Hadronic molecules with hidden charm and bottom

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Based on:

FKG, C. Hidalgo-Duque, J. Nieves, M. Pavón Valderrama, PRD88(2013)054007

FKG, C. Hidalgo-Duque, J. Nieves, A. Ozpineci, M. Pavón Valderrama, EPJC74(2014)2885

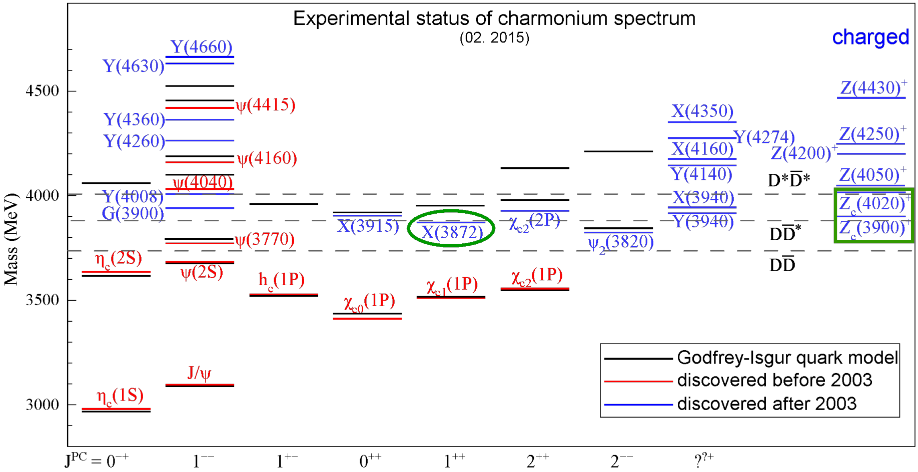
FKG, C. Hanhart, Y. Kalashnikova, U.-G. Meißner, A. Nefediev, PLB742(2015)394

M. Albaladejo, FKG, C. Hidalgo-Duque, J. Nieves, M. Pavón Valderrama, EPJC75(2015)547

M. Albaladejo, FKG, C. Hidalgo-Duque, J. Nieves, PLB755(2016)337

Y.-H. Chen, J. T. Daub, FKG, B. Kubis, U.-G. Meißner, B.-S. Zou, PRD93(2016)034030

Charmonium spectrum

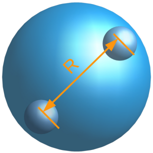


Note: $X(3915)$ is probably just the $\chi_{c2}(2P)$ with 2^{++} Z.-Y. Zhou et al., PRL115(2015)022001

Hadronic molecules (I)

- Hadronic molecule:
  dominant component is a composite state of 2 or more hadrons
- Concept at large distances, so that can be approximated by system of multi-hadrons at low energies
  Consider a 2-body bound state with a mass $M = m_1 + m_2 - E_B$

  size: $$R \sim \frac{1}{\sqrt{2\mu E_B}} \gg r_{\text{hadron}}$$



- Only narrow hadrons can be considered as components of hadronic molecules,
  $\Gamma_h \ll 1/r$, r: range of forces

Filin *et al.*, PRL105(2010)019101; FKG, Meißner, PRD84(2011)014013

Hadronic molecules (II)

- Why are hadronic molecules interesting?
  - ☞ one realization of color-neutral objects, analogue of light nuclei
  - ☞ important information for hadron-hadron interaction
  - ☞ model-independent statements can be made

    for S-wave, compositeness $(1-Z)$ related to measurable quantities

    Weinberg, PR137(1965); Baru *et al.*, PLB586(2004); Hyodo, IJMPA28(2013)1330045; ...

    see also, e.g., Weinberg's books: QFT Vol.I, Lectures on QM

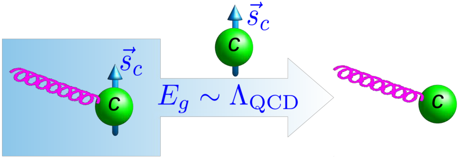
$$g_{\rm NR}^2 \approx (1-Z)\frac{2\pi}{\mu^2}\sqrt{2\mu E_B} \leq \frac{2\pi}{\mu^2}\sqrt{2\mu E_B}$$

$$a \approx -\frac{2(1-Z)}{(2-Z)\sqrt{2\mu E_B}}, \quad r_e \approx \frac{Z}{(1-Z)\sqrt{2\mu E_B}}$$

    scale separation: EFT can be applied

  - ☞ understanding the XYZ states, nice objects to apply heavy quark symmetries

Heavy quark spin symmetry (I)



- Heavy quark spin symmetry (HQSS):
  - ☞ define $\vec{s}_\ell \equiv \vec{J} - \vec{s}_Q$: total angular momentum of the light quark system
    $\vec{J}$: total angular momentum, $\vec{s}_Q$: heavy quark spin
    E.g., for D and D^*: $s_\ell^P = \frac{1}{2}^-$
  - ☞ s_ℓ is a good quantum number
  - ☞ spin multiplet: (D, D^*), $(\eta_c, J/\psi)$
- For hadronic molecules of $Q\bar{Q}$+light hadron FKG et al., PRL102(2009)242004
  - ☞ exchange at least two gluons, LO: chromo-electric
  - ☞ spin multiplet with approximately the same splitting as that for $Q\bar{Q}$
  - ☞ the same for hadro-quarkonium Cleven et al., PRD92(2015)014005

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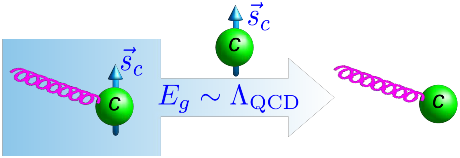

