Hidden charm pentaquark states and $\Sigma_c\bar{D}^{(*)}$ interaction in ChPT

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Based on arXiv:1905.07742 and work in preparation

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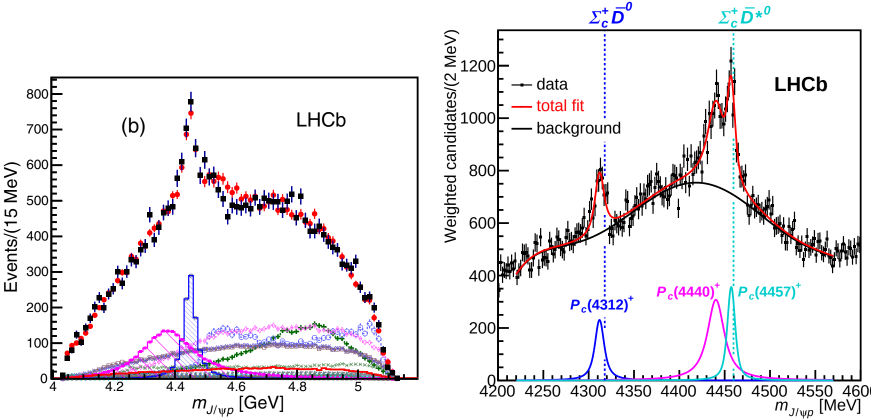
Contents

Introduction

P_c states in LHCb

- In 2015, $\Lambda_b \to J/\psi p K$, $P_c(4380)$ and $P_c(4450)$
- Recently, $P_c(4450) \Rightarrow P_c(4440) + P_c(4457)$; A new state $P_c(4312)$ with 7.3σ; $I = 1/2$?



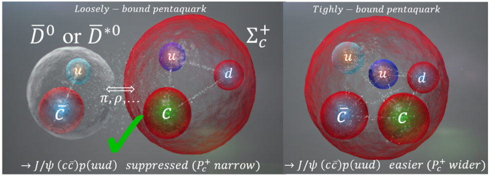
Phys.Rev.Lett. 115 (2015) 072001; arXiv:1904.03947;

Compact or molecular states ?

- Compact pentaquark states: tightly bounded states
- Molecular states: loosely bound states of two color singlet hadrons
- The three P_c states under the thresholds 9 MeV, 5 MeV and 22 MeV
- Three P_c states are the good candidates of molecular states
- Our work

  ⇒Obtain the $\Sigma_c\bar{D}^{(*)}$ potential in ChPT

  ⇒Solve the Schrödinger Eq.



arXiv:1904.03947; arXiv:1903.11013

Chiral perturbation theory

- QCD Lagrangian

$$\mathcal{L}_{QCD} = \sum_f \bar{q}_f (i\not{D} - \mathcal{M} q_f) - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a}$$
$$f = (u, d, s, c, b, t),$$
$$\mathcal{M} = diag(m_u, m_d, m_s, m_c, m_b, m_t)$$

S.Weinberg

- two approximate symmetry: chiral symmetry and heavy quark symmetry

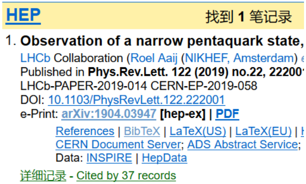
$$m_u, m_d, m_s \ll 1\text{GeV}, \quad m_c, m_b \gg \Lambda_{QCD} \tag{1}$$

- Chiral perturbation theory (ChPT) and heavy quark effective theory (HQET)
- $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \to \mathrm{SU}(3)_V \quad \Rightarrow$ 8 Goldstone bosons
- Quark masses break the chiral symmetry explicitly: $m_\pi^2 \sim m_q$
- Freedom: Goldstone bosons and matter fields, e.g. N, D and Σ_c
- Expansion $\epsilon/\Lambda_\chi, \quad \Lambda_\chi \approx 4\pi F_\pi \approx m_\rho$

  $\epsilon : m_\pi$, momentum of pion and residue momentum of matter fields

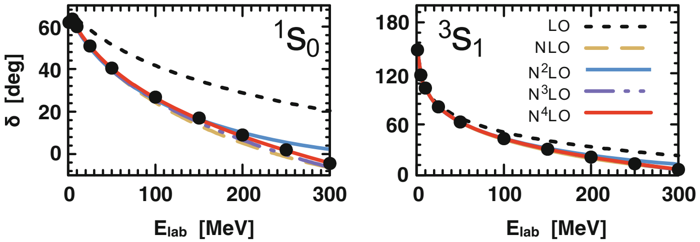
Why Chiral perturbation theory (ChPT)?

- Effective theory, model independence
- Systematically expansion, controllable and estimable error
- Loop diagrams
- Lattice QCD: chiral extrapolation


HEP 找到 1 笔记录

1. **Observation of a narrow pentaquark state,**
LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam)
Published in **Phys.Rev.Lett. 122 (2019) no.22, 22200**
LHCb-PAPER-2019-014 CERN-EP-2019-058
DOI: 10.1103/PhysRevLett.122.222001
e-Print: arXiv:1904.03947 **[hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) |
CERN Document Server; ADS Abstract Service;
Data: INSPIRE | HepData
详细记录 - Cited by 37 records

- Modern theory of nucleon force Phys. Rept. 503, 1 (2011).; Rev. Mod. Phys. 81, 1773 (2009).



