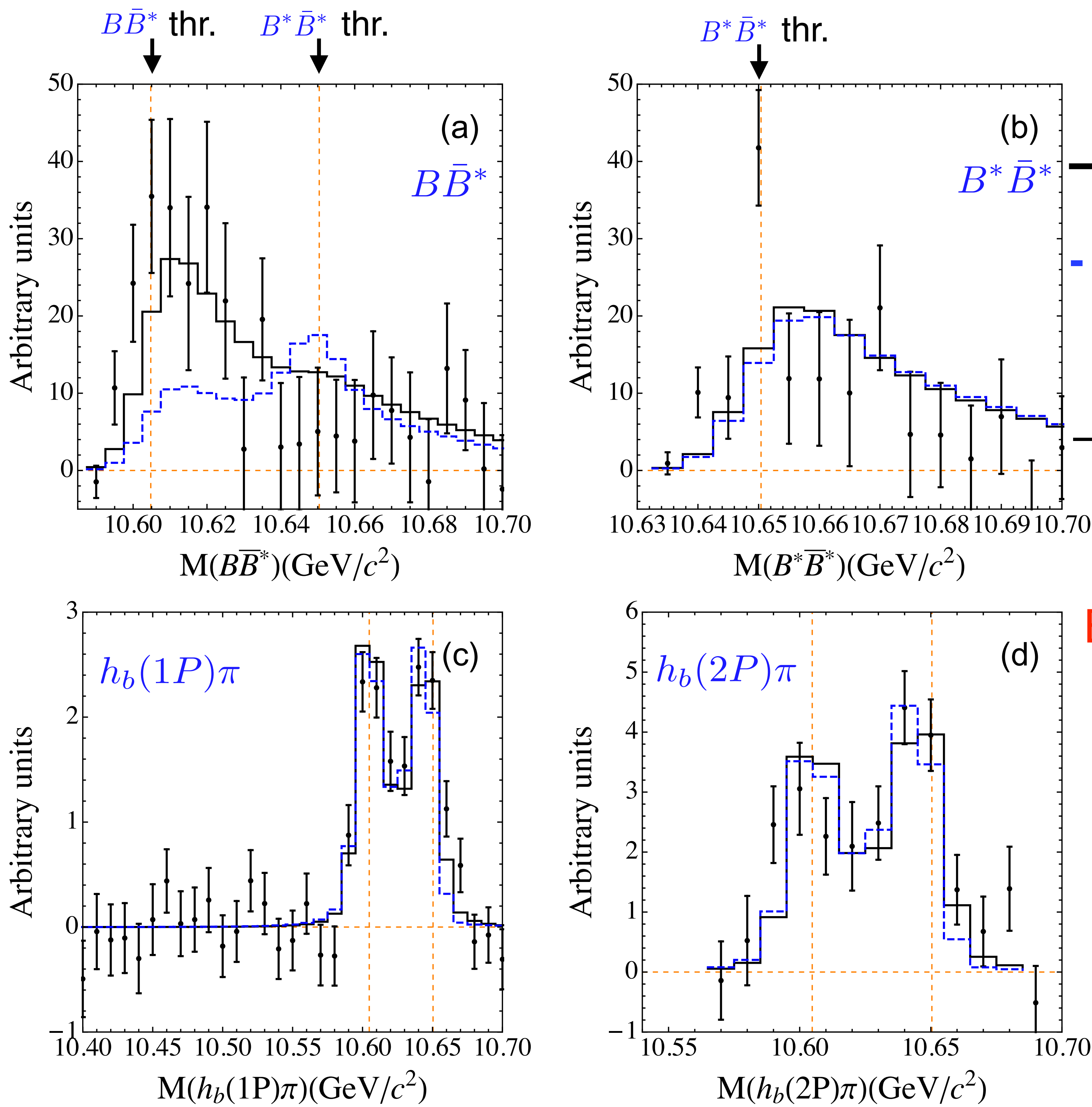
fit A: LO CT's χ^2=1.25

— HQSS is preserved in the potentials

—consistent with the parameterisation by Guo et al. (2016)