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HQSS (II)

- Consider S-wave interaction between a pair of $s_\ell^P = \frac{1}{2}^-$ (anti-)heavy mesons:

$$
\begin{aligned}
0^{++}: &\quad D\bar{D}, \quad D^*\bar{D}^* \\
1^{+-}: &\quad \frac{1}{\sqrt{2}}\left(D\bar{D}^* + D^*\bar{D}\right), \quad D^*\bar{D}^* \\
1^{++}: &\quad \frac{1}{\sqrt{2}}\left(D\bar{D}^* - D^*\bar{D}\right) \\
2^{++}: &\quad D^*\bar{D}^*
\end{aligned}
$$

- Heavy quark spin irrelevant $\Rightarrow$ interaction matrix elements:

$$\left\langle s_{\ell 1}, s_{\ell 2}, s_L \left| \hat{\mathcal{H}} \right| s'_{\ell 1}, s'_{\ell 2}, s_L \right\rangle$$

For each isospin, 2 independent terms

$$\left\langle \frac{1}{2}, \frac{1}{2}, 0 \left| \hat{\mathcal{H}} \right| \frac{1}{2}, \frac{1}{2}, 0 \right\rangle, \qquad \left\langle \frac{1}{2}, \frac{1}{2}, 1 \left| \hat{\mathcal{H}} \right| \frac{1}{2}, \frac{1}{2}, 1 \right\rangle$$

$\Rightarrow$ 6 pairs grouped in 2 multiplets with $s_L = 0$ and 1, respectively

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HQSS(III)

- In the limit $m_c \to \infty$, D and D^* degenerated, convenient to use the basis of states: $s_L^{PC} \otimes s_{c\bar{c}}^{PC}$
  - ☞ S-wave: $s_L^{PC}, s_{c\bar{c}}^{PC} = 0^{-+}$ or 1^{--}
  - ☞ multiplet with $s_L = 0$:

$$0_L^{-+} \otimes 0_{c\bar{c}}^{-+} = 0^{++}, \qquad 0_L^{-+} \otimes 1_{c\bar{c}}^{--} = 1^{+-}$$

  - ☞ multiplet with $s_L = 1$:

$$1_L^{--} \otimes 0_{c\bar{c}}^{-+} = 1^{+-}, \qquad 1_L^{--} \otimes 1_{c\bar{c}}^{--} = 0^{++} \oplus 1^{++} \oplus 2^{++}$$

$\Rightarrow$ if $X(3872)$ is a 1^{++} $D\bar{D}^*$ molecule, then its $s_L = 1$ Voloshin, PLB604(2004)69

- Multiplets in strict heavy quark limit:
  - ☞ might be 6 molecules: Z_b, Z_b' and W_{b0}, W_{b0}', W_{b1} and W_{b2} (for $I = 1$)

Bondar et al., PRD84(2011)054010; Voloshin, PRD84(2011)031502;
Mehen, Powell, PRD84(2011)114013

  - ☞ $X(3872)$ has three partners with 0^{++}, 2^{++} and 1^{+-}

Hidalgo-Duque et al., PLB727(2013)432; Baru et al., arXiv:1605.09649

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  - ☞ S-wave: $s_L^{PC}, s_{c\bar{c}}^{PC} = 0^{-+}$ or 1^{--}
  - ☞ multiplet with $s_L = 0$:

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- Calculations using physical D and D^* masses
  - ☞ the effective Lagrangian for the LO interaction between spin multiplets,

AlFiky et al., PLB640(2006)238 …

$$
\begin{aligned}
\mathcal{L}_{4H} = \quad & C_A \,\mathrm{Tr}\left[\bar{H}_a^{(Q)} H_a^{(Q)} \gamma_\mu\right] \mathrm{Tr}\left[H_b^{(\bar{Q})} \bar{H}_b^{(\bar{Q})} \gamma^\mu\right] \\
& + C_A^{(\tau)} \,\mathrm{Tr}\left[\bar{H}_a^{(Q)} \vec{\tau}_{ab} H_b^{(Q)} \gamma_\mu\right] \mathrm{Tr}\left[H_c^{(\bar{Q})} \vec{\tau}_{cd} \bar{H}_d^{(\bar{Q})} \gamma^\mu\right] \\
& + C_B \,\mathrm{Tr}\left[\bar{H}_a^{(Q)} H_a^{(Q)} \gamma_\mu \gamma_5\right] \mathrm{Tr}\left[H_b^{(\bar{Q})} \bar{H}_b^{(\bar{Q})} \gamma^\mu \gamma_5\right] \\
& + C_B^{(\tau)} \,\mathrm{Tr}\left[\bar{H}_a^{(Q)} \vec{\tau}_{ab} H_b^{(Q)} \gamma_\mu \gamma_5\right] \mathrm{Tr}\left[H_c^{(\bar{Q})} \vec{\tau}_{cd} \bar{H}_d^{(\bar{Q})} \gamma^\mu \gamma_5\right]
\end{aligned}
$$

$\vec{\tau}$: Pauli matrices in isospin space; $H_a^{(Q)}$: D, D^*; $H_a^{(\bar{Q})}$: $\bar{D}, \bar{D}^*$

Isospin $I = 0$ or 1 $\Rightarrow$ 4 independent terms:

$C_{0A}, C_{0B}; C_{1A}, C_{1B}$: linear combinations of $C_{A,B}^{(\tau)}$

$$C_{0\phi} = C_\phi + 3C_\phi^{(\tau)}, \qquad C_{1\phi} = C_\phi - C_\phi^{(\tau)}, \qquad \text{for } \phi = A, B$$

