

H-dibaryon in Holographic QCD

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(in collaboration with Hideo Suganuma, Yuya Nakagawa)

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Contents

1. Introduction

2. Chiral Soliton Model

3. Holographic QCD

4. Results

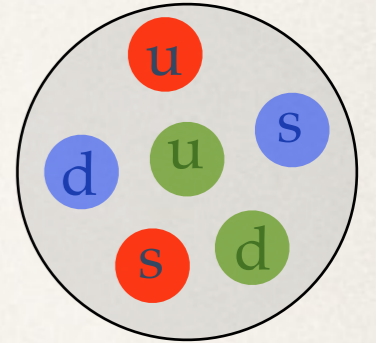
5. Summary

Introduction

- ❖ The aim of this study is to investigate the properties of **H-dibaryon** in **chiral limit** using a recent new method of **non-perturbative QCD**.
- ❖ In particular, H-dibaryon mass is interesting from the viewpoint of “**existence**” of H-dibaryon.

What is H-dibaryon?

- ❖ H-dibaryon: **B=2 flavor singlet** state (uuddss)
 $(J^\pi = 0^+, I = 0, B = 2, S = -2, Y = 0)$



- In 1977, Jaffe first predicted the existence of H-dibaryon in the discussion of color-magnetic interaction by using MIT bag model. [R. L. Jaffe, Phys. Rev. Lett. 38 (1977) 195]

- In this model, the H-dibaryon mass is $M_H = 2150 \text{ MeV}$.

(cf. $\Lambda\Lambda(2231\text{MeV})$, $N\Xi(n\Xi^0: 2254\text{MeV}, p\Xi^-: 2260\text{MeV})$,
 $\Sigma\Sigma(\Sigma^0\Sigma^0: 2385\text{MeV}, \Sigma^+\Sigma^-: 2387\text{MeV})$)

\therefore The H-dibaryon mass may be **smaller** than the $\Lambda\Lambda$ threshold!

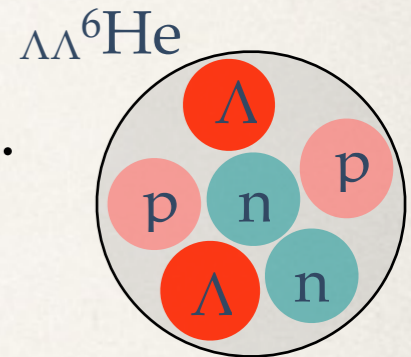
- ❖ After that, H-dibaryon mass was also investigated by using **Skyrme model**, and the result is: [A. P. Balachandran et al., Nucl. Phys. B256 (1985) 525]
 [R. L. Jaffe et al., Nucl. Phys. B258 (1985) 468]

$$M_H \simeq 1.92M_{B=1} (< 2M_{B=1}) \quad (\text{in chiral limit})$$

- This result seems to support Jaffe's prediction.

Experimental Status

- ❖ However, the prediction of the low-mass H-dibaryon is **denied** experimentally in 1991 (at physical point):
 - Instead, the double hyper nuclei $\Lambda\Lambda^6\text{He}$ was found by Imai group.
[K. Imai, Nucl. Phys. A527, 181(1991)]
[H. Takahashi et al., Phys. Rev. Lett. 87, 212502(2001)]
 - In fact, H-dibaryon is not a stable state, that is, **there is no-deeply-bound H particle at least at the physical point.**
- ❖ Then, current interests of H-dibaryon are:
 - H-dibaryon may exist as a resonance at physical point.
 - How is the stability of H **at unphysical points** such as flavor SU(3) symmetric case ($m_u=m_d=m_s$) ?

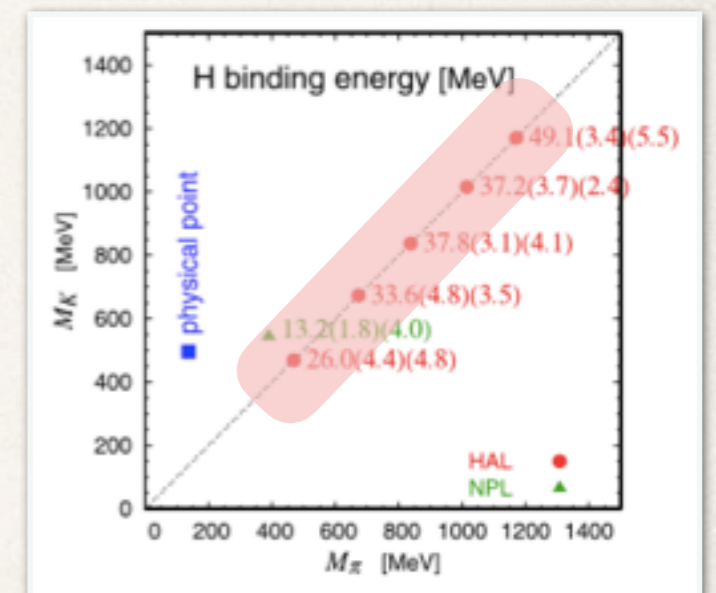


Lattice QCD Studies of H-dibaryon

- ❖ As a recent progress, Lattice QCD calculation indicates the existence of H-dibaryon at “unphysical points”:

[NPLQCD (S. Beane et al.), Phys. Rev. Lett. 106 (2011)162001]
[HAL QCD (T. Inoue et al.), Phys. Rev. Lett. 106 (2011) 162002]
[HAL QCD (T. Inoue et al.), Nucl. Phys. A881, 28 (2012)]

- H is stable at the flavor SU(3) symmetric ($m_u=m_d=m_s$) and large quark-mass region.
- ❖ Then, how about in chiral limit?
 - Lattice QCD calculation is usually a powerful tool to evaluate hadron masses, but it is difficult to take the chiral limit. (large-size box is required)
- ❖ For the study of the chiral limit, some model approach such as Skyrme model would be useful instead of lattice QCD.
 - It is desirable to use some QCD-based model for the calculation.



Contents

1. Introduction

2. Chiral Soliton Model

3. Holographic QCD

4. Results

5. Summary

Skyrme Model

- ❖ Skyrme model [T. H. R. Skyrme, Nucl. Phys. 31 (1962) 556]

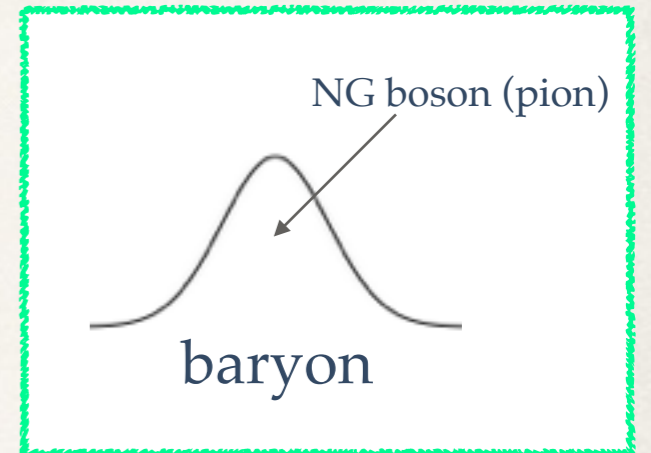
$$\mathcal{L} = \frac{f_\pi^2}{4} \text{tr}(L_\mu L^\mu) + \frac{1}{32e^2} \text{tr}[L_\mu, L_\nu]^2 \quad (+ \text{WZW term})$$

kinetic term

“Skyrme term”
(introduced by hand)

$$L_\mu \equiv \frac{1}{i} U^\dagger \partial_\mu U$$

chiral field: $U(x) = e^{i\pi(x)/f_\pi} \in SU(N_f)$



- This is the first theory of chiral solitons which describe **baryons in terms of pions**.
- This picture is qualitatively supported in the large N_c argument (by E. Witten, 1979).
- The soliton solution of this model is called “**Skymion**”.
To investigate Skymions, **hedgehog Ansatz** is usually used.

