Properties of Baryons in Holographic QCD

Shigeki Sugimoto (IPMU)

Based on

arXiv:0806.3122 K.Hashimoto, T.Sakai and S.S.

hep-th/0701280 H.Hata, T.Sakai, S.S. and S.Yamato

Closely related works:

arXiv:0807.0033 K.Y.Kim and I.Zahed

arXiv:0803.0180 H.Hata, M.Murata and S.Yamato

hep-th/0701276, arXiv:0705.2632, **arXiv:0710.4615, …**
D.K.Hong, M.Rho, H.U.Yee and P.Yi

Seminar @ IPMU 2008/10/28

Part I

① Introduction

② Brief summary of the model

----- 5 minutes break -----

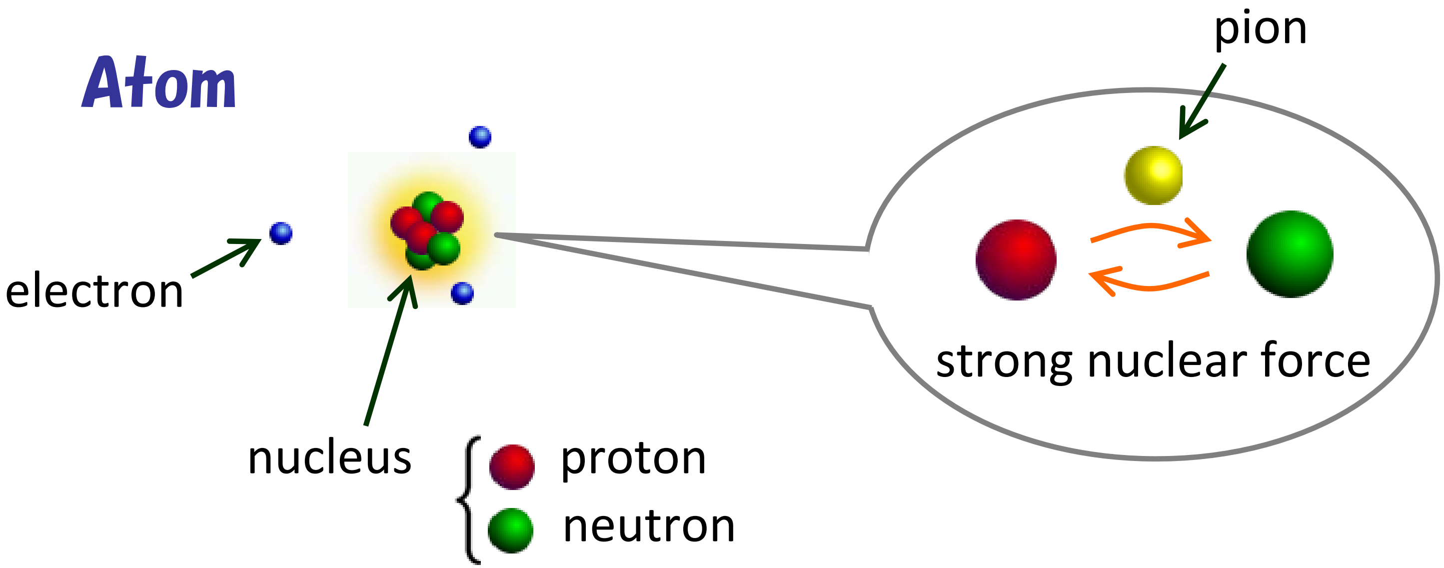
Part II

③ Baryons as instantons

⋮

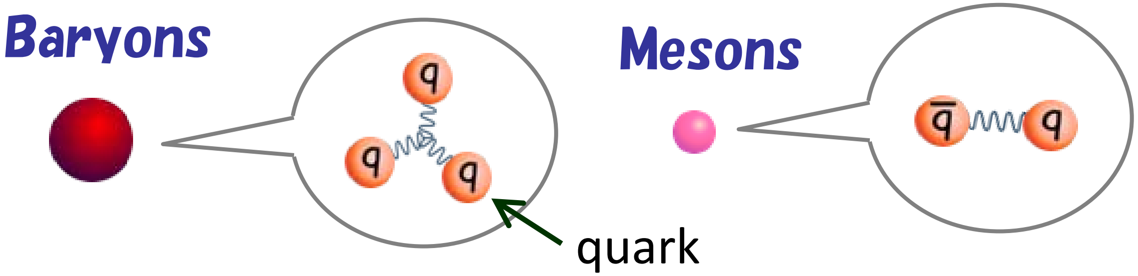
① Introduction

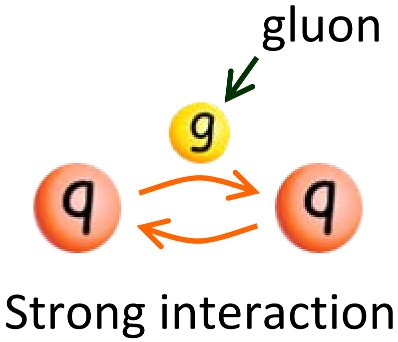
Baryons and Mesons



hadron
- **baryon** p n Λ Σ Δ etc.
- **meson** π K η ρ ω etc.

Quark model and QCD





QCD

$SU(N_c)$ gauge theory $(N_c = 3)$

A_μ ψ^i $i = 1, 2, \cdots, N_f$

g q (u d s $\cdots$)

(gluon) (quark)

- In this talk, we mainly consider light quarks: u d ($N_f = 2$)

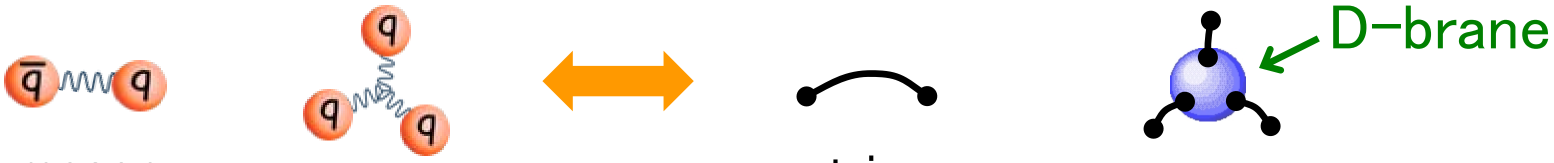
Claim :

Hadrons can be described by ***string theory***
without using quarks !