HQSS (V)

- Some channels have the same linear combination of contact terms

$$V(D\bar{D}^*, 1^{++}) = V(D^*\bar{D}^*, 2^{++}) = C_{IA} + C_{IB}$$

$$V(D\bar{D}^*, 1^{+-}) = V(D^*\bar{D}^*, 1^{+-}) = C_{IA} - C_{IB}$$

$D\bar{D}$ does not have the same: $V(D\bar{D}, 0^{++}) = C_{IA}$

- This would suggest spin multiplets. Good candidates:

☞ $X(3872)$ and $X_2(4013)$ (not observed yet!); $Z_c(3900)$ and $Z_c(4020)$

Nieves, Valderrama, PRD86(2012)056004; ...

$$M_{X_2(4013)} - M_{X(3872)} \approx M_{Z_c(4020)} - M_{Z_c(3900)} \approx M_{D^*} - M_D$$

☞ $Z_b(10610)$ and $Z_b(10650)$: Bondar et al., PRD84(2011)054010; ...

$$M_{Z_b(10650)} - M_{Z_b(10610)} \approx M_{B^*} - M_B$$

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Inputs and predictions (I)

- Solve Lippmann–Schwinger equation regularized with a Gaussian form factor, bound states appear as poles in the first Riemann sheet below threshold
- Inputs:
  - ☞ Mass of $X(3872)$ $\Rightarrow$ $C_{0A} + C_{0B}$
  - ☞ Mass of $Z_b(10610)$ $\Rightarrow$ $C_{1A} - C_{1B}$
- Predicted many partners of $X(3872)$ and $Z_b(10610)$ FKG et al., PRD88(2013)
  - ☞ Partners of $X(3872)$ [1^{++}]:

$I(J^{PC})$	States	Thresholds	Masses ($\Lambda = 0.5$ GeV)
$0(1^{++})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$	3875.87	**3871.68 (input)**
$0(2^{++})$	$D^*\bar{D}^*$	4017.3	4012^{+4}_{-5}
$0(1^{++})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* - B^*\bar{B})$	10604.4	10580^{+9}_{-8}
$0(2^{++})$	$B^*\bar{B}^*$	10650.2	10626^{+8}_{-9}
$0(2^{+})$	D^*B^*	7333.7	7322^{+6}_{-7}

Here $V(D\bar{D}^*) = V(\bar{B}B^*)\left[1 + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_c}\right)\right], \ldots$ assumed

Inputs and predictions (II)

☞ Partners of $Z_b(10610)$ [1^{+-}]:

$I(J^{PC})$	States	Thresholds	Masses ($\Lambda = 0.5$ GeV)
$1(1^{+-})$	$\frac{1}{\sqrt{2}}(B\bar{B}^* + B^*\bar{B})$	10604.4	10602.4 ± 2.0 **(input)**
$1(1^{+-})$	$B^*\bar{B}^*$	10650.2	10648.1 ± 2.1
$1(1^{+-})$	$\frac{1}{\sqrt{2}}(D\bar{D}^* + D^*\bar{D})$	3875.87	3871^{+4}_{-12} (V)
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Two virtual states in charm sector, could correspond to $Z_c(3900)$ and $Z_c(4020)$

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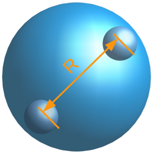
What can we say about productions and decays (I)

- Essential point of in the spirit of effective field theory: scale separation
  - ☞ to include all relevant d.o.f. at the given scale
  - ☞ to study near-threshold structures, one has to take into account the corresponding channel, unless the coupling is weak,
    no matter what structure was used as the starting point
    $\Rightarrow$ for $X(3872)$: has to consider $D\bar{D}^*$
- Hadronic molecular structure: a long-distance concept
  $\Rightarrow$ not all processes are sensitive to it !



What can we say about the productions and decays (II)

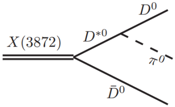
- For processes dominated by long-distance physics:

  calculable with controlled uncertainties using low-energy EFT

  Examples:

  $X(3872) \to D^0 \bar{D}^0 \pi^0$, $X(3872) \to D^0 \bar{D}^0 \gamma$

  Voloshin (2004); . . .



- For processes dominated by short-distance physics (unknown in low-energy EFT): order-of-magnitude estimate at best

  Examples:

  ☞ $X(3872) \to e^+e^-$ Denig, FKG, Hanhart, Nefediev, PLB736(2014)221

  estimate: $\Gamma(X \to e^+e^-) \gtrsim 0.03$ eV

  BESIII: $\Gamma(X \to e^+e^-)_{\text{exp}} < 4.3$ eV BESIII: PLB749(2015)414

  ☞ production of $X(3872)$ in B decays, at hadron colliders with large p_T

  ☞ $X(3872) \to J/\psi\gamma$

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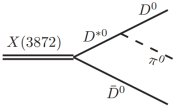

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Decays: $X(3872) \to \psi\gamma$

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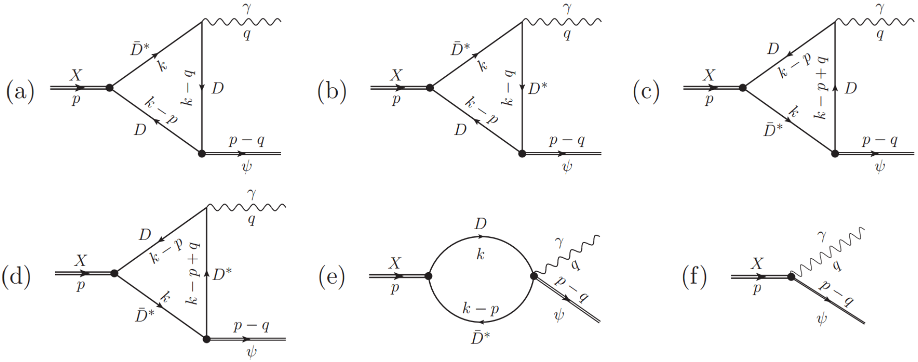