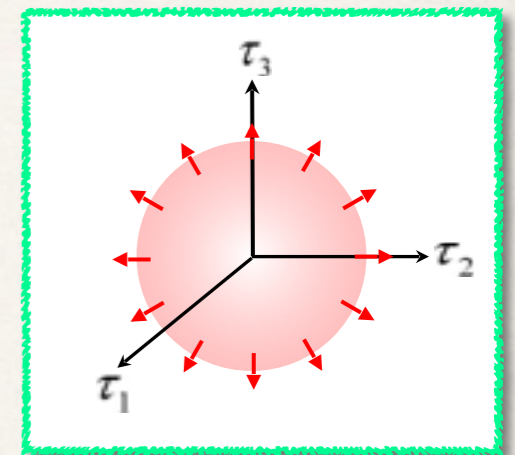
Skyrme Model in B=1 SU(2) Flavor Case

Hedgehog Ansatz $N_f = 2$ case (ud flavor)
 for $B=1$ particle (Nucleon)
 [T. H. R. Skyrme, Nucl. Phys. 31 (1962) 556]

❖ SU(2) hedgehog Ansatz:

$$U(\mathbf{x}) = e^{i(\boldsymbol{\tau} \cdot \hat{\mathbf{x}})F(r)} \in \text{SU}(2)$$

It has one function $F(r)$ ($\tau_{i=1,2,3}$: Pauli matrices)



hedgehog Ansatz

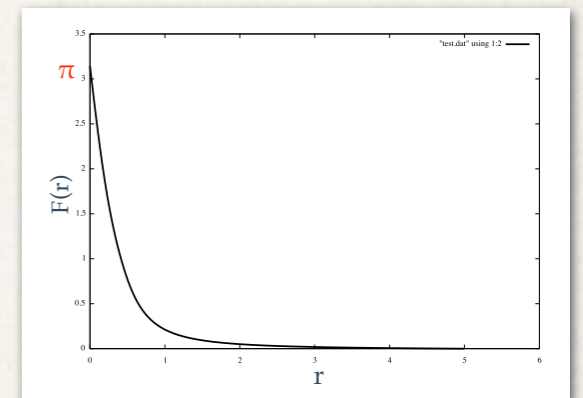
⇒ #baryon = $n \in \mathbb{Z}$

❖ $B = 1$ Skyrmion
 in SU(2) flavor case
 corresponds to nucleon.

with

boundary condition

$$\begin{cases} F(0) = \pi \\ F(\infty) = 0 \end{cases}$$



❖ The $B=2$ Skyrmion corresponding to H-dibaryon can be obtained by using hedgehog Ansatz of $\text{SO}(3)$ subalgebra of $\text{SU}(3)$ flavor, instead of SU(2) flavor.

Skyrme Model for H-dibaryon as SO(3) soliton

Hedgehog Ansatz $N_f = 3$ case (uds flavor)

$SU(3) \supset SU(2), SO(3)$

[A. P. Balachandran et al., Nucl. Phys. B256 (1985) 525]

[R. L. Jaffe et al., Nucl. Phys. B258 (1985) 468]

- SO(3) subalgebra:

$$\Lambda_1 = \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \Lambda_2 = -\lambda_5 = \begin{pmatrix} 0 & 0 & i \\ 0 & 0 & 0 \\ -i & 0 & 0 \end{pmatrix} \quad \Lambda_3 = \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$[\Lambda_i, \Lambda_j] = i\epsilon_{ijk}\Lambda_k$$

symmetric for flavor (u, d, s)

- SO(3) hedgehog Ansatz:

$$U(\mathbf{x}) = e^{i[(\mathbf{\Lambda} \cdot \hat{\mathbf{x}})F(r) + ((\mathbf{\Lambda} \cdot \hat{\mathbf{x}})^2 - 2/3)\phi(r)]} \in SU(3) \quad \text{It has 2 functions } F(r), \phi(r)$$

\Rightarrow #baryon = $4n$ or $4n+2$ ($n \in \mathbb{Z}$)

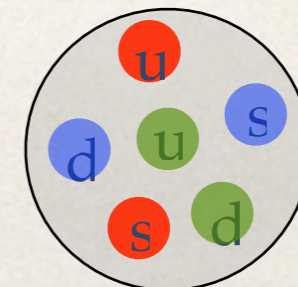
✦ $B = 2 \Rightarrow$ dibaryon (stable)

with

boundary condition

$$\begin{aligned} \cos F(\infty) &= 1 & \cos F(0) &= -1 \\ e^{i\varphi(\infty)/3} &= 1 & e^{i\varphi(0)/3} &= -e^{i2\pi k/3} \\ G(\infty) &= 0 & G(0) &= 0 \end{aligned}$$

We can obtain stable dibaryon as Skyrminion by using “SO(3)” hedgehog Ansatz.