QCD

dual !

String theory
(in a certain curved background)



meson

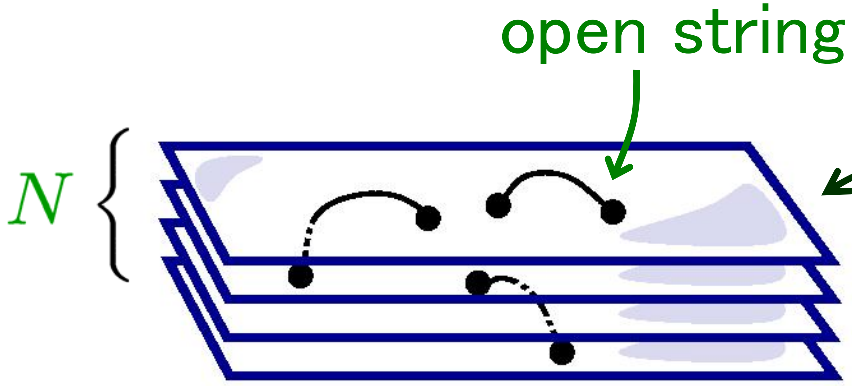
baryon

string

D−brane with N_c strings

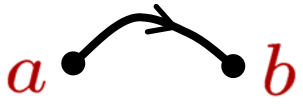
② Brief summary of the model

D-brane and Gauge theory



Dp-brane

$\simeq$ (p+1) dim. plane,
on which open strings
can end.



$a, b = 1 \sim N$

→ massless mode

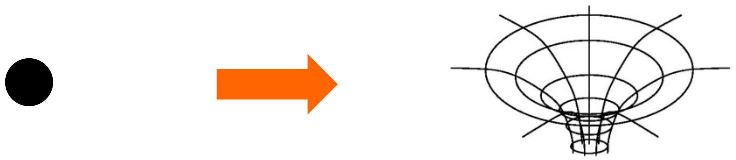
$(A_\mu)^a{}_b$ etc.

$U(N)$ gauge field

➡ (p+1) dim. $U(N)$ gauge theory
is realized on the Dp-brane.

Gauge / string duality

- In general relativity, a (heavy) particle is represented as a curved background



Solution of Einstein eq.

- In string theory, a D-brane system is represented as a curved background

Solution of supergravity EOM

$U(N_c)$ gauge theory ↔ String theory in this background

dual

Recently, we proposed

[Sakai-S.S. 2004]

Type IIA string theory
in Witten's D4 background

\+ N_f Probe D8-branes
(assuming $N_c \gg N_f$)

dual ⟷

↑ at low energy

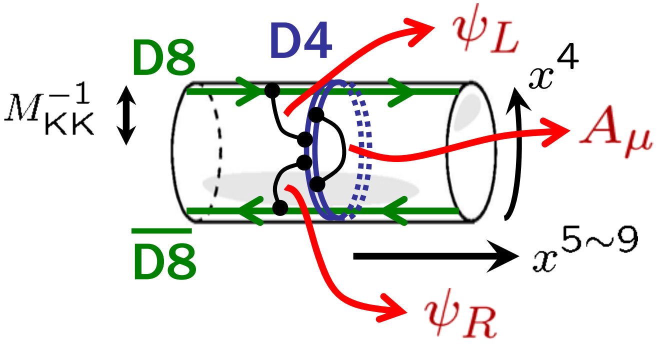
4 dim QCD with
N_f massless quarks

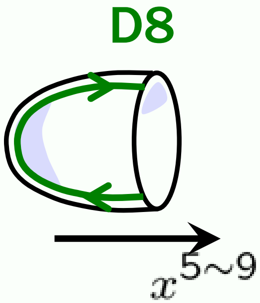
$\overset{N_c}{\text{D4}}$-$\overbrace{\text{D8-}\overline{\text{D8}}}^{N_f \text{ pairs}}$ system
on S^1 (with ~~SUSY~~ b.c.)

QCD with N_f massless quarks
(at low energy)

dual

String theory
in the D4 background
\+ N_f probe D8-branes
(assuming $N_c \gg N_f$)

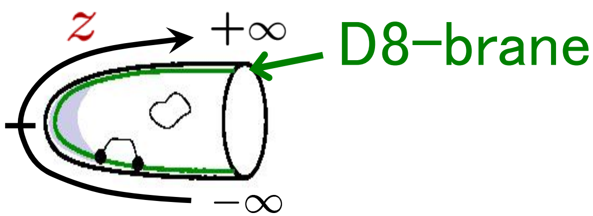




Hadrons in the model

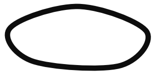
The topology of the D4 background is

$$\underset{x^\mu}{\mathbf{R}^{1,3}} \times \underset{(y,z)}{\mathbf{R}^2} \times S^4$$



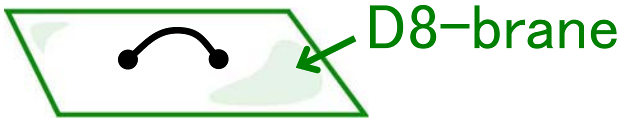
D8−branes are extended along $(x^\mu, z) \times S^4$

- Closed strings → glueballs



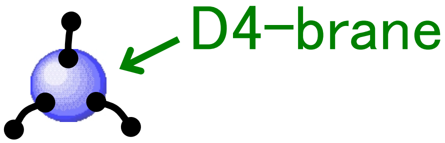
[Csaki-Ooguri-Oz-Terning 1998,
Koch-Jevicki-Mihailescu-Nunes 1998,
A.Hashimoto-Oz 1998,
Brower-Mathur-Tan 2000, etc etc]

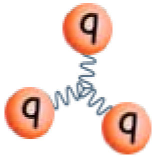
- Open strings on D8 → mesons



[Sakai-S.S. 2004,2005]

