Chiral Doubling of Heavy Baryons from the Bound State Approach

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at チャームバリオンの構造と生成
(J-PARC, September 11, 2013)

Based on

・ M.H. and Y.L.Ma, Phys. Rev. D 87, 056007 (2013)

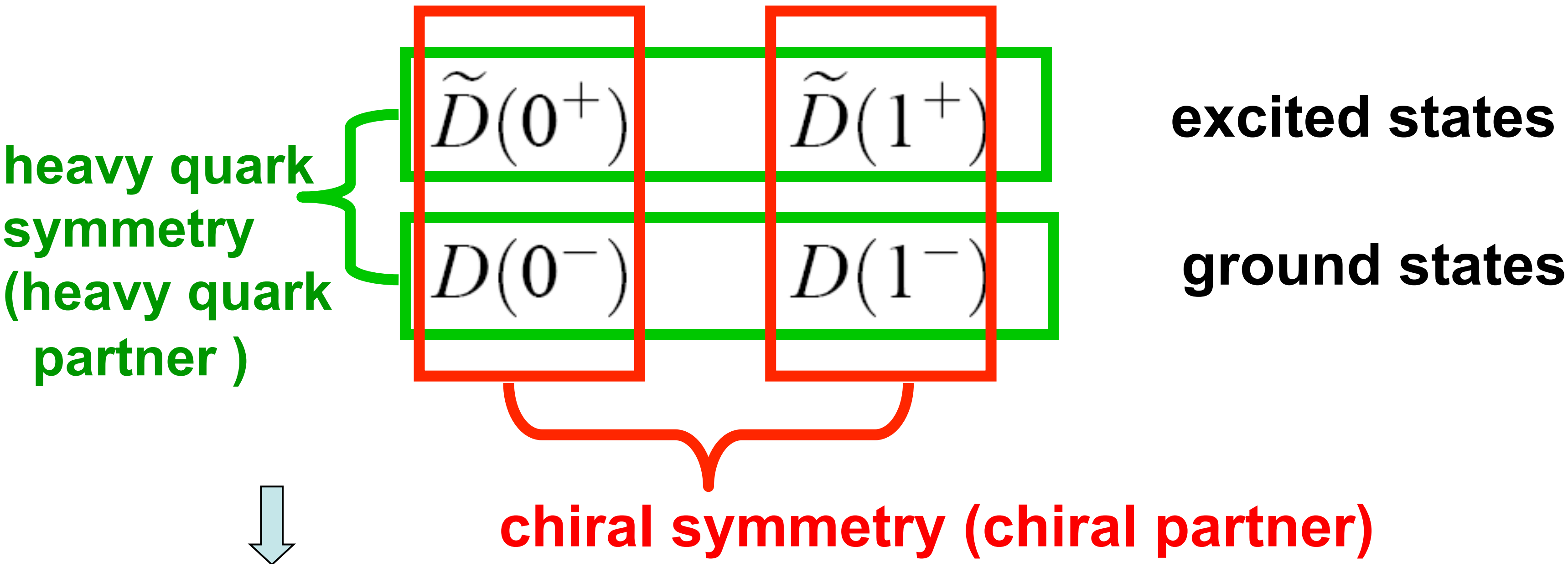
1. Introduction

Chiral partner structure

- Chiral symmetry breaking generates the mass splitting between chiral partners.
- examples :
  - N(940) left ⇔ N(940) right
    [N(940) ⇔ N*(1535)]
  - pi(130) ⇔ sigma(600)
    [pi(130) ⇔ rho(770)]
  - (D, D*) ⇔ (D_0*, D_1)

“chiral doubling”

M.A.Nowak, M.Rho and I.Zahed, PRD**48**, 4370 (1993)



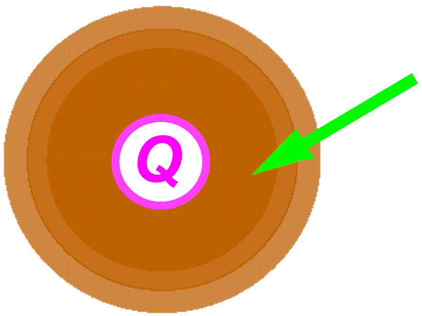
$$M(0^+) - M(0^-) \simeq M(1^+) - M(1^-) \sim M_{\text{constituent}}$$

$$M_{D^*_{sJ}(2317)} - M_{D_s^\pm} = 349.3 \pm 0.5\,\text{MeV}$$

$$\mathbf{M_{D(0+,1+)} - M_{D(0-,1-)} \sim 0.43\ GeV}$$

Chiral doubling seems to work.

☆ Heavy-Light Mesons ($Q\bar{q}$ type) Baryons (Qqq)



"Light-quark cloud" (Brown Muck)
・・・ made of light quarks and gluons

typical energy scale ～ Λ_{QCD}

◎ Heavy mesons ・・・ 3 or 3^{bar}, … of $SU(3)_l$

◎ Heavy baryons ・・・ 6, … of $SU(3)_l$

Flavor representations, which do not exist in the light quark sector, give a new clue to understand the hadron structure.

chiral doubling of heavy baryons

- ◆ In this show, I shall show main results of M.H. and Y.L.Ma, Phys. Rev. D 87, 056007 (2013).
- We studied the chiral partner structure of heavy baryons using the the bound state approach by binding the heavy-light mesons to the nucleon as the soliton in an effective Lagrangian for the pseudoscalar and vector mesons based on hidden local symmetry.
- We focus
  - the chiral partner to Λ_c ?
  - charmed pentaquark ?