Results: LO CT's + OPE

arXiv: 1805.07453



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

fit A: LO CT's χ^2=1.25

fit B: fit A + OPE χ^2=1.72

— dynamical HQSS violation due to OPE

— OPE: clear bump structure at B*B* thr. due to coupled-channels

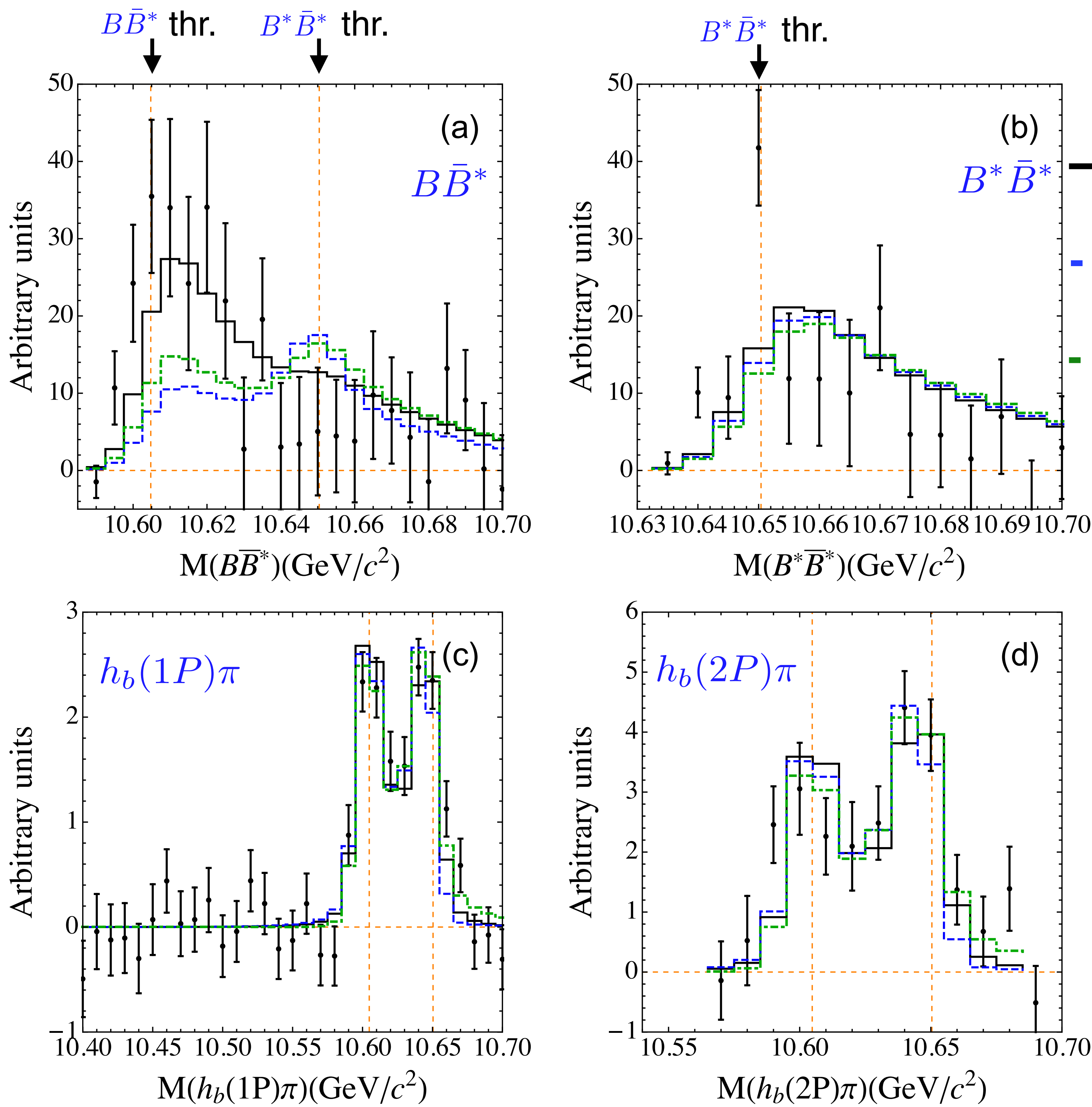
— Data by Belle: no structure

"Light-quark spin symmetry"
Voloshin (2016)

