QCDから原子核へ

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2. ハドロン物理の生い立ち

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はじめに

QCDから原子核への道

- QCD = クォーク + グルーオン
  カラー電荷によるゲージ相互作用
  エネルギースケール: Λ_{QCD} ~200 MeV, $m_{u,d}$ ~ 5 MeV

↓

- ハドロン: メソン, バリオン, 共鳴
  強い相互作用 (no color), 対称性の破れ
  M_h ~700-1000 MeV, f_π~90 MeV

↓

- 原子核 = 核子 + . . . （不純物？）
  核力 (特異な性質), 強い縮退
  B/A ~ 8 MeV, Ex ~ 0.1 MeV
  QCD/hadron からはかなり遠い

はじめに

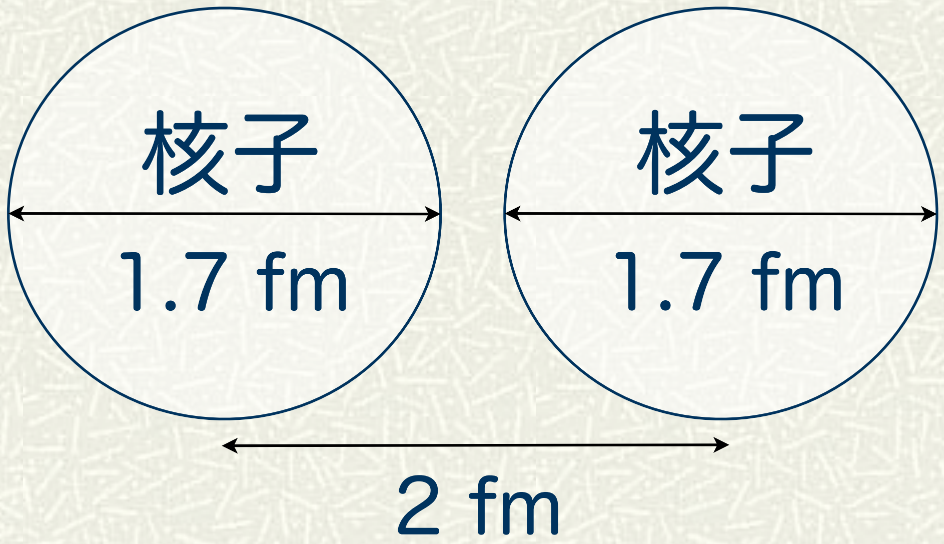
- 原子核にQCDは必要か?
  - QCD/ハドロン

    核子の大きさ　R_N ~ 0.8-0.9 fm (charge rms)

    σ(string tension) ~ 1GeV/fm
  - 原子核

    核力の到達距離 ~ 1.4 fm

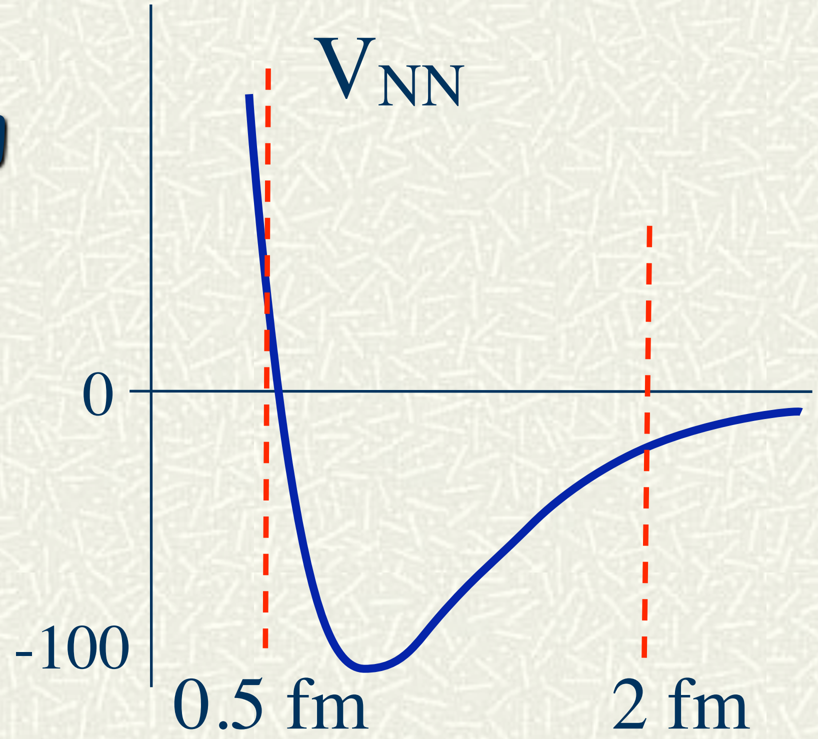
    核子間距離 ~ 2 fm



  - 長さのスケールでは共存しているのに、なぜエネルギースケールが違うのか？

はじめに

- 核力の特異性
  - 核力 ＝ OPE + 中距離引力 + 短距離斥力
  - 引力と斥力 ~ 数100 MeV
    - ⇔ 重陽子の束縛エネルギー 2 MeV
  - OBEの到達距離 ~ 1 fm
    - ⇔ 重陽子のサイズ ~ 4 fm

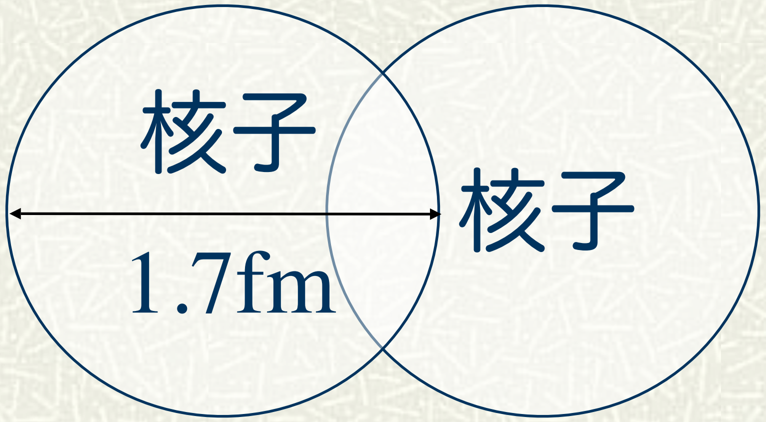


- 短距離核力 < 0.5 fm
  - 核子の励起状態 300 ~ 500 MeV
  - 斥力芯の強さ 500 ~ 1000 MeV

はじめに

- 他のバリオン間の力も同じ性質を持つのか？
  - 中間子交換力はSU(3)対称性を用いて一般化
    - OBEP　ex. Nijmegenポテンシャル
  - 短距離斥力は共通なのか？　起源は？

