Interactons between two heavy mesons within chiral perturbation theory

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Introduction

Hadron spectrum

- Traditional quark model: Meson ($\bar{q}q$), Baryon (qqq)

  Discovery of doubly heavy baryon: Ξ_{cc}

  Ξ_{cc} was discovered by SELEX collaboration, and

  has been confirmed by LHCb group but with different mass in 2017

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    $D_s(2317)$: contribution of DK continuum

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    Deuteron: bound state of proton and neutron

    P_c states reported at LHCb recently; $Z_b(10610)$, $Z_b(10650)$

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    P_c states reported at LHCb recently; $Z_b(10610)$, $Z_b(10650)$
  - other exotic states

    X, Y, Z states, debate with different interpretations:

    molecules? tetraquark? ordinary charmonium? two diquark? kinetic effects?

Hadron interactions at low energy

- Spectrum $\rightleftarrows$ Interactions
- interactions cannot be perturbatively solved at low energy

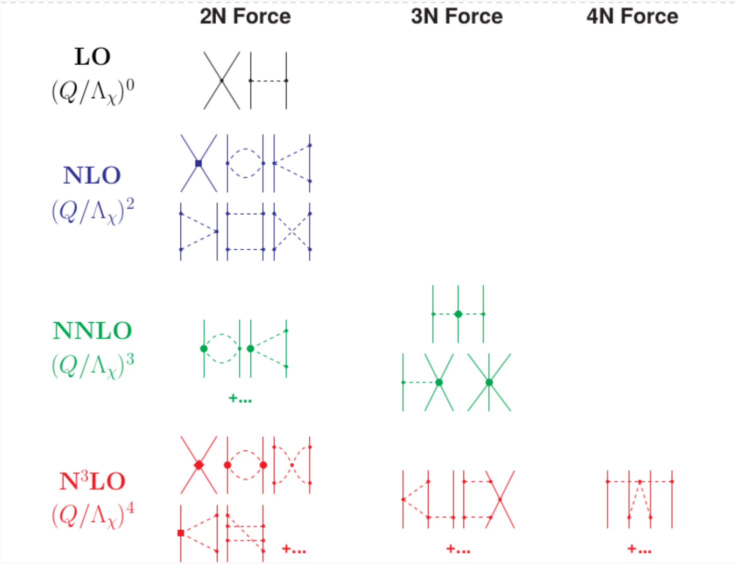
  because of large strong coupling α_s
- Different models and approaches
  - lattice QCD simulation
  - QCD sum rule
  - one-boson-exchange model
  - chiral perturbation theory
  - Hamiltonian effective field theory
  - diquark model
  - ...

Study of Interactions within chiral perturbation theory (ChPT)

- ChPT with respect on symmetries of QCD
- Power counting
  - NOT in power series: α_s, α_s^2, α_s^3, ...
  - expanded with small momentum
  - systematically study, order by order, error controlled
  - check of standard model
- Natual extension

  2-body force, 3-body force,...
- Wide applications

Nucleon-nucleon interaction



ChPT with heavy hadrons involved

- Dealing systems with light mesons

  ChPT results can be expanded as power series of

  $$m_\phi/\Lambda_\chi,\ q/\Lambda_\chi,\ \ldots$$

- Power Counting Breaking (PCB) in systems with heavy hadrons involved

  large masses of heavy hadrons make q^μ is never small again

  power counting can be recovered with the help of residual momentum $\tilde{q}^\mu$

  $$\tilde{q}^\mu = q^\mu - m(1, \vec{0}).$$

Solutions for systems with one heavy hadron

- Heavy hadron effective field theory (EFT)

  nonrelativistic reduction at Lagrangian level, breaking of analyticity.

  Simple and still correct if not analytically extending results too far away
- Infrared regularization

  relativistic Lagrangian, drop PCB terms at regularization

  good power counting and analyticity
- Extended on-mass-shell scheme

  relativistic Lagrangian, drop PCB terms at final results

  good power counting and analyticity

Results with three different schemes will be same if

- being summarized at ALL orders, or
- the mass of heavy hadron becomes infinite.

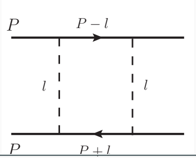
ChPT with few hadrons involved—new trouble

The amplitude of following 2-Particle-Reducible diagram contains [1]

$$\mathcal{I} \equiv i \int dl^0 \frac{i}{l^0 + P^0 - \vec{P}^2/(2m_N) + i\varepsilon} \frac{i}{-l^0 + P^0 - \vec{P}^2/(2m_N) + i\varepsilon} \approx \frac{-\pi}{\vec{P}^2/(2m_N) + i\varepsilon}. \tag{1}$$

- naïve power counting scheme $\rightarrow \mathcal{I} \sim O(1/|\vec{P}|)$
- eq. (1) $\rightarrow \mathcal{I} \sim O(m_N/|\vec{P}|^2)$

$\mathcal{I}$ is actually enhanced by a large factor $m_N/|\vec{P}|$.



