Heavy quark symmetry and hadronic molecules

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International Workshop on QCD Exotics, 07–12 June 2015, Jinan

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Based on:

FKG, C. Hanhart, U.-G. Meißner, PRL102(2009)242004

FKG, C. Hidalgo-Duque, J. Nieves, M. Pavón Valderrama, PRD88(2013)054007; 054014

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

FKG, Meißner, Yang, PLB740(2015)42

FKG, Hanhart, Kalashnikova, Meißner, Nefediev, PLB742(2015)394

M. Albaladejo, FKG, C. Hidalgo-Duque, J. Nieves, M. Pavón Valderrama, arXiv:1504.00861 [hep-ph]

Hadronic molecules (I)

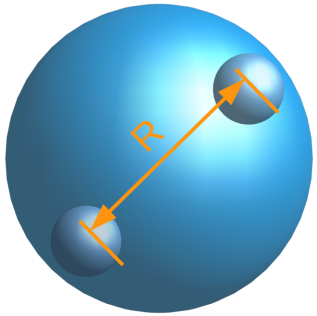
- Hadronic molecule:

  dominant component is 2 or more hadrons

- Extended, so that can be approximated by system of multi-hadrons

  Consider a 2-body bound state with a mass $M = m_1 + m_2 - E_B$

size: $$R \sim \frac{1}{p} \sim \frac{1}{\sqrt{2\mu E_B}}$$



- 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

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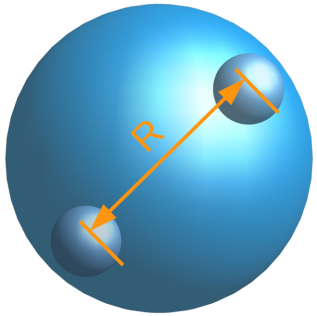

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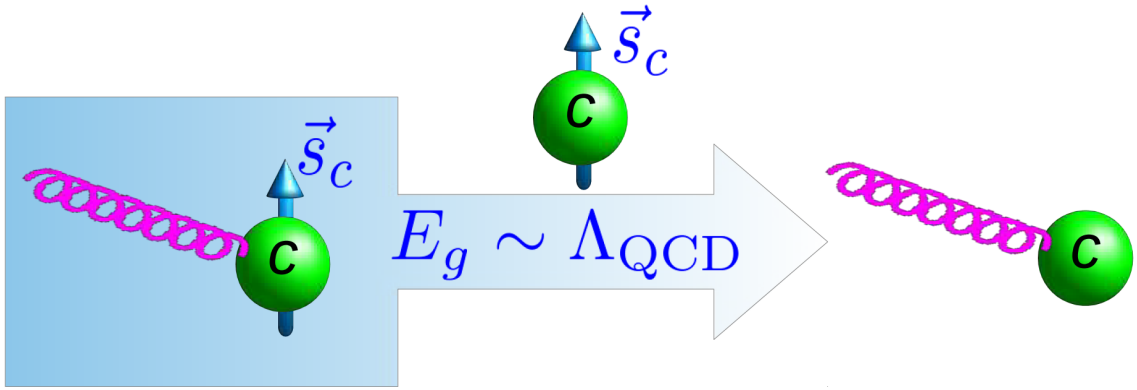
Hadronic molecules (II)

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

    see also talks by C. Hanhart and H.-Q. Zheng
  - ☞ understanding the XYZ states, nice objects to apply heavy quark symmetries

Heavy quark spin symmetry (I)



- Heavy quark spin symmetry (HQSS) implies spin multiplets for heavy hadrons, heavy quarkonium, e.g. (D, D^*), $(\eta_c, J/\psi)$
- $\Rightarrow$ spin partners of hadronic molecules
- For hadronic molecules of the form $Q\bar{Q}$+light hadron

FKG, Hanhart, Meißner, PRL102(2009)242004

☞ exchange at least two gluons, LO interaction independent of heavy quark spin

☞ spin multiplet with approximately the same splitting as that for $Q\bar{Q}$

☞ the same for hadro-quarkonium arXiv:1505.01771, see the talk by M. Cleven

HQSS (II)

- For hadronic molecules composed of two open-flavor heavy mesons
  - ☞ more complicated, but can be studied by writing down the effective Lagrangian for the LO interaction between spin multiplets. e.g.