- 短距離斥力の起源をクォーク構造に求めて
  - クォーククラスター模型 Oka, Yazaki (1980)
  - 核力はカラー分極を誘起するか？



- 原子核内でクォーク・カラーが見られるか？
  - EMC効果 (1983)　10%程度の効果
  - 核媒質中でのハドロン　カイラル対称性が回復すると？
    - color-transparency, 重イオン

ハドロン物理の生い立ち

原子核

中性子の発見（1932）

原子核 = 陽子+中性子

pionの予言、発見（1935）

核力 = 中間子交換

核子と中間子は別物

ハドロン

strangenessの発見（1947）

SU(3), クォーク (1964)

ハドロン = バリオン + メソン

PCAC (1960)

カイラル対称性の自発的破れ

ハドロン物理の生い立ち

標準理論

ゲージ理論（1954）による統一

QCD (1973) 誕生

charmの発見（1974）

クォーク模型

QCDによれば、．．．（1974- ）

しかし、QCDは解けない。．．．

3つの論文

Quark Models from QCD

- E. Eichten, et al., Phys. Rev. Lett. 34 (1975) 369

Spectrum of Charmed Quark-Antiquark Bound States*

E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 17 December 1974)

- De Rujula, Georgi, Glashow, Phys. Rev. D12 (1975) 147

Hadron masses in a gauge theory*

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory, Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 24 February 1975)

- A. Chodos, et al., Phys. Rev. D9 (1974) 3471

New extended model of hadrons*

A. Chodos, R. L. Jaffe, K. Johnson, C. B. Thorn, and V. F. Weisskopf
Laboratory for Nuclear Science and Department of Physics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 25 March 1974)

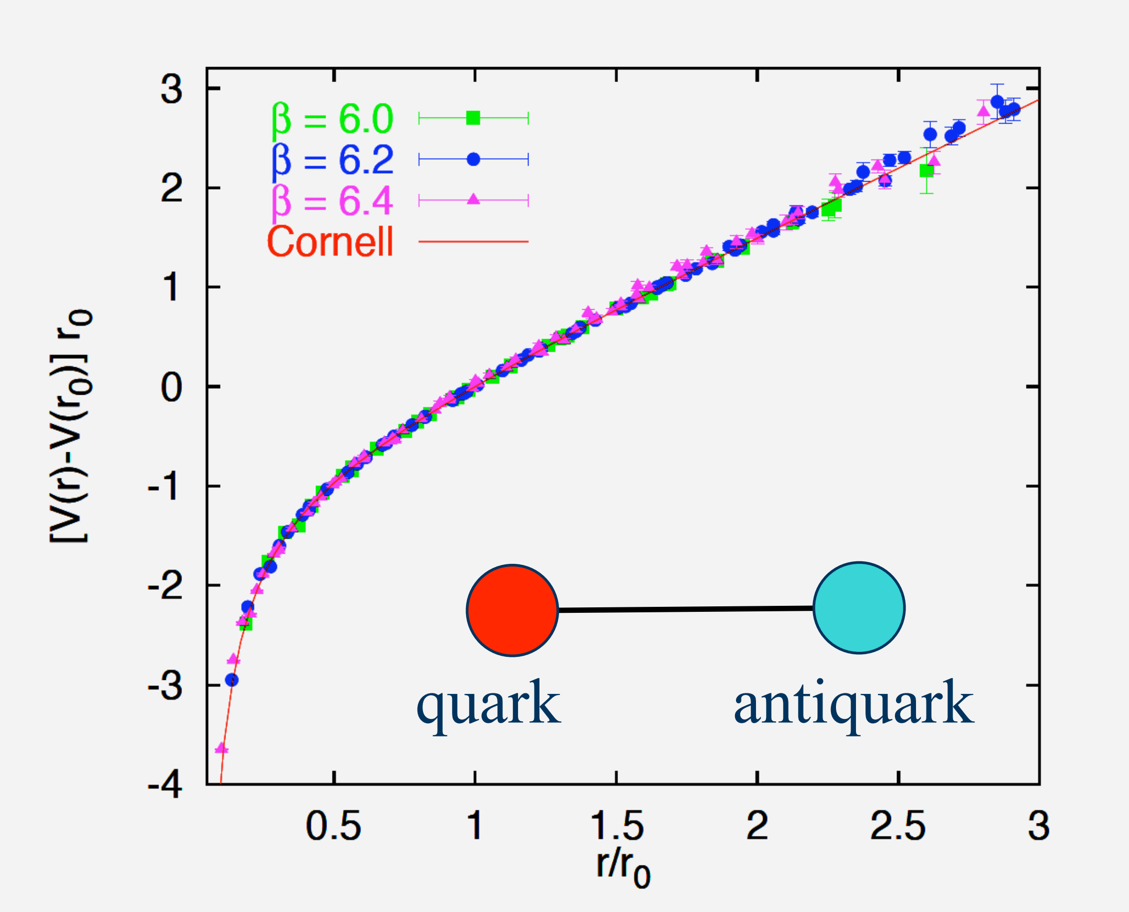
Heavy quarks

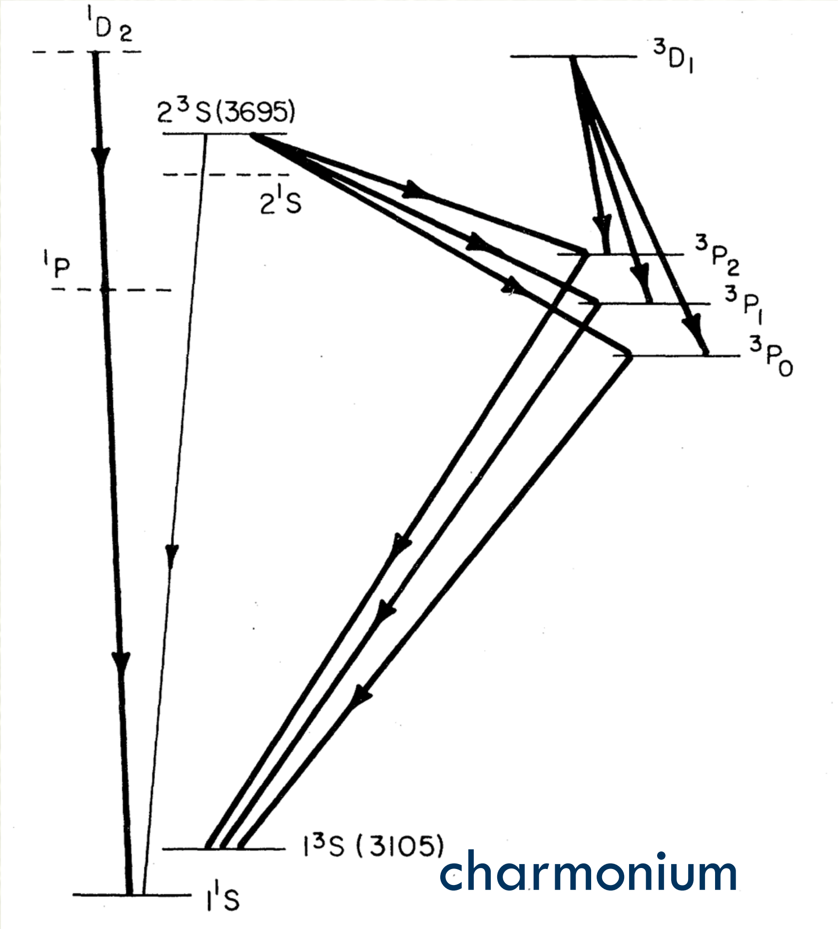
- Cornell potential (Eichten et al.)