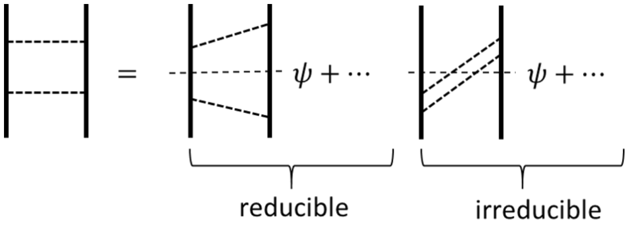
Lect.Notes Phys. 957 (2019) 1-396

$\Sigma_c \bar{D}^{(*)}$ interaction in ChPT

Weinberg's formalism

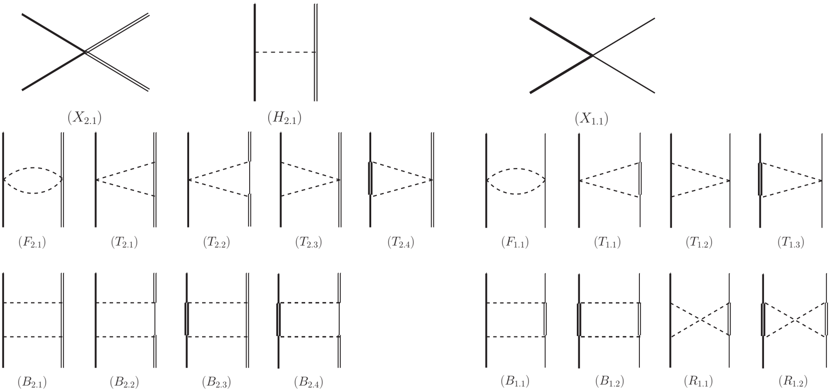
- Enhanced by pinch singularity, two nucleon on-shell, power count fails
- Time-ordered perturbation theory

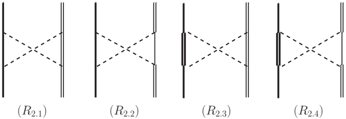
$$Amp = \langle NN|H_I|NN\rangle + \sum_\psi \frac{\langle NN|H_I|\psi\rangle\langle|H_I|NN\rangle}{E_{NN} - E_\psi} \tag{2}$$



- Only include the two particle irreducible (2PIR) graphs in potential
- Potential as the kernel of Lippmann-Schwinger Eq. or Schrödinger Eq.
- The tree level one-pion exchange diagrams would be iterated to generate the 2PR contributions automatically

Feynman diagrams of $\Sigma_c\bar{D}^{(*)}$ to NLO



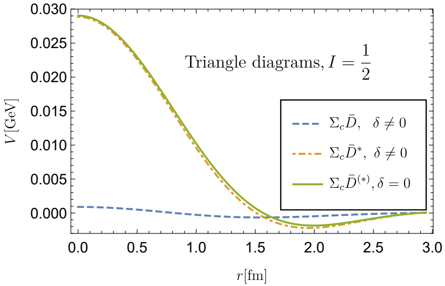


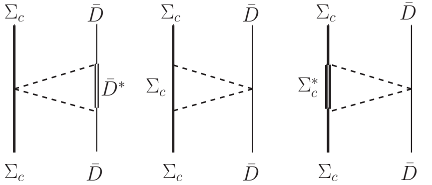
- The doublets (Σ_c, Σ_c^*) and $(\bar{D}, \bar{D}^*)$ in heavy quark symmetry (HQS)

- All intermediate states, keep mass splitting, HQS violation
- Unknown low energy constants (LECs): contact terms

Heavy quark symmetry: violation

- $\Lambda_{QCD}/m_c \simeq 0.2$, the HQS violation is sizable
- HQS with guidance for compact systems, (Σ_c^*, Σ_c) (2518,2454) MeV
- HQS violation effect is more significant for the $\Sigma_c\bar{D}$ system than $\Sigma_c\bar{D}^*$





- Minimum of potential with the loosely bound state: -0.06-0.15 GeV.

It may be misleading to adopt the HQS to calculate the molecular states.

