Effective field theory approach to exotic Z-states with heavy quarks

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1. V. Baru, E. Epelbaum, A.A. Filin, C. Hanhart, R.V. Mizuk, AN, S. Ropertz, *Insights into $Z_b(10610)$ and $Z_b(10650)$ from dipion transitions from $\Upsilon(10860)$*, Phys. Rev. **D103**, 034016 (2021)
2. V. Baru, E. Epelbaum, A. A. Filin, C. Hanhart, AN, Q. Wang, *Spin partners W_{bJ} from the line shapes of the $Z_b(10610)$ and $Z_b(10650)$*, Phys. Rev. **D99**, 094013 (2019)
3. Q. Wang, V. Baru, A. A. Filin, C. Hanhart, AN, J.-L. Wynen, *The line shapes of the $Z_b(10610)$ and $Z_b(10650)$ in the elastic and inelastic channels revisited*, Phys. Rev. **D98**, 074023 (2018)

Exotic XYZ states

- X's are new exotic states

$$X(3872) \quad X(3915) \quad X(4140) \quad \ldots$$

- Y's are exotic vector states (to tell from neat $\bar{c}c$ quarkonia ψ's)

$$Y(4230) \quad Y(4260) \quad Y(4360) \quad Y(4660) \quad \ldots$$

- Z's are charged exotic states

$$Z_c(3900) \quad Z_c(4020) \quad Z_c(4430) \quad Z_{cs}(3985) \quad Z_b(10610) \quad Z_b(10650) \quad \ldots$$

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Many XYZ states reside near hadronic thresholds that hints their molecular interpretation

What is hadronic molecule?

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

- Proximity of strong thresholds
  $\Longrightarrow$ large admixture of meson-meson component in the w.f.
- Different nature of the resonance
  $\Longrightarrow$ pole location is a dynamical problem
- Different binding mechanisms
  $\Longrightarrow$ different models for interaction

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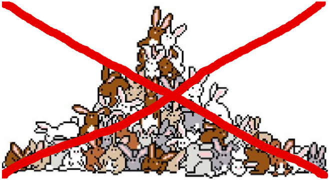
Deuteron is a prominent example of hadronic molecule

Approach needed

- All parameters possess clear physical interpretation (no blind parameters replication!)



- All data available analysed simultaneously

EFT for hadronic molecules

$\Longrightarrow$ Goal: systematically improvable approach to $(\bar{Q}q)$-$(\bar{q}Q)$ molecules

$\Longrightarrow$ Application: combined analysis of line shapes in

- open-flavour (elastic) channels $(\bar{Q}q)(\bar{q}Q)$
- hidden-flavour (inelastic) channels $(\bar{Q}Q)(\bar{q}q)$

$\Longrightarrow$ Underlying idea: adapt (well-developed) EFT from nuclear physics

- Similarity:
  * Same well established formalism [Weinberg]
  * Same forces due to various exchanges [Voloshin,Okun'1976]
- Differences:
  * Coupled-channel effects
  * Additional symmetries: HQSS, flavour SU(3)

$\Longrightarrow$ Difficulties: such EFT for $(\bar{Q}q)$-$(\bar{q}Q)$ molecules cannot relate

* different isospins
* sectors with different heavy quarks Q [Baru et al'2019]

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)
- 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, Baru et al.'2016,2019)

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HQSS is a powerful tool to reduce the number of parameters and use data on one state to predict properties of another

EFT in charm and bottom sectors

- HQSS in potential $\Longrightarrow$ parameter $\Lambda_{\rm QCD}/m_Q \ll 1$ (caution in c-sector!)
- Potential expanded in Q/Λ with hard scale $\Lambda \simeq 1$ GeV

  Soft scale Q for coupled-channel dynamics:

  $$p_{\rm typ} = \sqrt{m_D \delta_D} \simeq \sqrt{m_B \delta_B} \simeq 500 \text{ MeV}$$

  $$\delta_D = m_{D^*} - m_D \approx 140 \text{ MeV}$$
  $$\delta_B = m_{B^*} - m_B \approx 45 \text{ MeV}$$

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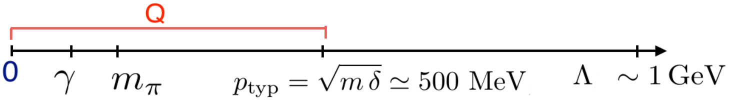