$$V(r) = -\frac{e}{r} + \sigma r$$

- quarkonium potential

  Lattice QCD: Wilson loop





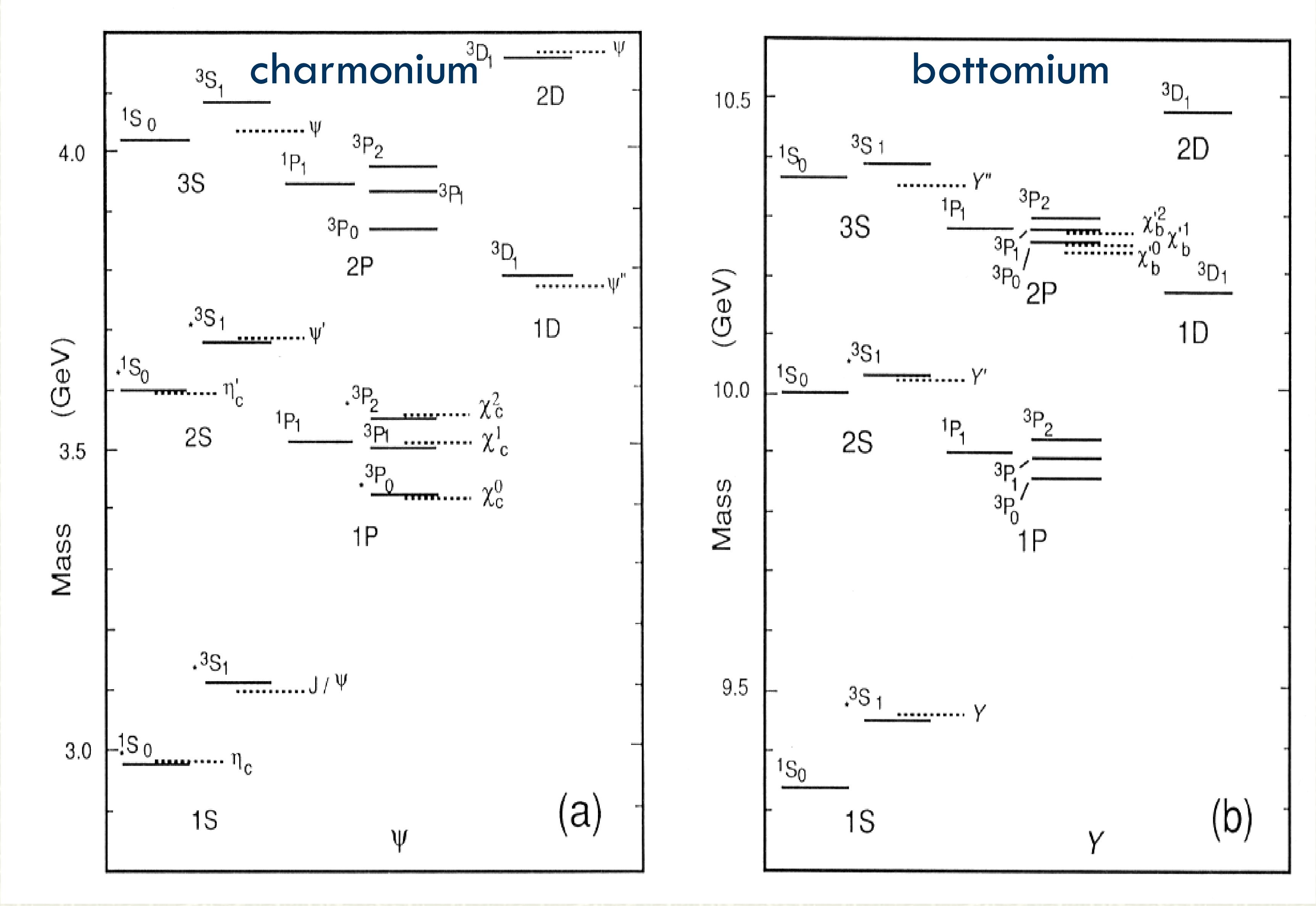
quenched r_0: Sommer scale

G.S. Bali / Phys. Rep. 343 (2001) 1

Heavy quarks

refined potential models

S.N. Mukherjee, et al., Phys. Rep. 231 (1993)



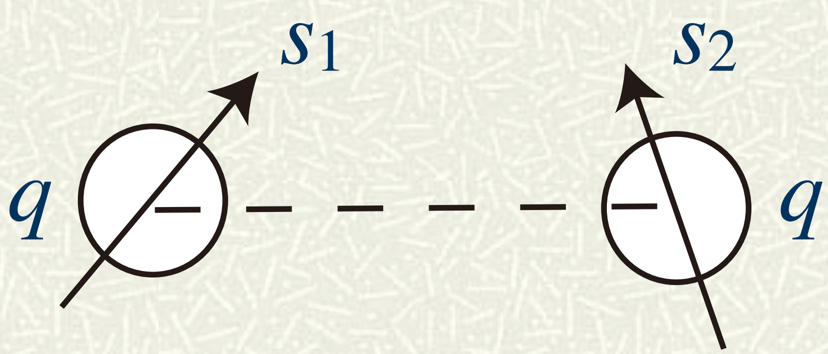
QCD-motivated Quark Model

De Rujula, Georgi, Glashow, Phys. Rev. D12 (1975) 147

$$H = L(\vec{r}_1, \vec{r}_2, \ldots) + \sum_i \left(m_i + \frac{\vec{p}_i^{\,2}}{2m_i} + \cdots \right) + \sum_{i>j} (\alpha Q_i Q_j + k\alpha_s) S_{ij}$$