- Strong coupled-channel dynamics from OPE is inconsistent with the data

Results : Including HQSS violation in the CT's

arXiv: 1805.07453



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

fit A: LO CT's χ^2=1.25

fit B: fit A + OPE χ^2=1.72

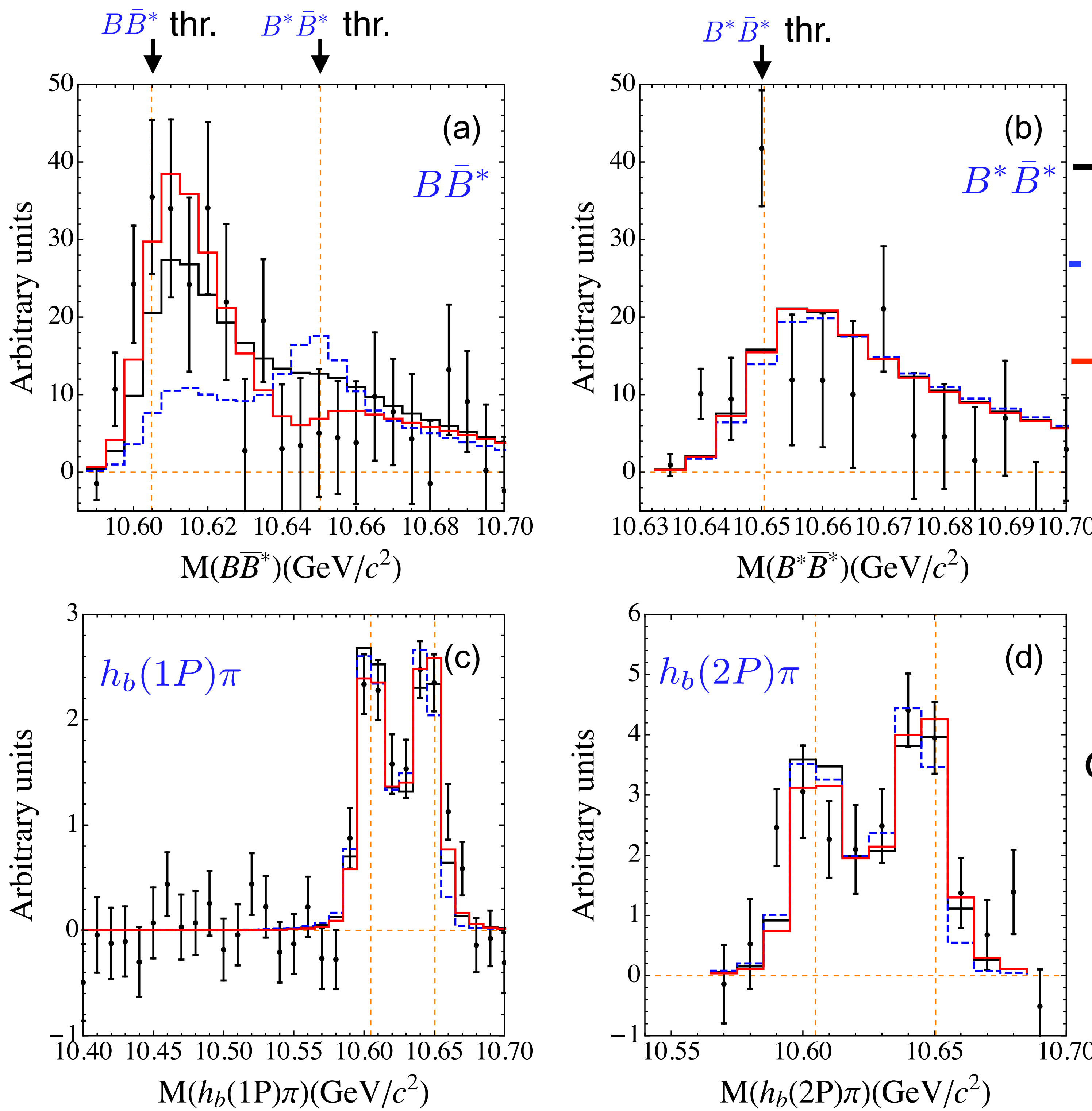
fit C: fit B + HQSS violation χ^2=1.57

☛ 7 new parameters are added due to HQSS violation

- Violation of HQSS in the contact potentials is not supported by the data!

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

arXiv: 1805.07453



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

fit A: LO CT's χ^2=1.25

fit B: fit A + OPE χ^2=1.72

fit D: fit B +NLO CT's χ^2=1.10

—back to HQSS preserving potentials!