AlFiky et al., PLB640(2006)238 ...

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

here

$\vec{\tau}$: Pauli matrices in isospin space

$H_a^{(Q)}$: D, D^*; $\qquad H_a^{(\bar{Q})}$: $\bar{D}, \bar{D}^*$

HQSS (III)

- Number of the contact terms can be easily understood:
  - ☞ 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^*: $s_\ell^P = \frac{1}{2}^-$
  - ☞ HQSS $\Rightarrow$ total angular momentum of light quarks is conserved
- Consider interaction between a pair of $s_\ell^P = \frac{1}{2}^-$ (anti-)heavy mesons, 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

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

Isospin $I = 0$ or 1 $\Rightarrow$ 4 independent terms in this case:
C_{0A}, C_{0B}; C_{1A}, C_{1B}: linear combinations of $C_{A,B}^{(\tau)}$

HQSS (IV)

- 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 interaction: $V(D\bar{D}, 0^{++}) = C_{IA}$

- This would suggest spin multiplets. Good candidates:

☞ $X(3872)$ and $X_2(4013)$; $Z_c(3900)$ and $Z_c(4020)$

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

☞ $Z_b(10610)$ and $Z_b(10650)$ in the bottom sector

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

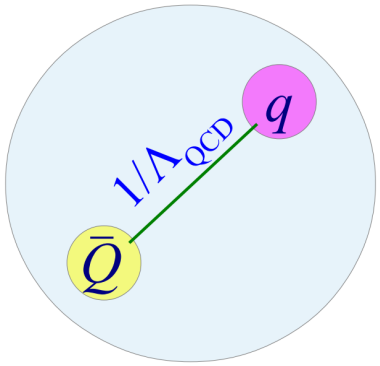
More symmetries

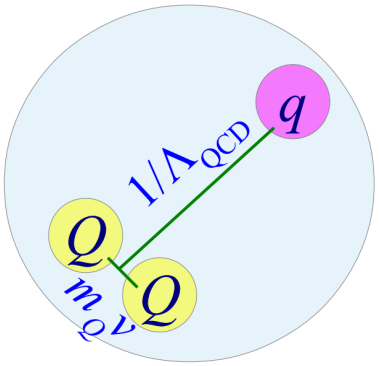
- heavy quark flavor symmetry

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

- heavy anti-quark–diquark symmetry

Savage, Wise (1990)





$$V\left(\Xi^*_{Q_1Q_2}B^*, \frac{5}{2}^-\right) = V(D\bar{D}^*, 1^{++}) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_c v}\right)$$

larger uncertainty, in particular $\sim 40\%$ for the charm sector!

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}

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)
$1(1^{+-})$	$D^*\bar{D}^*$	4017.3	4013^{+4}_{-11} (V)
$1(1^{+})$	D^*B^*	7333.7	$7333.6^{\dagger}_{-4.2}$ (V)

Two virtual states in charm sector, could correspond to $Z_c(3900)$ and $Z_c(4020)$

More investigations needed:

- only considered LO constant contact terms $\Rightarrow$ cannot get resonances
- no one-pion exchange, no coupled-channels see Nieves, Valderrama (2011,2012)
- so far, the assignments of the predicted states to the observed ones only based on masses, $\Rightarrow$ decays and productions

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What can we say about productions and decays (I)

- For hadronic molecules with a small binding energy $\Rightarrow$ extended object

$$\sqrt{2\mu E_B} \ll \Lambda_{\text{hadron}} \sim 1 \text{ GeV}$$

- Most important point of effective field theory: scale separation
  - ☞ loosely bound hadronic molecules can be studied with nonrelativistic EFT
  - ☞ to study near-threshold structures, one must take into account the channel with that threshold, unless the coupling is negligible,
    no matter what structure was used as the starting point
    $\Rightarrow$ for $X(3872)$: has to consider $D^0\bar{D}^{*0}$ XEFT: Fleming et al., PRD76(2007)
    $\Rightarrow$ depending on the specifics (cut-off) of the EFT, $D^+D^{*-} + c.c.$ as well
    comparison and consistency between XEFT and our NREFT