Outline

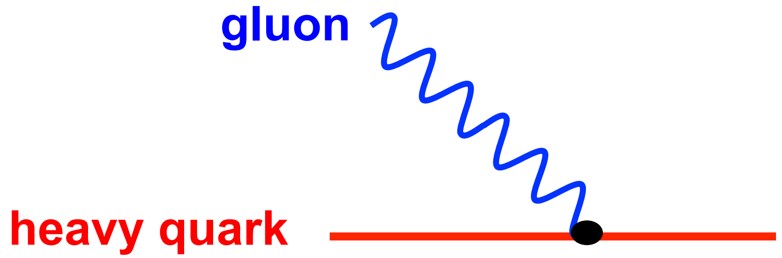
1. Introduction
2. A model for chiral doubling of heavy mesons with the HLS
3. Chiral doubling in heavy baryons
4. Summary

2. A MODEL FOR CHIURAL DOUBLING OF HEAVY MESONS WITH THE HLS

☆ Heavy quark symmetry

··· a symmetry of QCD at $M_Q \to \infty$ limit

◎ velocity super-selection rule



$$P_{\text{light}} \simeq \Lambda_{QCD}$$

$$P_{\text{heavy}} \simeq M_Q \cdot V$$

$$\delta V \simeq \frac{\Lambda_{\text{QCD}}}{M_Q} \xrightarrow[M_Q \to \infty]{} 0$$

The velocity of a heavy quark is not changed by the QCD interaction.

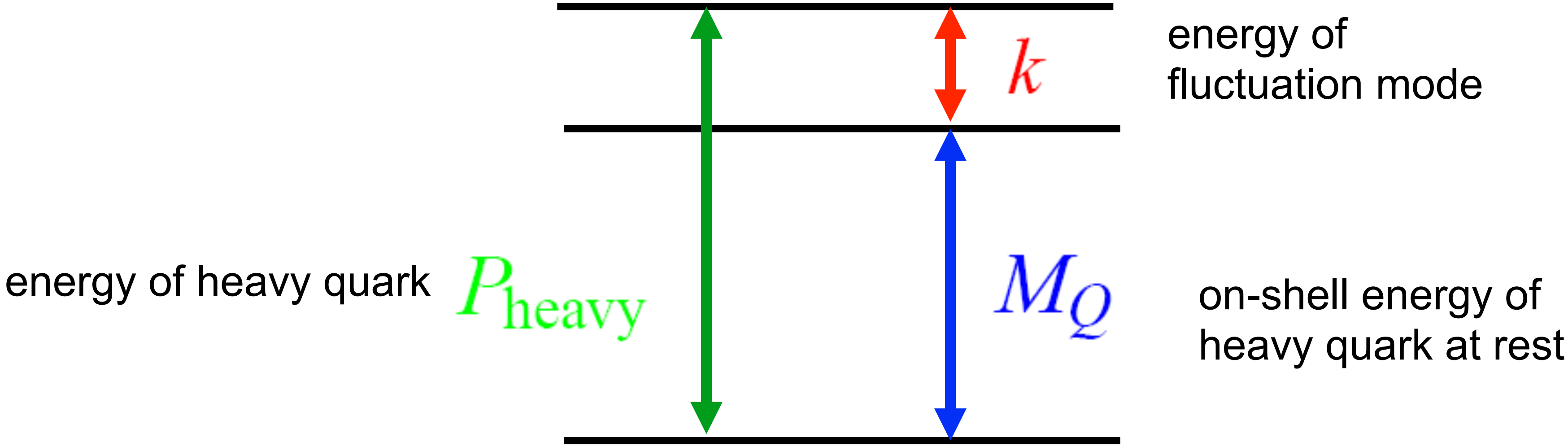
◎ Heavy quark number conservation

No pair production of heavy quarks by QCD interaction.

◎ SU(2) spin symmetry

QCD interaction cannot flip the spin of heavy quarks.

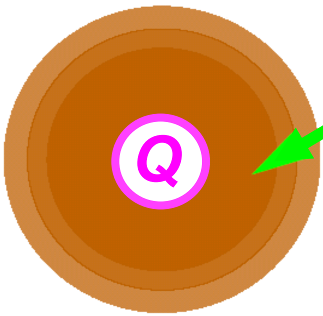
- **Fluctuation mode** around the On-shell Heavy Quark



$$P^{\mu}_{\rm heavy} = M_Q \cdot V^{\mu} + k^{\mu}$$

$$\frac{k^{\mu}}{M_Q} \simeq \frac{\Lambda_{\rm QCD}}{M_Q} \ll 1$$ ··· **Expansion parameter**

☆ Heavy-Light Mesons ($Q\bar{q}$ type)



"Light-quark cloud" (Brown Muck)

··· made of light quarks and gluons

typical energy scale ～ Λ_{QCD}

◎ spin of meson

$$\vec{J} = \vec{S}_Q + \vec{J}_l$$

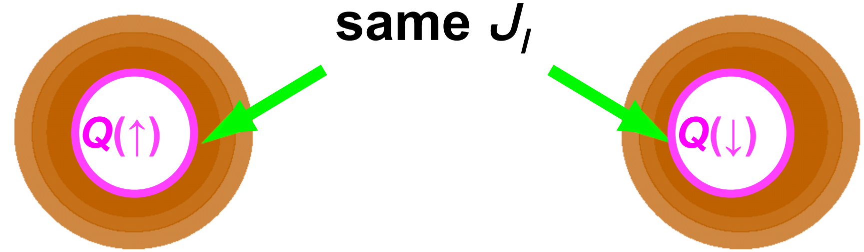
angular momentum carried by "Brown muck"

spin of heavy quark

・ $M_Q \to \infty$ limit

$$\left.\begin{array}{l}\left[\vec{S}_Q , H\right] = 0 \\ \left[\vec{J} , H\right] = 0\end{array}\right\} \Rightarrow \left[\vec{J}_l , H\right] = 0$$