The ratio $$\frac{\mathcal{B}(X(3872) \to \psi'\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$ LHCb, NPB886(2014)665

is insensitive to the molecular component of the $X(3872)$:

- ☞ loops are sensitive to unknown couplings $g_{\psi DD}/g_{\psi' DD}$
- ☞ loops are divergent, needs a counterterm (short-distance physics)!

see also Mehen, Springer, PRD83(2011)094009; Molnar et al., arXiv:1601.03366

Decays: $X(3872) \to D^0 \bar{D}^0 \pi^0$

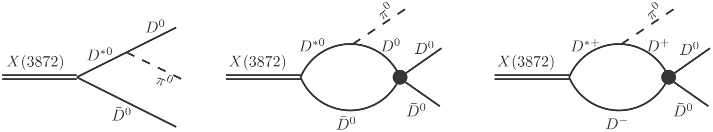
- A long-distance process, thus can be studied in nonrelativistic EFT
- Already studied by many authors

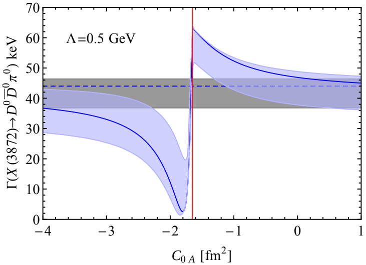
Voloshin (2004); Fleming et al (2007); Braaten, Lu (2007); Hanhart et al (2007); ...

Our new insight: FKG et al., EPJC74(2014)2885

If there is a near-threshold $D\bar{D}$ hadronic molecule $\Rightarrow$ a large impact

Problem: one unknown contact term C_{0A}





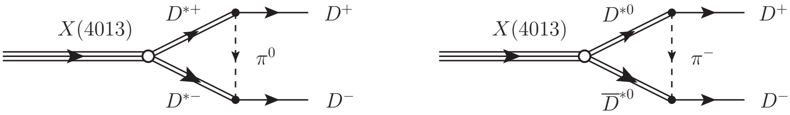
☞ grey band: tree-level result (consistent with Fleming et al., PRD76(2007))

☞ vertical line: a $D\bar{D}$ bound state at threshold

Phenomenology: $X_2(4013) \to D\bar{D}/D\bar{D}^*$

Albaladejo, FKG, Hidalgo-Duque, Nieves, Pavon Valderrama, EPJC75(2015)547

- $X_2(4013)$: 2^{++}, above $D\bar{D}$, $D\bar{D}^*$ thresholds
  dominant decay modes: $D\bar{D}$ and $D\bar{D}^* + c.c.$ in D-wave



- Order-of-magnitude estimate: $\Gamma(X_2) \sim$ a few MeV–tens of MeV

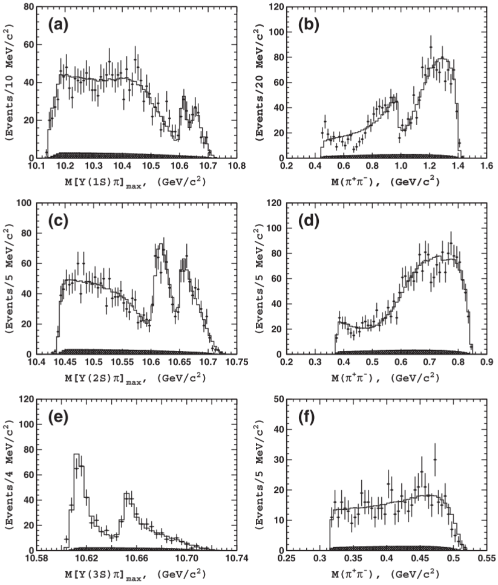
[MeV]	without pion-exchange FF		with pion-exchange FF	
	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV
$\Gamma(D^+D^-)$	$3.3^{+3.4}_{-1.4}$	$7.3^{+7.9}_{-2.1}$	$0.5^{+0.5}_{-0.2}$	$0.8^{+0.7}_{-0.2}$
$\Gamma(D^0\bar{D}^0)$	$2.7^{+3.1}_{-1.2}$	$5.7^{+7.8}_{-1.8}$	$0.4^{+0.5}_{-0.2}$	$0.6^{+0.7}_{-0.2}$

- Fresh calculation with nonperturbative pion: $\Gamma(X_2) \sim 50$ MeV

Baru et al., arXiv:1605.09649

Phenomenology: Z_b (I)

Observation of two Z_b structures at around 10.61 GeV and 10.65 GeV — Belle (2011)



Phenomenology: Z_b (II)

- Such a Z_b was first proposed by Voloshin in 1982 to explain the transition $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$

Possible four-quark isovector resonance in the family of Υ particles

M. B. Voloshin
Institute of Theoretical and Experimental Physics

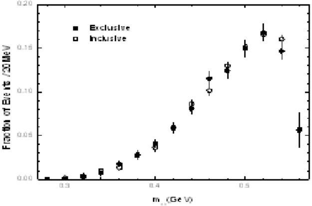
(Submitted 15 November 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 1, 58–60 (5 January 1983)

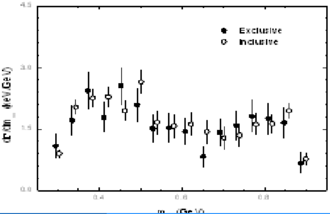
It is suggested, on the basis of data on the pion spectrum in the decay $\Upsilon'' \to \Upsilon\pi^+\pi^-$, that there is an isovector resonance with a mass near the Υ'' mass.