—The effect from two S-S NLO contact terms $\mathcal{D}_d,\ \mathcal{D}_l$ is small

fit E: fit D + 1η χ^2=1.11

$\Longrightarrow$ Indistinguishable from fit D

- A single contact term $\mathcal{D}_{SD}$ at NLO cancels largely the S-D OPE and improves the fit
- 1π and 1η can be largely absorbed into redefinition of the contact terms at NLO

Extracting the poles

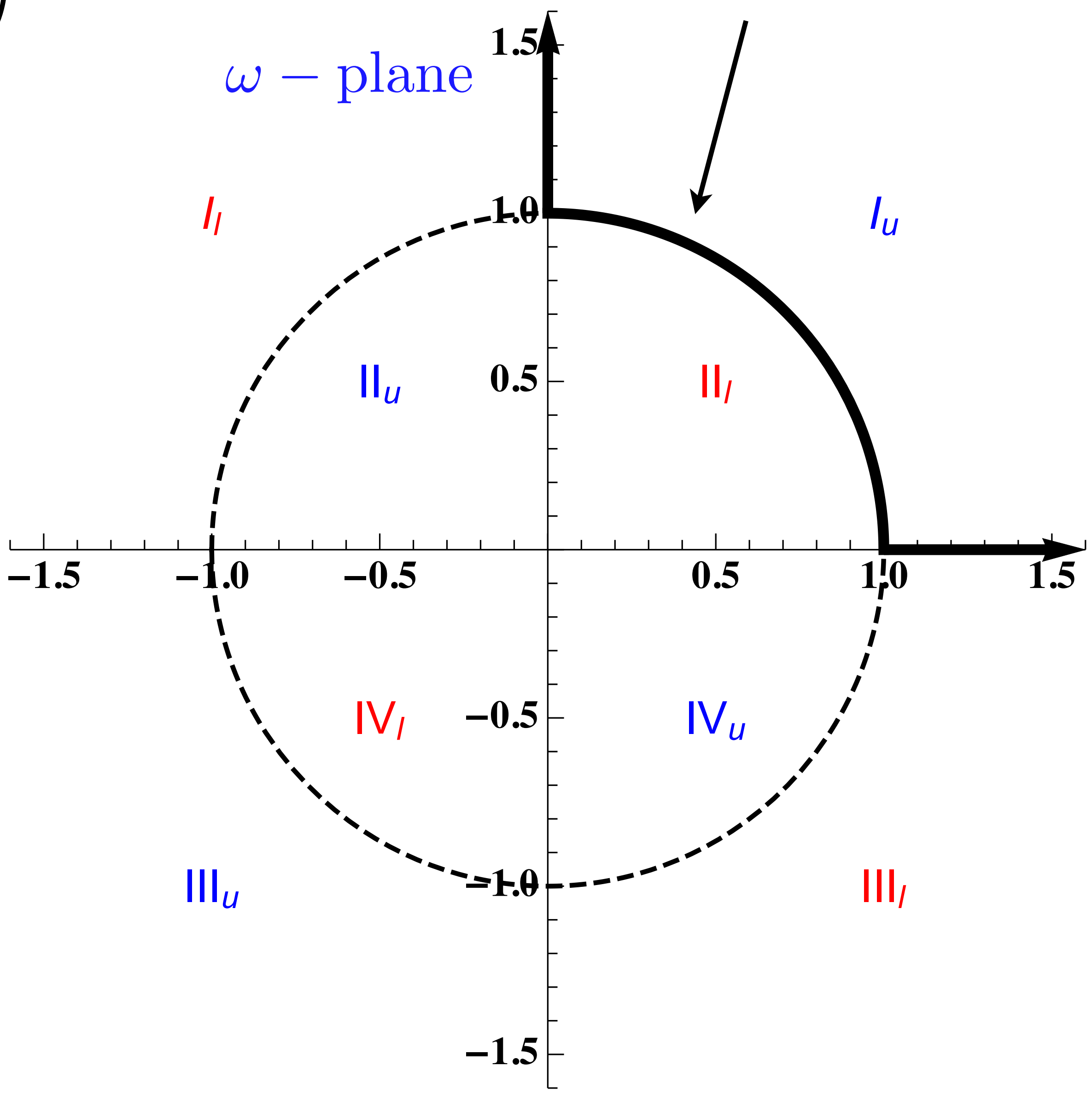
- W/O inelastic channels two-channel problem: BB* and B*B*

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):