same J_l



$J = J_l + \frac{1}{2}$ $\quad$ $J = J_l - \frac{1}{2}$

conservation of J_l

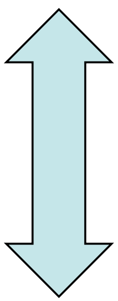
⇒ classification of hadrons by J_l

Heavy Meson Multiplet

··· degenerate masses

Heavy meson multiplets

- **Ground states** ・・・ $J_l = 1/2$; $J^P = (0^-, 1^-)$
  - Pseudoscalar meson D ; Vector meson D^*
  - $D = (D^0, D^+)$ $D^* = (D^{*0}, D^{*+})$



chiral partner

- **Excited states** ・・・ $J_l = 1/2$; $J^P = (0^+, 1^+)$
  - Scalar meson D_0^* ; Axial-vector meson D_1
  - $D_0^* = (D_0^{*0}, D_0^{*+})$ $D_1 = (D_1^0, D_1^+)$

Heavy meson effective field

☆ **Ground states** ··· $J_l = 1/2$; $J^P = (0^-, 1^-)$

Pseudoscalar meson ***D*** ; **Vector meson** ***D****

$D = (D^0, D^+)$ $D^* = (D^{*0}, D^{*+})$

· **Bi-spinor field** $H \sim Q\bar{\Psi}$; Ψ ··· **light constiuent quark field**

$$H = \frac{1+\not{v}}{2}\left[D^{*\mu}\gamma_\mu + iD\gamma_5\right]$$

annihilates heavy mesons (not generate)

☆ **Excited states** ··· $J_l = 1/2$; $J^P = (0^+, 1^+)$

Scalar meson D_0^* ; **Axial-vector meson** D_1

$D_0^* = (D_0^{*0}, D_0^{*+})$ $D_1 = (D_1^0, D_1^+)$

$$G = \frac{1+\not{v}}{2}\left[-iD_1^\mu\gamma_\mu\gamma_5 + D_0^*\right]$$

Heavy meson Lagrangian

◎ chiral doubler fields for heavy mesons

$$\mathcal{H}_L = \frac{1}{\sqrt{2}}[G + iH\gamma_5], \qquad \mathcal{H}_R = \frac{1}{\sqrt{2}}[G - iH\gamma_5]$$

$$\mathcal{H}_L \to \mathcal{H}_L g_L^\dagger, \qquad \mathcal{H}_R \to \mathcal{H}_R g_R^\dagger \qquad g_{L,R} \in SU(2)_{L,R}$$

◎ chiral field for pion

$$U = e^{2i\pi/f_\pi} \to g_L U g_R^\dagger$$

Δ term generates mass difference between (D, D*) and (D_0*, D_1).

☆ model Lagrangian

$$\begin{aligned}
\mathcal{L}_{\text{heavy}} = & \frac{1}{2}\text{Tr}\left[\bar{\mathcal{H}}_L i(v\cdot\partial)\mathcal{H}_L\right] + \frac{1}{2}\text{Tr}\left[\bar{\mathcal{H}}_R i(v\cdot\partial)\mathcal{H}_R\right] \\
& - \frac{\Delta}{2}\text{Tr}\left[\bar{\mathcal{H}}_L\mathcal{H}_L + \bar{\mathcal{H}}_R\mathcal{H}_R\right] - \frac{g_\pi F_\pi}{4}\text{Tr}\left[U^\dagger\bar{\mathcal{H}}_L\mathcal{H}_R + U\bar{\mathcal{H}}_R\mathcal{H}_L\right] \\
& + i\frac{g_A}{2}\text{Tr}\left[\gamma^5\gamma^\mu\partial_\mu U^\dagger\bar{\mathcal{H}}_L\mathcal{H}_R - \gamma^5\gamma^\mu\partial_\mu U\bar{\mathcal{H}}_R\mathcal{H}_L\right]
\end{aligned}$$

Inclusion of vector mesons with HLS

$$[SU(2)_L \times SU(2)_R]_{global} \times [U(2)_V]_{local} \to [SU(2)_V]_{global}$$

$$U = e^{2i\pi/F_\pi} = \xi_L^\dagger \xi_R$$

$$\xi_{L,R} = e^{i\sigma/F_\sigma} e^{\pm i\pi/F_\pi} \to h\,\xi_{L,R}\,g_{L,R}^\dagger$$

$$\begin{cases} h \in [U(2)_v]_{local} \\ g_{L,R} \in SU(2)_{L,R} \end{cases}$$

F_π , F_σ ・・・ Decay constants of π and σ

- Maurer-Cartan 1-forms

$$\hat{\alpha}^\mu_{\perp,\parallel} = \left(D^\mu\xi_L \cdot \xi_L^\dagger \mp D^\mu\xi_R \cdot \xi_R^\dagger\right)/(2i)$$

$$D_\mu\xi_L = \partial_\mu\xi_L - iV_\mu\xi_L \qquad D_\mu\xi_R = \partial_\mu\xi_R - iV_\mu\xi_R$$

$$V_\mu = \frac{g}{2}(\omega_\mu + \rho_\mu)$$: HLS gauge field

変換性： $\hat{\alpha}^\mu_{\perp,\parallel} \to h\,\hat{\alpha}^\mu_{\perp,\parallel}\,h^\dagger$

Heavy meson Lagrangian with HLS

◎ Introduce new fields for heavy mesons

$$\hat{\mathcal{H}}_L = \mathcal{H}_L \xi_L^\dagger, \quad \hat{\mathcal{H}}_R = \mathcal{H}_R \xi_R^\dagger,$$

$$\hat{\mathcal{H}}_L \to \hat{\mathcal{H}}_L h^\dagger(x), \quad \hat{\mathcal{H}}_R \to \hat{\mathcal{H}}_R h^\dagger(x).$$