Heavy quark symmetry: quark model

- The heavy dof.: spectators; light dof.: interactions

$$V_{\mathrm{quark-level}} = \left[V_a + \tilde{V}_a \boldsymbol{l}_1 \cdot \boldsymbol{l}_2\right] + \left[\frac{V_c}{m_c}\boldsymbol{l}_1 \cdot \boldsymbol{h}_2 + \frac{V_d}{m_c}\boldsymbol{l}_2 \cdot \boldsymbol{h}_1 + \frac{V_e}{m_c^2}\boldsymbol{h}_1 \cdot \boldsymbol{h}_2\right],$$

$$V_{\Sigma_c \bar{D}} = V_1, \quad V_{\Sigma_c \bar{D}^*} = V_2 + \tilde{V}_2 \boldsymbol{S}_1 \cdot \boldsymbol{S}_2,$$
$$V_{\Sigma_c^* \bar{D}} = V_3, \quad V_{\Sigma_c^* \bar{D}^*} = V_4 + \tilde{V}_4 \boldsymbol{S}_1 \cdot \boldsymbol{S}_2. \quad (3)$$

- Ignoring mass splittings in loops, the HQS manifests itself

  M. Z. Liu, et.al arXiv:1903.11560 [hep-ph].

- In QM, the HQS violation vanishes for $\Sigma_c \bar{D}$ system

$$\langle \boldsymbol{l_1} \cdot \boldsymbol{h}_2 \rangle = \langle \boldsymbol{l}_2 \cdot \boldsymbol{h}_1 \rangle = \langle \boldsymbol{h}_1 \cdot \boldsymbol{h}_2 \rangle = 0 \quad (4)$$

- QM: analytical terms; Loop diagrams: nonanalytical structures
- Another eg. enhancement of isospin violation in loop diagrams

  F. K. Guo, H. J. Jing, U. G. Meißner and S. Sakai, Phys. Rev. D 99, no. 9, 091501 (2019).

Loops bring novel effects.

Numerical results

Contact terms

$$\mathcal{V}^{X_{1.1}}_{\Sigma_c\bar{D}} = -D_1 - \tilde{D}_1(2\boldsymbol{I}_1\cdot\boldsymbol{I}_2), \tag{5}$$

$$\mathcal{V}^{X_{2.1}}_{\Sigma_c\bar{D}^*} = -\left(D_1 + \frac{1}{3}D_2\boldsymbol{\sigma}\cdot\boldsymbol{T}\right) - \left(\tilde{D}_1 + \frac{1}{3}\tilde{D}_2\boldsymbol{\sigma}\cdot\boldsymbol{T}\right)(2\boldsymbol{I}_1\cdot\boldsymbol{I}_2),$$

- Package heavy mesons exchanged interaction like ρ and ω
- Renormalization

  $\Rightarrow$ absorb the divergence in the loops

  $\Rightarrow$ remove the scale dependence.
- Contact or pion-exchange? depend on regularization schemes

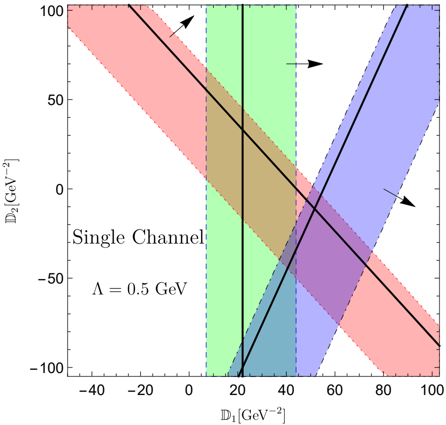
  Phys. Rev. D91, 034002 (2015).
- Depend on chiral truncation order; types of regulator and values of cutoff

  Phys. Rept. 503, 1 (2011).
- Dimensional regularization, $\overline{MS}$-scheme, $\Lambda_\chi = 1.0$ GeV; Gaussian regulator Λ=0.5 GeV

$$V(r) = \frac{1}{(2\pi)^3}\int d^3\boldsymbol{q}\, e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\mathcal{V}(\boldsymbol{q})\mathcal{F}(\boldsymbol{q}), \quad \mathcal{F}(\boldsymbol{q}) = \exp(-\boldsymbol{q}^{2n}/\Lambda^{2n}) \tag{6}$$

Scenario II: single channel

For $I = 1/2, \quad \mathcal{V}^{X_{1.1}}_{\Sigma_c \bar{D}} = -\mathbb{D}_1, \quad \mathcal{V}^{X_{2.1}}_{\Sigma_c^* D} = -\left(\mathbb{D}_1 + \frac{1}{3}\mathbb{D}_2 \boldsymbol{\sigma} \cdot \boldsymbol{T}\right)$ (7)

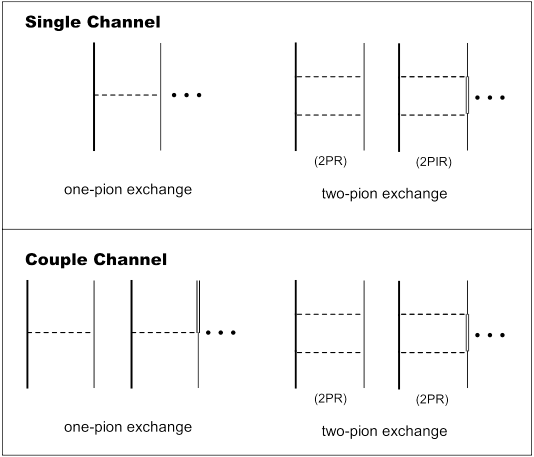


- There is a very SMALL region where three states coexist as the molecular states
- Restricting the binding energy in exp., it is hard to reproduce three states as molecules simultaneously

$$\langle \boldsymbol{\sigma} \cdot \boldsymbol{T} \rangle = \begin{cases} 2 & J = 1/2 \\ -1 & J = 3/2 \end{cases}$$