    T. Mehen, arXiv:1503.02719 [hep-ph]

  - different processes have different energy scales, not all are sensitive to the hadronic molecule structure

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

- For processes dominated by long-distance physics:
  calculable with controlled uncertainties using 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:
  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: arXiv:1505.02559 [hep-ex]
  - ☞ $X(3872) \to \psi\gamma$

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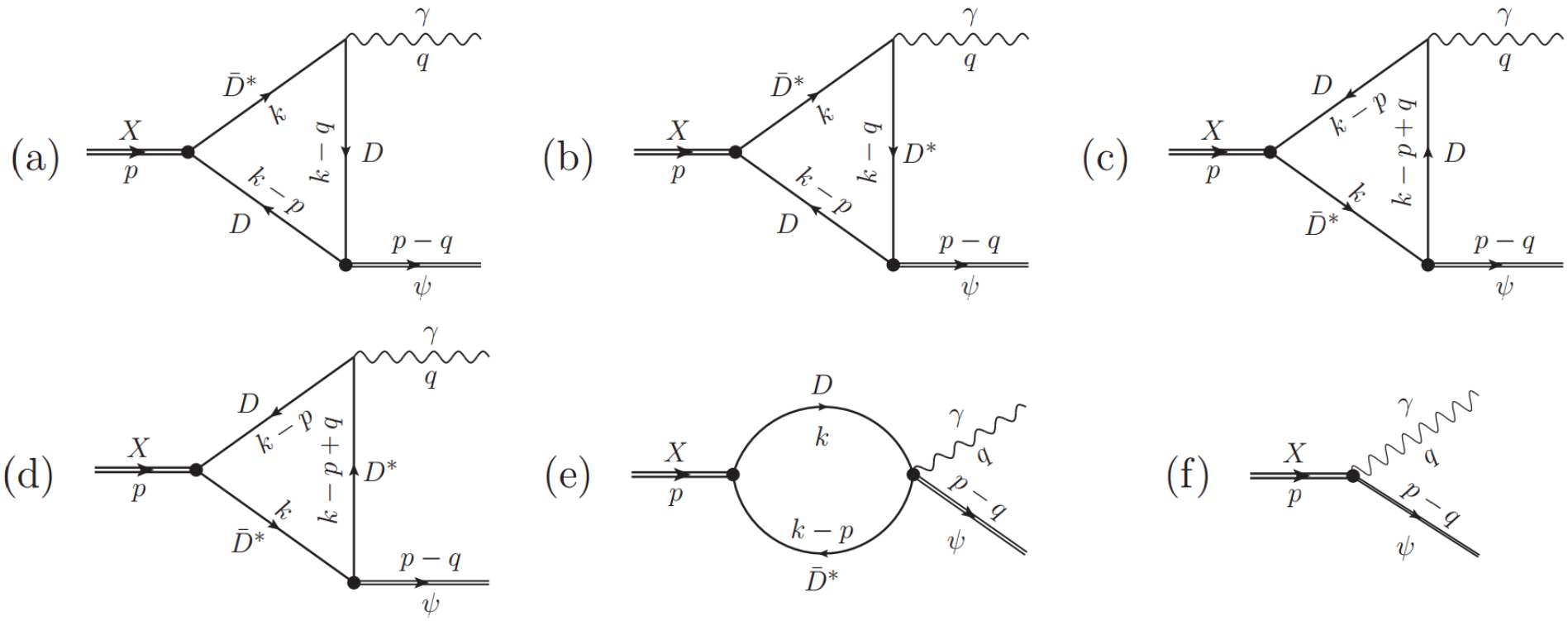
FKG, Hanhart, Kalashnikova, Meißner, Nefediev, PLB742(2015)394