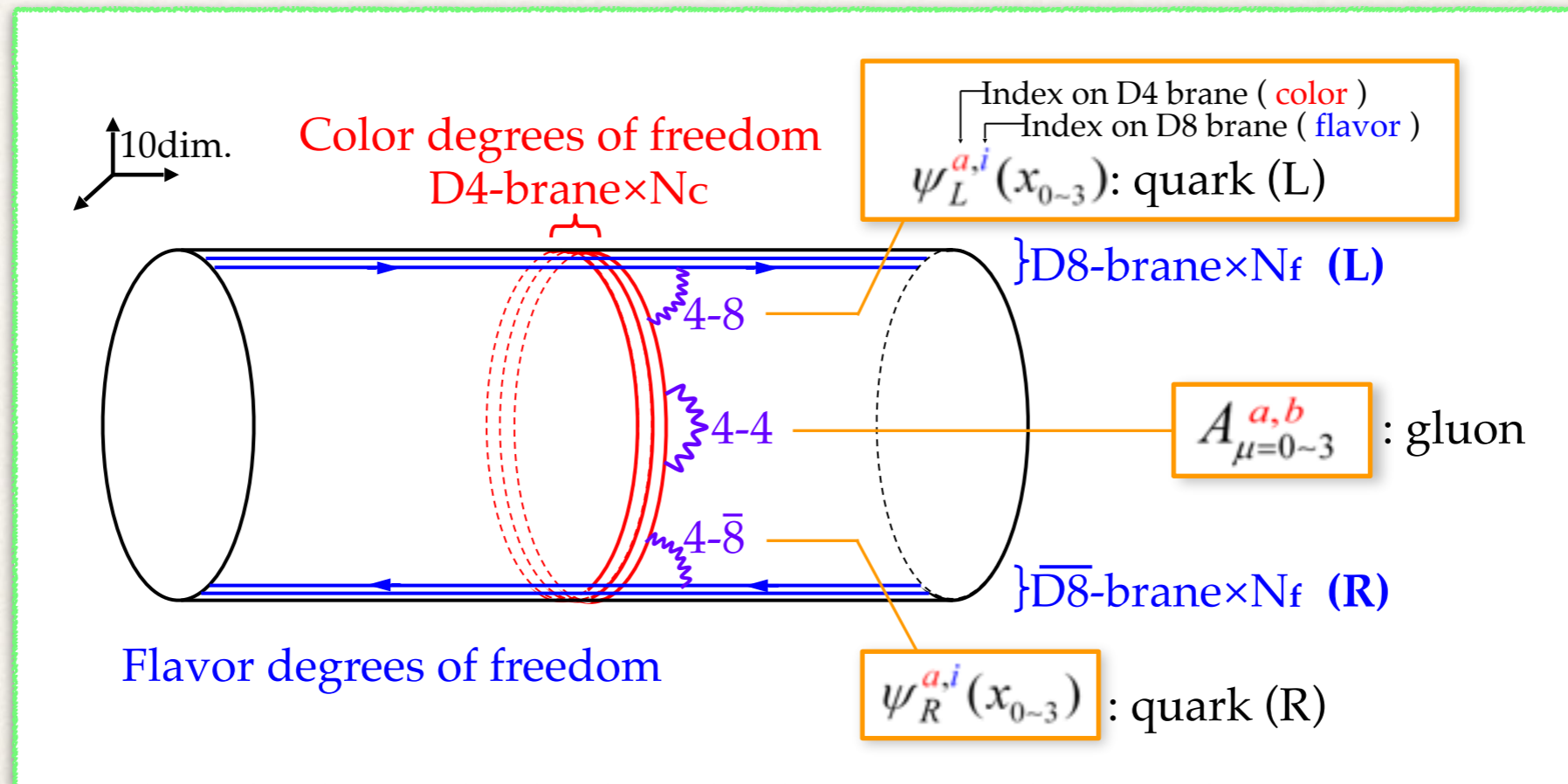
Contents

1. Introduction
2. Chiral Soliton Model
3. Holographic QCD
4. Results
5. Summary

Holographic QCD

Sakai-Sugimoto Model [T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113 (2005) 843.]

- ❖ **QCD-equivalent D-brane system (D4 / D8 / $\overline{D8}$)** can be constructed in superstring theory.

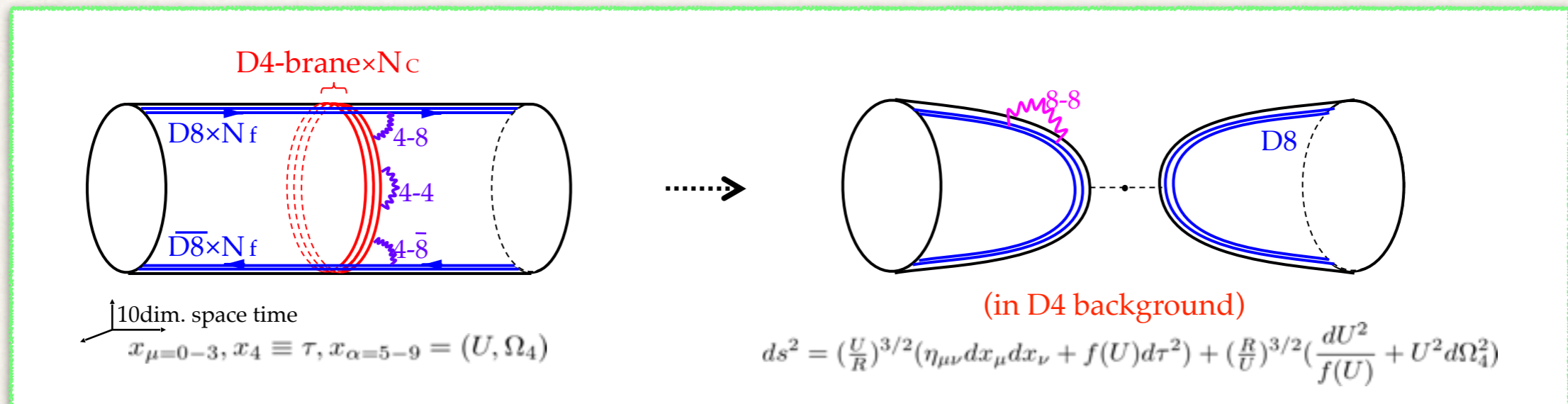


Holographic QCD

[T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113 (2005) 843.]

Large N_c limit

In **large N_c limit**, N_c D4-branes are extremely massive
 \Rightarrow replaced by **gravitational background**



$\Rightarrow N_f$ D8-branes are treated as “probes” in the SUGRA background solution of N_c D4-branes in large N_c limit.

Note: For the reliability of SUGRA description, large 't Hooft coupling ($\lambda \equiv g_{\text{YM}}^2 N_c$) is also needed. (g_{YM} : coupling const. of gauge theory)

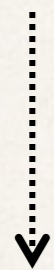
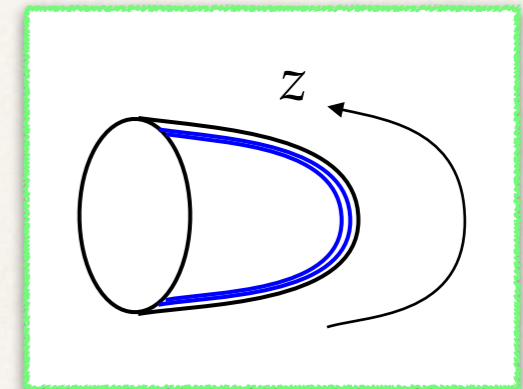
Holographic QCD

[T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113 (2005) 843.]

DBI action of D8-brane

- ❖ In large N_c (& large λ) limit, probe D8-brane can be express by the **Dirac-Born-Infeld action**: ($M_{KK} = 1$ unit)

$$S_{D8}^{DBI} = T_8 \int d^9 x e^{-\phi} \sqrt{-\det(g_{MN} + 2\pi\alpha' F_{MN})}$$



integrate over S^4 (degree of freedom of spherical coordinate of x_{5-9}) and expand in terms of $\alpha' F_{\mu\nu}$ (field strength on D8-brane) according to $1/N_c, 1/\lambda$

$$S_{HQCD} \sim \kappa \int d^4 x dz \text{tr} \left(\frac{1}{2} K(z)^{-1/3} F_{\mu\nu} F_{\mu\nu} + K(z) F_{\mu z} F_{\mu z} \right) + O(F^4) \quad (\text{Euclid. metric})$$

“5-dimensional Effective action of D8-brane”

$$F_{MN} = \partial_M A_N - \partial_N A_M + i[A_M, A_N] \quad (M, N = 0-3, z)$$

$$K(z) \equiv 1 + z^2 \quad ; \quad \kappa = \lambda N_c / 108\pi^3$$

$$T_8: \text{surface tension of D8-brane} / \alpha' \equiv l_s^2$$

note: the gravitational energy is abbreviated above

- ❖ Furthermore, the **4-dimensional meson effective theory** can be derived by performing **mode expansion** of gauge field $A_{\mu=0-3}(x_\nu, z)$ **along z-direction**.

Holographic QCD

[T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113 (2005) 843.]

Construction of 4D Meson Effective Theory

❖ First, we take $A_z = 0$ gauge in the 5D effective action S_{HQCD} .