$$S_{ij} = \frac{1}{|\vec{r}|} - \frac{1}{2m_i m_j}\left(\frac{\vec{p}_i \cdot \vec{p}_j}{|\vec{r}|} + \frac{\vec{r}\cdot(\vec{r}\cdot\vec{p}_i)\vec{p}_j}{|\vec{r}|^3} \right) - \frac{\pi}{2}\delta^3(\vec{r})\left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \boxed{\frac{16\vec{s}_i\cdot\vec{s}_j}{3m_i m_j}} \right) \rightarrow \text{Color-Magnetic interaction}$$

$$- \frac{1}{2|\vec{r}|^3}\left\{ \frac{1}{m_i^2}\vec{r}\times\vec{p}_i\cdot\vec{s}_i - \frac{1}{m_j^2}\vec{r}\times\vec{p}_j\cdot\vec{s}_j + \frac{1}{m_i m_j}\left[2\vec{r}\times\vec{p}_i\cdot\vec{s}_j - 2\vec{r}\times\vec{p}_j\cdot\vec{s}_i - 2\vec{s}_i\cdot\vec{s}_j + 6\frac{(\vec{s}_i\cdot\vec{r})(\vec{s}_j\cdot\vec{r})}{|\vec{r}|^2} \right] \right\} + \cdots$$



vector part of gluon exchange

$$\frac{\vec{\gamma}_1\cdot\vec{\gamma}_2}{q^2} \sim \frac{(\vec{s}_1\cdot\vec{q})}{m_1}\frac{(\vec{s}_2\cdot\vec{q})}{m_2}\frac{1}{q^2} \rightarrow \frac{1}{3}\frac{(\vec{s}_1\cdot\vec{s}_2)}{m_1 m_2}$$

QCD-motivated Quark Model

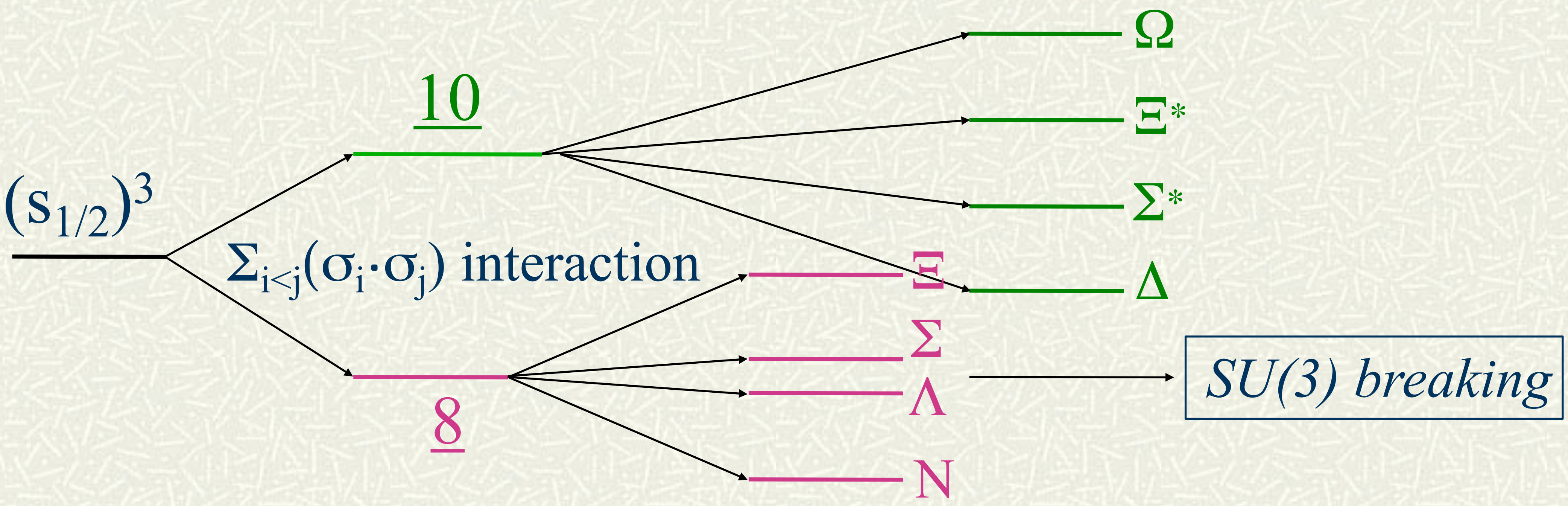
- **Single particle motion**

  $(s_{1/2})^3$ ***J* = 1/2**   **<u>8</u>**

  ***J* = 3/2**   **<u>10</u>**

  hyperfine interaction

$$\Delta_{\mathrm{ss}} \sum_{i<j} \vec{\sigma}_i \cdot \vec{\sigma}_j$$



QCD-motivated Quark Model

HF interaction in the baryon

- N-Δ mass splitting (300 MeV) ↔ Δ_{ss} ~ 50 MeV
- Λ–Σ mass splitting (~77 MeV) from SU(3) breaking

$$\Sigma_{\mathrm{HF}} = \boxed{\Delta_{\mathrm{ss}}}\{\vec{\sigma}_u \cdot \vec{\sigma}_d + \boxed{\xi} \times \vec{\sigma}_s \cdot (\vec{\sigma}_d + \vec{\sigma}_u)\}$$

50 MeV

Λ : $(ud)_{I=0,S=0}\,s$ 50MeV x [(-3) + 0 * ξ]