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

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

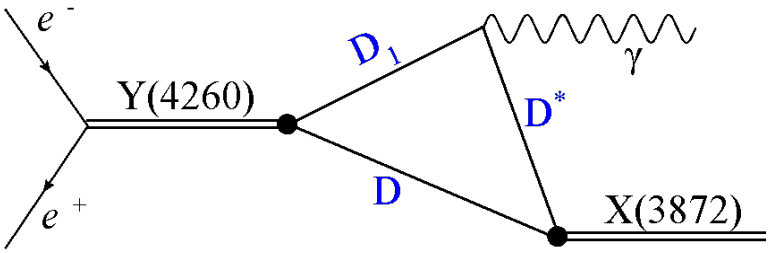
- ☞ loops are sensitive to unknown couplings $g_{\psi DD}/g_{\psi' DD}$
- ☞ loops are divergent, needs a counterterm (short-distance physics)

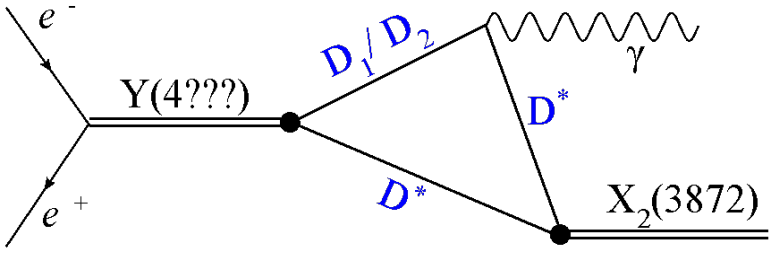
see also Mehen, Springer, PRD83(2011)094009

Production: $e^+e^- \to \gamma X_2(4013)$

FKG, Meißner, Yang, PLB740(2015)42

- BESIII observed $e^+e^- \to \gamma X(3872)$ at $\sqrt{s} = 4.26$ GeV BESIII, PRL112(2014)092001
- Analogous process: $e^+e^- \to \gamma X_2(4013)$





- Optimized energy region for searching:

$$\sqrt{s} \sim 4.26 \text{ GeV} + \left(M_{D_1/D_2} + M_{D^*}\right) - \left(M_{D_1} + M_D\right) \sim [4.4, 4.5] \text{ GeV}$$

- can be facilitated if there is an analogue/analogues of $Y(4260)$ in that region, plausible see talk by M. Cleven

For an estimate of the production at hadron colliders, see talk by W. Wang

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

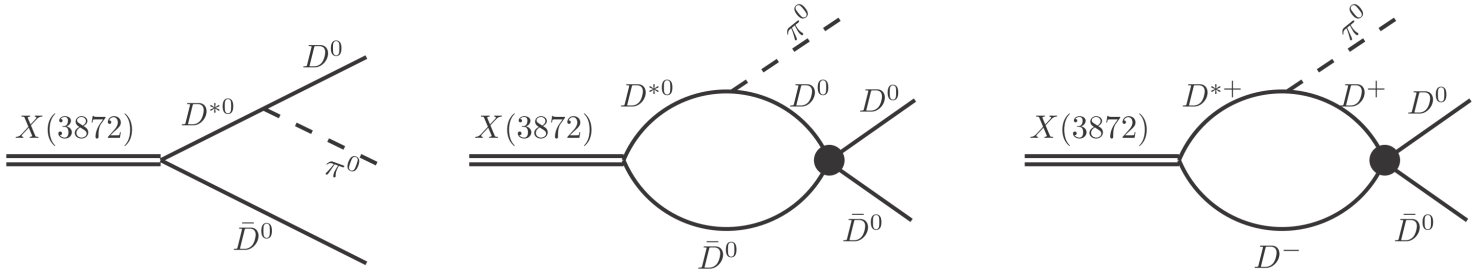
- A long-distance process, thus can be studied in nonrelativistic EFT
- Already studied by many authors