- D4 wrapped on S^4 → baryons

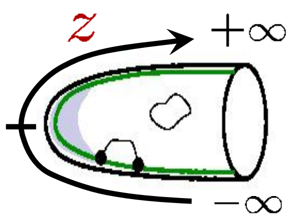




[Witten, Gross-Ooguri 1998]

The effective theory of mesons (open strings)

N_f D8-branes extended along $(x^\mu, z)\times S^4 \subset \mathbf{R}^{1,3}\times\boxed{\mathbf{R}^2}\times S^4$



← Low energy

9 dim $U(N_f)$ gauge theory

← Reducing S^4 (Here we only consider *SO(5)* invariant states)

5 dim $U(N_f)$ YM-CS theory

$A_\mu(x^\nu, z), A_z(x^\nu, z)$ $\mu,\nu = 0 \sim 3$

5 dim gauge field

$$S_{\text{5dim}} \simeq S_{\text{YM}} + S_{\text{CS}}$$

$k(z) = 1 + z^2$

CS5-form

$$S_{\text{YM}} = \kappa \int d^4x dz \, \text{Tr}\left(\frac{1}{2}h(z)F_{\mu\nu}^2 + k(z)F_{\mu z}^2\right) \qquad S_{\text{CS}} = \frac{N_c}{24\pi^2}\int_5 \omega_5(A)$$

$h(z) = (1+z^2)^{-1/3}$

$\kappa = \frac{\lambda N_c}{216\pi^3} \equiv a\lambda N_c$

$(M_{\text{KK}} = 1 \text{ unit})$

[See also, Son-Stephanov 2003]

5 dim YM-CS theory = 4 dim meson theory

$$A_\mu(x^\mu, z) = \sum_{n\geq 1} B_\mu^{(n)}(x^\mu)\psi_n(z)$$

$$A_z(x^\mu, z) = \sum_{n\geq 0} \varphi^{(n)}(x^\mu)\phi_n(z)$$

complete sets

Chosen to diagonalize kinetic & mass terms of $B_\mu^{(n)}, \varphi^{(n)}$

$\varphi^{(0)} \sim$ pion $\quad B_\mu^{(1)} \sim \rho$ meson $\quad B_\mu^{(2)} \sim a_1$ meson $\quad \cdots$

$$\boxed{S_{\text{5dim}}(A) \;=\; S_{\text{4dim}}(\pi, \rho, a_1, \rho', a_1', \cdots)}$$

- Reproduces old phenomenological models
  - Vector meson dominance [Gell-Mann-Zachariasen 1961, Sakurai 1969]
  - Gell-Mann Sharp Wagner model [Gell-Mann -Sharp-Wagner 1962]
  - Hidden local symmetry [Bando-Kugo-Uehara-Yamawaki-Yanagida 1985]
- Masses and couplings roughly agree with experiments.

Quantitative tests

[Sakai-S.S. 2004, 2005]

(Our model vs Experiment)

Meson mass

mass	ρ	a_1	ρ'
exp.(MeV)	776	1230	1465
our model	[776]	1189	1607
ratio	[1]	1.03	0.911

↑ input $(M_{\text{KK}} \simeq 949\ \text{MeV})$

coupling

coupling		fitting m_ρ and f_π	experiment
f_π	$1.13 \cdot \kappa^{1/2} M_{\text{KK}}$	[92.4 MeV]	92.4 MeV
L_1	$0.0785 \cdot \kappa$	0.584×10^{-3}	$(0.1 \sim 0.7) \times 10^{-3}$
L_2	$0.157 \cdot \kappa$	1.17×10^{-3}	$(1.1 \sim 1.7) \times 10^{-3}$
L_3	$-0.471 \cdot \kappa$	-3.51×10^{-3}	$-(2.4 \sim 4.6) \times 10^{-3}$
L_9	$1.17 \cdot \kappa$	8.74×10^{-3}	$(6.2 \sim 7.6) \times 10^{-3}$
L_{10}	$-1.17 \cdot \kappa$	-8.74×10^{-3}	$-(4.8 \sim 6.3) \times 10^{-3}$
$g_{\rho\pi\pi}$	$0.415 \cdot \kappa^{-1/2}$	4.81	5.99
g_ρ	$2.11 \cdot \kappa^{1/2} M_{\text{KK}}^2$	$0.164\ \text{GeV}^2$	$0.121\ \text{GeV}^2$
$g_{a_1\rho\pi}$	$0.421 \cdot \kappa^{-1/2} M_{\text{KK}}$	4.63 GeV	$2.8 \sim 4.2$ GeV

Outline of Part II

Baryon = D4-brane wrapped on S^4

= "**instanton**" on D8-brane

Gauge config. with $\frac{1}{8\pi^2}\int_{\Sigma_4} \mathrm{Tr}\, F \wedge F \neq 0$

4 dim space $\Sigma_4 \ni (\vec{x}, z)$

$\Downarrow$

Quantization

$\Downarrow$

Baryon spectrum, charge radii,
magnetic moments, form factor, etc.

5 minutes break

Part I

✓ ① Introduction
✓ ② Brief summary of the model

----- 5 minutes break -----

Part II

③ Baryons as instantons
④ Quantization
⑤ Currents
⑥ Exploration
⑦ Conclusion

③ Baryons as instantons

Baryon as wrapped D4-brane

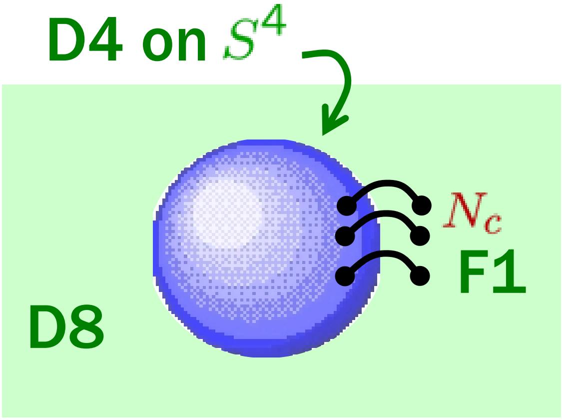
- Baryons in the AdS/CFT context are constructed by wrapped D-branes

[Witten 1998, Gross-Ooguri 1998]

In our case,

Baryon $\simeq$ D4-brane wrapped on the S^4

- RR flux $\frac{1}{2\pi}\int_{S^4} dC_3 = N_c$ forces N_c F-strings to be attached on it.