◎ Heavy meson Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{heavy}} = {} & \frac{1}{2}\mathrm{Tr}\left[\hat{\mathcal{H}}_L (iv\cdot\widetilde{D})\bar{\hat{\mathcal{H}}}_L\right] + \frac{1}{2}\mathrm{Tr}\left[\hat{\mathcal{H}}_R (iv\cdot\widetilde{D})\bar{\hat{\mathcal{H}}}_R\right] - \frac{\Delta}{2}\mathrm{Tr}\left[\bar{\hat{\mathcal{H}}}_L\hat{\mathcal{H}}_L + \bar{\hat{\mathcal{H}}}_R\hat{\mathcal{H}}_R\right] \\ & - \frac{g_\pi F_\pi}{4}\mathrm{Tr}\left[\bar{\hat{\mathcal{H}}}_L\hat{\mathcal{H}}_R + \bar{\hat{\mathcal{H}}}_R\hat{\mathcal{H}}_L\right] - g_A \mathrm{Tr}\left[\gamma^5\gamma^\mu\hat{\alpha}_{\perp\mu}\left(\bar{\hat{\mathcal{H}}}_L\hat{\mathcal{H}}_R + \bar{\hat{\mathcal{H}}}_R\hat{\mathcal{H}}_L\right)\right]\end{aligned}$$

$$\widetilde{D}_\mu = \partial_\mu - iV_\mu - i\kappa\alpha_{\parallel\mu}$$

3. Chiral doubling in heavy baryons

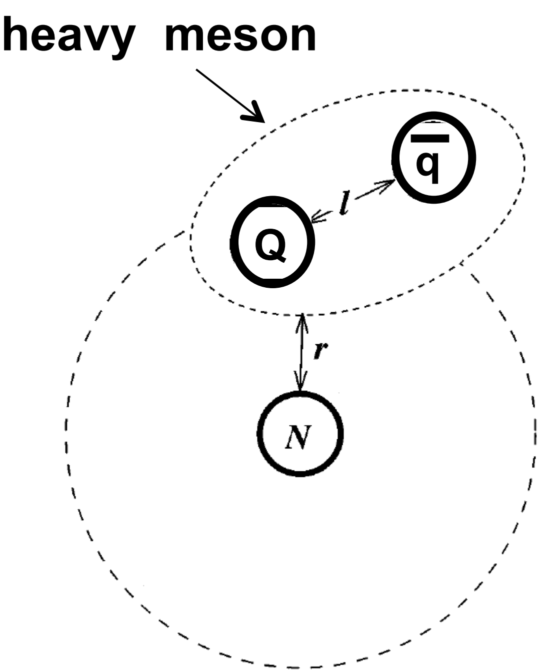
Chiral doubling in heavy baryons

・・・ based on the boundstate approach to heavy baryons

☆ Boundstate approach

heavy baryons (qqQ type)

= heavy meson ($q^{bar}Q$) bound to nculeon (qqq) as a soliton



	r = 0	r = 1
l=0 D(0^-,1^-)	$\Lambda_Q(\frac{1}{2}^+)$ $\{\Sigma_Q(\frac{1}{2}^+),\Sigma_Q(\frac{3}{2}^+)\}$	$\{\Lambda_Q(\frac{1}{2}^-),\Lambda_Q(\frac{3}{2}^-)\}$ $\Sigma_Q(\frac{1}{2}^-)$ $\{\Sigma_Q(\frac{1}{2}^-),\Sigma_Q(\frac{3}{2}^-)\}$ $\{\Sigma_Q(\frac{3}{2}^-),\Sigma_Q(\frac{5}{2}^-)\}$
l=1 D(0^+,1^+) D(1^+,2^+)	$\Lambda_Q(\frac{1}{2}^-)$ $\{\Lambda_Q(\frac{1}{2}^-),\Lambda_Q(\frac{3}{2}^-)\}$ $\{\Lambda_Q(\frac{3}{2}^-),\Lambda_Q(\frac{5}{2}^-)\}$ $\{\Sigma_Q(\frac{1}{2}^-),\Sigma_Q(\frac{3}{2}^-)\}$	...
⋮		

・kinematical structure is same as the constituent quark model

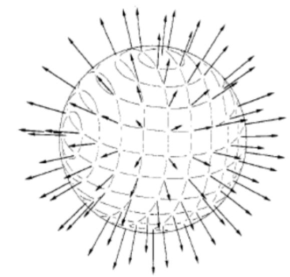
M.H., F.Sannino, J.Schechter and H.Weigel, PRD56, 4098 (1997)

Nucleon as Skyrme soliton

Skyrme model

$$\mathcal{L}_{\rm Skyr} = \frac{F_\pi^2}{4}{\rm Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] + \frac{\epsilon^2}{4}{\rm Tr}\left\{\left[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U\right]\left[U^\dagger\partial^\mu U, U^\dagger\partial^\nu U\right]\right\}$$

hedgehog ansatz



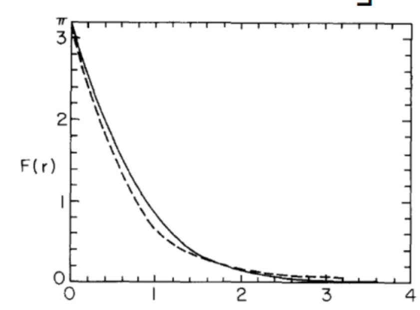
$$U(\mathbf{x}) = \exp\left(i\boldsymbol{\tau}\cdot\hat{\mathbf{x}}F(r)\right) = \cos F(r) + i\boldsymbol{\tau}\cdot\hat{\mathbf{x}}\sin F(r)$$