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

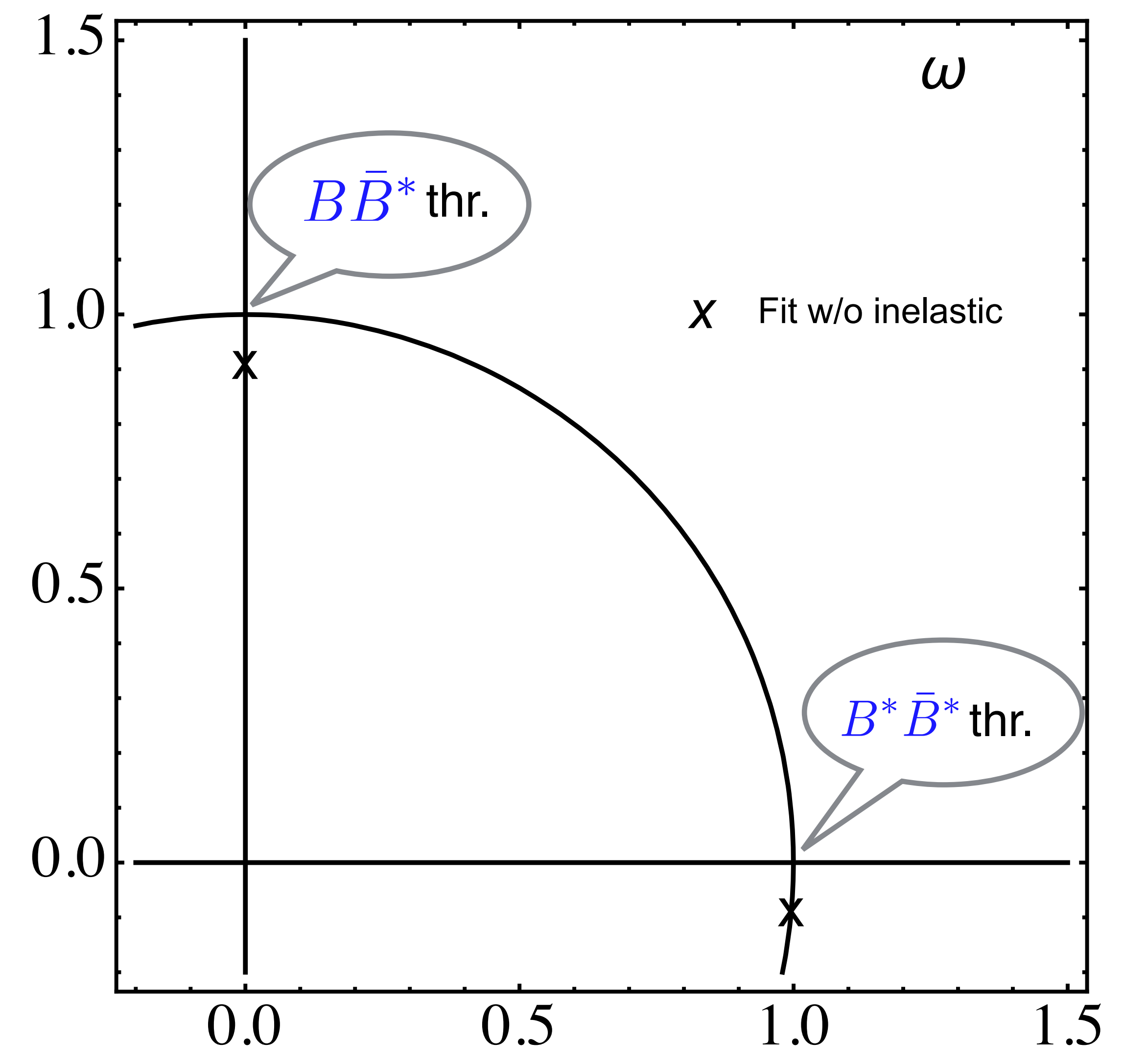
Energy relative to the BB* threshold:

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

- Only the poles close to the physical region are relevant

Poles of Zb(10610) and Zb(10650)

- NO inelastic channels: both states are virtual with energies just below their thresholds



Poles of Zb(10610) and Zb(10650)

- Include inelastic ch. and treat them all as a third distant channel (k_{in}): 4 RS $\Longrightarrow$ 8 RS