→ **Bound state of N_c quarks**

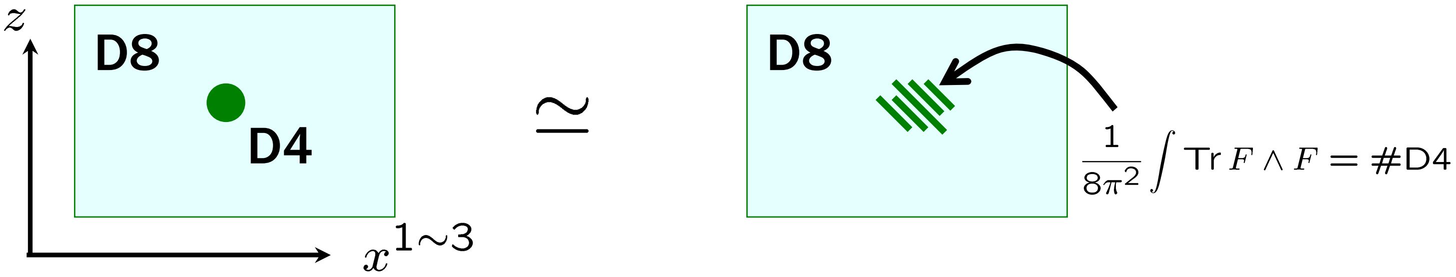
→ **Baryon**

Baryon mass ($\propto$ vol. of S^4) is generated by the geometry!

Baryon as instanton

- In our model, the wrapped D4 can be embedded in D8.

D4 within D8 $\simeq$ **instanton on D8** [Douglas 1995]



$$\frac{1}{8\pi^2}\int \mathrm{Tr}\, F \wedge F = \#\mathrm{D4}$$

➡

baryon # **Instanton #**

$$N_B = \frac{1}{8\pi^2}\int \mathrm{tr} F \wedge F$$

Prototype : Skyrme model

- In 1961, Skyrme proposed

Baryons are solitons (Skyrmion) in a pion effective theory.

Pion field: $U(\vec{x}) \in U(N_f) \quad (\vec{x} \in \mathbf{R}^3)$ with $U(\infty) = 1$

→ classified by $\pi_3(U(N_f)) \simeq \mathbf{Z}$ ← # **baryon**

- In 1983, Adkins-Nappi-Witten (ANW)

succeeded to calculate the static properties of baryons (mean square radii, magnetic moment, axial coupling, etc.) by quantizing the collective modes of the Skyrmion.

→ Roughly agree with the experimental data!

Q. Can we apply the idea of ANW to our system?

Classical solution (We consentrate on the $N_f = 2$ case.)

- The instanton solution for the Yang-Mills action

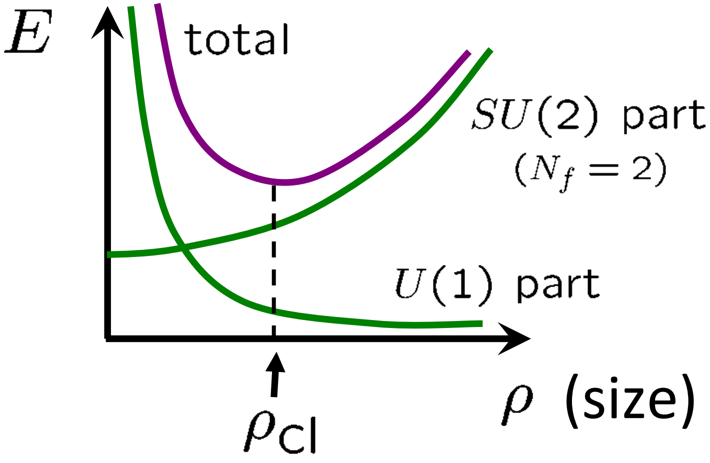
$$S_{\mathrm{YM}} = \kappa \int d^4x dz\, \mathrm{Tr}\left(\frac{1}{2}h(z)F_{\mu\nu}^2 + k(z)F_{\mu z}^2\right)$$

shrinks to zero size !

- The Chern-Simons term makes it larger

$$S_{\mathrm{CS}} = \frac{N_c}{24\pi^2}\int_5 \omega_5(A) = \frac{N_c}{16\pi^2}\int d^4x dz\, \overset{U(1)\text{ part}}{A_0^{U(1)}}\, \underbrace{\epsilon^{ijk}\mathrm{Tr}F_{ij}F_{kz}}_{\text{Non-zero for instanton}} + \cdots$$

→ source of the U(1) charge

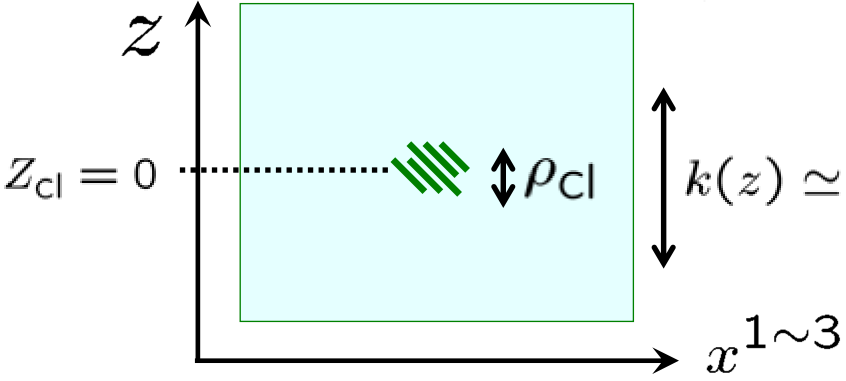


→ $$\boxed{\text{Stabilized at } \rho_{\mathrm{cl}}^2 = \frac{N_c}{8\pi^2\kappa}\sqrt{\frac{6}{5}}}$$

[Hong-Rho-Yee-Yi 2007]
[Hata-Sakai-S.S.-Yamato 2007]

- Note that $\rho_{\rm cl} \sim \mathcal{O}(\lambda^{-1/2})$

If λ is large enough, the 5 dim space-time can be approximated by the flat space-time. (The effect of the non-trivial z-dependence is taken into account perturbatively.)