Solid line for nucleon, dashed line for pion.

(P represents the residual momentum)

Box Diagram.

[1] we have not listed the parts preserving power counting

Weinberg scheme

- not directly calculate physical observables with perturbation theory
- systematically study effective potentials first (without 2PR contribution)
- solve the dynamical equation to get the physical observables (equivalent to recover the 2PR contributions)

Effective potentials between two heavy mesons

With Heavy Meson EFT, we study the systems made up of

- DD
- $D^* D$
- $D^* D^*$

Similar for $B^{(*)} B^{(*)}$ and corresponding anti-meson pair system.

We have not studied systems like $D\bar{D}$ because there exist annihilation effects.

Lagrangians

- Leading order vertice

  contact terms: $D^{(*)}D^{(*)}D^{(*)}D^{(*)}$ vertice

  $D^{(*)}D^{(*)}\pi$, $D^{(*)}D^{(*)}\pi\pi$ vertice

- Next-to-leading order vertice

  they absorb divergences, provide finite higher-order corrections

$$
\begin{aligned}
\mathcal{L}_{4H}^{(0)} &= D_a \,\mathrm{Tr}\,[H\gamma_\mu \bar{H}]\,\mathrm{Tr}\,[H\gamma^\mu \bar{H}] + D_b \,\mathrm{Tr}\,[H\gamma_\mu\gamma_5 \bar{H}]\,\mathrm{Tr}\,[H\gamma^\mu\gamma_5 \bar{H}] \\
&\quad + E_a \,\mathrm{Tr}\,[H\gamma_\mu \lambda^a \bar{H}]\,\mathrm{Tr}\,[H\gamma^\mu \lambda_a \bar{H}] + E_b \,\mathrm{Tr}\,[H\gamma_\mu\gamma_5\lambda^a \bar{H}]\,\mathrm{Tr}\,[H\gamma^\mu\gamma_5\lambda_a \bar{H}], \\
\mathcal{L}_{H\phi}^{(1)} &= -\langle (iv\cdot\partial H)\bar{H}\rangle - \langle Hv\cdot\Gamma\bar{H}\rangle + g\langle H\not{u}\gamma_5\bar{H}\rangle - \frac{1}{8}\Delta\langle H\sigma^{\mu\nu}\bar{H}\sigma_{\mu\nu}\rangle,
\end{aligned}
$$

Lagrangians

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$$
\begin{aligned}
\mathcal{L}_{4H}^{(2)} \quad = \quad & D_a^h \,\mathrm{Tr}\,[H\gamma_\mu \bar{H}]\,\mathrm{Tr}\,[H\gamma^\mu \bar{H}]\,\mathrm{Tr}\,(\chi_+) + \ldots \\
& + D_a^d \,\mathrm{Tr}\,[H\gamma_\mu \tilde{\chi}_+ \bar{H}]\,\mathrm{Tr}\,[H\gamma^\mu \bar{H}] + \ldots \\
& + D_1^q \,\mathrm{Tr}\,[(D^\mu H)\gamma_\mu\gamma_5(D^\nu \bar{H})]\,\mathrm{Tr}\,[H\gamma_\nu\gamma_5 \bar{H}] + \ldots
\end{aligned}
$$

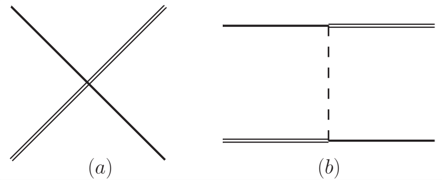
Diagrams

- Leading order

  contact, one-pion exchange

- Next-to-leading order

  two-pion exchange, renormalization to $D^{(*)}D^{(*)}\pi$ coupling, loop corrections to contact term, tree diagrams with NL vertice



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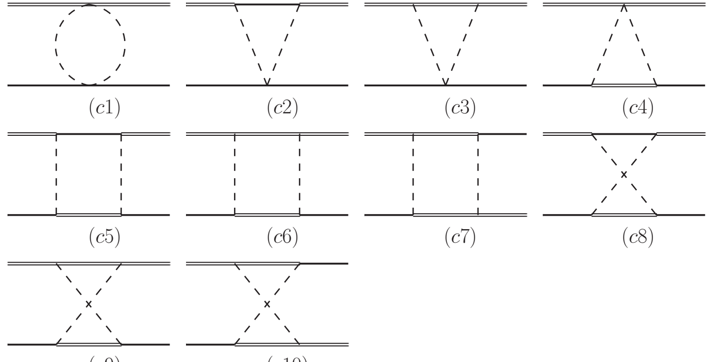