- Anisovich et al. revisited it and suggested its mass to be within [10.4, 10.8] GeV

PRD51(1995)378(R)

- Data of $M_{\pi\pi}$ distributions for $\Upsilon(2S, 3S) \to \Upsilon(1S)\pi\pi$ CLEO (1998, 1994)

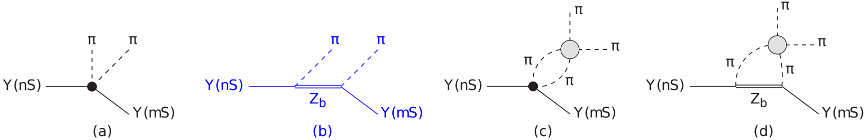




Phenomenology: Z_b (III)

Y.-H. Chen, J. T. Daub, FKG, B. Kubis, U.-G. Meißner, B.-S. Zou, PRD93(2016)034030

- Reexamine with measured Z_b properties



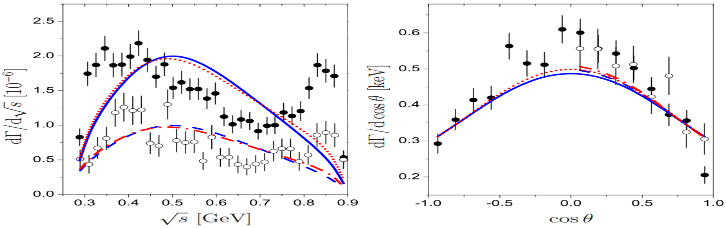
- Use dispersion relation to account for the $\pi\pi$ FSI Anisovich, Leutwyler, PLB375(1996)335

$$\mathcal{M}^{\text{full}}(s,\cos\theta) = \epsilon_{\Upsilon(nS)} \cdot \epsilon_{\Upsilon(mS)} \sum_{l=0}^{\infty} \left[M_l(s) + \hat{M}_l(s) \right] P_l(\cos\theta),$$

$$M_l(s) = \Omega_l^0(s) \left\{ P_l^{n-1}(s) + \frac{s^n}{\pi} \int_{4M_\pi^2}^{\infty} \frac{\mathrm{d}x}{x^n} \frac{\hat{M}_l(x) \sin\delta_l^0(x)}{|\Omega_l^0(x)|(x-s)} \right\}$$

Omnès function: $\Omega_l^I(s) = \exp\left\{ \frac{s}{\pi} \int_{4M_\pi^2}^{\infty} \frac{\mathrm{d}x}{x} \frac{\delta_l^I(x)}{x-s} \right\}$

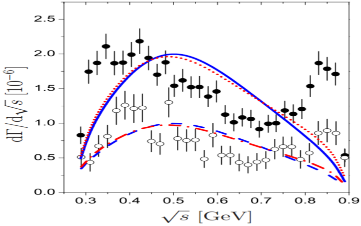
- w/o Z_b or w/ Z_b but using the $Z_b\Upsilon\pi$ coupling constants fixed from the branching fractions reported by Belle in arXiv:1209.6450 [hep-ex]

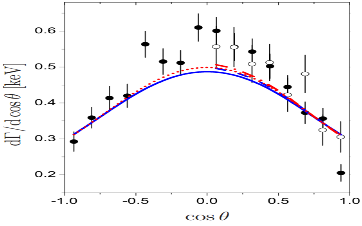


- But best fit gives a much larger $Z_b\Upsilon\pi$ coupling

Phenomenology: Z_b (IV)

- w/o Z_b or w/ Z_b but using the $Z_b\Upsilon\pi$ coupling constants fixed from the branching fractions reported by Belle in arXiv:1209.6450 [hep-ex]





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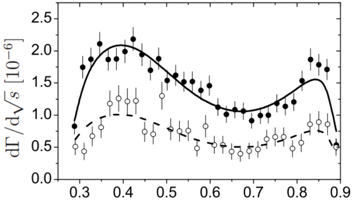
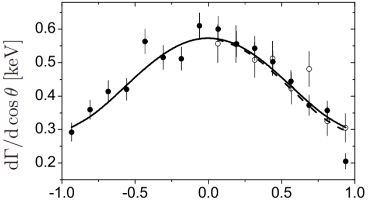


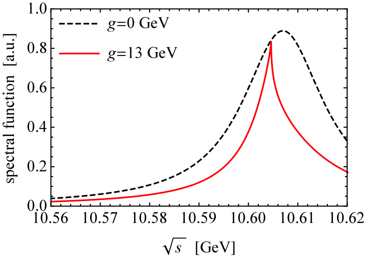


Phenomenology: Z_b (V)

- Belle used BW parameterization in fit/extraction of branching fractions
- $Z_b^{(\prime)}$ located at the $B^{(*)}\bar{B}^*$ threshold $\Rightarrow$ use Flatté parameterization

$$\frac{1}{\left|s - m_{Z_b}^2 + i m_{Z_b}\left[\Gamma_1 + \Gamma_{B\bar{B}^*}(s)\right]\right|^2}$$

here $\Gamma_{B\bar{B}^*}(s) = \frac{g^2}{8\pi m_{Z_b}^2}\left[k\,\theta(\sqrt{s} - m_B - m_{B^*}) + i\,\kappa\,\theta(-\sqrt{s} + m_B + m_{B^*})\right]$



using $m_{Z_b} = 10.607$ GeV and $\Gamma_1 = 20$ MeV

- Γ_1 larger than the nominal peak width $\Rightarrow$ data need be reanalyzed using Flatté

Summary

- hadronic molecule structure should be detected in processes sensitive to long-distance physics
- heavy quark symmetry can provide interesting predictions/insights to hadronic molecules
- should go beyond the mass spectrum because important structure information is contained in the coupling

  $\Rightarrow$ decays and productions
- decay width of $X_2(4013)$ estimated to be narrow
- effects of virtual Z_b in $\Upsilon(3S)$ decays; Z_b data should be reanalyzed to get the correct partial widths

Thank you !