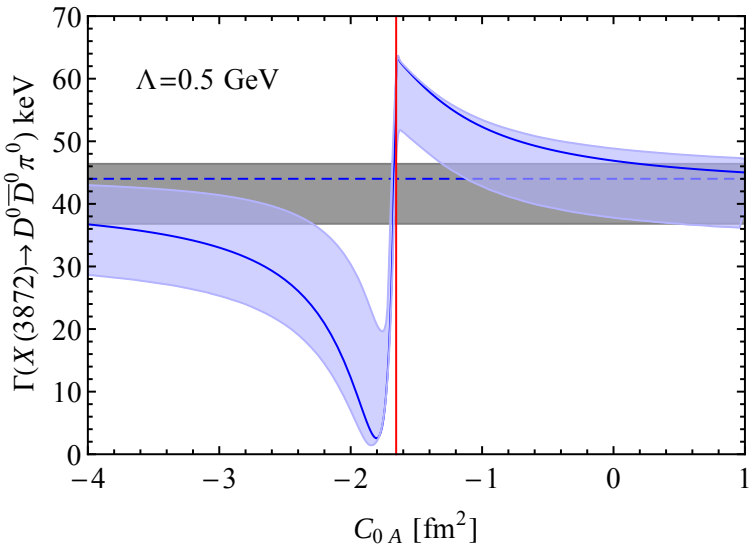
Voloshin (2004); Fleming et al (2007); Braaten, Lu (2007); Hanhart et al (2007); ...

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}



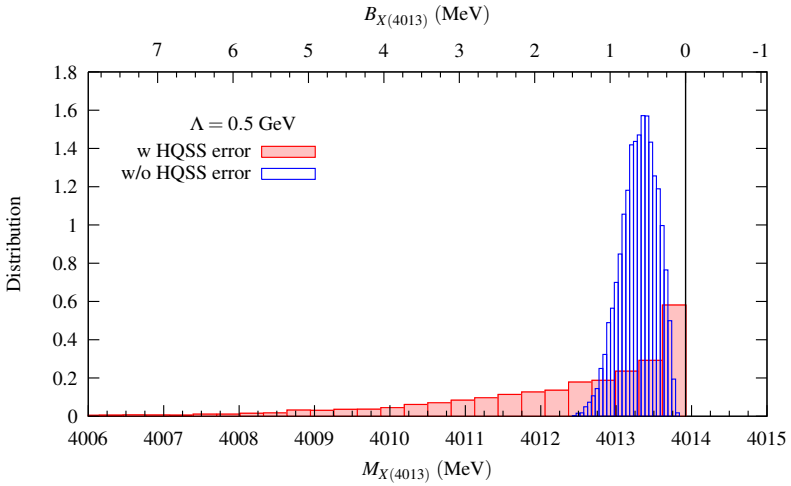


☞ grey band: tree-level result (consistent with Fleming et al., PRD76(2007))

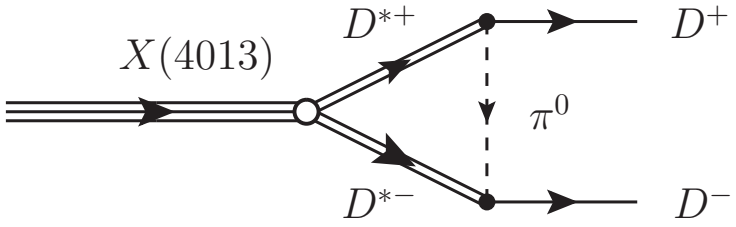
☞ vertical line: a $D\bar{D}$ bound state at threshold

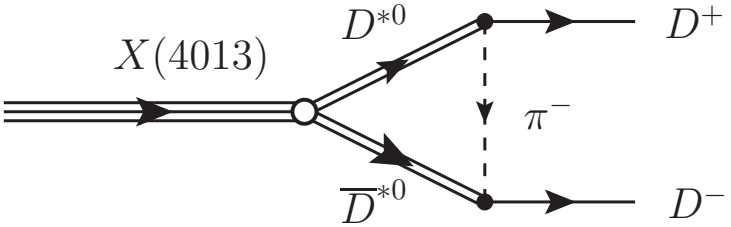
Decays: $X_2(4013) \to D\bar{D}/D\bar{D}^*$ (I)

- $X_2(4013)$:
  2^{++}, above $D\bar{D}$, $D\bar{D}^*$ thresholds
  we expect it to decay dominantly into $D\bar{D}$
  and $D\bar{D}^* + c.c.$ in D-wave



- assuming that the one-pion exchange can be treated perturbatively,
  decay width calculated in Albaladejo et al., arXiv:1504.00861 [hep-ph]





Parameters:

☞ $D^*D\pi$ coupling: very-well measured, $g = 0.570 \pm 0.006$

☞ $X_2D^*\bar{D}^*$ coupling: calculable, residue of the T-matrix

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

- Two P-wave vertices: divergent loop integral?