☆ EoM for F(r)

$$F'' + \frac{2}{r}F' - \frac{1}{r^2}\sin 2F - 8\frac{\varepsilon^2}{F_\pi^2}\left[\frac{\sin 2F\sin^2 F}{r^4} - \frac{F'^2\sin 2F}{r^2} - \frac{2F''\sin^2 F}{r^2}\right] = 0$$

☆ Solution with Baryon number = 1

$$F(r=0) = \pi, \qquad F(r\to\infty) = 0.$$



☆ Soliton mass

$$M_{\rm Skyr} = 4\pi\int_0^\infty r^2 dr\left\{\frac{F_\pi^2}{2}\left[F'^2 + \frac{2\sin^2 F}{r^2}\right] + 4\varepsilon^2\frac{\sin^2 F}{r^2}\left[2F'^2 + \frac{\sin^2 F}{r^2}\right]\right\}$$

Nucleon as Soliton in the HLS

Y. -L. Ma, Y. Oh, G. -S. Yang, M. Harada, H. K. Lee, B. -Y. Park and M. Rho, Phys. Rev. D 86, 074025 (2012).
Y. -L. Ma, G. -S. Yang, Y. Oh and M. Harada, Phys. Rev. D 87, 034023 (2013).

$$\mathcal{L}_{\rm HLS} = \mathcal{L}_{(2)} + \mathcal{L}_{(4)} + \mathcal{L}_{\rm anom},$$

$$\mathcal{L}_{(2)} = f_\pi^2 \,\mathrm{Tr}\left(\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\right) + a f_\pi^2 \,\mathrm{Tr}\left(\hat{\alpha}_{\parallel\mu}\hat{\alpha}_\parallel^\mu\right) - \frac{1}{2g^2}\mathrm{Tr}\left(V_{\mu\nu}V^{\mu\nu}\right),$$

$$\begin{aligned}\mathcal{L}_{(4)y} = {} & y_1 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\hat{\alpha}_{\perp\nu}\hat{\alpha}_\perp^\nu\right] + y_2 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_\perp^\mu\hat{\alpha}_\perp^\nu\right] + y_3 \mathrm{Tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\parallel^\nu\right] + y_4 \mathrm{Tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_\parallel^\nu\right] \\ & + y_5 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\parallel^\nu\right] + y_6 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_\parallel^\nu\right] + y_7 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_\parallel^\nu\hat{\alpha}_\parallel^\mu\right] \\ & + y_8 \left\{\mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_{\perp\nu}\hat{\alpha}_\parallel^\nu\right] + \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\perp^\nu\hat{\alpha}_\parallel^\mu\right]\right\} + y_9 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\perp^\mu\hat{\alpha}_\parallel^\nu\right],\end{aligned}$$

$$\mathcal{L}_{(4)z} = i z_4 \mathrm{Tr}\left[V_{\mu\nu}\hat{\alpha}_\perp^\mu\hat{\alpha}_\perp^\nu\right] + i z_5 \mathrm{Tr}\left[V_{\mu\nu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_\parallel^\nu\right],$$

$$\mathcal{L}_{\rm anom} = \frac{N_c}{16\pi^2}\sum_{i=1}^{3} c_i \mathcal{L}_i$$

$$\begin{aligned}\mathcal{L}_1 &= i\,\mathrm{Tr}[\hat{\alpha}_{\rm L}^3\hat{\alpha}_{\rm R} - \hat{\alpha}_{\rm R}^3\hat{\alpha}_{\rm L}], \\ \mathcal{L}_2 &= i\,\mathrm{Tr}[\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R}\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R}], \\ \mathcal{L}_3 &= \mathrm{Tr}[F_{\rm V}\,(\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R} - \hat{\alpha}_{\rm R}\hat{\alpha}_{\rm L})],\end{aligned}$$

We determined 17 parameters from holographic QCD model ⇒

$M_{\rm sol}$	1184
Δ_M	448
$\sqrt{\langle r^2\rangle_W}$	0.433
$\sqrt{\langle r^2\rangle_E}$	0.608

Heavy baryon as bound state

- We solve the equation of motion for the heavy meson field with the background nucleon as soliton.

$$\mathcal{L}_{\text{heavy}} =$$

$$\frac{1}{2}\mathrm{Tr}\left[\hat{\mathcal{H}}_L(iv\cdot\widetilde{D})\bar{\hat{\mathcal{H}}}_L\right]+\frac{1}{2}\mathrm{Tr}\left[\hat{\mathcal{H}}_R(iv\cdot\widetilde{D})\bar{\hat{\mathcal{H}}}_R\right]-\frac{\Delta}{2}\mathrm{Tr}\left[\bar{\hat{\mathcal{H}}}_L\hat{\mathcal{H}}_L+\bar{\hat{\mathcal{H}}}_R\hat{\mathcal{H}}_R\right]$$

$$-\frac{g_\pi F_\pi}{4}\mathrm{Tr}\left[\bar{\hat{\mathcal{H}}}_L\hat{\mathcal{H}}_R+\bar{\hat{\mathcal{H}}}_R\hat{\mathcal{H}}_L\right]-g_A\mathrm{Tr}\left[\gamma^5\gamma^\mu\hat{\alpha}_{\perp\mu}\left(\bar{\hat{\mathcal{H}}}_L\hat{\mathcal{H}}_R+\bar{\hat{\mathcal{H}}}_R\hat{\mathcal{H}}_L\right)\right]$$

- Ansaz for classical solution

$$\hat{H}=\begin{pmatrix}0 & \mathbb{H}\\ 0 & 0\end{pmatrix},\ \hat{G}=\begin{pmatrix}\mathbb{G} & 0\\ 0 & 0\end{pmatrix}$$

$$\mathbf{H}^{\dagger a}_{lh}=u(\mathbf{x})(\boldsymbol{\tau}\cdot\hat{\mathbf{x}})_{ad}\psi_{dl}\chi_h$$