Summary

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Thank you !

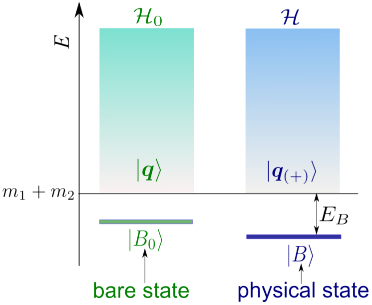
Backup slides

Compositeness (I)

Weinberg, PR137(1965); Baru *et al.*, PLB586(2004); . . .

see also, e.g., Weinberg's books: QFT Vol.I, Lectures on QM

Model-independent result for S-wave loosely bound composite states:



Consider a system with Hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + V$$

$\mathcal{H}_0$: free Hamiltonian, V: interaction potential

- Compositeness:

  the probability of finding the physical state $|B\rangle$ in the 2-body continuum $|\boldsymbol{q}\rangle$

$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left|\langle \boldsymbol{q}|B\rangle\right|^2$$

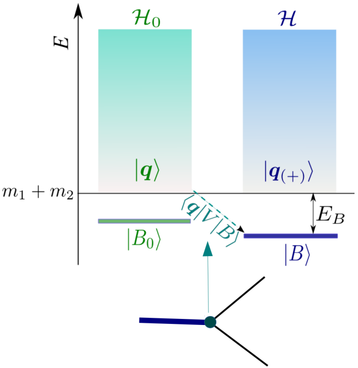
- $Z = \left|\langle B_0|B\rangle\right|^2, \qquad 0 \le (1-Z) \le 1$

  ☞ $Z = 0$: pure bound (composite) state

  ☞ $Z = 1$: pure elementary state

Compositeness (II)

Compositeness : $1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left|\langle \boldsymbol{q}|B\rangle\right|^2$



- Schrödinger equation

$$(\mathcal{H}_0 + V)|B\rangle = -E_B|B\rangle$$

multiplying by $\langle \boldsymbol{q}|$ and using $\mathcal{H}_0|\boldsymbol{q}\rangle = \frac{\boldsymbol{q}^2}{2\mu}|\boldsymbol{q}\rangle$

$$\langle \boldsymbol{q}|B\rangle = -\frac{\langle \boldsymbol{q}|V|B\rangle}{E_B + \boldsymbol{q}^2/(2\mu)}$$

- S-wave, small binding energy so that $R = 1/\sqrt{2\mu E_B} \gg r$, r: range of forces

$$\langle \boldsymbol{q}|V|B\rangle = g_{\rm NR}\left[1 + \mathcal{O}(r/R)\right]$$

- Compositeness:

$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \frac{g_{\rm NR}^2}{\left[E_B + \boldsymbol{q}^2/(2\mu)\right]^2}\left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right] = \frac{\mu^2 g_{\rm NR}^2}{2\pi\sqrt{2\mu E_B}}\left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right]$$

Compositeness (III)

- Coupling constant measures the compositeness for an S-wave bound state with a small binding energy (model-independent)

$$g_{\rm NR}^2 \approx (1-Z)\frac{2\pi}{\mu^2}\sqrt{2\mu E_B} \le \frac{2\pi}{\mu^2}\sqrt{2\mu E_B}$$

- Z can be measured directly from observables, such as scattering length a and effective range r_e Weinberg (1965)

$$a = -\frac{2R(1-Z)}{2-Z}\left[1+\mathcal{O}\left(\frac{r}{R}\right)\right], \quad r_e = \frac{RZ}{1-Z}\left[1+\mathcal{O}\left(\frac{r}{R}\right)\right]$$

- Example: deuteron as pn bound state. Exp.: $E_B = 2.2$ MeV, $a_{^3S_1} = -5.4$ fm

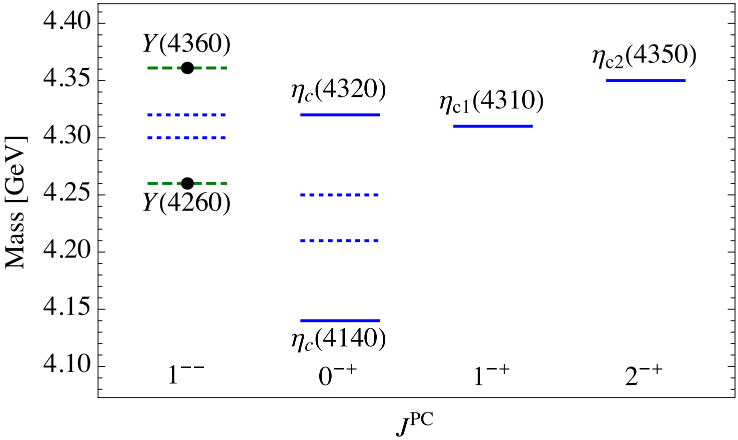
$$a_{Z=1} = 0 \text{ fm}, \qquad a_{Z=0} = (-4.3 \pm 1.4) \text{ fm}$$