EFT convergence parameter $p_{\rm typ}/\Lambda \simeq 1/2 \lesssim 1$

- 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 $\Longrightarrow$ proceed to NLO

Coupled-channel problem

Elastic potential:

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

Coupled channels (P — pseudoscalar meson, P^* — vector meson):

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

Coupled-channel problem

Elastic potential:

$$V_{\text{el-el}} = V_{\text{CT}}(\text{to order } O(p^0)) + V_{\pi,\eta}(S\text{-wave})$$

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$$1^{++} : P\bar{P}^*({}^3S_1,+), P\bar{P}^*({}^3D_1,+), P^*\bar{P}^*({}^5D_1)$$
$$2^{++} : P^*\bar{P}^*({}^5S_2), P\bar{P}({}^1D_2), P\bar{P}^*({}^3D_2),$$
$$P^*\bar{P}^*({}^1D_2), P^*\bar{P}^*({}^5D_2), P^*\bar{P}^*({}^5G_2)$$

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$$\begin{aligned}
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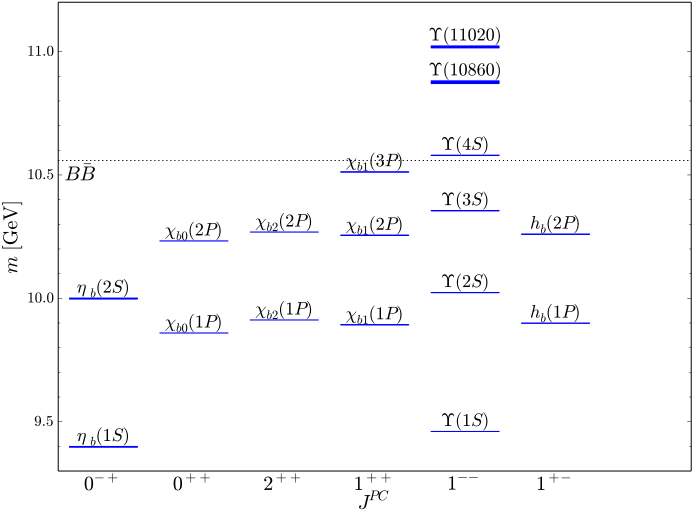
&\quad P^*\bar{P}^*({}^1D_2), P^*\bar{P}^*({}^5D_2), P^*\bar{P}^*({}^5G_2)
\end{aligned}$$

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

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

Bottomonium spectrum



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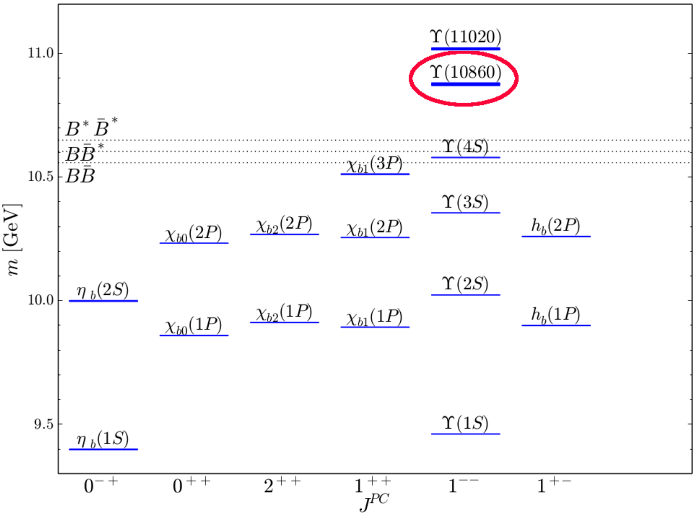
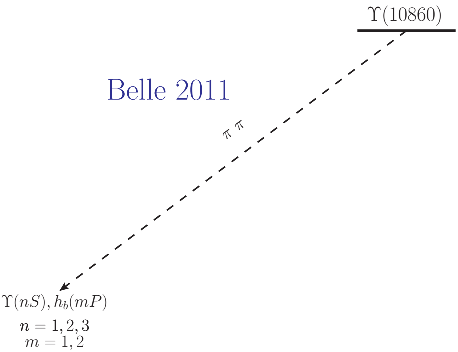