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

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

only convergent part contributes! reason: D-wave decay, $l^i l^j \to q_D^i q_D^j$

- so it seems straightforward to calculate the widths, use the same Gaussian cutoff

but, a problem:

☞ a large dependence on the cutoff Λ

[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

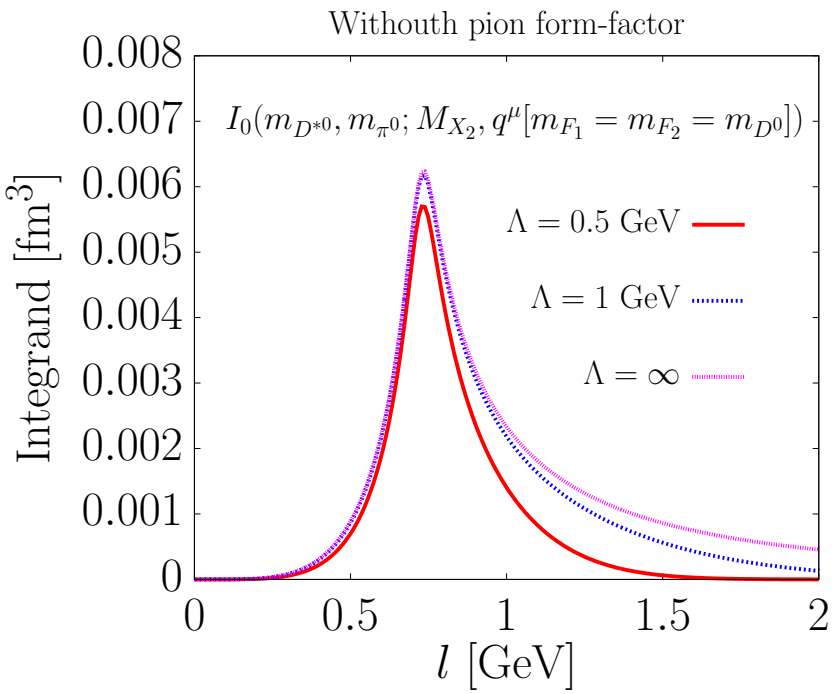
Decays: $X_2(4013) \to D\bar{D}/D\bar{D}^*$ (III)

- 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

- Next, order-of-magnitude estimate by modelling

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

- Order-of-magnitude estimate:

  introduce a pion-exchange vertex form factor to suppress the contribution from high-momentum modes

$$\frac{\Lambda_\pi^2}{l^2+\Lambda_\pi^2}, \qquad \Lambda_\pi \simeq 1 \text{ GeV}$$

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

- $\Gamma(X_2 \to D\bar{D}^*/D^*\bar{D})$: similar problem happens, partial widths similar
- Estimated width for $X_2(4013)$: narrow

$$\Gamma(X_2) \approx \Gamma(D\bar{D}) + \Gamma(D\bar{D}^*) + \Gamma(D^*\bar{D}) \sim \text{ a few MeV}$$