$k(z) \simeq h(z) \simeq 1 \quad (\text{for } |z| \ll 1)$

➡ The leading order classical solution is the BPST instanton with $\rho = \rho_{\rm cl}$ and $Z = Z_{\rm cl} = 0$

$$A_M^{\rm cl} = -i \frac{\xi^2}{\xi^2 + \rho^2} g \partial_M g^{-1} \qquad g = \frac{(z - Z) - i(\vec{x} - \vec{X}) \cdot \vec{\tau}}{\xi}$$

$$\xi = \sqrt{(\vec{x} - \vec{X})^2 + (z - Z)^2}$$

ρ **: size** $(\vec{X}, Z)$ **: position of the instanton**

④ Quantization

[Hata-Sakai-S.S.-Yamato 2007]

- Consider a slowly moving (rotating) baryon configuration.

moduli space approximation method :

Instanton moduli $\mathcal{M} \ni (X^\alpha) \rightarrow (X^\alpha(\underset{\substack{\uparrow \\ \textbf{time}}}{t}))$ $(\alpha = 1, 2, \cdots, \dim \mathcal{M})$

$$\boxed{A_M(t,x) \sim A_M^{\text{cl}}(x; X^\alpha(t))}$$

$$\downarrow$$

$S_{\text{5dim}} \rightarrow$ **Quantum Mechanics for** $X^\alpha(t)$

- For SU(2) one instanton,

$$\mathcal{M} \simeq \{(\underbrace{\vec{X}, Z}_{\text{position}}, \underset{\substack{\nwarrow \\ \text{size}}}{\rho})\} \times \underset{\substack{\cup \\ \mathbf{a} \;\leftarrow\; \textit{SU(2)}\text{ orientation}}}{SU(2)}/\mathbf{Z_2} \qquad \mathbf{Z}_2 : \mathbf{a} \to -\mathbf{a}$$

$$\rightarrow \quad L_{\text{QM}} = \frac{G_{\alpha\beta}}{2}\dot{X}^\alpha \dot{X}^\beta - U(X^\alpha) \qquad U(X^\alpha) = 8\pi^2\kappa\left(1 + \left(\frac{\rho^2}{6} + \frac{3^6\pi^2}{5\,\lambda^2\rho^2} + \frac{Z^2}{3}\right) + \cdots\right)$$

<u>**Note**</u> $(\vec{X}, \mathbf{a})$: genuine moduli (the same as in the Skyrme model)

(ρ, Z) : new degrees of freedom, added since they are light compared with the other massive modes.

- Solving the Schrodinger equation for this Quantum mechanics, we obtain the baryon states

→ Generalization of Adkins-Nappi-Witten including vector mesons and ρ , Z modes

We can construct baryon states for

$$n, p, \Delta(1232), N(1440), N(1530), \cdots$$

Example Nucleon wave function:

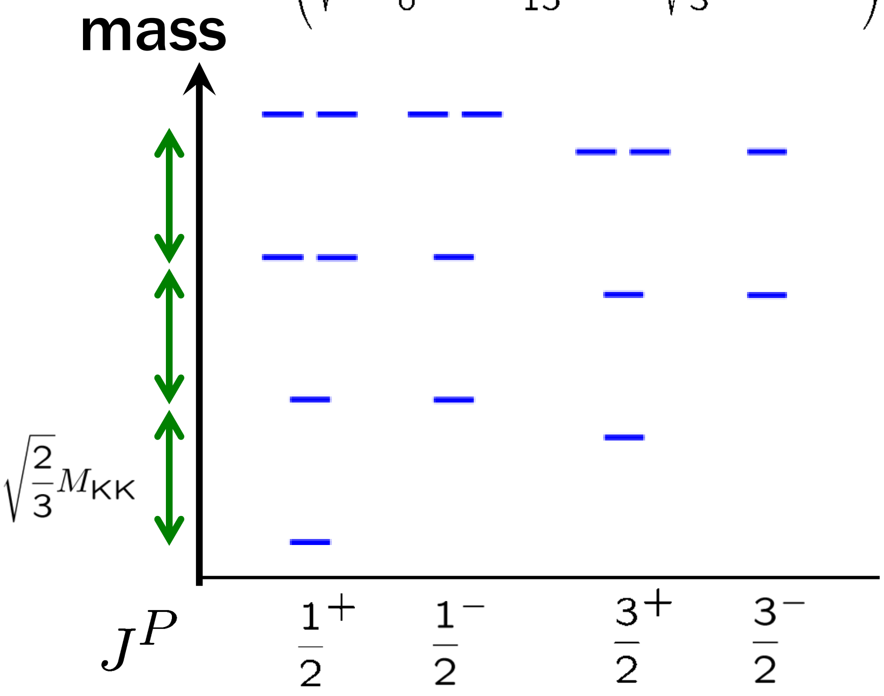
$$\psi(\vec{X}, \mathbf{a}, \rho, Z) \propto e^{i\vec{p}\cdot\vec{X}} R(\rho)\psi_Z(Z)T(\mathbf{a})$$

$$\left(\begin{array}{ll} R(\rho) = \rho^{\tilde{l}} e^{-A\rho^2} & \tilde{l} = -1 + 2\sqrt{1 + N_c^2/5} \\ \psi_Z(Z) = e^{-AZ^2} & A = \frac{8\pi^2\kappa}{\sqrt{6}} \\ T(\mathbf{a}) = a_1 + ia_2 \text{ for } |p\uparrow\rangle \quad \text{etc.} & \end{array} \right)$$