Two-pion decays of $\Upsilon(10860)$



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

$\Upsilon(10860)$

Belle 2011

$\pi\,\pi$

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

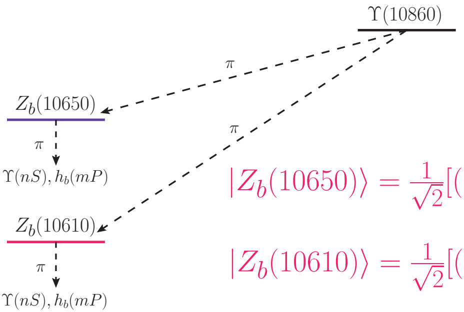
$n = 1, 2, 3$
$m = 1, 2$

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

Heavy quark spin flip — No spin flip

Huge HQSS violation?!

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

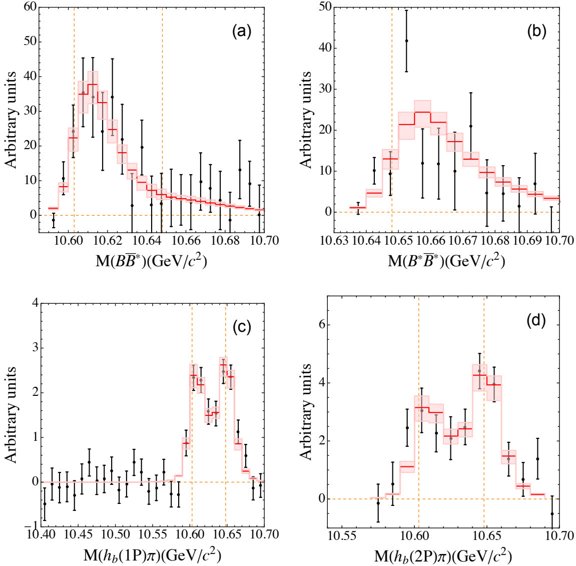


$$|Z_b(10650)\rangle = \frac{1}{\sqrt{2}}[(0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}) - (1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q})]$$

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

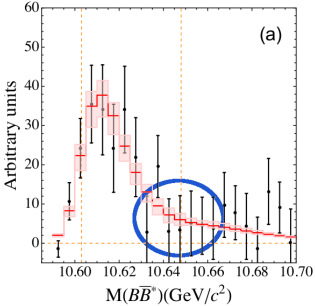
Bondar et al. 2011

Combined fit to the data for Z_b's

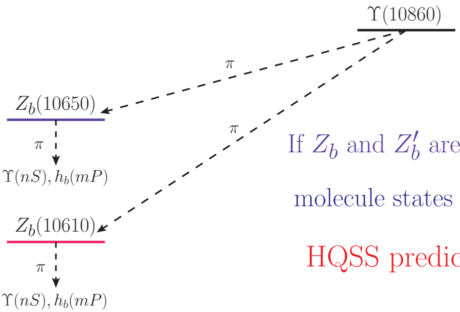


Results and conclusions for Z_b's

- Description of data is nearly perfect ($\chi^2/\text{d.o.f} = 0.83$)
- Parameters (LEC's and couplings) are extracted directly from data
- Data are consistent 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