$a \cdots$ isospin of heavy light meson

$l \cdots$ spin of the light degree of freedom

$h \cdots$ heavy quark spin

Heavy meson Lagrangian

☆ Integrating out scalar mesons and keeping pion only $(M \rightarrow F_\pi U)$

$$\mathcal{L}_{\text{heavy}} = \frac{1}{2}\text{Tr}\left[\bar{\mathcal{H}}_L i(v\cdot\partial)\mathcal{H}_L\right] + \frac{1}{2}\text{Tr}\left[\bar{\mathcal{H}}_R i(v\cdot\partial)\mathcal{H}_R\right] - \frac{\Delta}{2}\text{Tr}\left[\bar{\mathcal{H}}_L\mathcal{H}_L + \bar{\mathcal{H}}_R\mathcal{H}_R\right] - \frac{g_\pi F_\pi}{4}\text{Tr}\left[U^\dagger\bar{\mathcal{H}}_L\mathcal{H}_R + U\bar{\mathcal{H}}_R\mathcal{H}_L\right] + i\frac{g_A}{2}\text{Tr}\left[\gamma^5\gamma^\mu\partial_\mu U^\dagger\bar{\mathcal{H}}_L\mathcal{H}_R - \gamma^5\gamma^\mu\partial_\mu U\bar{\mathcal{H}}_R\mathcal{H}_L\right]$$

- Redefine the fields as $\hat{\mathcal{H}}_L = \mathcal{H}_L\xi_L^\dagger, \quad \hat{\mathcal{H}}_R = \mathcal{H}_R\xi_R^\dagger \qquad U = \xi_L^\dagger\xi_R$

$$\hat{\mathcal{H}}_L = \frac{1}{\sqrt{2}}[\hat{G} - i\hat{H}\gamma_5], \quad \hat{\mathcal{H}}_R = \frac{1}{\sqrt{2}}[\hat{G} + i\hat{H}\gamma_5]$$

- Ansaz for classical solution

$$\hat{H} = \begin{pmatrix} 0 & \mathbb{H} \\ 0 & 0 \end{pmatrix}, \hat{G} = \begin{pmatrix} \mathbb{G} & 0 \\ 0 & 0 \end{pmatrix}$$

$$\mathbf{H}_{lh}^{\dagger a} = u(\mathbf{x})(\tau\cdot\hat{\mathbf{x}})_{ad}\psi_{dl}\chi_h$$

a ⋯ isospin of heavy light meson

l ⋯ spin of the light degree of freedom

h ⋯ heavy quark spin

Quantum number & Binding energy

- Spin of heavy baryon (bound state)

$$\vec{J} = \vec{S}_{\rm heavy} + \vec{r} + \vec{K} \qquad \vec{K} = \vec{J}_{\rm light} + \vec{I}_{\rm light}$$

$\vec{S}_{\rm heavy}$: heavy quark spin

$\vec{r}$: relative angular momentum between heavy meson and nucleon

- Binding energy for H ~ (D, D*) with r = 0 (ground state)

$$V_H = -\int d^3x \mathcal{L}^H_{\rm heavy} = \frac{1}{2}(1+\kappa)g\,\omega(0) - g_A F'(0)\left[k(k+1) - \frac{3}{2}\right]$$

$$F'(0) = 626.1 \text{ MeV}; \qquad \omega(0) = -74.5 \text{ MeV}$$

Y. -L. Ma, Y. Oh, G. -S. Yang, M. Harada, H. K. Lee, B. -Y. Park and M. Rho, Phys. Rev. D 86, 074025 (2012).
Y. -L. Ma, G. -S. Yang, Y. Oh and M. Harada, Phys. Rev. D 87, 034023 (2013).

- **Assume g_A > 0 and $|\kappa| \leq 1$ to have a bound state in K=0**
  ⇒ $\Lambda_c(1/2^+)$ is the ground state

Heavy Baryon Masses

$$m^M_{I,j} = M_{\rm sol} + \bar{M}_M + V_M + H_{\rm coll}$$

- $M_{\rm sol}$: Soliton mass.
- $\bar{M}_M$: weight-averaged heavy meson masse, $\bar{M}_H = (3m_{D^*} + m_D)/4$ and $\bar{M}_G = (3m_{D'_1} + m_{D^*_0})/4$.
- $V_M(M = H, G)$: the binding energy

$$\begin{aligned} V_{\rm H} &= \frac{1}{2}(1+\kappa)g\omega(0) + g_A F'(0)\left[k(k+1) - \frac{3}{2}\right], \\ V_{\rm G} &= \frac{1}{2}(1+\kappa)g\omega(0) - g_A F'(0)\left[k(k+1) - \frac{3}{2}\right]. \end{aligned}$$

- The collective rotated Hamiltonian

$$\begin{aligned} H_{\rm coll} &= \frac{1}{2\mathcal{I}_{\rm HLS}}\left[[1-\chi(k)]\mathbf{I}^2 + \chi(k)[\chi(k)-1]\mathbf{K}^2 + \chi(k)(\mathbf{j}-\mathbf{r})^2\right], \\ \chi(k) &= [k(k+1) + 3/4 - j_l(j_l+1)]\,/\,[2k(k+1)]. \end{aligned}$$

$\Lambda_c(1/2^+)$

$M(\Lambda(1/2+)) = M_N + M_{D(0-,1-)} + V_H$ ($H_{coll} = 0$)

$$V_H = -0.177(1+\kappa) + 0.626 g_A\left[k(k+1) - \frac{3}{2}\right] [\mathrm{GeV}].$$

$M_{D(0-,1-)} = (M_{D(0-)} + 3\, M_{D(1-)})/4 \sim 1.97$ (GeV)

$M_N = 0.94$ (GeV)

$g_A = 0.56$ from $D(1^-) \rightarrow D(0^-) + \pi$ decay

$M(\Lambda(1/2^+))^{exp} = 2.286$ (GeV)
is used to determin $\kappa = -0.83$

Chiral partner to $\Lambda_c(1/2^+)$?