If the $Y(4260)$ and $Y(4360)$ are mixed hadro-charmonia with h_c and ψ' core,

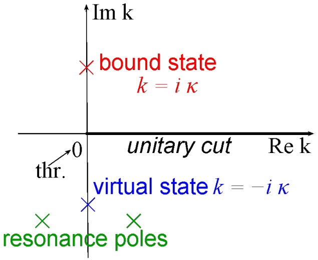
Li, Voloshin, MPLA29(2014)1450060

implications of HQSS for hadro-charmonia:

Cleven et al., PRD92(2015)014005



Bound state and virtual state (I)



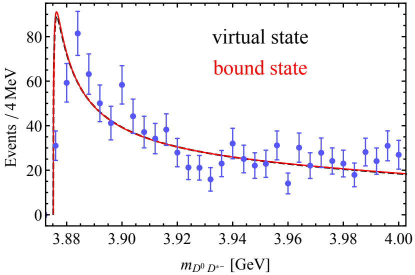
Suppose the scattering length is very large, the S-wave scattering amplitude

$$f_0(k) = \frac{1}{k\cot\delta_0(k) - ik} \simeq \frac{1}{-1/a - ik}$$

- bound state pole: $1/a = \kappa \equiv \sqrt{2\mu b}$
- virtual state pole: $1/a = -\kappa$

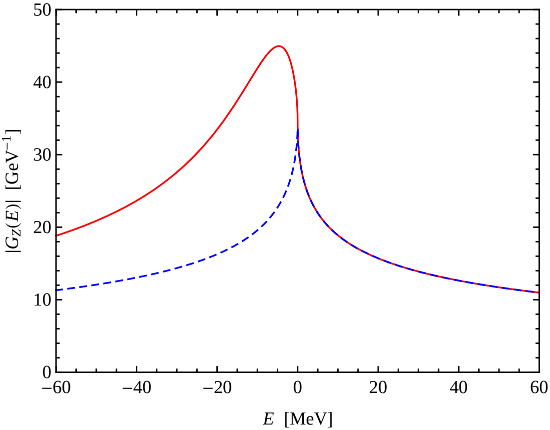
- If the same “binding” energy, cannot be distinguished above threshold (k is real):

$$|f_0(k)|^2 \sim \frac{1}{\kappa^2 + k^2}$$



Bound state and virtual state (II)

- Different line shapes below threshold ⇒ in inelastic channel



A bound state and virtual state with a 5 MeV binding energy, a width to the inelastic channel is allowed.

Cleven et al., EPJA47(2011)120

$X_2(4013) \to D\bar{D}/D\bar{D}^*$ (backup–I)

- Two P-wave vertices: divergent loop integral?

$$\epsilon_{ij} \int \frac{d^4 l}{(2\pi)^4} \frac{l^i\, l^j}{\left[(l+q)^2 - M^2 + i\varepsilon\right]\left[(k-l)^2 - M^2 + i\varepsilon\right](l^2 - m^2 + i\varepsilon)}$$

here ϵ_{ij}: polarization tensor, symmetric, traceless

only convergent part contributes! reason: D-wave decay

- so it seems straightforward to calculate the widths, however, a problem:

☞ a large dependence on the cutoff using the same Gaussian form factor

[MeV]	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV
$\Gamma(D^+D^-)$	$3.3^{+3.4}_{-1.4}$	$7.3^{+7.9}_{-2.1}$
$\Gamma(D^0\bar{D}^0)$	$2.7^{+3.1}_{-1.2}$	$5.7^{+7.8}_{-1.8}$

Errors in the table: HQSS breaking (20% in potential) + $X(3872)$ input

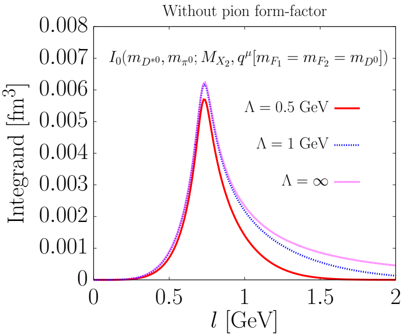
$X_2(4013) \to D\bar{D}/D\bar{D}^*$ (backup–II)

- Reason for the large cutoff dependence: large external momenta

$$q_D \simeq 730 \text{ MeV} \qquad [q_D \simeq 510 \text{ MeV for } D\bar{D}^*]$$

$\Rightarrow$ momentum of the exchanged pion can be large

- a large contribution from $l \gtrsim 1$ GeV, (l: pion momentum)

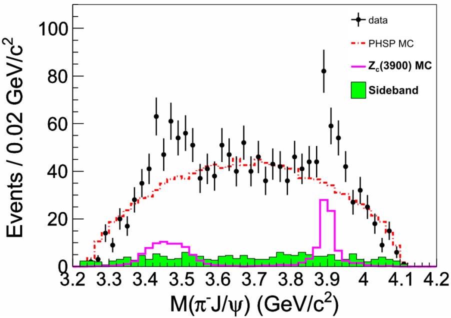


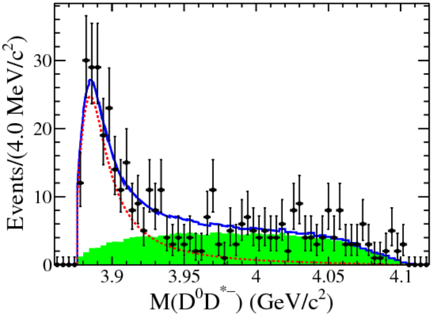
reaches the valid/invalid edge of EFT, NO reliable/precise prediction can be made