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



If Z_b and Z_b' are near-threshold

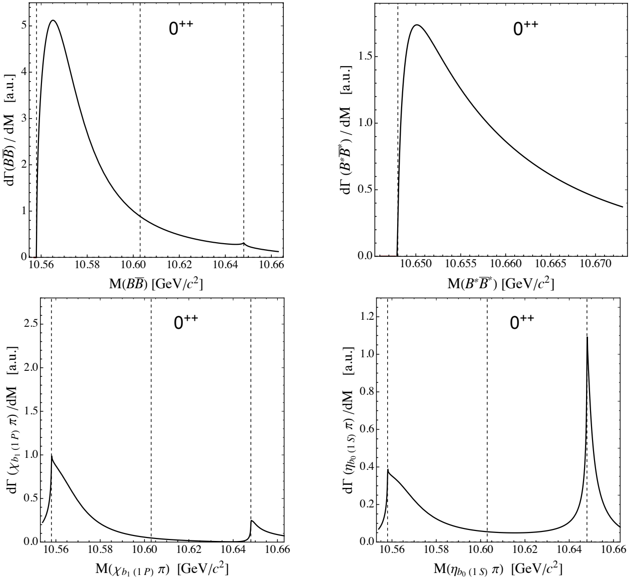
molecule states with $J^{PC} = 1^{+-}$

HQSS predicts existence of

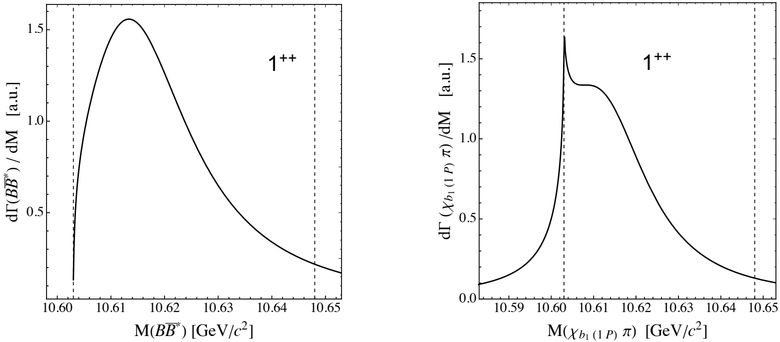
Additional molecular states with $J^{PC} = J^{++}$ $(J = 0, 1, 2)$

(Bondar et al. 2011, Voloshin 2011)

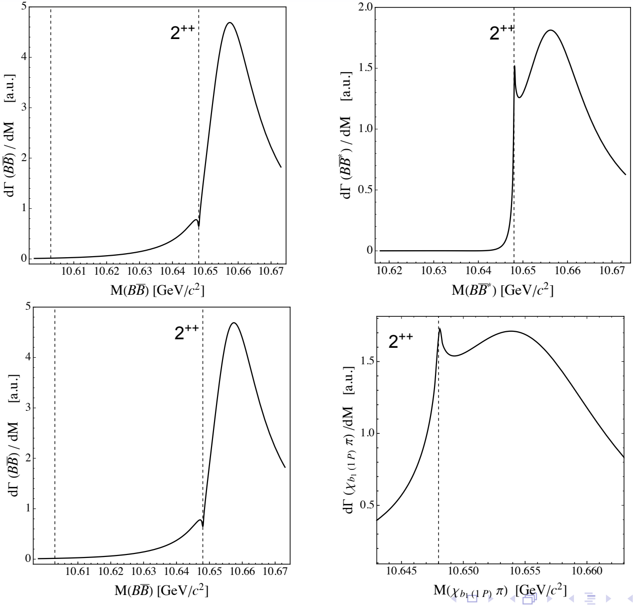
Predicted line shapes for W_{b0}



Predicted line shapes for W_{b1}



Predicted line shapes for W_{b2}



Pole positions (mirror poles not shown)

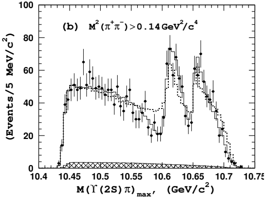
J^{PC}	State	Threshold	E_B w.r.t. threshold, [MeV]	Residue at pole
1^{+-}	Z_b	$B\bar{B}^*$	$(-2.3 \pm 0.5) - i(1.1 \pm 0.1)$	$(-1.2 \pm 0.2) + i(0.3 \pm 0.2)$
1^{+-}	Z'_b	$B^*\bar{B}^*$	$(1.8 \pm 2.0) - i(13.6 \pm 3.1)$	$(1.5 \pm 0.2) - i(0.6 \pm 0.3)$
0^{++}	W_{b0}	$B\bar{B}$	$(2.3 \pm 4.2) - i(16.0 \pm 2.6)$	$(1.7 \pm 0.6) - i(1.7 \pm 0.5)$
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}	$B^*\bar{B}^*$	$(7.4 \pm 2.8) - i(9.9 \pm 2.2)$	$(0.7 \pm 0.1) - i(0.3 \pm 0.1)$

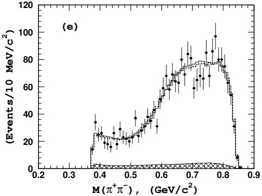
- Relevant pole = pole with the shortest path to the physical region
- Riemann sheet is fixed by combination of signs of Im(p) for all channels
- Relevant pole can be bound state, virtual state, resonance
- Virtual state enhances threshold cusp
- Resonance distorts line shape above threshold (hump for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