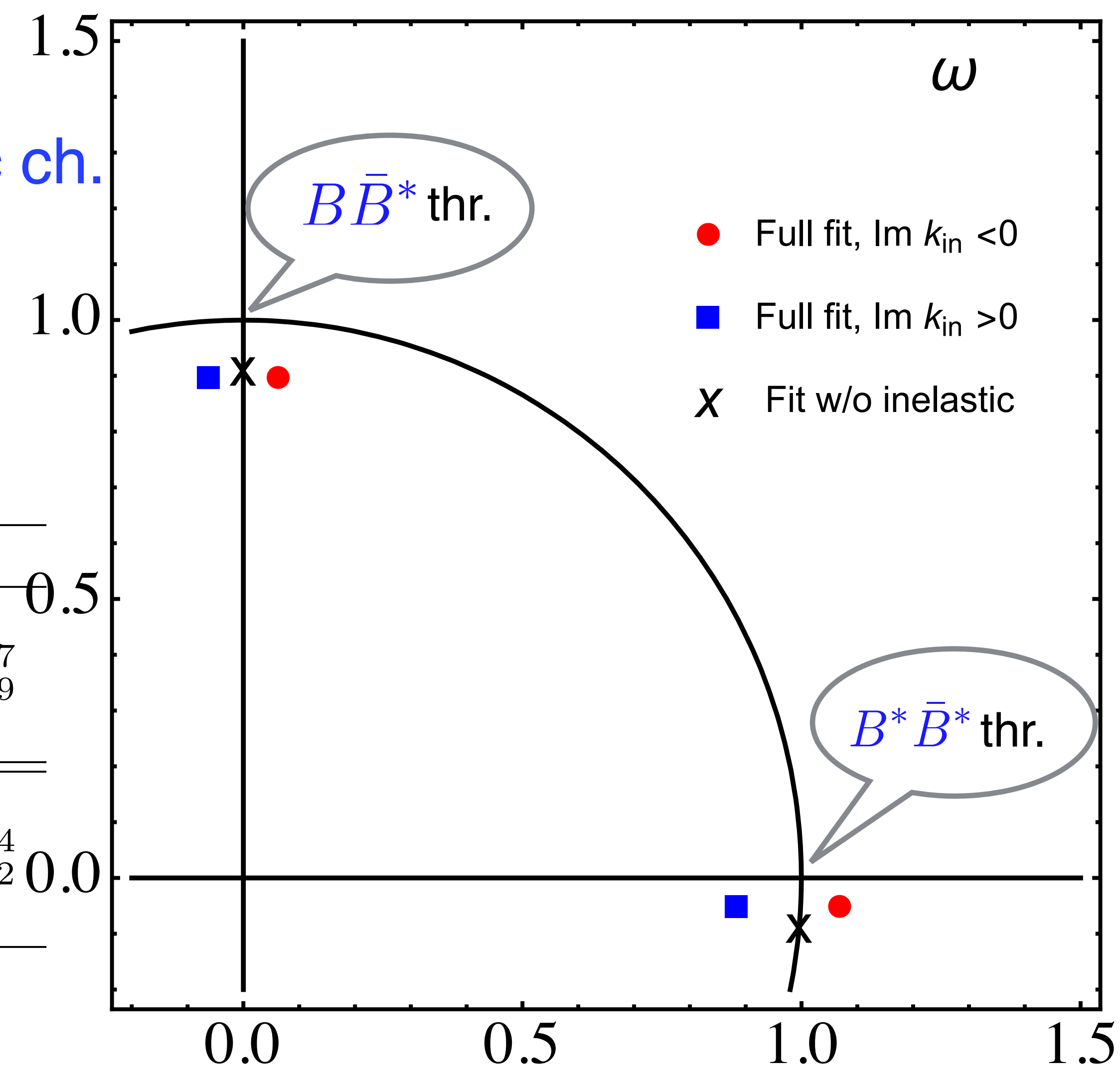
$\Longrightarrow$ number of poles doubles

Poles are close to the one pole scenario w/o inelastic ch.

$\Longrightarrow$ Role of inelastic channels is subleading

<ins>The poles</ins>

scheme	E_{Z_b}(MeV)	$E_{Z_b'}$(MeV)
full fit in HQSS limit (Im $k_{\rm in} < 0$)	$-0.28^{-0.21}_{+0.30} - i0.67^{-0.41}_{+0.51}$	$+0.11^{-0.28}_{+1.02} - i0.29^{-0.97}_{+0.39}$
full fit in HQSS limit (Im $k_{\rm in} > 0$)	$-0.28^{-0.21}_{+0.30} + i0.67^{-0.51}_{+0.41}$	$+0.54^{-0.37}_{+0.46} + i0.63^{-0.74}_{+0.52}$