❖ Next, we perform mode expansion of $A_\mu(x_\nu, z)$ in z -direction:

$$A_\mu(x_\nu, z) = l_\mu(x_\nu)\psi_+(z) + r_\mu(x_\nu)\psi_-(z) + \sum_{n \geq 1} B_\mu^{(n)}(x_\nu)\psi_n(z)$$

left/right current by pion (axial) vector meson

pion (NG mode) $\left\{ \begin{array}{l} l_\mu(x_\nu) \equiv \frac{1}{i}\xi_+(x_\nu)\partial_\mu\xi_+^{-1}(x_\nu) \quad r_\mu(x_\nu) \equiv \frac{1}{i}\xi_-(x_\nu)\partial_\mu\xi_-^{-1}(x_\nu) \quad \xi_\pm(x_\mu) \in U(N_f) \end{array} \right.$

- Chiral Field: $U(x_\mu) = e^{i\pi(x_\mu)/f_\pi} = \xi_+^{-1}(x_\mu)\xi_-(x_\mu) \in U(N_f)$

- Vector Meson Field: $B_\mu^{(n)} = B_\mu^{a(n)}T_a$

❖ For the construction of low-energy QCD effective theory, here we consider NG bosons and the lightest vector meson,

only “ ρ -meson”:

[K. Nawa, H. Suganuma, T. Kojo, Phys. Rev. D75, 086003 (2007)]

$$A_\mu(x_\nu, z) \simeq l_\mu(x_\nu)\psi_+(z) + r_\mu(x_\nu)\psi_-(z) + \rho_\mu(x_\nu)\psi_1(z)$$

proper orthogonal basis
 $\{\psi_\pm(z), \psi_n(z)(n = 1, 2, \dots)\}$
 $\psi_\pm(z) \equiv \frac{1}{2} \pm \hat{\psi}_0(z)$
 $\hat{\psi}_0(z) \equiv \frac{1}{\pi} \arctan z$
 $-K(z)^{1/3} \frac{d}{dz} [K(z) \frac{d\psi_n}{dz}] = \lambda_n \psi_n$

Holographic QCD

[T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113 (2005) 843.]
 [K. Nawa, H. Suganuma, T. Kojo, Phys. Rev. D75, 086003 (2007)]

Construction of Meson Effective Theory

- By the mode expansion of $A_\mu(x_\nu, z)$, we can derive the 4D meson effective theory in terms of pion & vector meson fields from holographic QCD:

$$A_\mu(x_\nu, z) \simeq l_\mu(x_\nu)\psi_+(z) + r_\mu(x_\nu)\psi_-(z) + \rho_\mu(x_\nu)\psi_1(z)$$

$$\begin{cases} \text{axial vector current: } \alpha_\mu(x_\nu) \equiv l_\mu(x_\nu) - r_\mu(x_\nu) \\ \text{vector current: } \beta_\mu(x_\nu) \equiv \frac{1}{2}\{l_\mu(x_\nu) + r_\mu(x_\nu)\} \end{cases}$$

- Here we can see:
 - this theory has just **two parameters** (M_{KK} & κ) such as f_π, m_ρ . (other coupling constants depend only on M_{KK} & κ .)
 - this effective theory is “derived” from QCD, so it is considered as **QCD-based model**.

substitute

$$\begin{aligned} S_{\text{HQCD}} &= \kappa \int d^4x dz \text{tr} \left\{ \frac{1}{2} K(z)^{-\frac{1}{2}} F_{\mu\nu} F_{\mu\nu} + K(z) F_{\mu z} F_{\mu z} \right\} \\ &= \frac{f_\pi^2}{4} \int d^4x \text{tr} (L_\mu L_\mu) \quad (\text{chiral term}) \\ &+ \frac{1}{2} \frac{1}{16e^2} [i^2] \int d^4x \text{tr} [L_\mu, L_\nu]^2 \quad (\text{Skyrme term}) \\ &+ \frac{1}{2} \int d^4x \text{tr} (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu)^2 \quad (\rho\text{-kinetic term}) \\ &+ m_\rho^2 \int d^4x \text{tr} (\rho_\mu \rho_\mu) \quad (\rho\text{-mass term}) \\ &+ \frac{1}{2} 2g_{3\rho} [-i] \int d^4x \text{tr} \{ (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu) [\rho_\mu, \rho_\nu] \} \quad (3\rho \text{ coupling}) \\ &+ \frac{1}{2} g_{4\rho} [(-i)^2] \int d^4x \text{tr} [\rho_\mu, \rho_\nu]^2 \quad (4\rho \text{ coupling}) \\ &+ i g_1 \int d^4x \text{tr} \{ [\alpha_\mu, \alpha_\nu] (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu) \} \quad (\partial\rho\text{-}2\alpha \text{ coupling}) \\ &+ g_2 \int d^4x \text{tr} \{ [\alpha_\mu, \alpha_\nu] [\rho_\mu, \rho_\nu] \} \quad (2\rho\text{-}2\alpha \text{ coupling}) \\ &+ g_3 \int d^4x \text{tr} \{ [\alpha_\mu, \alpha_\nu] ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu]) \} \quad (\rho\text{-}2\alpha\text{-}\beta \text{ coupling}) \\ &- i g_4 \int d^4x \text{tr} \{ (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu) ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu]) \} \quad (\rho\text{-}\partial\rho\text{-}\beta \text{ coupling}) \\ &- g_5 \int d^4x \text{tr} \{ [\rho_\mu, \rho_\nu] ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu]) \} \quad (3\rho\text{-}\beta \text{ coupling}) \\ &- \frac{1}{2} g_6 \int d^4x \text{tr} ([\alpha_\mu, \rho_\nu] + [\rho_\mu, \alpha_\nu])^2 \quad (2\rho\text{-}2\alpha \text{ coupling}) \\ &- \frac{1}{2} g_7 \int d^4x \text{tr} ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu])^2 \quad (2\rho\text{-}2\beta \text{ coupling}). \end{aligned}$$

H-dibaryon in Holographic QCD

The **Soliton Solution** of the Meson Effective Theory S_{HQCD}

- ❖ The B=1 SU(2) case has been investigated: [K. Nawa, H. Suganuma, T. Kojo, Phys. Rev. D75, 086003 (2007)]
- ❖ Here we consider **the SU(3) flavor case** to describe H-dibaryon in the chiral limit in holographic QCD for the first time. [A. P. Balachandran et al., Nucl. Phys. B256 (1985) 525]
[R. L. Jaffe et al., Nucl. Phys. B258 (1985) 468]
- ❖ We study H-dibaryon in holographic QCD in the following manner:

- Action (Euclid. metric)

$$S_{\text{HQCD}} = \int d^4x \left\{ \frac{f_\pi^2}{4} \text{tr}(L_\mu L_\mu) - \frac{1}{32e^2} \text{tr}[L_\mu, L_\nu]^2 \right\} + \frac{1}{2} \text{tr}(\partial_\mu \rho_\nu - \partial_\nu \rho_\mu)^2 + m_\rho^2 \text{tr}(\rho_\mu \rho_\mu) + (\text{int. term}) \}$$

- Meson Field \rightarrow **“SO(3)” Hedgehog Ansatz ($N_f = 3$)**

- Chiral Field: $U(\mathbf{x}) = e^{i[(\mathbf{\Lambda} \cdot \hat{\mathbf{x}})F(r) + ((\mathbf{\Lambda} \cdot \hat{\mathbf{x}})^2 - 2/3)\varphi(r)]} \in SU(3)$

- lowest SO(3) vector-meson field “ ρ -meson”: $\rho_0(\mathbf{x}) = 0, \rho_i(\mathbf{x}) = \{\epsilon_{ijk} \hat{x}_j G(r)\} \Lambda_k$

“Wu-Yang-’t Hooft-Polyakov Ansatz”

\Rightarrow Energy (static soliton mass): $E[F(r), \varphi(r), G(r)] \equiv S_{\text{HQCD}}|_{\text{hedgehog}}$