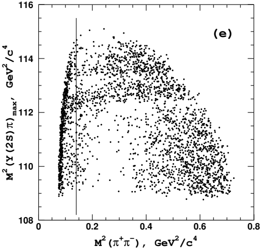
Conclusion: All Z_b's and W_{bJ}'s are resonances
(without pions — virtual states)

$\Upsilon(10860) \to \pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$ decays

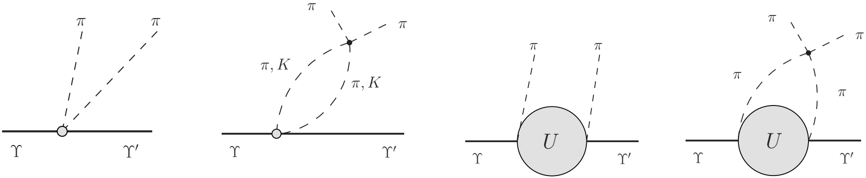
Belle high-statistic data







Pions (kaons) FSI needs to be included



...and Dalitz plot analysed with U taken from our previous analysis

$\Upsilon(10860) \to \pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$ **decays**

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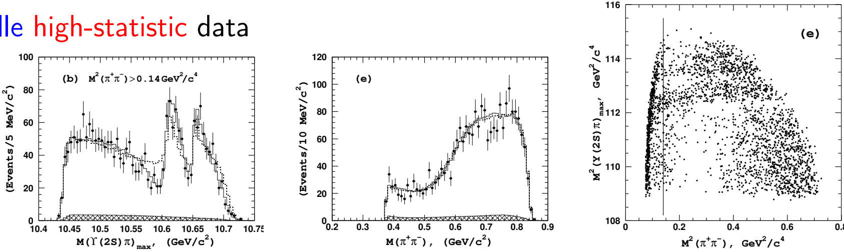

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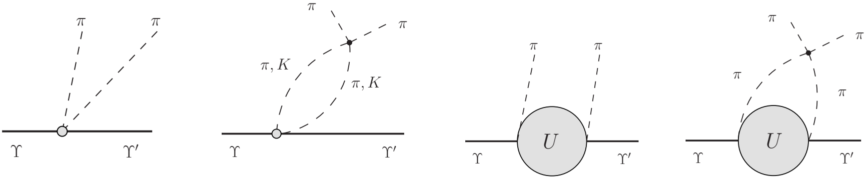

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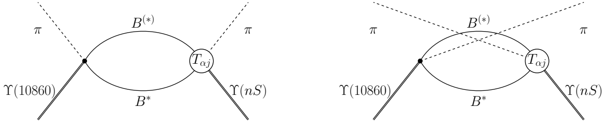
Disentangle physics of Z_b's and $\pi\pi/K\bar{K}$ FSI

$\Upsilon(10860) \to \pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$ decays

- No-FSI amplitude: left-hand cuts only, U — the full coupled-channel amplitude

$$M_{\text{no-FSI}}(t,u) = U(t) + U(u) = M_0^L + M_{\text{higher}} = \frac{1}{2}\int_{-1}^{1} dz\, M_{\text{no-FSI}}(t,u) + M_{\text{higher}}$$



- Amplitude with FSI: right-hand cut included, M_0^R restored dispersively from M_0^L

$$M(s,t,u) = M_{\text{no-FSI}}(t,u) + \frac{\Omega_0(s)}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{\Omega_0^{-1}(s')T(s')\sigma(s')M_0^L(s')}{s'-s-i0}$$

$$\Omega_0(s) = \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{T^*(s')\sigma(s)\Omega_0(s')}{s'-s-i0} \qquad T(s) = \begin{pmatrix} T_{\pi\pi\to\pi\pi} & T_{\pi\pi\to K\bar{K}} \\ T_{K\bar{K}\to\pi\pi} & T_{K\bar{K}\to K\bar{K}} \end{pmatrix}$$

$\Upsilon(10860) \to \pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$ decays