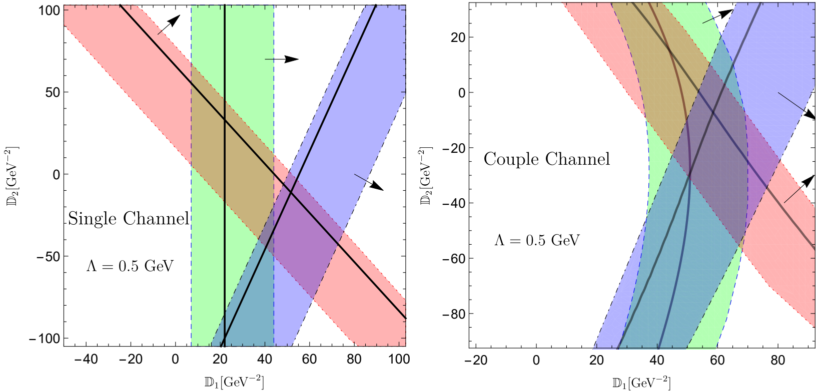
Spin-Spin interaction is an obstacle.

Scenario III: couple channel



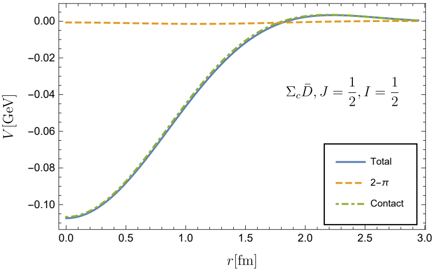
Channel	1	2	3	4
$J=\frac{1}{2}$	$\boldsymbol{\Sigma_c\bar{D}}$	$\boldsymbol{\Sigma_c\bar{D}^*}$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c^*\bar{D}$
$J=\frac{3}{2}$	$\boldsymbol{\Sigma_c\bar{D}^*}$	$\Sigma_c^*\bar{D}$	$\Sigma_c^*\bar{D}^*$	

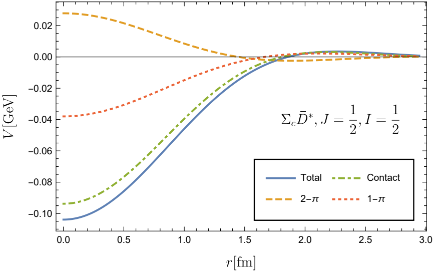
Scenario III: couple channel

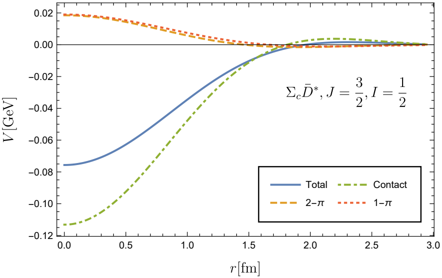


S-III	Exp.(MeV)	Mass(MeV)	RMS(fm)	$P_1(\%)$	$P_2(\%)$	$P_3(\%)$
$P_c(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	4305	1.21	99.4	0.5	0.1
$P_c(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	4446	1.22	1.0	98.0	0.9
$P_c(4457)$	$4457.3 \pm 1.3^{+0.6}_{-4.1}$	4458	1.28	96.8	2.5	0.7

Scenario III: couple channel







- Reproduce the three P_c states as molecular states simultaneously
- Attraction mainly stems from the contact interaction
- The couple channel effect is important
- Minimum of potential

Summary and Outlook

Summary and Outlook

- $\Sigma_c\bar{D}^{(*)}$ potential in ChPT to NLO

  $\Rightarrow$ contact, $1-\pi$, $2-\pi$

  $\Rightarrow$ HQS breaking effect, IMPORTANT !

  $\Rightarrow$ Couple channel effect

  $\Rightarrow$ Reproduce three P_c states simultaneously as molecular states

- Outlook

  $\Rightarrow$ Lattice QCD simulation on $\Sigma_c\bar{D}^{(*)}$ potential is called for

  $\Rightarrow$ Chiral extrapolation

  $\Rightarrow$ Three P_c states are HQSS partner states, more HQSS and HQFS partner states in molecular scheme? 1903.11560; 1904.01296...

  $\Rightarrow$ HQS breaking effect? $\Sigma_c^*\bar{D}^{(*)}$ and $\Sigma_c^{(*)}D^{(*)}$ system (on-going)

  $\Rightarrow$ Test the ChPT in the charm sector

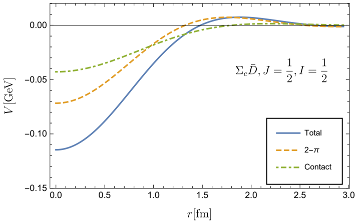
  for chiral dynamics, $c(qq)_{s=1}^{I=1} = \Sigma_c + \Sigma_c^*$

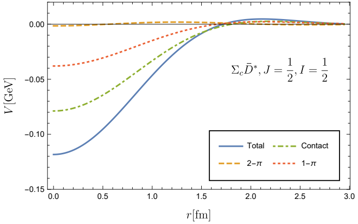
Thanks for your attention!