Contents

1. Introduction
2. Chiral Soliton Model
3. Holographic QCD
4. Results
5. Summary

Effective Action on SU(3) Flavor

We derive the effective action for H-dibaryon as **SO(3)-type hedgehog soliton** in terms of profile functions $F(r)$, $\varphi(r)$, $G(r)$ from holographic QCD (Euclid. metric).

$$\begin{aligned}
 S_{\text{HQCD}} &= \kappa \int d^4x dz \text{tr} \left\{ \frac{1}{2} K(z)^{-\frac{1}{3}} F_{\mu\nu} F_{\mu\nu} + K(z) F_{\mu z} F_{\mu z} \right\} \\
 &= \frac{f_\pi^2}{4} \int d^4x \text{tr} (L_\mu L_\mu) \quad (\text{chiral term}) \\
 &+ \frac{1}{2} \frac{1}{16e^2} [i^2] \int d^4x \text{tr} [L_\mu, L_\nu]^2 \quad (\text{Skyrme term}) \\
 &+ \frac{1}{2} \int d^4x \text{tr} (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu)^2 \quad (\rho\text{-kinetic term}) \\
 &+ m_\rho^2 \int d^4x \text{tr} (\rho_\mu \rho_\mu) \quad (\rho\text{-mass term}) \\
 &+ \frac{1}{2} 2g_{3\rho} [-i] \int d^4x \text{tr} \{ (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu) [\rho_\mu, \rho_\nu] \} \quad (3\rho \text{ coupling}) \\
 &+ \frac{1}{2} g_{4\rho} [(-i)^2] \int d^4x \text{tr} [\rho_\mu, \rho_\nu]^2 \quad (4\rho \text{ coupling}) \\
 &+ i g_1 \int d^4x \text{tr} \{ [\alpha_\mu, \alpha_\nu] (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu) \} \quad (\partial\rho\text{-}2\alpha \text{ coupling}) \\
 &+ g_2 \int d^4x \text{tr} \{ [\alpha_\mu, \alpha_\nu] [\rho_\mu, \rho_\nu] \} \quad (2\rho\text{-}2\alpha \text{ coupling}) \\
 &+ g_3 \int d^4x \text{tr} \{ [\alpha_\mu, \alpha_\nu] ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu]) \} \quad (\rho\text{-}2\alpha\text{-}\beta \text{ coupling}) \\
 &- i g_4 \int d^4x \text{tr} \{ (\partial_\mu \rho_\nu - \partial_\nu \rho_\mu) ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu]) \} \quad (\rho\text{-}\partial\rho\text{-}\beta \text{ coupling}) \\
 &- g_5 \int d^4x \text{tr} \{ [\rho_\mu, \rho_\nu] ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu]) \} \quad (3\rho\text{-}\beta \text{ coupling}) \\
 &- \frac{1}{2} g_6 \int d^4x \text{tr} ([\alpha_\mu, \rho_\nu] + [\rho_\mu, \alpha_\nu])^2 \quad (2\rho\text{-}2\alpha \text{ coupling}) \\
 &- \frac{1}{2} g_7 \int d^4x \text{tr} ([\beta_\mu, \rho_\nu] + [\rho_\mu, \beta_\nu])^2 \quad (2\rho\text{-}2\beta \text{ coupling}).
 \end{aligned}$$

Substituting SO(3) hedgehog Ansatz,

$$U(\mathbf{x}) = e^{i[(\mathbf{\Lambda} \cdot \hat{\mathbf{x}})F(r) + ((\mathbf{\Lambda} \cdot \hat{\mathbf{x}})^2 - 2/3)\varphi(r)]}$$

$$\rho_0(\mathbf{x}) = 0$$

$$\rho_i(\mathbf{x}) = \{ \epsilon_{ijk} \hat{x}_j G(r) \} \Lambda_k$$

and after some calculation, we derive the effective theory of H-dibaryon.

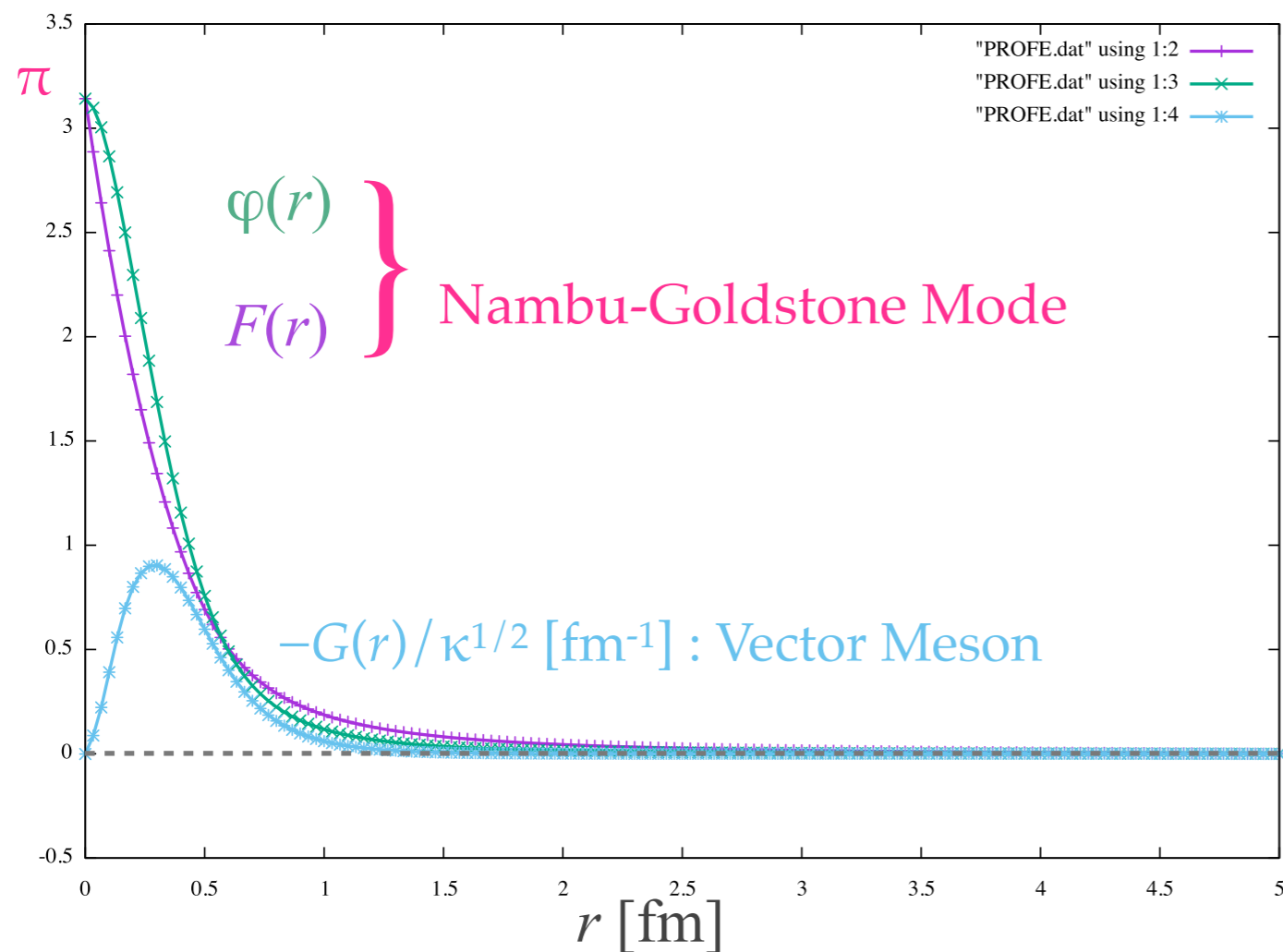
Effective Action on SU(3) Flavor

We derive the effective action for H-dibaryon as **SO(3)-type hedgehog soliton** in terms of profile functions $F(r)$, $\varphi(r)$, $G(r)$ from holographic QCD as follows:

$$\begin{aligned}
 S_{\text{HQCD}} &\sim \kappa \int d^4x dz \text{tr} \left(\frac{1}{2} K(z)^{-1/3} F_{\mu\nu} F_{\mu\nu} + K(z) F_{\mu z} F_{\mu z} \right) + O(F^4) \\
 &\sim \int d^4x \left\{ \frac{f_\pi^2}{4} \left[2F'^2 + \frac{2}{3} \varphi'^2 + \frac{8}{r^2} (1 - \cos F \cos \varphi) \right] \right. && \text{(chiral term)} \\
 &\quad + \frac{1}{32e^2} \frac{16}{r^2} \left[(\varphi'^2 + F'^2) (1 - \cos F \cos \varphi) + 2\varphi' F' \sin F \sin \varphi \right. \\
 &\quad \quad \left. \left. + \frac{1}{r^2} \left\{ (1 - \cos F \cos \varphi)^2 + 3 \sin^2 F \sin^2 \varphi \right\} \right] \right. && \text{(Skyrme term)} \\
 &\quad + \frac{1}{2} \left[8 \left(\frac{3}{r^2} G^2 + \frac{2}{r} G G' + G'^2 \right) \right] + m_\rho^2 [4G^2] && \text{(Q-kinetic term / Q-mass term)} \\
 &\quad + g_{3\rho} \left[8 \frac{G^3}{r} \right] + \frac{1}{2} g_{4\rho} [4G^4] && \text{(3Q coupling / 4Q coupling)} \\
 &\quad - g_1 \left[\frac{16}{r} \left\{ \left(\frac{1}{r} G + G' \right) \left(F' \sin \frac{F}{2} \cos \frac{\varphi}{2} + \varphi' \cos \frac{F}{2} \sin \frac{\varphi}{2} \right) + \frac{1}{r^2} G (1 - \cos F \cos \varphi) \right\} \right] && \text{(\partial Q-2}\alpha \text{ coupling)} \\
 &\quad - g_2 \left[\frac{8}{r^2} G^2 (1 - \cos F \cos \varphi) \right] && \text{(2Q-2}\alpha \text{ coupling)} \\
 &\quad + g_3 \left[\frac{16}{r^3} G \left\{ 3 \sin F \sin \frac{F}{2} \sin \varphi \sin \frac{\varphi}{2} + \left(1 - \cos \frac{F}{2} \cos \frac{\varphi}{2} \right) (1 - \cos F \cos \varphi) \right\} \right] && \text{(Q-2}\alpha\text{-}\beta \text{ coupling)} \\
 &\quad - g_4 \left[\frac{16}{r^2} G^2 \left(1 - \cos \frac{F}{2} \cos \frac{\varphi}{2} \right) \right] && \text{(Q-}\partial\text{Q-}\beta \text{ coupling)} \\
 &\quad - g_5 \left[\frac{8}{r} G^3 \left(1 - \cos \frac{F}{2} \cos \frac{\varphi}{2} \right) \right] && \text{(3Q-}\beta \text{ coupling)} \\
 &\quad + g_6 [4G^2 (F'^2 + \varphi'^2)] && \text{(2Q-2}\alpha \text{ coupling)} \\
 &\quad \left. + g_7 \left[\frac{8}{r^2} G^2 \left\{ 3 \sin^2 \frac{F}{2} \sin^2 \frac{\varphi}{2} + \left(1 - \cos \frac{F}{2} \cos \frac{\varphi}{2} \right)^2 \right\} \right] \right\} && \text{(2Q-2}\beta \text{ coupling)}
 \end{aligned}$$

Numerical Results

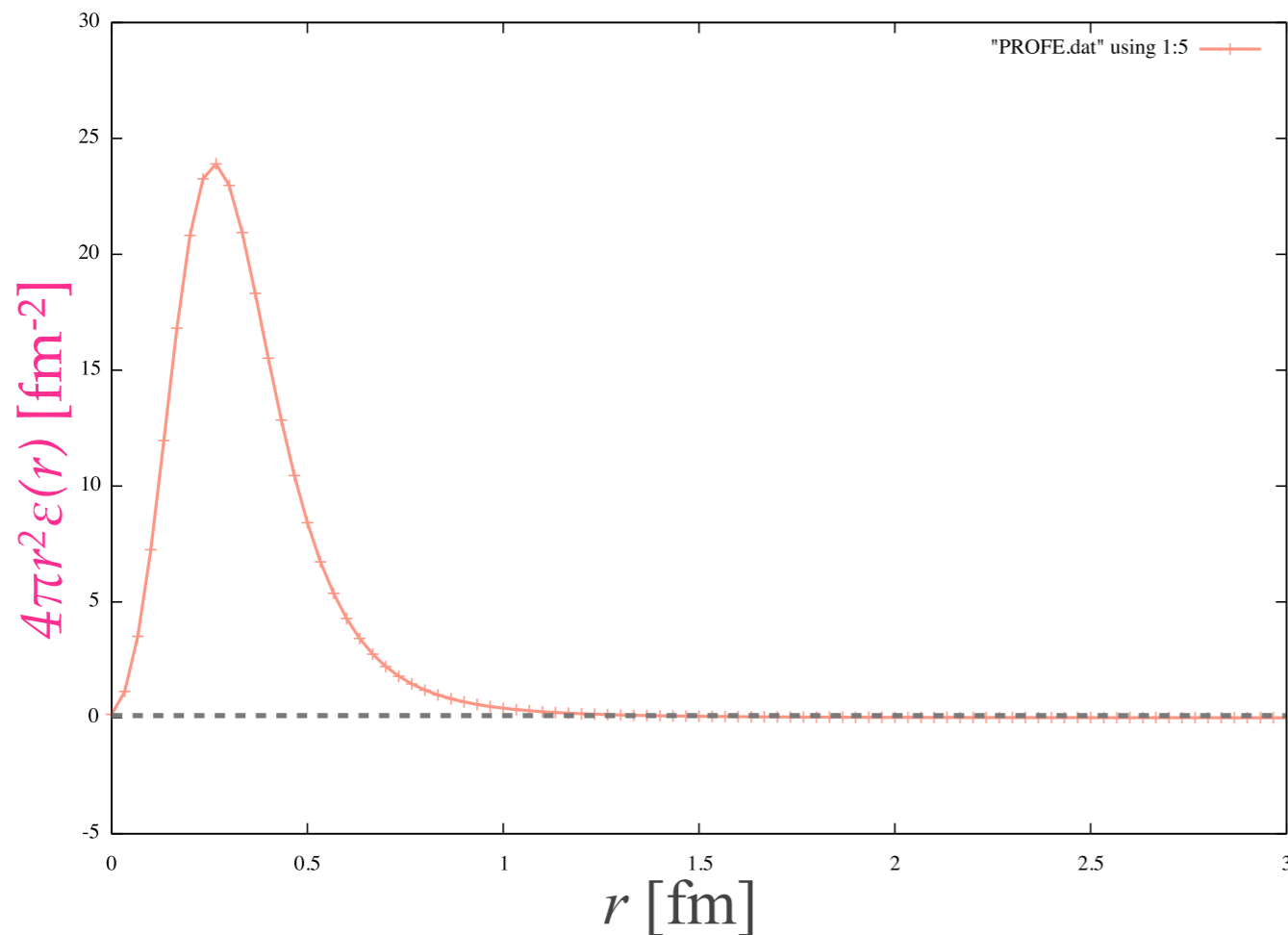
Profile Functions of H-dibaryon



- ❖ SO(3) hedgehog soliton solution exists in this framework.
- ❖ This soliton solution corresponds to H-dibaryon in chiral limit.