- Diminish dependence on the large-s tail of Omnés

  $\Longrightarrow$ Two subtractions in dispersive integral

  $\Longrightarrow$ Second order polynomial $c_1 + c_2 s$ added to amplitude

- $\mathrm{Im}M_0^L$ under control (including anomalous pieces)

  $\Longrightarrow$ Real subtraction constants c_1 and c_2 [as opposed to Molnar et al'2019]

- Low-energy $\pi\Upsilon$ scattering is described by chiral Lagrangian

  $\Longrightarrow$ Matching c_1 and c_2 to chiral expansion

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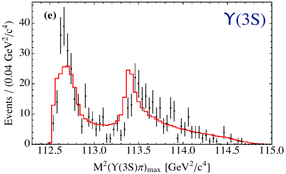
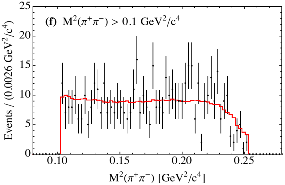
3 real fitting parameters: c_1, c_2, $\mathcal{N}$

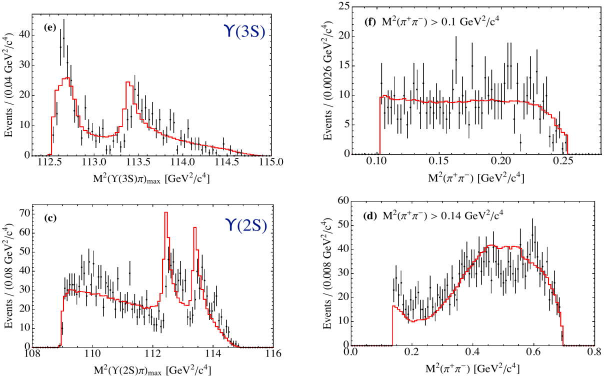
Fit to data on $\Upsilon(10860) \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2, 3$)





- Data dominated by Z_b's
- No structures in $M_{\pi\pi}$

Fit to data on $\Upsilon(10860) \to \pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$



- Data dominated by Z_b's
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- Additional structures in both $M^2(\pi\Upsilon)$ and $M^2(\pi\pi)$
- $\pi\pi$ FSI captures gross features

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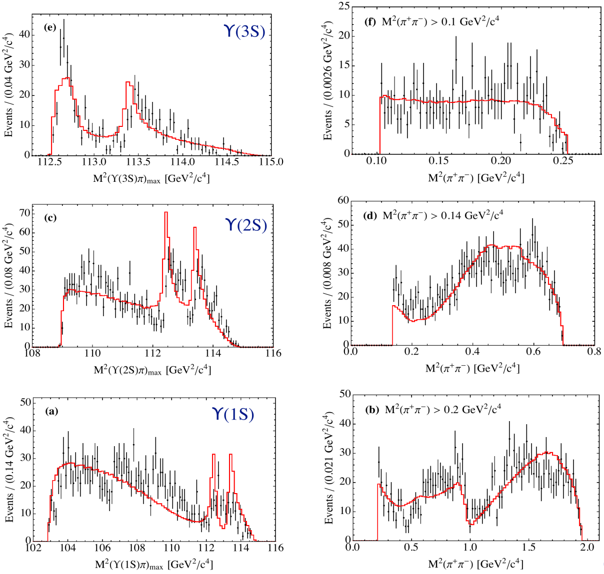

- Data dominated by Z_b's
- No structures in $M_{\pi\pi}$

- Additional structures in both $M^2(\pi\Upsilon)$ and $M^2(\pi\pi)$
- $\pi\pi$ FSI captures gross features

- Left shoulder in $M^2(\pi\Upsilon)$
- Highly nontrivial $M^2(\pi\pi)$
- $\pi\pi$ & $K\bar{K}$ FSI important

Conclusions

- We propose a powerful and systematically improvable approach to a combined data analyses for exotic states
- Both 3D Dalitz plots and their 2D projections can be fitted
- Potential of the method is confirmed by its succesfull application to the Z_b bottomonium-like states
- Generalisation to the light-quark $SU(3)$ is straightforward (in progress)
- Generalisation to different production mechanisms is important for application to BES-III data on charmonia (in progress)
- Additional experimental data are strongly needed to
    - Stronger constrain the parameters
    - Verify predictions for spin partners
    - Pinpoint particular production mechanism (Z_c production via Y's)