◎ Binding energy for G ~ (D_0, D_1*) with r = 0

$$V_G = -0.177(1+\kappa) - 0.626 g_A\left[k(k+1) - \frac{3}{2}\right] \text{[GeV]}$$

- **$g_A = 0.56$, $\kappa = -0.83$ ⇒ bound state is realized for $K = 1$**

Chiral partner to $\Lambda_c(1/2^+)$ = [$\Lambda_c(1/2^-)$, $\Lambda_c(3/2^-)$]

◎ Mass **$M_{D(0+,1+)} = (M_{D(0+)} + 3 M_{D(1+)})/4 \sim 2.4$(GeV)**

$M(\Lambda) = M_N + M_{D(0+,1+)} + V_G + H_{coll} = 3.13$ (GeV)

- **Λ_c(1/2-;2595) is unlikely the chiral partner to Λ_c(1/2+;2286)**
- **{Λ_c(1/2-;2595) , Λ_c(3/2-;2625) }**
  ･･･ r = 1 boundstate of D(0-,1-) and nucleon

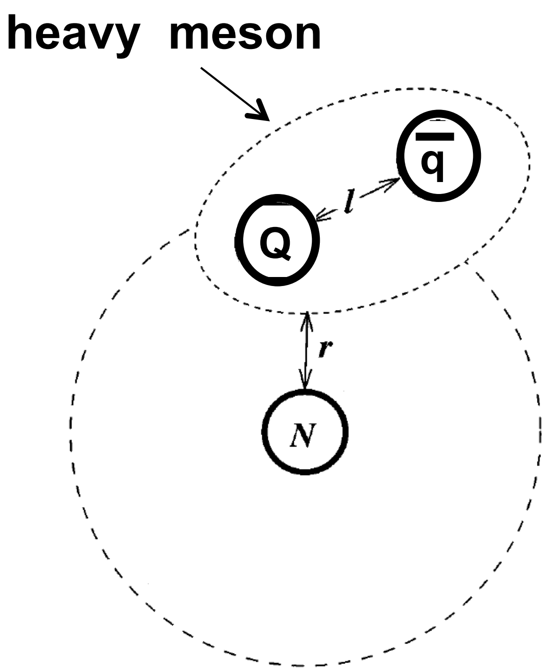
☆ Chiral partner to Λ(1/2+)

◎ **excited heavy baryons (qqQ type)**

= **heavy meson** + **nculeon** **with angular momentum**

or

excited heavy meson + **nucleon**



r, *l* : angular momentum

	r = 0	r = 1
l=0 D(0⁻,1⁻)	$\Lambda_Q(\frac{1}{2}^+)$ $\{\Sigma_Q(\frac{1}{2}^+),\Sigma_Q(\frac{3}{2}^+)\}$	$\{\Lambda_Q(\frac{1}{2}^-),\Lambda_Q(\frac{3}{2}^-)\}$ $\Sigma_Q(\frac{1}{2}^-)$ $\{\Sigma_Q(\frac{1}{2}^-),\Sigma_Q(\frac{3}{2}^-)\}$ $\{\Sigma_Q(\frac{3}{2}^-),\Sigma_Q(\frac{5}{2}^-)\}$
l=1 D(0⁺,1⁺) D(1⁺,2⁺)	$\Lambda_Q(\frac{1}{2}^-)$ $\{\Lambda_Q(\frac{1}{2}^-),\Lambda_Q(\frac{3}{2}^-)\}$ $\{\Lambda_Q(\frac{3}{2}^-),\Lambda_Q(\frac{5}{2}^-)\}$ $\{\Sigma_Q(\frac{1}{2}^-),\Sigma_Q(\frac{3}{2}^-)\}$	**3.13 GeV** ⋯
⋮		

Prediction for Σ_c and bottomed baryosn

TABLE I. Predicted mass for the charmed baryon for the H doublet.

I	j	States	M^H (MeV)
0	0	$\Lambda_c(\frac{1}{2}^+)$	2286.46 (input)
1	1	$\Sigma_c(\frac{1}{2}^+)$, $\Sigma_c(\frac{3}{2}^+)$	2481.13

TABLE II. Predicted mass for the charmed baryon for the G doublet.

I	j	$I(j_B^P)$	M^G (MeV)
0	1	$\Lambda_c(\frac{1}{2}^-)$, $\Lambda_c(\frac{3}{2}^-)$	3131.66
1	0	$\Sigma_c(\frac{1}{2}^-)$	3131.66
1	1	$\Sigma_c(\frac{1}{2}^-)$, $\Sigma_c(\frac{3}{2}^-)$	3228.99
1	2	$\Sigma_c(\frac{3}{2}^-)$, $\Sigma_c(\frac{5}{2}^-)$	3423.66

TABLE III. Predicted mass for the bottom baryon for the H doublet.

I	j	$I(j_B^P)$	M^H (MeV)
0	0	$\Lambda_b(\frac{1}{2}^+)$	5625.07
1	1	$\Sigma_b(\frac{1}{2}^+)$, $\Sigma_b(\frac{3}{2}^+)$	5819.74

TABLE IV. Predicted mass for the bottom baryon for the G doublet.