Numerical Results

Energy Density of H-dibaryon



$$E[F(r), \varphi(r), G(r)] = 4\pi \int dr r^2 \varepsilon(r)$$

- ✦ By using the energy density, the radius of H-dibaryon can be calculated:

$$\langle r^2 \rangle = \frac{\int dr r^2 \cdot r^2 \varepsilon(r)}{\int dr r^2 \varepsilon(r)}$$

(mean square radius)

Numerical Results

Mass & Radius of H-dibaryon

- ❖ Holographic QCD has just **two** parameters:
 - M_{KK} : energy scale of the theory
 - κ : large- N_c effective theory
- ❖ We determine these two parameters to reproduce **pion decay constant** and **ρ -meson mass**:

$$f_\pi = 92.4 \text{ MeV} , \quad m_\rho = 776.0 \text{ MeV}$$

- ❖ Then, the mass and radius of H-dibaryon (in chiral limit) are:

$$\text{Mass: } M_{\text{H}} \simeq 1673 \text{ MeV} , \quad \text{Radius: } \sqrt{\langle r^2 \rangle} \simeq 0.413 \text{ fm}$$

Comparison to B=1 Soliton Results

Mass: $M_H \simeq 1673 \text{ MeV}$, Radius: $\sqrt{\langle r^2 \rangle} \simeq 0.413 \text{ fm}$

- ❖ The mass and radius of **B=1 hedgehog baryon** in holographic QCD (in chiral limit) are $M_{B=1} \simeq 834.0 \text{ MeV}$, $\sqrt{\langle r^2 \rangle} \simeq 0.37 \text{ fm}$

[K. Nawa, H. Suganuma, T. Kojo, Phys. Rev. D75, 086003 (2007)]

so, we find

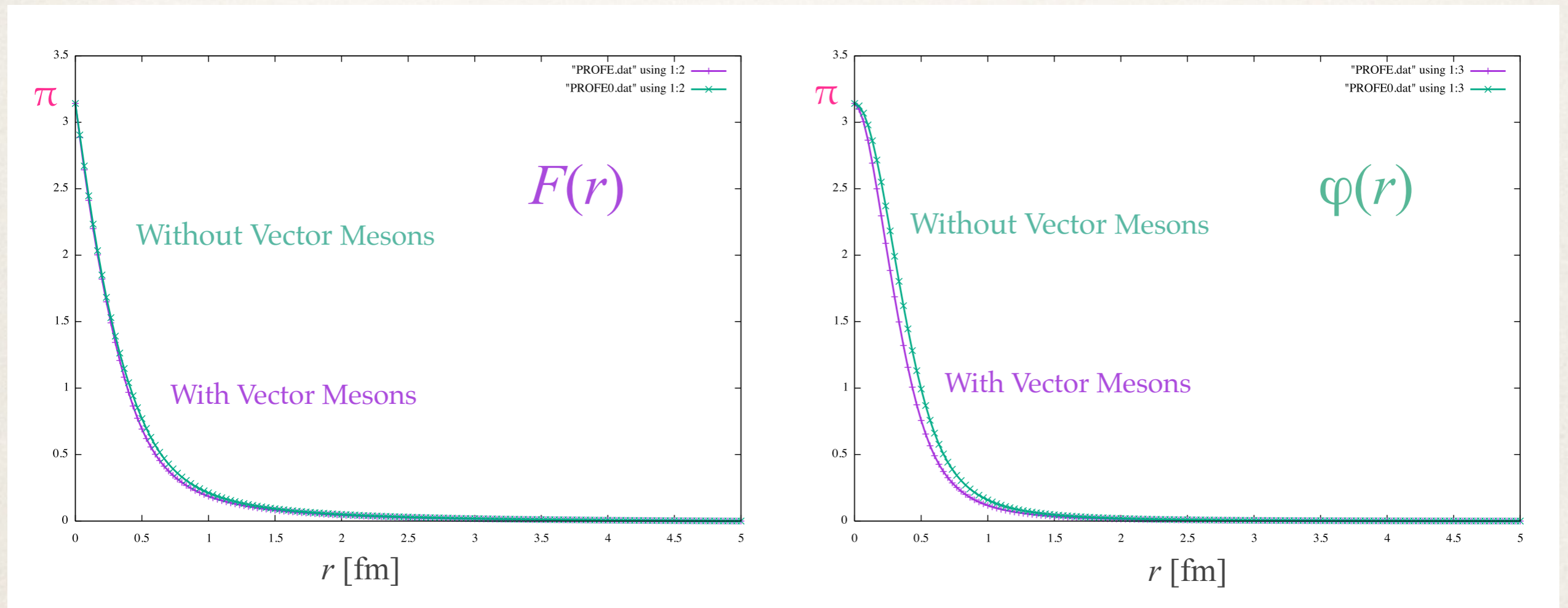
$$M_H \simeq 2.006 M_{B=1} \quad (\text{in chiral limit})$$

- With this result, we can see that the H-dibaryon mass is almost equal to two B=1 hedgehog baryon mass ($M_H \simeq 2M_{B=1}$).
- Then, **H mass is expected to be smaller than two nucleon mass in the chiral limit:**
 - In fact, nucleon (flavor-octet baryon) mass M_N is larger than hedgehog mass $M_{B=1}$ by rotational energy:
 $M_N = M_{B=1} + (\text{rotational energy}) (> M_{B=1})$, and satisfies $M_H < 2M_N$.

(cf. In standard Skyrmion, rotational energy is estimated about 150MeV.)