Baryon spectrum

Theory

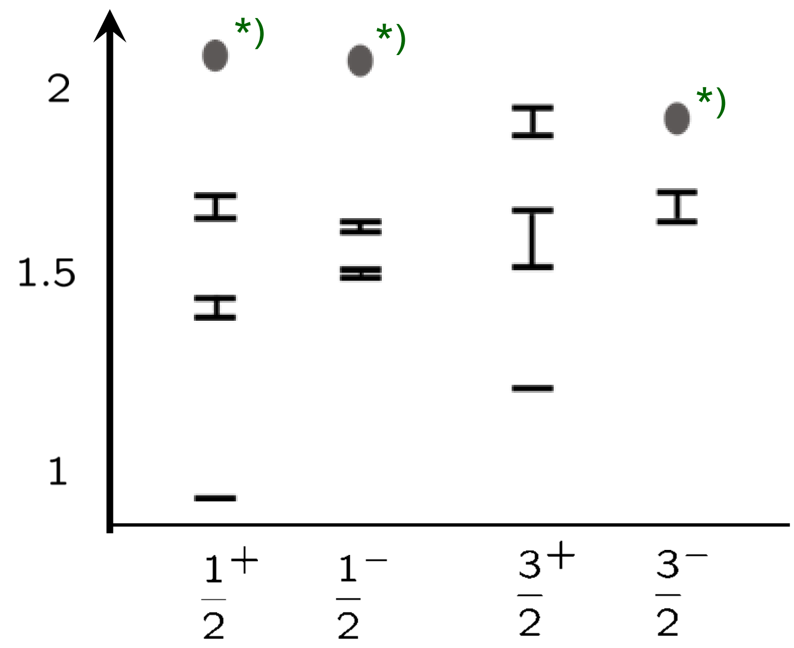
$$M \simeq M_0 + \left(\sqrt{\frac{(l+1)^2}{6} + \frac{2}{15}N_c^2} + \sqrt{\frac{2}{3}}(n_\rho + n_z)\right) M_{\rm KK}$$



Experiment

($I = J$ states from PDG)

*) Evidence for existence is poor



Note:

- We only consider the mass difference, since $\mathcal{O}(N_c^0)$ term in M_0 is not known.
- $M_{\rm KK} \simeq 949$ MeV (fixed by ρ -meson mass) is a bit too large. It looks better if $M_{\rm KK}$ were around 500 MeV .

⑤ Currents

[Hashimoto-Sakai-S.S.2008]

[See also, Hata-Murata-Yamato 2008]

- Chiral symmetry

$$U(N_f)_L \times U(N_f)_R \xrightarrow{\text{gauge}} (A_{L\mu}(x), A_{R\mu}(x))$$

- Interpreted as

$$A_{L\mu}(x) = \lim_{z\to+\infty} A_\mu(x,z) \qquad A_{R\mu}(x) = \lim_{z\to-\infty} A_\mu(x,z)$$

$$\Rightarrow \quad S_{5\,\mathrm{dim}}\Big|_{\mathcal{O}(A_L,A_R)} = -\int d^4x \left(A^a_{L\mu} J^{a\mu}_L + A^a_{R\mu} J^{a\mu}_R\right)$$

with

$$\boxed{J_{L\mu} = -\kappa\left(k(z)F_{\mu z}\right)\Big|_{z=+\infty} \qquad J_{R\mu} = +\kappa\left(k(z)F_{\mu z}\right)\Big|_{z=-\infty}}$$

- vector and axial vector currents

$$J^\mu_V \equiv J^\mu_L + J^\mu_R = -\kappa\left[k(z)F^{\mu z}\right]^{z=+\infty}_{z=-\infty}$$

$$J^\mu_A \equiv J^\mu_L - J^\mu_R = -\kappa\left[\psi_0(z)k(z)F^{\mu z}\right]^{z=+\infty}_{z=-\infty} \quad (\psi_0(\pm\infty) = \pm 1)$$

How to calculate

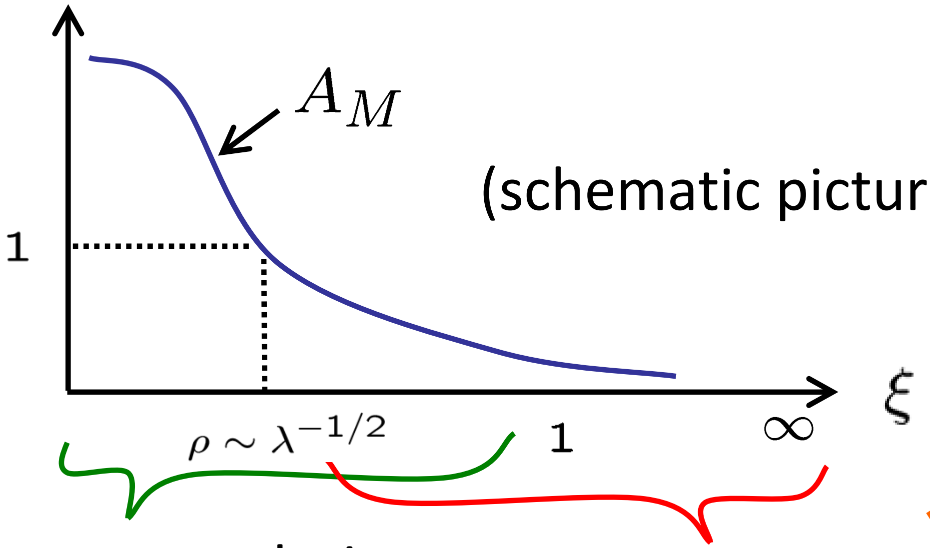
- We need to know how $F_{\mu z}(x,z)$ behaves at $z \to \pm\infty$

  ➡ We cannot use the solution in the flat space.

- The EOM are complicated non-linear equations.

  ➡ difficult to solve exactly.

- We use the following trick to calculate the currents.



(schematic picture)

Instanton solution in the flat space

Non-linear terms are small

➡ Approximated by linearized EOM

↳ Now we can solve!

⑥ Exploration

[Hashimoto-Sakai-S.S.2008]

[See also, Hong-Rho-Yee-Yi 2007,
Hata-Murata-Yamato 2008,
Kim-Zahed 2008]

Now we are ready to calculate various physical quantities

But, don't trust too much !

- λ may not be large enough.
- Higher derivative terms may contribute.
- $N_c = 3$ is not large enough.
- The model deviates from real QCD at high energy $\sim M_{\rm KK}$
- We use $M_{\rm KK} \simeq 949\ {\rm MeV}$ (value consistent with ρ meson mass)
  But we know this is too large to fit the baryon mass differences.