Phenomenology: $Z_c(3900)$ (I)

- structure around 3.9 MeV seen in both $J/\psi\pi$ and $D\bar{D}^*$, discovered by BESIII and Belle

see talks by Z.-Y. Wang and C.-P. Shen

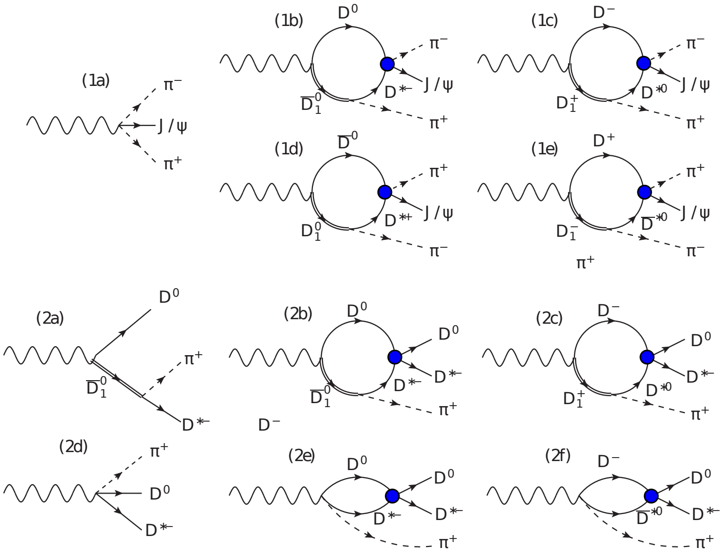




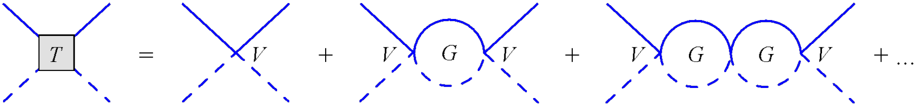
BESIII, PRL110(2013)252001; PRD92(2015)092006

Phenomenology: $Z_c(3900)$ (II)

M. Albaladejo, FKG, C. Hidalgo-Duque, J. Nieves, PLB755(2016)337

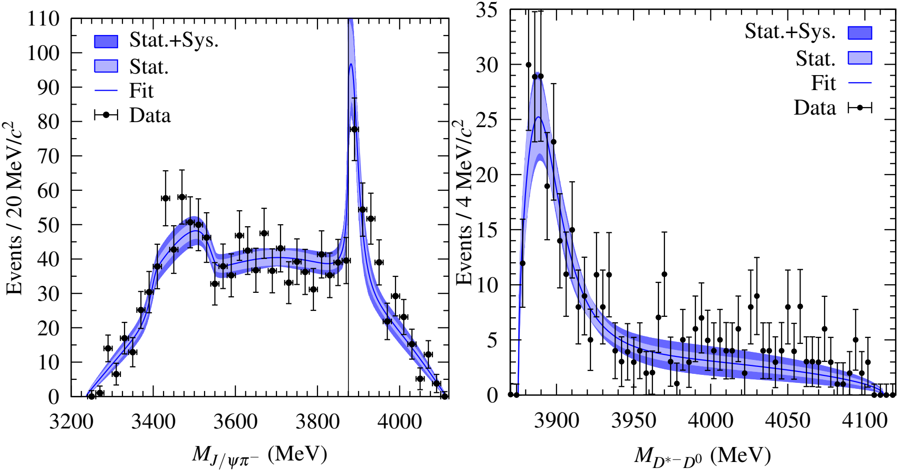


Blobs in the figure:



- Two channels: 1: $J/\psi\pi$, 2: $D\bar{D}^* + c.c.$
- $V_{ij} = 4\sqrt{m_{i1}m_{i2}}\sqrt{m_{j1}m_{j2}}\, e^{-q_i^2/\Lambda_i^2} e^{-q_j^2/\Lambda_j^2} C_{ij}$
- $J/\psi\pi$ interaction very weak: $|a_{J/\psi\pi}| \lesssim 0.02$ fm Liu, FKG, Epelbaum, EPJC73(2013)2284
  $\Rightarrow$ taking $C_{11} = 0$
- $C_{22} = C_{1Z} + b(E - m_D - m_{D^*})$
- 3 parameters: C_{1Z}, b and C_{12}

Phenomenology: $Z_c(3900)$ (IV)



Phenomenology: $Z_c(3900)$ (V)

	M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
	3899 ± 6	23 ± 11	BESIII, PRL110	$J/\psi\,\pi$
	3895 ± 8	32 ± 18	Belle, PRL110	$J/\psi\,\pi$
	3886 ± 5	19 ± 5	Xiao et al., PLB727	$J/\psi\,\pi$
	3884 ± 5	12 ± 6	BESIII, PRL112	$\bar{D}^* D$
	3882 ± 3	13 ± 5	BESIII, PRD92	$\bar{D}^* D$
$b \neq 0$	$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	$\Lambda_2 = 1.0$ GeV	$J/\psi\,\pi$, $\bar{D}^* D$
	$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	$\Lambda_2 = 0.5$ GeV	$J/\psi\,\pi$, $\bar{D}^* D$
$b = 0$	$3831 \pm 26^{+7}_{-28}$	virtual state	$\Lambda_2 = 1.0$ GeV	$J/\psi\,\pi$, $\bar{D}^* D$
	$3844 \pm 19^{+12}_{-21}$	virtual state	$\Lambda_2 = 0.5$ GeV	$J/\psi\,\pi$, $\bar{D}^* D$

Phenomenology: $Z_c(3900)$ (VI)