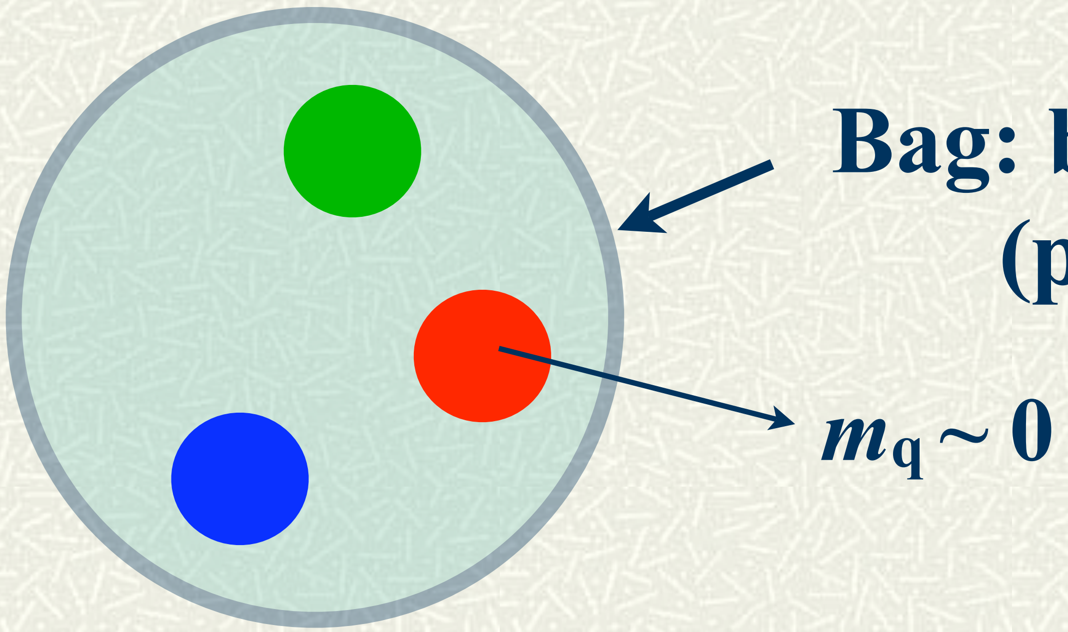
Σ : $(ud)_{I=1,S=1}\,s$ 50MeV x [1 + (-4) * ξ]

ξ - factor: s-u, s-d HF interaction is weaker than u-d.

for ξ = 3/5 → Σ – Λ = (8/15) x150 MeV = 80 MeV

QCD-motivated Quark Model

MIT bag model, A. Chodos et al.



Confinement is achieived by the bag boundary condition.
A quark has a single particle energy due to localization.
The bag has a volume energy to stabilize hadrons.
The confined gluon field has color-magnetic energy.

The MIT bag and the DGG give the same spectrum for the ground state.

QCD-motivated Quark Model

- **Isgur-Karl model**

  N. Isgur, G. Karl ***Shell model of hadrons***

  P Wave Baryons in the Quark Model: Phys. Rev. D18 (1978) 4187

  Positive Parity Excited Baryons in a Quark Model with Hyperfine Interactions: Phys. Rev. D19 (1979) 2653

- **And many others**

  potential models

  confinement potential, string, flux tube, . .

  spin-flavor-color dependent terms

  relativised models

  bag models

  can describe excited states? deformed, oscillating

  soliton-like bags

- **The right degrees of freedom (except valence quarks)?**

  gluon, bag, string, soliton, . . .

Quark model の危機

- ***H dibaryon*** **:** $\boldsymbol{S = -2}$**,** $\boldsymbol{B = 2}$

  is predicted from the CMI strong attraction

  a rough estimate:

  $$M_{\mathrm{H}} = 4\, m_{\mathrm{q}} + 2\, m_{\mathrm{s}} + \langle V_{\mathrm{cm}} \rangle_{\mathrm{H}} = 360\mathrm{x}4 + 540\mathrm{x}2 - 450 \approx 2070 \text{ MeV}$$

  $\Lambda\Lambda$ threshold 2230 MeV

R.L. Jaffe, Perhaps a Stable Dihyperon: PRL 38 (1977) 195

Oka, Shimizu, Yazaki,
The Dihyperon state in the quark cluster model, PL B130 (1983) 365

20-year searches were NOT successful. What's wrong?

Quark model の危機

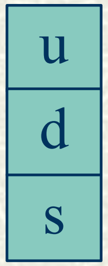
Instanton-induced-interaction (III)

aka Kobayashi-Maskawa-'t Hooft (KMT)

- **III (2-body)**
  spin-dependent attraction

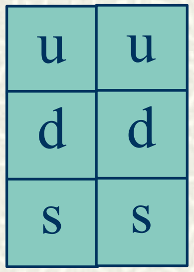
$$\Sigma_{\rm III} = \Delta_{\rm III}\Sigma_{i<j}\mathcal{A}^f_{ij}\xi_{ij}[1-\frac{1}{5}(\vec{\sigma}_i\cdot\vec{\sigma}_j)]$$

E.V. Shuryak, J.L. Rosner, Phys. Lett. B218 (1989) 72
M. Oka, S. Takeuchi, Phys. Rev. Lett. 63 (1989)1780



- **III (3-body)**
  3-body repulsion *flavor singlet* (*u-d-s*)

repulsive for the flavor-singlet ***H dibaryon***



Quark model の危機

- H dibaryon
  なぜ存在しないのか
  インスタントン、カイラルクォーク模型
- Exotic quarkonium
  ポテンシャル模型では説明できない状態：X, Y, Z, D_s ???
  4-quark states, hadron molecules?
- pentaquark　why?
  Bag模型、ポテンシャル模型も（あまり）うまくいかない
  幅が狭い
  カイラル対称性？　カイラルクォーク模型？
- Oset
  ハドロン至上主義 !?

Quark model の危機

- QCDは “quark model” を救えるか
- なぜ “quark model” が必要か

  自由度の数が正しい（と思われる）

  gluonがあらわに必要なハドロンが見つからない

  （クォークのカラーだけで白色）

  Exotic (multi-quark) hadron を「理解」する

- QCDに立ち返って“quark model”を精査する

  “constituent quark”はQCDの”quark”と何が違うのか

  ハドロン中のクォークの数とは?

- QCDを直接用いて、原子核にアプローチする

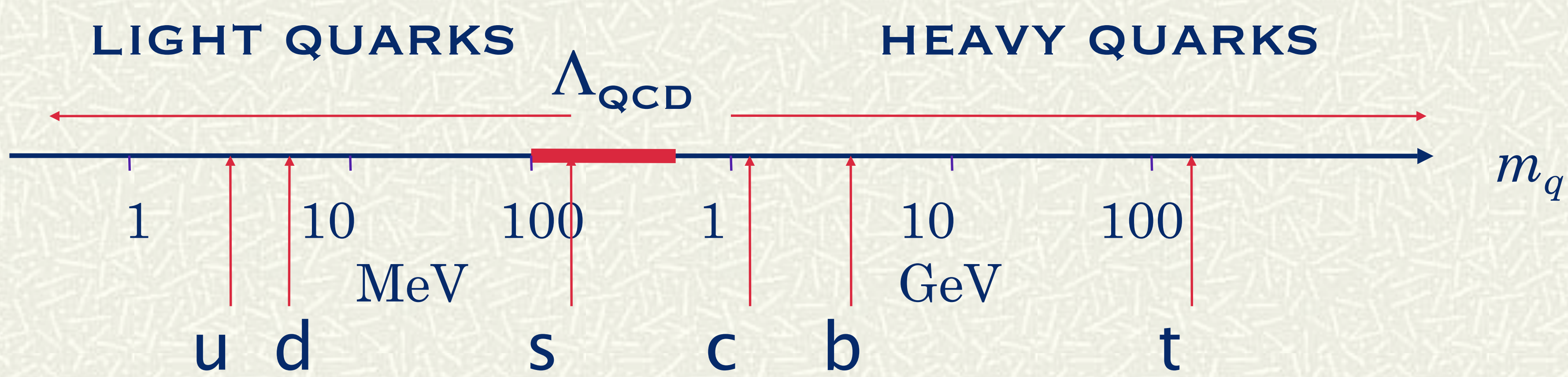
Quarks in QCD

QCD Lagrangian

$$\mathcal{L} = \bar{q}(i\not{D} - m)q - \frac{1}{4}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