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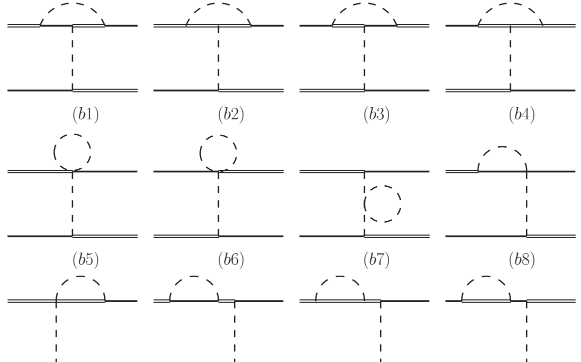

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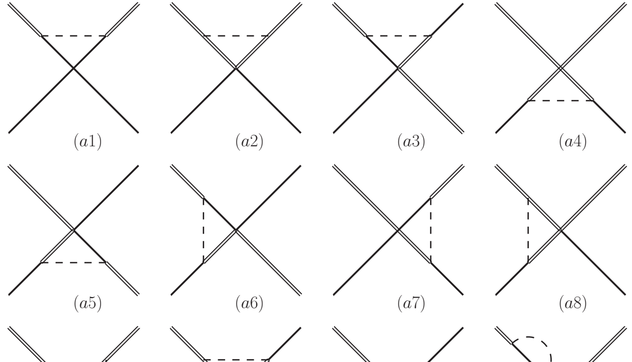

Regularization and renormalization

We calculate diagrams with dimension regularization and modified minimal subtraction scheme.

We have checked that the potentials are finite after the renormalization of the wavefunctions and vertice.

Determination of low-energy constants

- fit to experimental data
- first principle of QCD
- fit to data of Lattice QCD
- phenomenological models

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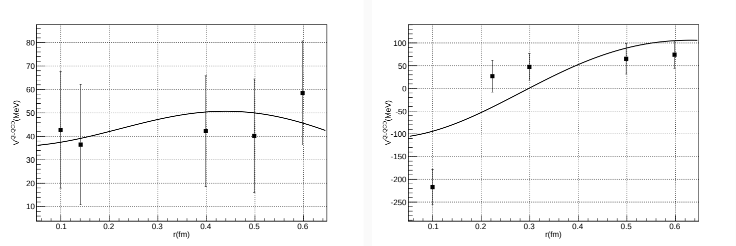

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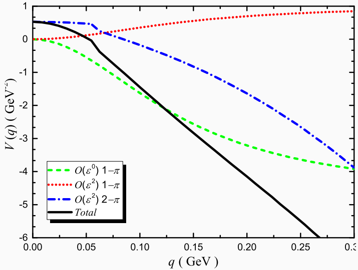
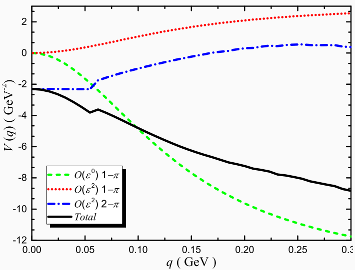
Effective potentials in momentum space



$DD^* : I = 1$



$DD^* : I = 0$

Possible molecular states

Search for new states

- Potentials→ partial waves, dynamical equation (momentum space)

  → T matrices → poles

- Potentials→ Fourier transform, dynamical equation (coordinate space)

  → eigenvalues of bound states for different partial waves

Taking DD^* as an example

- $I = 0$: bound state with around $E = 21$ MeV.

  $I = 1$: no bound state.

- Comparison with one-boson-exchange model

  ρ contribution is covered not only by the two-pion-exchange part but also by contact terms. [2]

[2] Similar results as those in Phys. Rev. D 88, 114008 (2013).

$\bar{B}^{(*)}\bar{B}^{(*)}$ systems

We use similar approaches to study the system of $\bar{B}^{(*)}\bar{B}^{(*)}$ in S wave

- $\bar{B}\bar{B}$: $I(J^P) = 1(0^+)$
- $\bar{B}\bar{B}^*$: $I(J^P) = 1(1^+)$, $I(J^P) = 0(1^+)$
- $\bar{B}^*\bar{B}^*$: $I(J^P) = 1(0^+)$, $I(J^P) = 1(2^+)$, $I(J^P) = 0(1^+)$