I	j	$I(j_B^P)$	M^G (MeV)
0	1	$\Lambda_b(\frac{1}{2}^-)$, $\Lambda_b(\frac{3}{2}^-)$	6470.27
1	0	$\Sigma_b(\frac{1}{2}^-)$	6470.27
1	1	$\Sigma_b(\frac{1}{2}^-)$, $\Sigma_b(\frac{3}{2}^-)$	6567.6
1	2	$\Sigma_b(\frac{3}{2}^-)$, $\Sigma_b(\frac{5}{2}^-)$	6762.27

Application to pentaquark

$$V_{\rm H}^{5} = 0.177(1+\kappa) - 0.626 g_A \left[k(k+1) - \frac{3}{2} \right] [\rm GeV] = -0.146\,GeV$$

K = 1 gives a bound state.

M(Θ_c(1/2-, 3/2-)) ~ 2.75 (GeV)

cf : M(Θ_c(1/2-)) ~ 2.7 GeV without ω contribution.

Y.Oh, B.-Y.Park, and D.P.Min, PLB331, 362 (1994)

note : CHORUS exp. did not observe Θ_c(2710). NPB 763 (2007) 268

☆ **chiral partner to pentaquark ?**

$$V_{\rm G}^{5} = 0.177(1+\kappa) + 0.626 g_A \left[k(k+1) - \frac{3}{2} \right] [\rm GeV] = -0.496\,GeV$$

***K* = 0**

M(Θ_c(1/2+)) ~ 2.79 (GeV) !

cf : M(Θ_c(1/2+)) = 3052 ± 60 MeV M.A.Nowak et al., PRD70, 031503(2004)

Prediction for Bottomed pentaquarks

TABLE VII. Predicted mass for the bottom pentaquark state for the H doublet.

I	j	Candidates	M^{5,H_b} (MeV)
0	1	$\Theta_b(\frac{1}{2}^+)$	6083.76

TABLE VIII. Predicted mass for the bottom pentaquark state for the G doublet.

I	j	Candidates	M^{5,G_b} (MeV)
0	0	$\Theta_b(\frac{1}{2}^-)$	6130.39

4. Summary

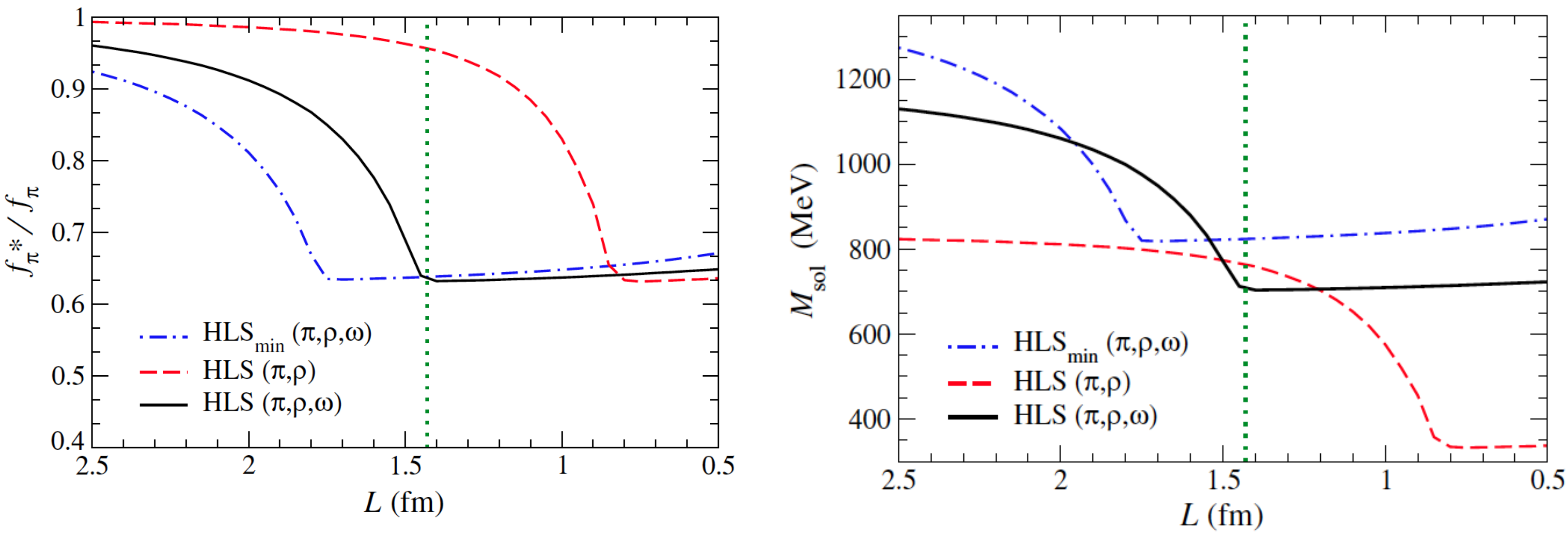
◆ Based on the chiral doubling structure of D mesons I showed our study on the chiral doubling of heavy baryons

- Our result implies that the chiral partner to $\Lambda_c(1/2^+)$ is [$\Lambda_c(1/2^-)$, $\Lambda_c(3/2^-)$], whose mass is 3.13 GeV.
- Then, $\{\Lambda_c(1/2-;2595)$, $\Lambda_c(3/2-;2625)\}$ is r = 1 boundstates of D(0-,1-) and nucleon
- Two types of pentaquarks exist below *Dp* threshold.
- $M(\Theta_c(1/2-, 3/2-)) = 2.75$ (GeV) ;
- $M(\Theta_c(1/2+)) = 2.79$ (GeV)

Medium modification ?

We studied the medium modification of the pion decay constant and soliton mass using the crystal structure.

Y.-L.Ma, M. Harada, H. K.Lee, Y.Oh, B.-Y.Park and M.Rho, ``Dense Baryonic Matter in Hidden Local Symmetry Approach: Half-Skyrmions and Nucleon Mass,'' Phys. Rev. D 88, 014016 (2013)



Medium modification of masses of heavy mesons and heavy baryons ?

The End