Baryon number current

$$J_B^\mu = -\frac{2}{N_c}\kappa\Big[k(z)F_{U(1)}^{\mu z}\Big]_{z=-\infty}^{z=+\infty}$$

U(1) part of the U(2) gauge field

$$\Downarrow$$

$$\boxed{J_B^0 \simeq \Big[k(z)\partial_z G\Big]_{z=-\infty}^{z=+\infty} \qquad J_B^i \simeq -\frac{J^j}{16\pi^2\kappa}\epsilon^{ijk}\partial_k J_B^0 + \cdots}$$

(G : Green's function $(h(z)\partial_i^2 + \partial_z k(z)\partial)G = \delta^3(\vec{x} - \vec{X})\delta(z - Z)$

J^j : Spin operator $J^j = -i4\pi^2\kappa\rho^2\,\mathrm{tr}(\tau^j \mathrm{a}^{-1}\dot{\mathrm{a}})$)

Note: $k(z) \sim z^2, \quad \partial_z G \sim 1/z^2$ at $z \to \pm\infty$

→ J_B^μ is non-zero, finite.

Isoscalar mean square radius

$$\langle r^2\rangle_{I=0} = \int d^3x\, r^2\, J_B^0 \simeq (0.742\ \mathrm{fm})^2$$

↑

Numerical estimate using $M_{\mathrm{KK}} \simeq 949\ \mathrm{MeV}$

(fixed by ρ -meson mass)

$$\left(\mathrm{cf.}\ \langle r^2\rangle_{I=0}^{1/2}\Big|_{\mathrm{exp}} = 0.806\ \mathrm{fm}\,,\ \langle r^2\rangle_{I=0}^{1/2}\Big|_{\mathrm{ANW}} = 0.59\ \mathrm{fm}\right)$$

↑

Results for the Skyrme model
(Adkins-Nappi-Witten 1983)

Isoscalar magnetic moment

$$\mu^i_{I=0} = \frac{1}{2}\epsilon^{ijk}\int d^3x\, x^j J^k_B \simeq \frac{J^i}{16\pi^2\kappa}$$

$$J^i_B \simeq -\frac{J^j}{16\pi^2\kappa}\epsilon^{ijk}\partial_k J^0_B + \cdots$$

For a spin up proton state $|p\uparrow\rangle$

Isoscalar g-factor

$$\langle p\uparrow|\,\mu^i_{I=0}\,|p\uparrow\rangle = \frac{\delta^{i3}}{32\pi^2\kappa} \equiv \frac{g_{I=0}}{4M_N}\delta^{i3}$$

Nucleon mass

($M_N \simeq 940$ MeV)

➡ $$g_{I=0} = \frac{M_N}{8\pi^2\kappa M_{\mathrm{KK}}} \simeq 1.68$$

$M_{\mathrm{KK}} \simeq 949$ MeV, $\kappa \simeq 0.00745$

(fixed by m_ρ) (fixed by f_π)

$$\left(\text{cf. } g_{I=0}\big|_{\exp} \simeq 1.76,\ \ g_{I=0}\big|_{\mathrm{ANW}} = 1.11\right)$$

Summary of the results

	our result	exp.	ANW
$\langle r^2 \rangle^{1/2}_{I=0}$	0.742 fm	0.806 fm	0.59 fm
$\langle r^2 \rangle^{1/2}_{I=1}$	0.742 fm	0.939 fm	∞ ※
$\langle r^2 \rangle^{1/2}_{A}$	0.537 fm	0.674 fm	—
$g_{I=0}$	1.68	1.76	1.11
$g_{I=1}$	7.03	9.41	6.38
g_A	0.734	1.27	0.61

※ pion loop contribution is log divergent in the chiral limit.
Our calculation corresponds to the tree level in ChPT.

- We can also evaluate these for excited baryons such as $\Delta(1232), N(1440), N(1535), \cdots$

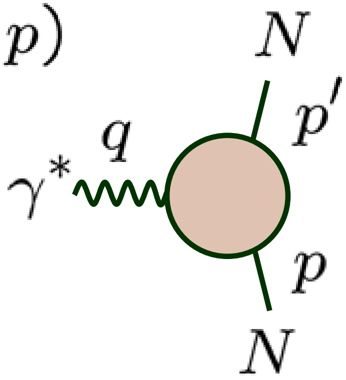
Form factors

Dirac form factor ↓ Pauli form factor ↓

$$\langle N,\vec{p}'|J^{\mu}_{\rm em}(0)|N,\vec{p}\rangle = \overline{u}(p',s')\left[\gamma^{\mu}F_1(q^2)+\frac{i}{2m_N}\sigma^{\mu\nu}q_{\nu}F_2(q^2)\right]u(p,s)$$

$$(q = p' - p)$$

Breit frame: $\vec{p}' = -\vec{p} = \vec{q}/2$



$$\langle N,\vec{q}/2|J^{0}_{\rm em}(0)|N,-\vec{q}/2\rangle = G_E(\vec{q}^2)\,\chi^{\dagger}_{s'}\chi_s$$

$$\langle N,\vec{q}/2|J^{i}_{\rm em}(0)|N,-\vec{q}/2\rangle = \frac{i}{2m_N}G_M(\vec{q}^2)\,\chi^{\dagger}_{s'}(\vec{q}\times\vec{\sigma})\chi_s$$

Sachs form factor

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_N^2}F_2(q^2)$$ Electric form factor

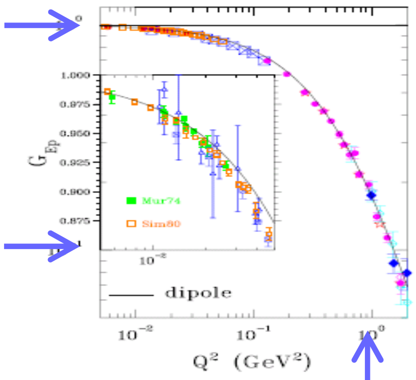
$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$ Magnetic form factor