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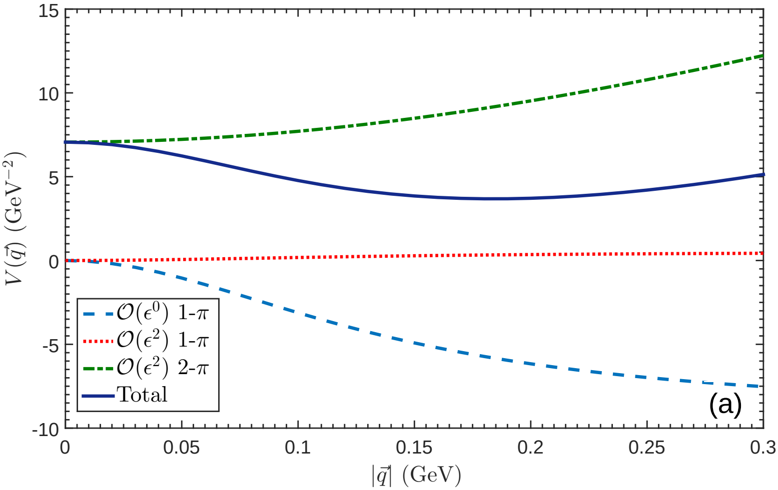
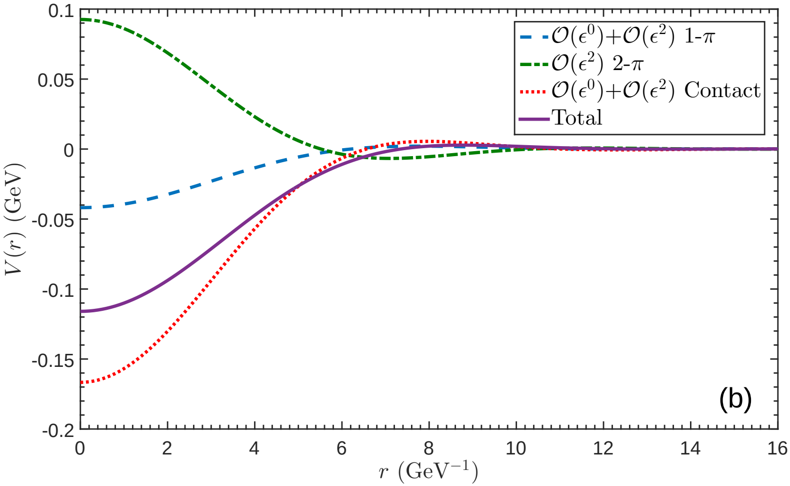
Example:

potentials for $\bar{B}^*\bar{B}^*$ with $I(J^P) = 0(1^+)$ in momentum space



Example:
potentials for $\bar{B}^*\bar{B}^*$ with $I(J^P) = 0(1^+)$ in coordinate space



Results for $\bar{B}^{(*)}\bar{B}^{(*)}$ systems

we find two bound states in the channels of $0(1^+)$ $\bar{B}\bar{B}^*$ and $\bar{B}^*\bar{B}^*$

- binding energies: $\Delta E_{\bar{B}\bar{B}^*} \simeq -12.6^{+9.2}_{-12.9}$ MeV, $\Delta E_{\bar{B}^*\bar{B}^*} \simeq -23.8^{+16.3}_{-21.5}$ MeV

  masses: $m_{\bar{B}\bar{B}^*} \simeq 10591.4^{+9.2}_{-12.9}$ MeV, $\quad m_{\bar{B}^*\bar{B}^*} \simeq 10625.5^{+16.3}_{-21.5}$ MeV
- strong decays is forbidden because of phase space

  they can be searched in $\bar{B}\bar{B}\gamma$ or $\bar{B}\bar{B}\gamma\gamma$

uncertainty of low-energy constants

Table 1: The binding energies of $0(1^+)$ $\bar{B}\bar{B}^*$ and $\bar{B}^*\bar{B}^*$ states obtained with different strategies in units of MeV.

Binding energy	No $\mathcal{O}(\epsilon^2)$ LECs	Strategy A	Strategy B
$\Delta E_{\bar{B}\bar{B}^*}$	$-12.6^{+9.2}_{-12.9}$	$-10.4^{+7.2}_{-9.7}$	$-15.9^{+9.7}_{-12.7}$
$\Delta E_{\bar{B}^*\bar{B}^*}$	$-23.8^{+16.3}_{-21.5}$	$-20.1^{+14.5}_{-20.0}$	$-28.2^{+18.6}_{-23.6}$

Summary

We have studied the potentials upto one-loop level between two heavy mesons within chiral perturbation theory.

By solving the Schrodinger equations, we found some bound states in some channels.

Thanks!

Thanks!

this report is mainly based on the following articles

- Phys.Rev. D99 (2019) no.3, 036007
- Phys.Rev. D99 (2019) no.1, 014027
- Phys.Rev. D89 (2014) no.7, 074015