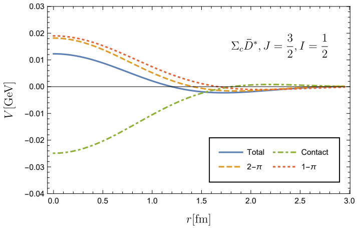
Scenario I: model

$$\mathcal{L}_{\text{quark}} = -\frac{1}{2}c_s\bar{q}q\bar{q}q - \frac{1}{2}c_t(\bar{q}\boldsymbol{\sigma}q)\cdot(\bar{q}\boldsymbol{\sigma}q), \tag{8}$$

$$\text{For } I=1/2, \quad \mathcal{V}^{X_{1.1}}_{\Sigma_c\bar{D}} = -\mathbb{D}_1, \quad \mathcal{V}^{X_{2.1}}_{\Sigma_c^*D} = -\left(\mathbb{D}_1 + \frac{1}{3}\mathbb{D}_2\boldsymbol{\sigma}\cdot\boldsymbol{T}\right) \tag{9}$$





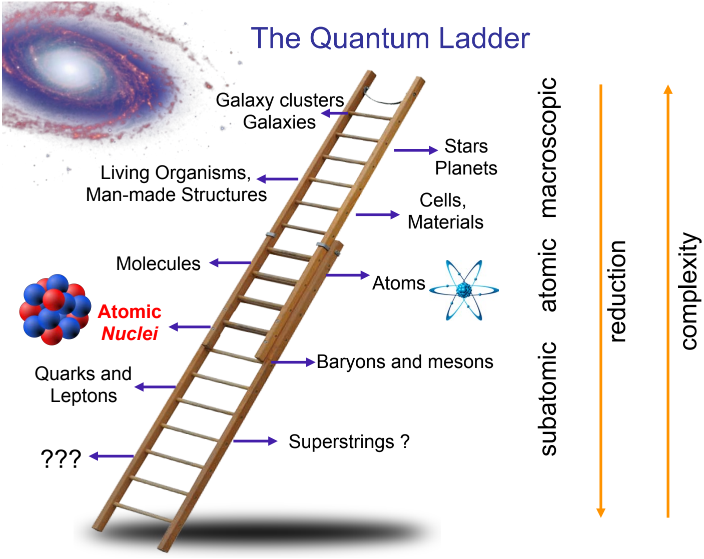


$[\Sigma_c\bar{D}]^{I=1/2}_{J=1/2}$: $E = -9.21$ MeV

$[\Sigma_c\bar{D}^*]^{I=1/2}_{J=1/2}$: $E = -18.93$ MeV

$[\Sigma_c\bar{D}^*]^{I=1/2}_{J=3/2}$: No bound states

Physics at the different scales never talk to each other



Effective field theory

- An effective field theory (EFT) is a low-energy approximation to some underlying, more fundamental theory.
  $\Rightarrow$ Large energy scale Λ
- The EFT Lagrangian: the most general Lagrangian with SYMMETRIES of the underlying theory.
  $\Rightarrow$ Low-energy constants (LECs)
- Expand the theory in powers of p/Λ
  $\Rightarrow$ Power counting law

$$\mathcal{M} = \sum_{\nu} \left(\frac{Q}{\Lambda}\right)^{\nu} f(Q/\mu, g_i) \qquad (10)$$

- Calculate and renormalize order-by-order
- Controllable and estimable error
- Prediction: experiment data as input