- Zb(10610) is a shallow virtual state just below $B\bar{B}^*$ threshold
- Zb(10650) resides just above $B^*\bar{B}^*$ threshold

Conclusions

A systematic EFT approach consistent with chiral and heavy quark symmetries to probe various molecular candidates in *c* and *b*-sectors is proposed

- Analysis of the line shapes $\Upsilon(10860) \to \pi Z_b^{(\prime)} \to \pi\alpha$ and partial BR's with $\frac{\chi^2}{\mathrm{dof.}} \simeq 1$

- Data are consistent with HQSS

- S-D tensor OPE force can strongly affect the line shapes due to coupled-channels

- Non-trivial cancellation of the OPE by a single S-D contact term at NLO

  — Origin: not yet understood — related to "light-quark spin symmetry"

- The poles of Zb(10610)/Zb(10650) are extracted:

  both are shallow states located in the vicinity of the nearby hadronic thresholds

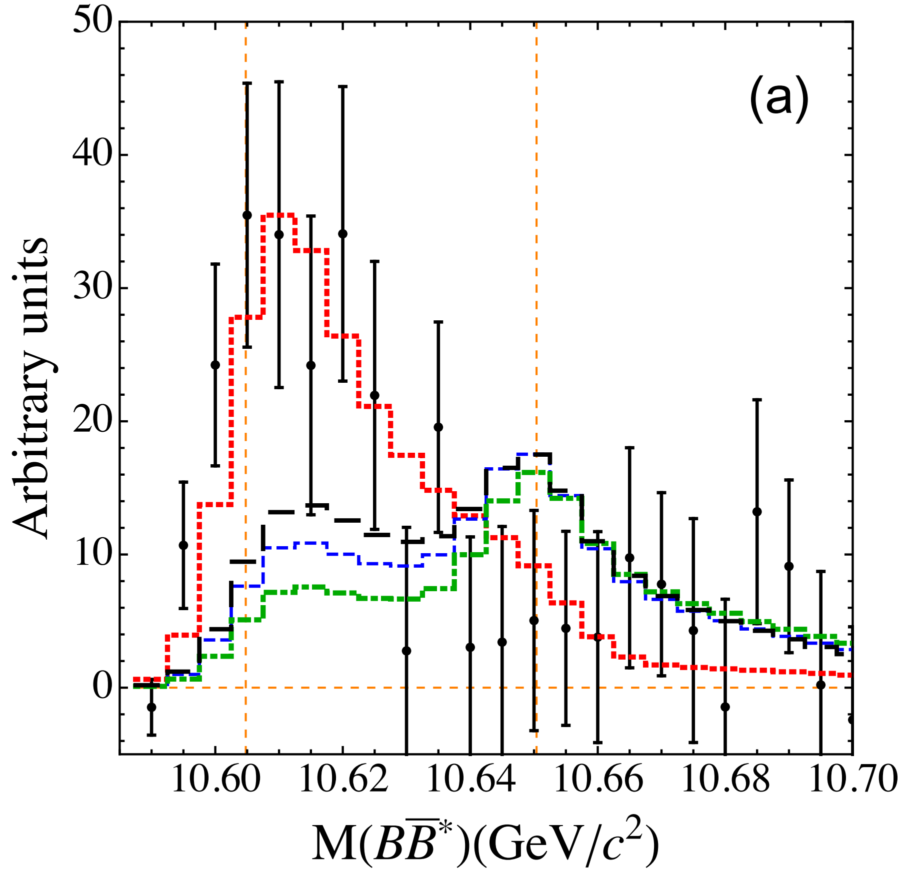
Outlook: — Parameter free predictions for spin partners (In progress)

— Reanalyse the role of OPE for spin partners (In progress)