$$D_\mu \equiv \partial_\mu + igA_\mu$$
$$A_\mu \equiv \frac{\lambda^a}{2}A^a_\mu$$
$$G_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu + ig[A_\mu, A_\nu]$$

Quark masses and scale of QCD



Quarks in QCD

- **How quarks get the "constituent" masses?**

  by *chiral symmetry breaking*

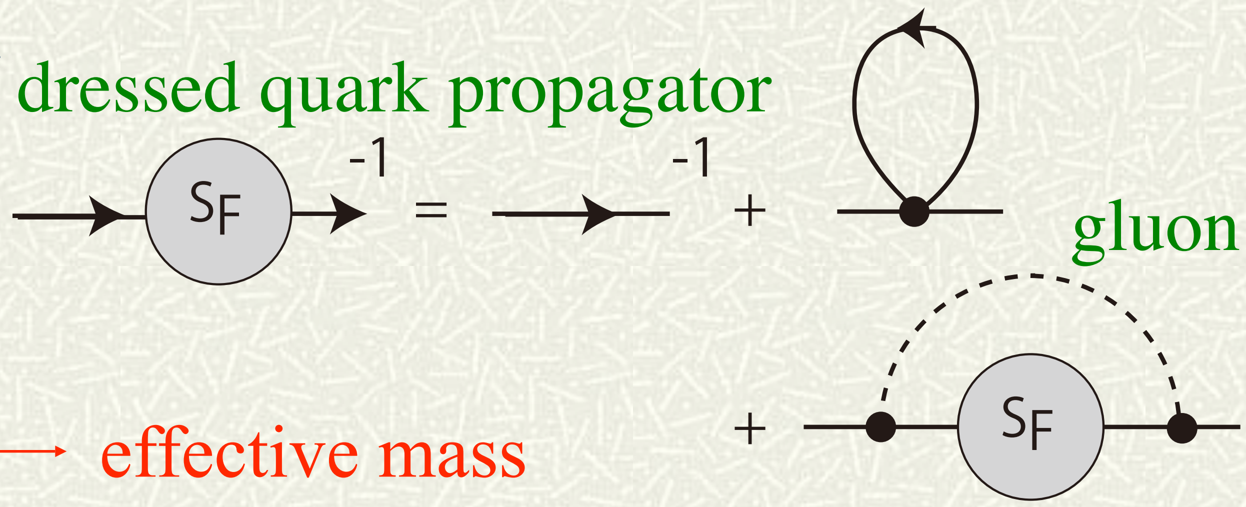
Dynamical model of elementary particles based on an analogy with superconductivity 1:
Y. Nambu, G. Jona-Lasinio, Phys. Rev. 122 (1961) 345

Chiral Quarks and the Nonrelativistic Quark Model:
A. Manohar, H. Georgi, Nucl. Phys. B234 (1984) 189

Dyson-Schwinger equation

$$
\begin{aligned}
S_F^{-1}(p) \quad &= \quad S_{F0}^{-1}(p) - \Sigma(p) \\
& \quad\; S_{F0}^{-1} = \not{p} - m \\
& \quad\; S_F^{-1} = A(p)\not{p} - \boxed{B(p)}
\end{aligned}
$$

effective mass



constiuent quark masses: $M_{u,d} \approx 350$ **MeV,** $M_s \approx 550$ **MeV**

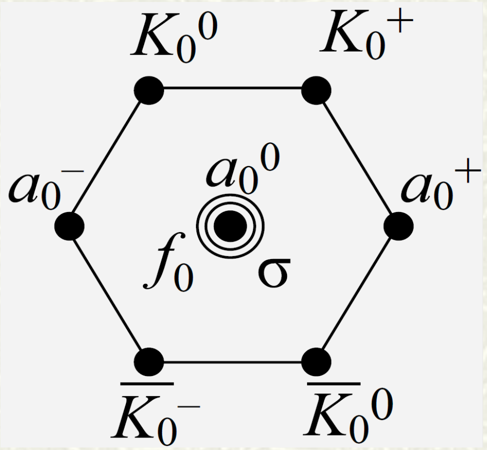
Number of quarks in hadrons

How shall we determine the number of constituent quarks in hadrons?

Which hadrons are exotic or do contain exotic multi-quark components?

The light scalar mesons

$f_0(600)$, $f_0(980)$, $a_0(980)$, $K_0(900)$



$\Lambda(1405)$ $J^\pi = 1/2^-$, flavor singlet

- **uds L=1 orbital excited state S=1/2 => $J=1/2^-$ and $3/2^-$**
- **(ud) (su) $\bar{u}$ L=0 ground state**

s=0 diquarks + antiquark: S=1/2 => J=1/2 isolated

The competition between the kinetic energy and the extra quark masses indicates possible mixing of the two Fock components.

Number of quarks in hadrons

So far, hadrons are regarded as bound states of “valence” quarks defined in the quark model.

What does QCD predict?

In QCD, all hadrons, even N(940), contain extra $q\bar{q}$ as meson clouds and/or sea quarks.

When do we identify the extra flavor-singlet $q\bar{q}$ (or glue) as "valence" components?

We need a "good" definition of multi-quark-ness.