S.Weinberg

Go for the messes - that's where the action is. Physica A96 (1979) 327-340

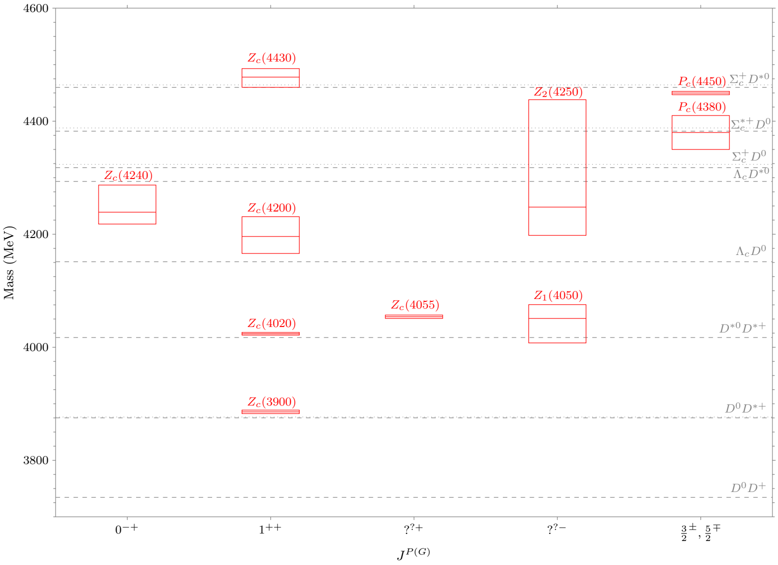
Contact terms of NN

C_S	C_T	Λ, channel	C_S	C_T	Λ, channel
Ordonez:1995rz			Epelbaum:2004fk		
112	13.5	$I=0$	-107.57	-11.64	$\{0.45, 0.5\}, np$
-26.6	-68.9	$I=1$	88.61	53.20	$\{0.6, 0.5\}, np$
Machleidt:2011zz			-121.08	-6.17	$\{0.45, 0.7\}, np$
-100.28	5.61	$\Lambda=0.5, np$	33.70	25.66	$\{0.6, 0.7\}, np$
-99.55	7.07	$\Lambda=0.6, np$			

$$\mathcal{L}_{NN}^{(0)} = -\frac{1}{2}C_S\bar{N}N\bar{N}N - \frac{1}{2}C_T\bar{N}\boldsymbol{\sigma}N\cdot\bar{N}\boldsymbol{\sigma}N, \tag{11}$$

$$\mathcal{V}_{NN} = C_S + C_T\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}. \tag{12}$$

XYZ states



4600
4400
4200
4000
3800
Mass (MeV)
$Z_c(4430)$
$Z_c(4240)$
$Z_c(4200)$
$Z_c(4020)$
$Z_c(3900)$
$Z_c(4055)$
$Z_2(4250)$
$Z_1(4050)$
$P_c(4450)$
$P_c(4380)$
$\Sigma_c^+ D^{*0}$
$\Sigma_c^{*+} D^0$
$\Sigma_c^+ D^0$
$\Lambda_c D^{*0}$
$\Lambda_c D^0$
$D^{*0} D^{*+}$
$D^0 D^{*+}$
$D^0 D^+$
0^{-+}
1^{++}
$?^{?+}$
$?^{?-}$
$\frac{3}{2}^\pm, \frac{5}{2}^\mp$
$J^{P(G)}$

Spontaneous symmetry breaking

- Chiral symmetry: Conservation charge Q_A^a

$$H_{QCD}^0|i,+\rangle = E_i|i,+\rangle, \quad P|i,+\rangle = +|i,+\rangle, \quad |\phi\rangle = Q_A^a|i,+\rangle \tag{13}$$

$$H_{QCD}^0|\phi\rangle = E_i|\phi\rangle, \quad P|\phi\rangle = -|\phi\rangle \tag{14}$$

- Degenerate states with different parity? $\rightarrow$ SSB
- Goldstone's theorem: spontaneous breaking of continuous global symmetries implies the existence of massless particles.
- NO. of Goldstone boson $= n_G - n_H$
  G: symmetry group of Lagrangian;
  H: the subgroup leaves the groud state invariant after SSB
- SU$(3)_L \times$ SU(3)$_R \rightarrow$ SU(3)$_V$ $\quad \Rightarrow$ 8 Goldstone bosons
- Quark masses break the chiral symmetry explicitly: $m_\pi^2 \sim m_q$

pinch singularities

$$V \sim \int \frac{d^d\lambda^{4-d}}{(2\pi)^d} \frac{1}{-v\cdot l + i\epsilon} \frac{1}{v\cdot l + i\epsilon} \frac{1}{l^2 - m_1^2 + i\epsilon} \frac{1}{(l+q)^2 - m_2^2 + i\epsilon} \quad (15)$$

$$\sim \int \frac{d^d\lambda^{4-d}}{(2\pi)^d} \frac{1}{-l^0 + i\epsilon} \frac{1}{l^0 + i\epsilon} \frac{1}{l^{02} - \omega_1^2 + i\epsilon} \frac{1}{l^{02} - \omega_2^2 + i\epsilon} \quad (16)$$

$$\frac{1}{-v\cdot l + i\epsilon} \frac{1}{v\cdot l + i\epsilon} \to \frac{1}{-v\cdot l - \frac{\boldsymbol{l}^2}{2M_1} + i\epsilon} \frac{1}{v\cdot l - \frac{\boldsymbol{l}^2}{2M_2} + i\epsilon} \quad (17)$$

$$\int dl^0 \frac{f(l^0)}{-l^0 - \frac{\boldsymbol{l}^2}{2M_1} + i\epsilon} \frac{1}{l^0 - \frac{\boldsymbol{l}^2}{2M_2} + i\epsilon} \quad (18)$$

$$\sim \frac{f(\frac{\boldsymbol{l}^2}{2M_2})}{-\frac{\boldsymbol{l}^2}{2M_2} - \frac{\boldsymbol{l}^2}{2M_1}} \sim f\frac{M}{\boldsymbol{l}^2} \quad (19)$$