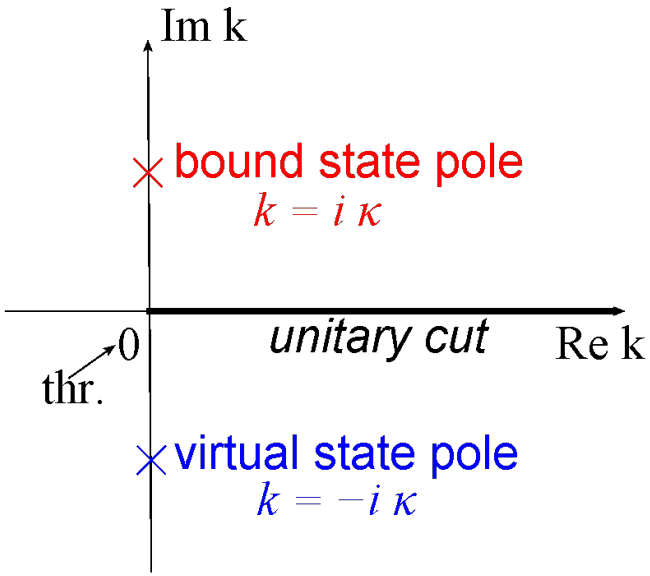
- also decays into $J/\psi\omega$ ($J/\psi\rho$ should be suppressed)

Summary

- heavy quark symmetry can provide interesting predictions/insights to hadronic molecules
  to other structures as well — see M. Cleven's talk
- should go beyond the mass spectrum because important structure information is contained in the coupling — see talks by C.Hanhart, H.-Q.Zheng
  $\Rightarrow$ decays and productions
- structure of hadronic molecules can only be discussed for processes sensitive to long-distance physics
- decay width of $X_2(4013)$ estimated to be a few MeV

Backup slides

Bound state and virtual state (I)



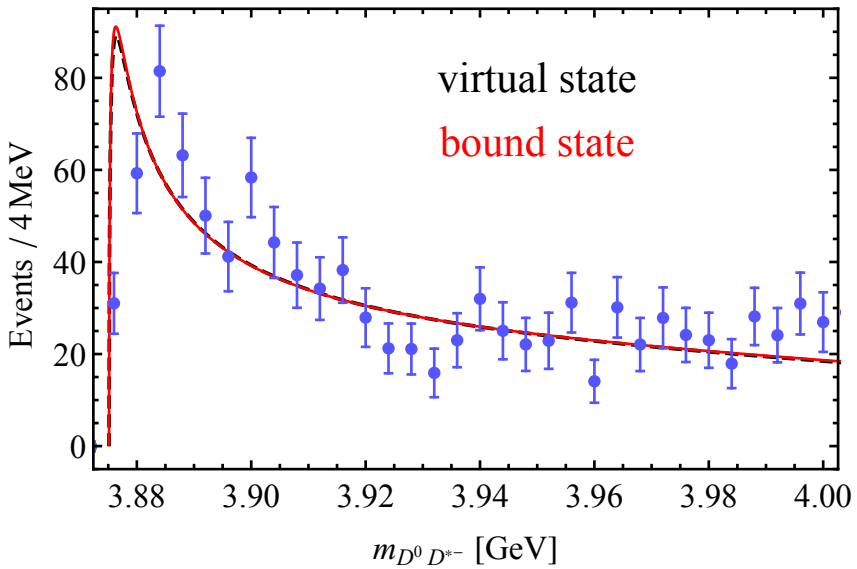
Suppose the scattering length is very large, the S-wave scattering amplitude