☛ Reanalyse the line shapes in the charm sector

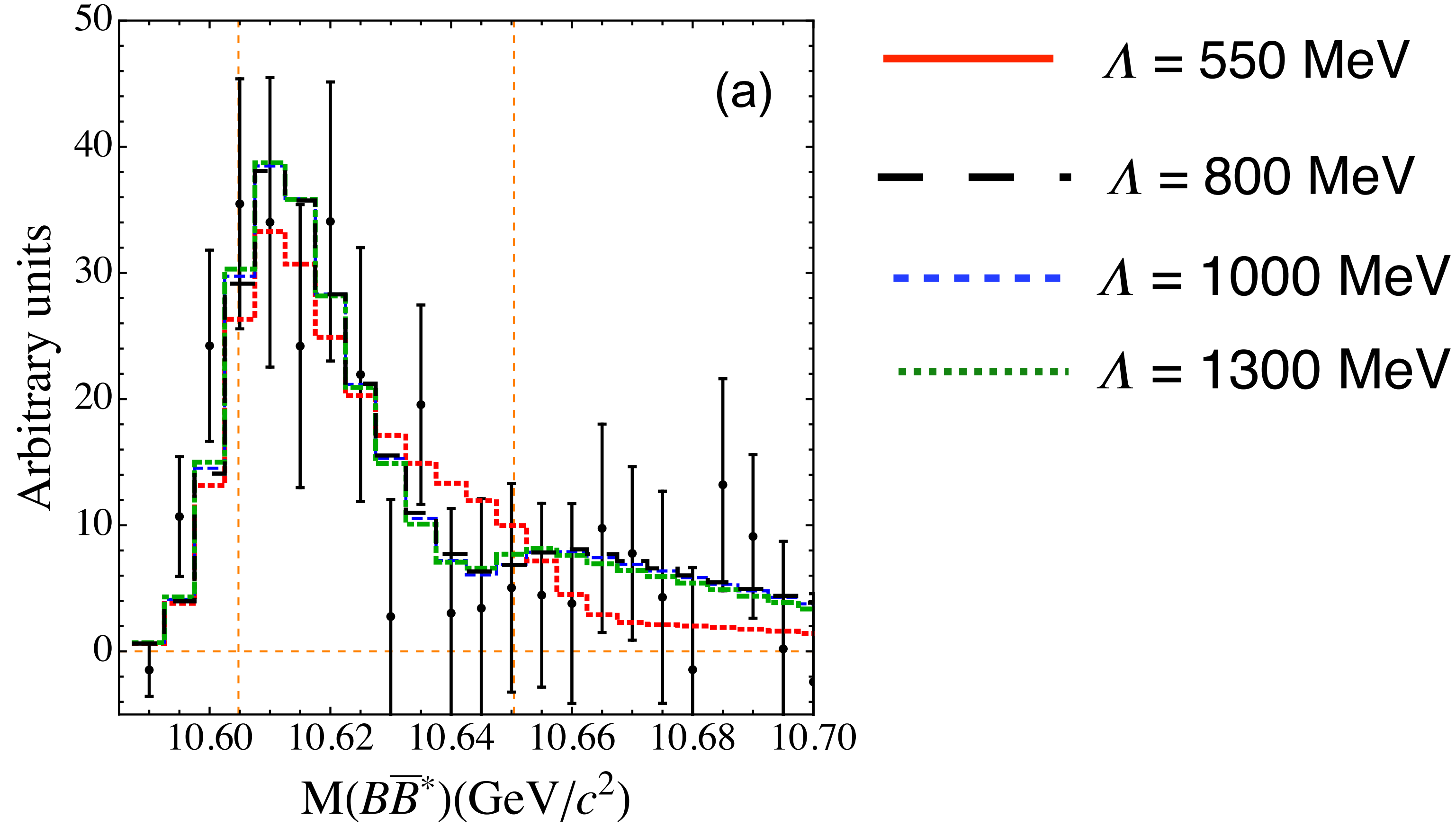
Dependence on the regulator

LO CT’s+OPE



Visible cutoff dependence

LO+NLO CT’s+OPE



Negligible cutoff dependence

Necessity for the NLO CT’s is indicated by renormalisability

Formalism for line shapes: long-range potentials

- Goldstone-Boson Lagrangian: $\mathcal{L}_\Phi = -\frac{g_Q}{4f_\pi}\mathrm{Tr}\left(\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}\Phi_{ab}\bar{H}_b\bar{H}_a^\dagger\right) + \mathrm{h.c.},$

Heavy fields — $H_a = B_a + \boldsymbol{B}_a^* \cdot \boldsymbol{\sigma}$,

$$\Phi = \begin{pmatrix} \pi^0 + \sqrt{\frac{1}{3}}\eta & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 + \sqrt{\frac{1}{3}}\eta \end{pmatrix}$$

—relevant part of SU(3) GB matrix

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

- Exemplary GB potential for OPE:

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

☛ TOPT propagators with NR heavy mesons and relativistic pions

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

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

One π and one η-exchange potentials are parameter free!