power counting: $\frac{1}{l}$, our calculation $\frac{M}{\boldsymbol{l}^2}$

The Lagrangians

$$\Sigma_c = \begin{pmatrix} \Sigma_c^{++} & \frac{\Sigma_c^{+}}{\sqrt{2}} \\ \frac{\Sigma_c^{+}}{\sqrt{2}} & \Sigma_c^{0} \end{pmatrix}, \; \Sigma_c^{*\mu} = \begin{pmatrix} \Sigma_c^{*++} & \frac{\Sigma_c^{*+}}{\sqrt{2}} \\ \frac{\Sigma_c^{*+}}{\sqrt{2}} & \Sigma_c^{*0} \end{pmatrix}^{\mu}, \qquad (20)$$

$$\tilde{P} = \begin{pmatrix} \bar{D}^{0} \\ \bar{D}^{-} \end{pmatrix}, \quad \tilde{P}^{*\mu} = \begin{pmatrix} \bar{D}^{*0} \\ \bar{D}^{*-} \end{pmatrix}, \qquad (21)$$

$$\psi^{\mu} = \mathcal{B}^{*\mu} - \sqrt{\tfrac{1}{3}}(\gamma^{\mu} + v^{\mu})\gamma^{5}\mathcal{B},$$

$$\tilde{H} = (\tilde{P}^{*}_{\mu}\gamma^{\mu} + i\tilde{P}\gamma_{5})\tfrac{1-\not{v}}{2} \qquad (22)$$

$$\mathcal{L}^{(0)}_{\Sigma_c\phi} = -\mathrm{Tr}[\bar{\psi}^{\mu} iv\cdot D\psi_{\mu}] + ig_a\epsilon_{\mu\nu\rho\sigma}\mathrm{Tr}[\bar{\psi}^{\mu}u^{\rho}v^{\sigma}\psi^{\nu}] + i\frac{\delta_a}{2}\mathrm{Tr}[\bar{\psi}^{\mu}\sigma_{\mu\nu}\psi^{\nu}].$$

$$\mathcal{L}^{(0)}_{\bar{D}\phi} = -i\langle\bar{\tilde{H}} v\cdot D\tilde{H}\rangle + g_b\langle\bar{\tilde{H}} u_{\mu}\gamma^{\mu}\gamma_5\tilde{H}\rangle - \frac{\delta_b}{8}\langle\bar{\tilde{H}}\sigma^{\mu\nu}\tilde{H}\sigma_{\mu\nu}\rangle, \qquad (23)$$

Building Block

- building block

	$D_\mu\psi$	ψ	$\bar\psi$	$\chi_\pm$	$f^\pm_{\mu\nu}$	u_μ	Γ_μ
CH	$KD_\mu\psi$	$K\psi$	$\bar\psi K^\dagger$	$K\chi_\pm K^\dagger$	$Kf^\pm_{\mu\nu}K^\dagger$	$Ku_\mu K^\dagger$	$K\Gamma^\mu K^\dagger - \partial^\mu KK^\dagger$
P	$\gamma^0 D^\mu\psi$	$\gamma^0\psi$	$\bar\psi\gamma^0$	$\pm\chi_\pm$	$\pm f^{\pm\mu\nu}$	$-u^\mu$	Γ^μ
C	$CD'^T_\mu\bar\psi^T$	$C\bar\psi^T$	$\psi^T C$	$\chi^T_\pm$	$\mp(f^\pm_{\mu\nu})$	$(u_\mu)^T$	$-(\Gamma_\mu)^T$

$$F^\pm_{\mu\nu} = u^\dagger F^R_{\mu\nu}u \pm uF^L_{\mu\nu}u^\dagger,$$

$$F^R_{\mu\nu} = \partial_\mu r_\nu - \partial_\nu r_\mu - i[r_\mu, r_\nu], \quad (24)$$

$$F^L_{\mu\nu} = \partial_\mu l_\nu - \partial_\nu l_\mu - i[l_\mu, l_\nu]. \quad (25)$$

$$\Gamma_\mu = \frac{1}{2}\left[u^\dagger(\partial_\mu - ir_\mu)u + u(\partial_\mu - il_\mu)u^\dagger\right], \quad (26)$$

$$u_\mu \equiv \frac{1}{2}i\left[u^\dagger(\partial_\mu - ir_\mu)u - u(\partial_\mu - il_\mu)u^\dagger\right], \quad (27)$$

$$\chi = 2B_0(s+ip), \qquad \chi_\pm = u^\dagger\chi u^\dagger \pm u\chi^\dagger u \quad (28)$$

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- Prediction: experiment data as input