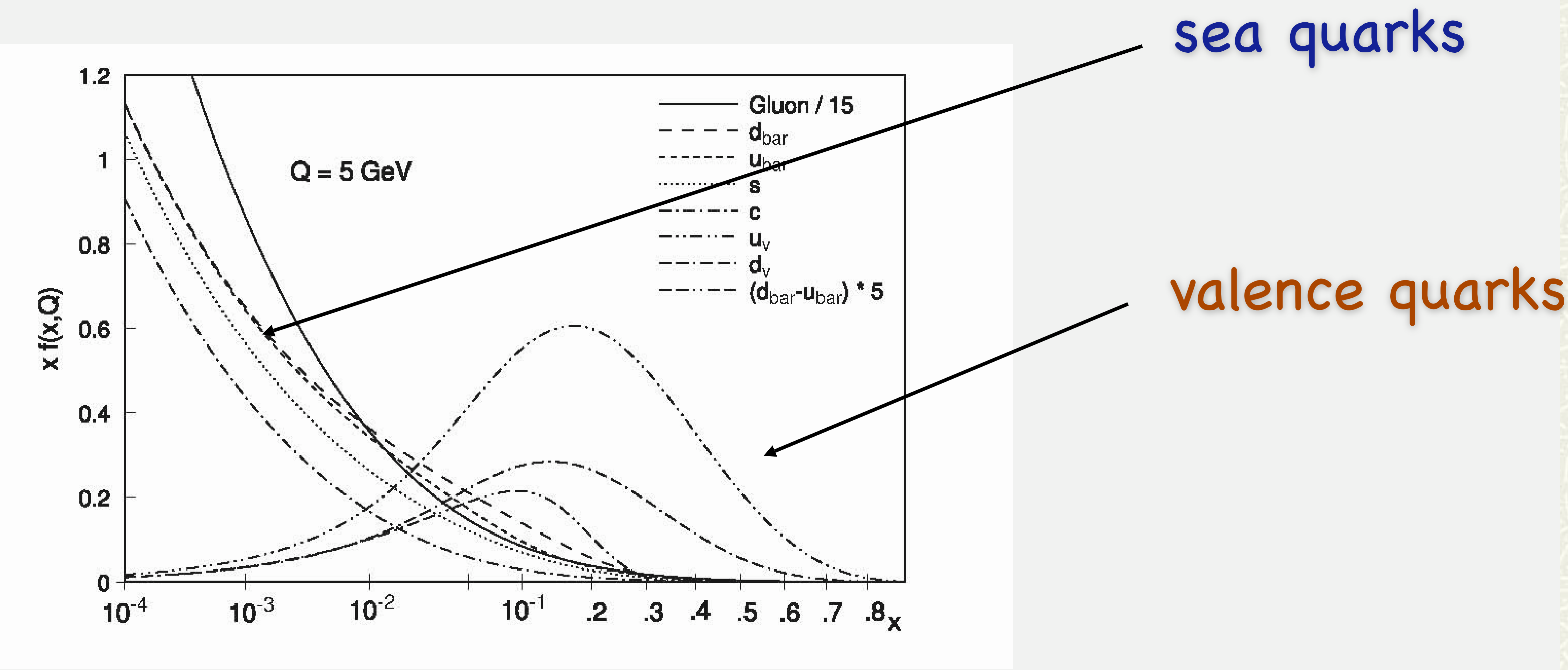
QCD multi-quark operators can couple to sea quarks.

The large “constituent” mass may correspond to the large *x* region of the quark-parton distribution function.

Number of quarks in hadrons

DIS and other high energy processes may identify "valence" quarks.

Parton distribution = valence + sea



Cannot measure the pdf of resonances: f_0, a_0, Λ^* etc.

Number of quarks in hadrons

New approach with the fragmentation functions

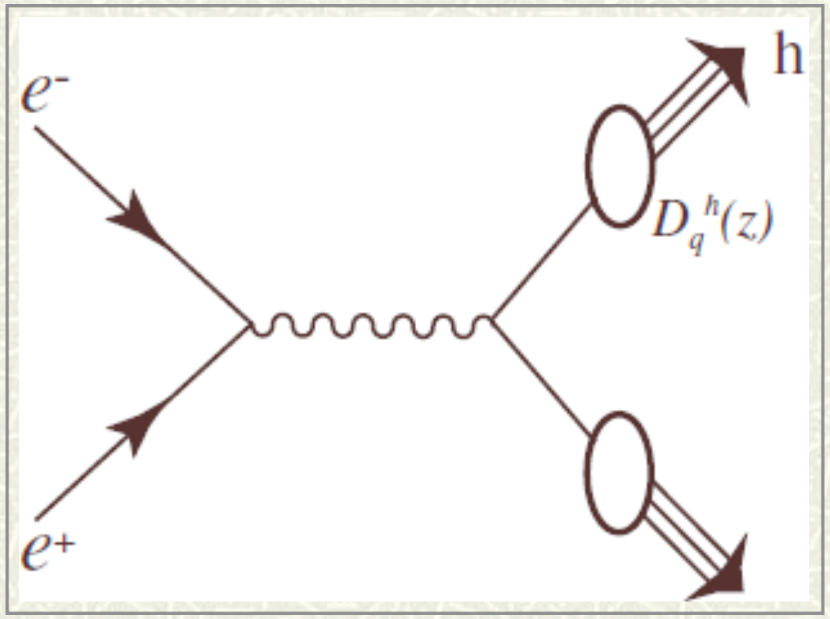
Exotic hadron search by fragmentation functions

M. Hirai,[1] S. Kumano,[2,3] M. Oka,[1] and K. Sudoh[2]

PR D77 (2008) 017504; arXiv:0708.1816v1 [hep-ph]

$$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}, \quad \sigma_{tot} = \sum_q \sigma_0^q \left(1 + \frac{\alpha_s(Q^2)}{\pi}\right)$$

$$\frac{d\sigma^h}{dz} = \sum_i \int_z^1 \frac{d\xi}{\xi} C_i(\xi, Q^2, \mu_{F,R}^2)\, D_i^h\left(\frac{z}{\xi}, \mu_F^2\right)$$