Vector Meson Effect

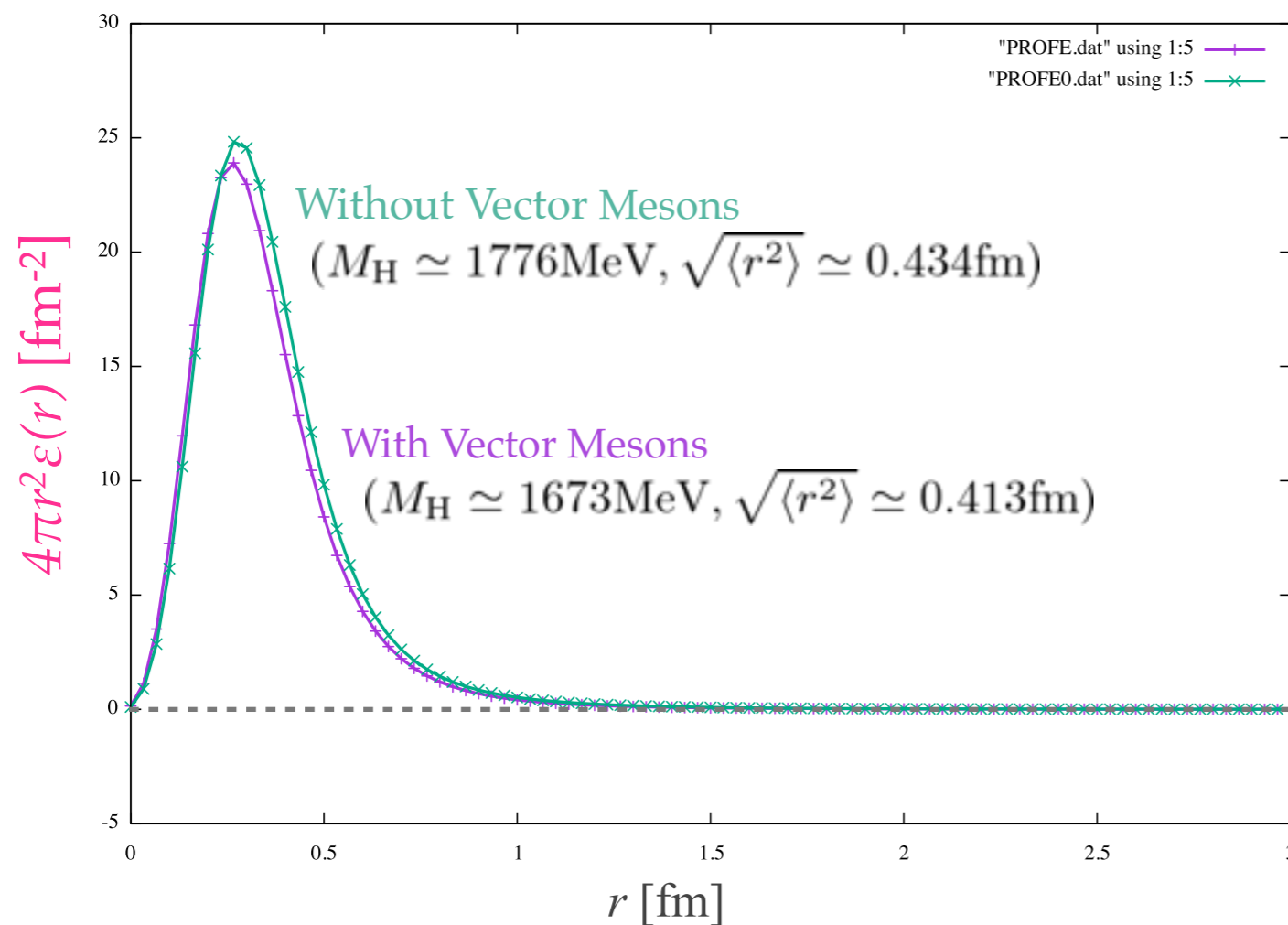
Vector Meson Effect for Chiral Functions $F(r)$, $\varphi(r)$ in H-dibaryon



- ❖ Chiral profiles $F(r)$, $\varphi(r)$ are almost unchanged and shrink slightly by the vector-meson effect.

Vector Meson Effect

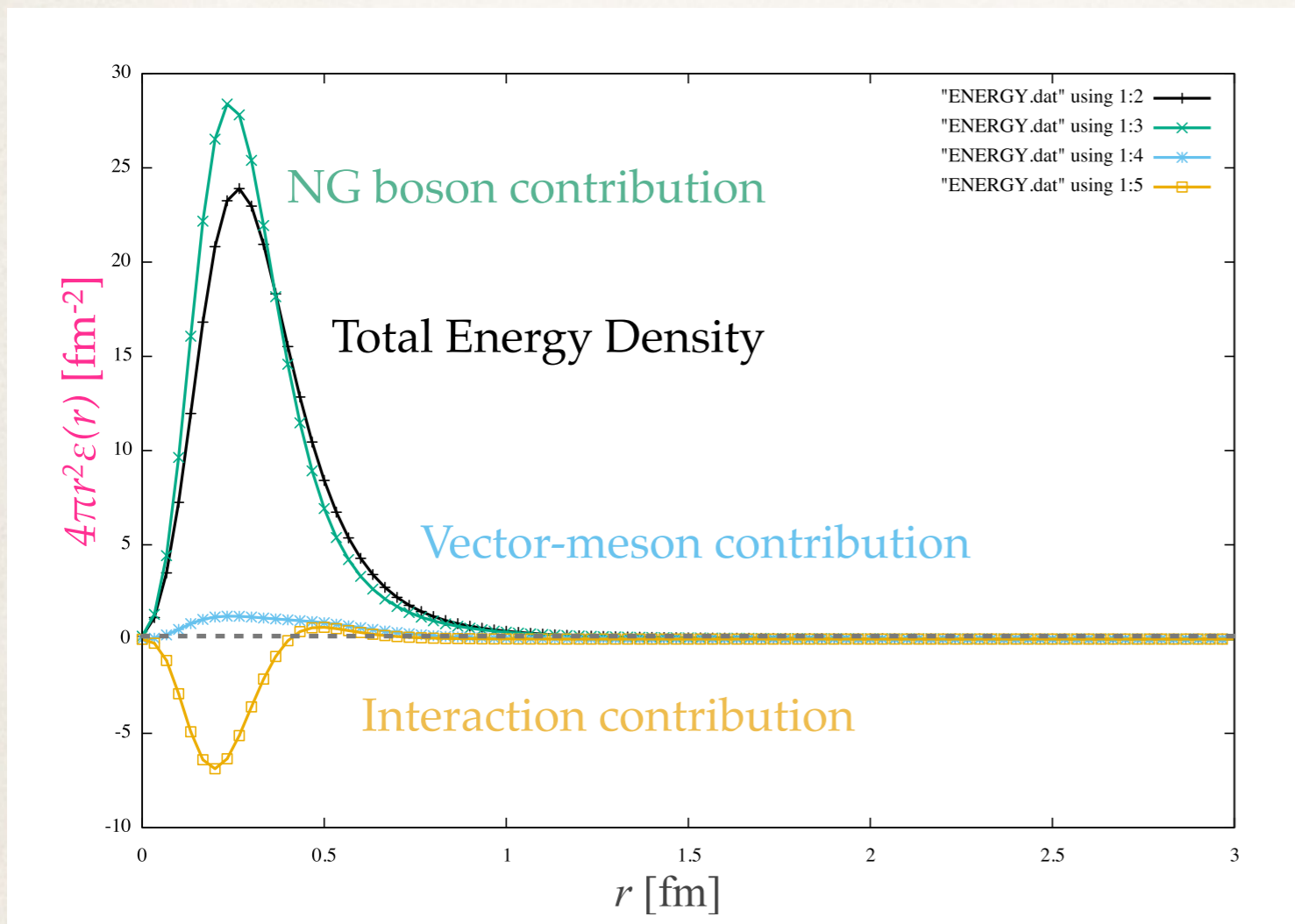
Vector Meson Effect to Energy Density in H-dibaryon



- ❖ The energy density also shrinks slightly by the vector meson effect.
- ❖ About **100MeV (6%) mass reduction** is occurred by the vector meson effect.

Details of Energy Density

Each Contribution to Energy Density in H-dibaryon



Each Contribution to the Energy

Total Energy of Soliton H
1673MeV (100)

NG-boson Contribution
1795MeV (107.3)

Vector-meson Contribution
119MeV (7.1)

Interaction Contribution
-241MeV (-14.4)

- ❖ The H-dibaryon mass is lowered by the interaction between NG bosons and Vector mesons in the interior region of the H-dibaryon.

Contents

1. Introduction
2. Chiral Soliton Model
3. Holographic QCD
4. Results
5. Summary

Summary

- ❖ We have formulated H-dibaryon (uuddss) in holographic QCD.
- ❖ We have investigated H-dibaryon as a soliton solution in holographic QCD, and have found that
 - the H-dibaryon mass is about **1.7GeV in the chiral limit**, which can be smaller than the two nucleon mass.
 - chiral profile functions $F(r)$, $\varphi(r)$ and energy density **shrink slightly** by the vector-meson effect.