Chiral Symmetry

- $m_u, m_d, m_s \ll 1\text{GeV} \leq m_c, m_b, m_t$; Chiral limit: $m_u, m_d, m_s = 0$
- The QCD Lagrangian in the chiral limit can then be written as

$$\mathcal{L}^0_{QCD} = \sum_{l=u,d,s} (\bar{q}_{R,l} i \not{D} \, q_{R,l} + \bar{q}_{L,l} i \not{D} \, q_{L,l}) - \frac{1}{4} \mathcal{G}_{\mu\nu,a} \mathcal{G}^{\mu\nu}_a . \tag{29}$$

where $P_{R,L} = \frac{1}{2}(1 \pm \gamma_5)$

- Chiral symmetry $\text{SU(3)}_L \times \text{SU(3)}_R \times \text{U(1)}_L \times \text{U(1)}_R$

$$\begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix} \mapsto U_L \begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix} = \exp\left(-i \sum_{a=1}^{8} \Theta^L_a \frac{\lambda_a}{2}\right) e^{-i\Theta^L} \begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix},$$

$$\begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix} \mapsto U_R \begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix} = \exp\left(-i \sum_{a=1}^{8} \Theta^R_a \frac{\lambda_a}{2}\right) e^{-i\Theta^R} \begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix}, \tag{30}$$

Spontaneous symmetry breaking

- Goldstone's theorem: spontaneous breaking of continuous global symmetries implies the existence of massless particles.
- NO. of Goldstone boson $= n_G - n_H$
  G: symmetry group of Lagrangian;
  H: the subgroup leaves the groud state invariant after SSB
- $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \to \mathrm{SU}(3)_V \quad \Rightarrow$ 8 Goldstone bosons
- nonlinear realization of chiral symmetry

$$U(x) = \exp\left(i\frac{\phi(x)}{F_0}\right), \quad U \to RUL^\dagger, \tag{31}$$

$$\phi(x) = \sum_{a=1}^{8} \lambda_a \phi_a(x) \equiv \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}. \tag{32}$$

- Quark masses break the chiral symmetry explicitly: $m_\pi^2 \sim m_q$

Effective Lagrangian and Power-Counting Scheme

- The Lagrangian is organized as the NO. of derivatives of Goldstone bosons
- The chiral dimension D of given diagrams

$$\mathcal{M}(tp_i, t^2 m_q) = t^D \mathcal{M}(p_i, m_q), \tag{33}$$

$$D = 2 + 2N_L + \sum_{n=1}^{\infty} N_{2n}(2n-2), \tag{34}$$

- Λ_{CSB} scale: either $4\pi F_0$ or m_ρ
- The leading order Lagrangian

$$\mathcal{L}_2 = \frac{F_0^2}{4}\text{Tr}[\nabla_\mu U(\nabla^\mu U)^\dagger] + \frac{F_0^2}{4}\text{Tr}(\chi U^\dagger + U\chi^\dagger). \tag{35}$$

S. Weinberg, Physica A 96, 327 (1979).

J. Gasser and H. Leutwyler, Annals Phys. 158, 142 (1984).

J. Gasser and H. Leutwyler, Nucl. Phys. B 250, 465 (1985).

Heavy baryon formalism

- the baryon mass does not vanish in the chiral limit
  $\Rightarrow$ mess up the power counting
- the heavy and light freedom

$$p_\mu = M v_\mu + l_\mu \tag{36}$$

$$\Psi = e^{-iMv\cdot x}(H+h), \text{with } \not{v}H = H, \quad \not{v}h = -h \tag{37}$$

$$\begin{aligned} \mathcal{L} &= \bar{\Psi}(i\not{\partial} - M)\Psi \\ &= \bar{H}(iv\cdot\partial)H - \bar{h}(iv\cdot\partial + 2M)h + \bar{H}i\not{\partial}^{\perp}h + \bar{h}i\not{\partial}^{\perp}H \end{aligned} \tag{38}$$

- Integrate the heavy field h,

$$\mathcal{L} = \bar{H}(iv\cdot\partial)H + \mathcal{O}\left(\frac{1}{2M}\right) \tag{39}$$

E. E. Jenkins and A. V. Manohar, Phys. Lett. B 255, 558 (1991),

V. Bernard, N. Kaiser, J. Kambor and U. G. Meissner, Nucl. Phys. B 388, 315 (1992).

Heavy baryon formalism

- Power counting for diagrams with only one baryon line
  $D = 2L + 1 + \sum_{n=2}^{\infty}(n-2)N_n^M + \sum_{n=1}^{\infty}(n-1)N_n^B$
- The leading order Lagrangian

$$\mathcal{L}^{(1)} = \bar{\Psi}(i\not{D} - M_H)\Psi + \frac{\tilde{g}_A}{2}\bar{\Psi}\gamma^\mu\gamma_5 u_\mu \Psi \tag{40}$$

$$\mathcal{L}^{(1)} = \bar{H}(iv\cdot D)H + \tilde{g}_A \,\mathrm{Tr}\bar{H}S^\mu u_\mu H, \tag{41}$$

  where $S_\mu = \frac{i}{2}\gamma_5\sigma_{\mu\nu}v^\nu$ is the covariant spin-operator.
- In this work,

$$Q_B = \mathrm{diag}(2,1,1) \text{ and } Q_M = \mathrm{diag}(2/3,-1/3,-1/3)$$

$$r_\mu = l_\mu = -eQA_\mu; \qquad F_{\mu\nu}^{+} = -2eQF_{\mu\nu} + ...$$

- Traceless part and trace part: $\hat{A}$ and $\mathrm{Tr}(A)$