Dipole behavior

Experimental data suggest

dipole $(\Lambda \simeq 0.71 \text{ GeV}^2)$

$$G_E^p(Q^2) \simeq \frac{1}{\mu_p} G_M^p(Q^2) \simeq \frac{1}{\mu_n} G_M^n(Q^2) \simeq \frac{1}{(1+\frac{Q^2}{\Lambda^2})^2} \qquad G_E^n(Q^2) \simeq 0$$

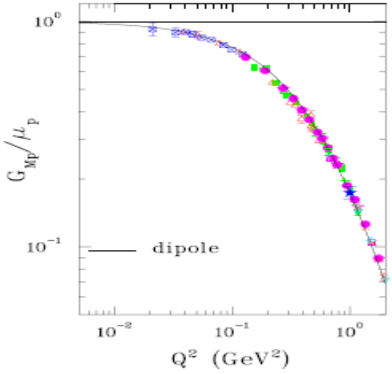


G_E^p

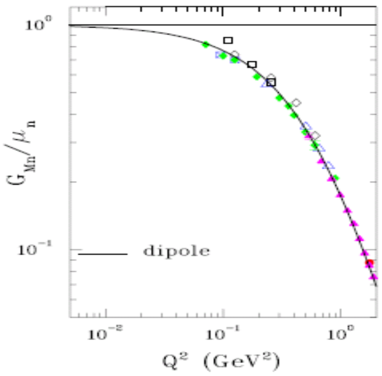
1 →

0.1 →

↑ 1 GeV²



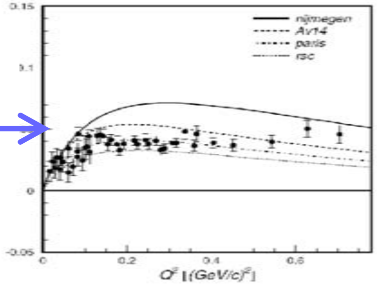
G_M^p/μ_p



G_M^n/μ_n

—— : dipole

dots : data



G_E^n

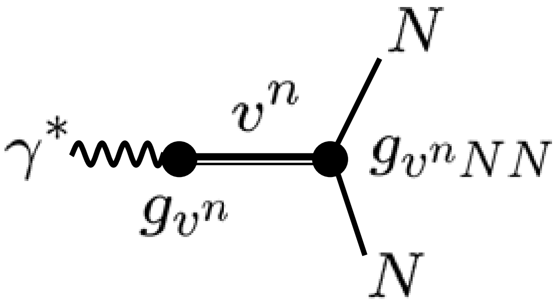
0.05 →

Our result

$$G_E^p(Q^2) = \frac{1}{\mu_p} G_M^p(Q^2) = \frac{1}{\mu_n} G_M^n(Q^2) = \sum_{n \geq 1} \frac{g_{v^n} g_{v^n NN}}{Q^2 + m_n^2} \qquad G_E^n(Q^2) = 0$$

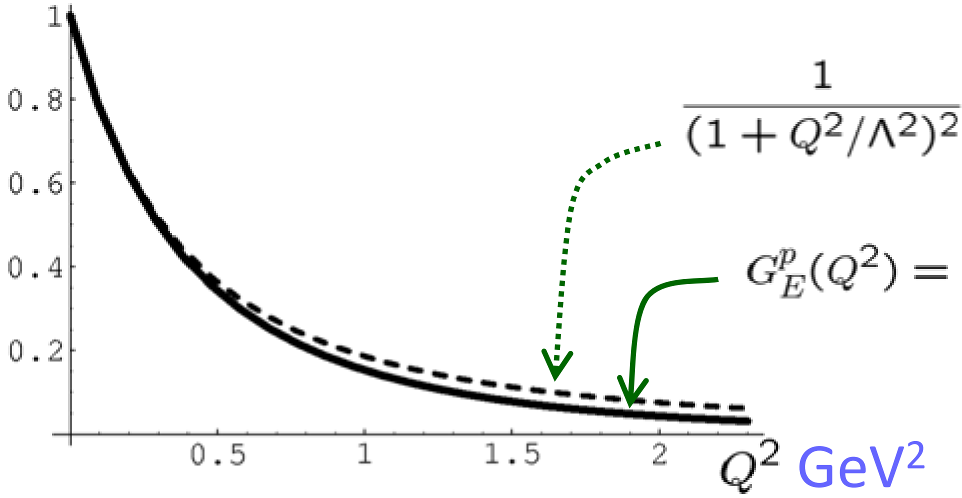
with $g_{v^n} = -2\kappa(k(z)\partial_z \psi_{2n-1})\Big|_{z=+\infty}$

$$g_{v^n NN} = \langle \psi_{2n-1}(Z) \rangle$$



Vector meson dominance

- Can this be compatible with dipole?



$\frac{1}{(1+Q^2/\Lambda^2)^2}$ dipole

$G_E^p(Q^2) = \sum_{n\geq 1} \frac{g_{v^n} g_{v^n NN}}{Q^2 + m_n^2}$ our result

- Taylor expansion

(※ here we use the approximation $g_{v^n NN} = \langle \psi_{2n-1}(Z) \rangle \simeq \psi_{2n-1}(0)$)

$$G_E^p(Q^2) \simeq 1 - 2.38Q^2 + 4.02(Q^2)^2 - 6.20(Q^2)^3 + 9.35(Q^2)^4 - 14.0(Q^2)^5 + \cdots$$

$$\frac{1}{(1+Q^2/\Lambda^2)^2} \simeq 1 - 2.38Q^2 + 4.24(Q^2)^2 - 6.71(Q^2)^3 + 9.97(Q^2)^4 - 14.2(Q^2)^5 + \cdots$$

$(M_{\rm KK} = 1 \text{ unit})$

with $\Lambda^2 = 0.758\ \text{GeV}^2$

⑤ Conclusion

- We proposed a new method to analyze static properties of baryons.
- Our model automatically includes the contributions from various massive vector and axial-vector mesons.
- Compared with the similar analysis in the Skyrme model (ANW), the agreement with the experimental values are improved in most of the cases.
- But, we should keep in mind that our analysis is still very crude and there are a lot of ambiguities remain unsolved.