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

- ☞ bound state pole: $1/a = \kappa$
- ☞ virtual state pole: $1/a = -\kappa$

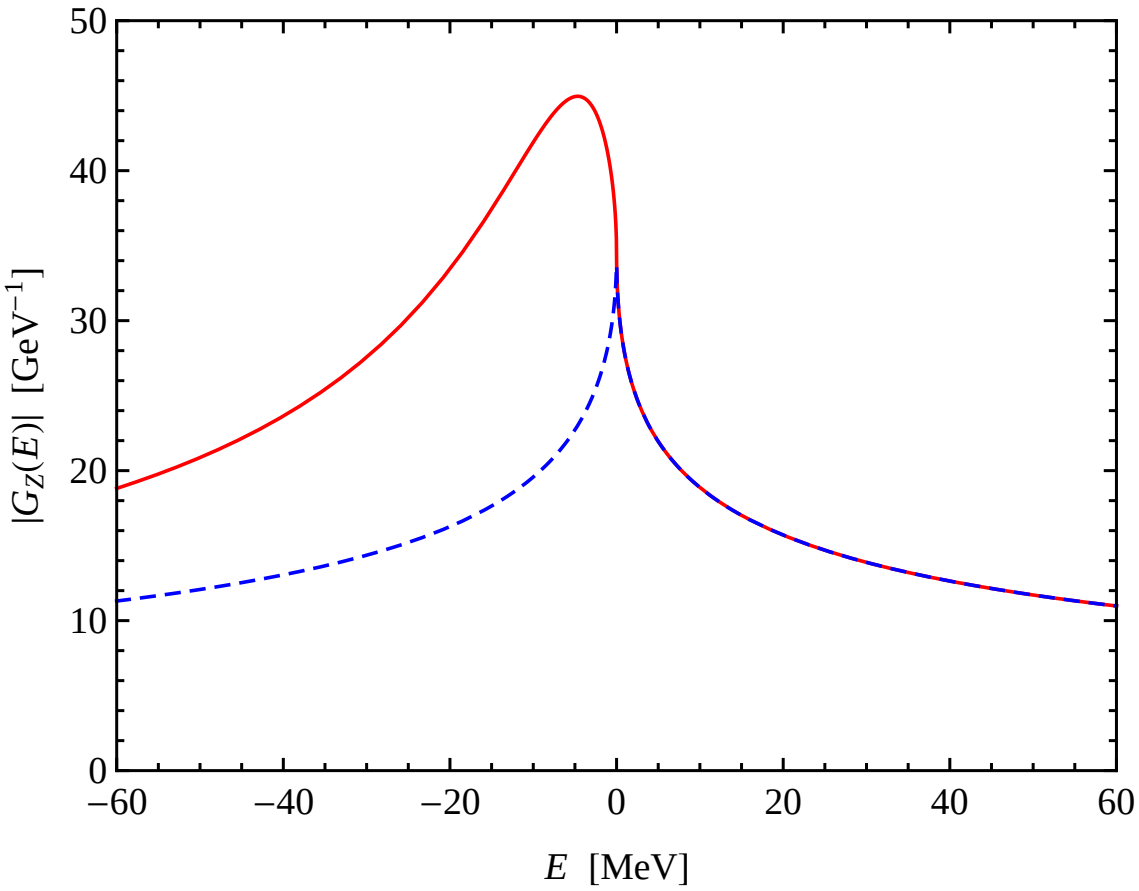
- If the same binding energy, cannot be distinguished above threshold (k is real):

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



Bound state and virtual state (II)

- Bound state and virtual state with a small binding energy should be distinguished in inelastic channel



A bound state and virtual state with a 5 MeV binding energy, a small residual width to the inelastic channel is allowed. Cleven et al., EPJA47(2011)120

X_b and X_{b2}

- X_b: analogue of $X(3872)$, 1^{++}, $M \simeq 10.58$ GeV FKG et al., PRD88(2013)054007
  - ☞ X_b has a binding energy much larger than that of the $X(3872)$
  - ☞ isospin $I = 0$, and isospin breaking effects should be small:

$$M_{B^0} - M_{B^\pm} = (0.32 \pm 0.06) \text{ MeV}, \quad M_{X_b} - M_{\Upsilon(1S)} - M_{\omega/\rho} \gtrsim 300 \text{ MeV}$$

$\Rightarrow$ $\mathcal{B}(X_b \to \Upsilon(1S)\pi\pi) \lesssim 10^{-2}$, better to search for it in

$\Upsilon\pi^+\pi^-\pi^0$, $\Upsilon(nS)\gamma$ and $\chi_{bJ}\pi^+\pi^-$

FKG et al., PRD88(2013)054007; FKG et al., EPJC74(2014)3063

- its spin partner X_{b2}: $M_{X_{b2}} \simeq M_{X_b} + 45$ MeV, $X_{b2} \to B\bar{B}$ (D-wave)
  - ☞ $\Gamma(X_2) \sim$ a few MeV Albaladejo et al., arXiv:1504.00861 [hep-ph]