Coefficient Function
calculable in pQCD

Fragmentation Function
extracted from experiments

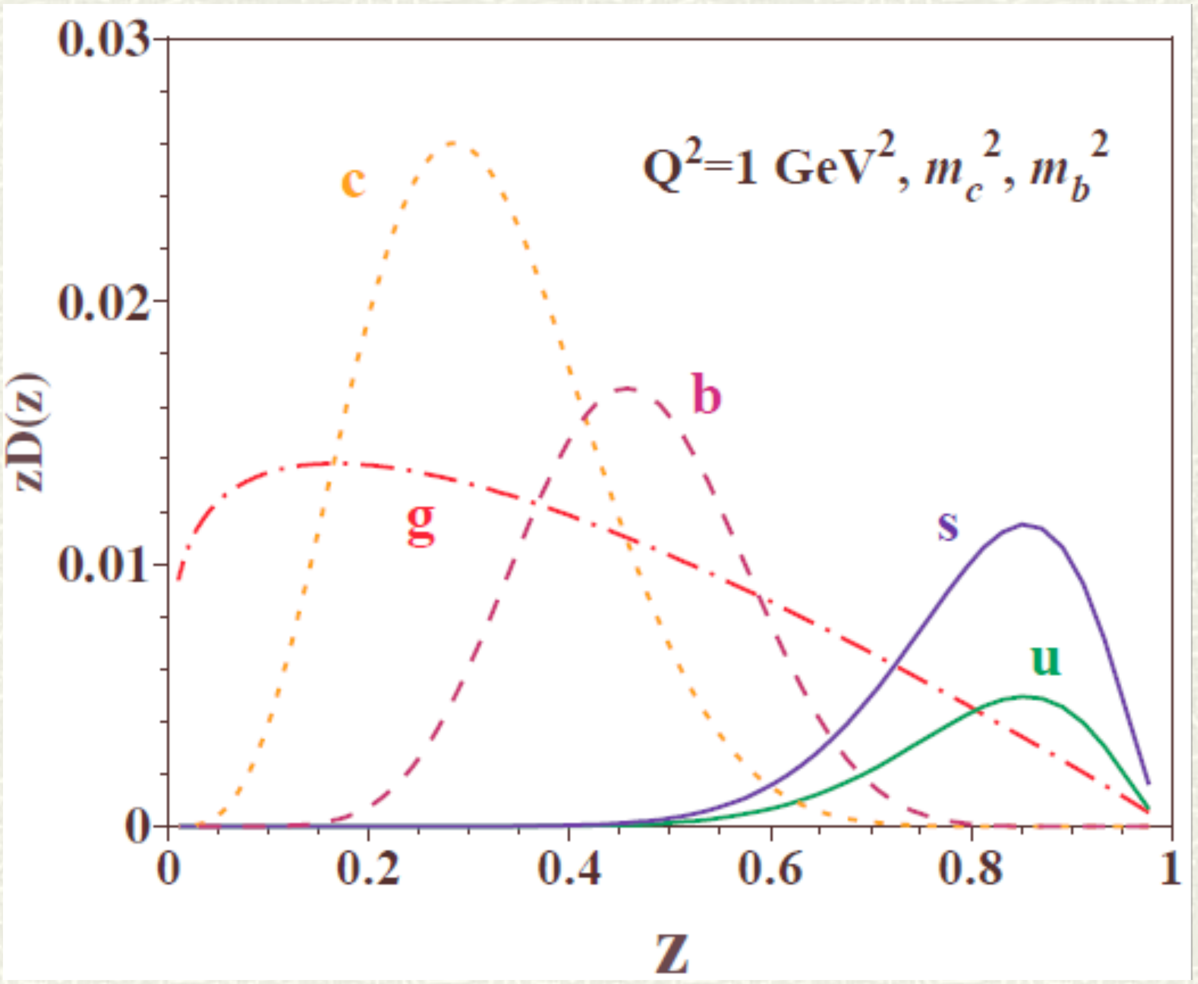
Number of quarks in hadrons

Fragmentation function $f_0(980)$

- χ^2/d.o.f. = 0.907
    - Total Number of data: 23
- Tetra-quark configuration
    - favored FF: u and s quarks
    - Peak at large-z (z~0.85)
    - $z_u^{max} \sim z_s^{max}$

or

- $s\bar{s}$ configuration
    - $M_u < M_s$
    - (M_u/M_s=0.43 ± 6.73)
- Large uncertainty
    - Need further precise data



- 2^{nd} moments
    - M_u=0.0012 ± 0.0107
    - M_s=0.0027 ± 0.0183
    - M_g=0.0090 ± 0.0046

Number of quarks in hadrons: summary

- "Number of quarks" is not conserved in QCD.
- We need a good definition(s) of "number of quarks" in order to identify exotic multi-quark component in hadrons.
- We propose a plausible way of searching exotic hadrons using the fragmentation functions in high energy collisions.
  - Applied to the global analysis of FFs of the $f_0(980)$ production.
  - Indicating tetra-quark and/or $s\bar{s}$ configuration
  - Large uncertainty of the current production data does not allow to distinguish them.

QCDから原子核へ

- **QCD を（大きい）原子核に直接適用できるか。**

  Not now. Maybe, in future.

- **QCD が原子核物理に与える情報はなにか**

  核力　メソン交換部分

  短距離部分

  カイラル有効理論のパラメータ

- **Lattice QCD mostly numerical**

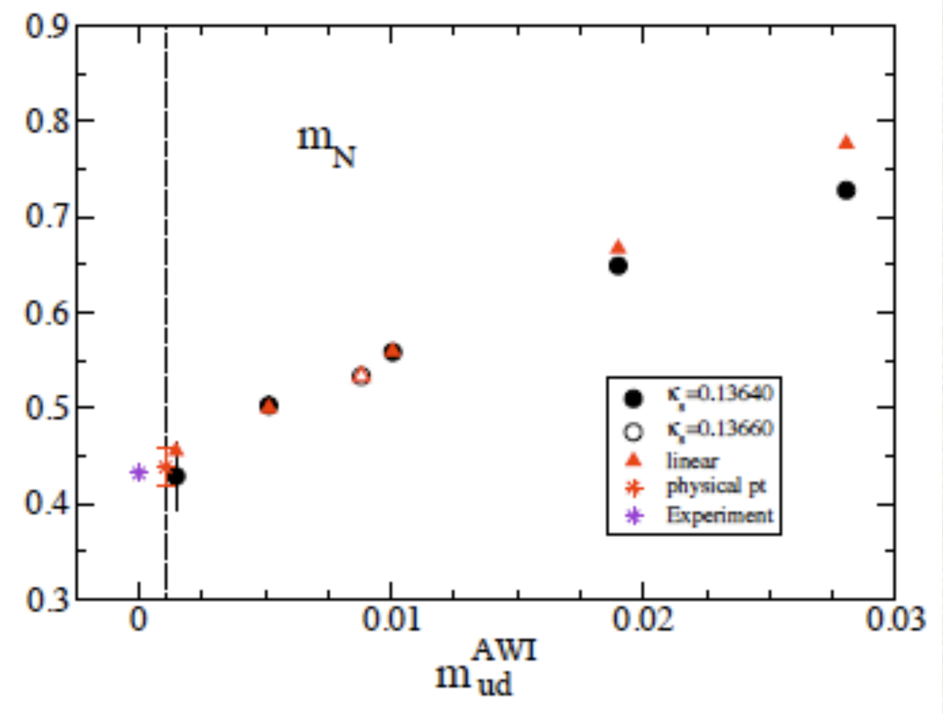
  Other semi-analytic methods

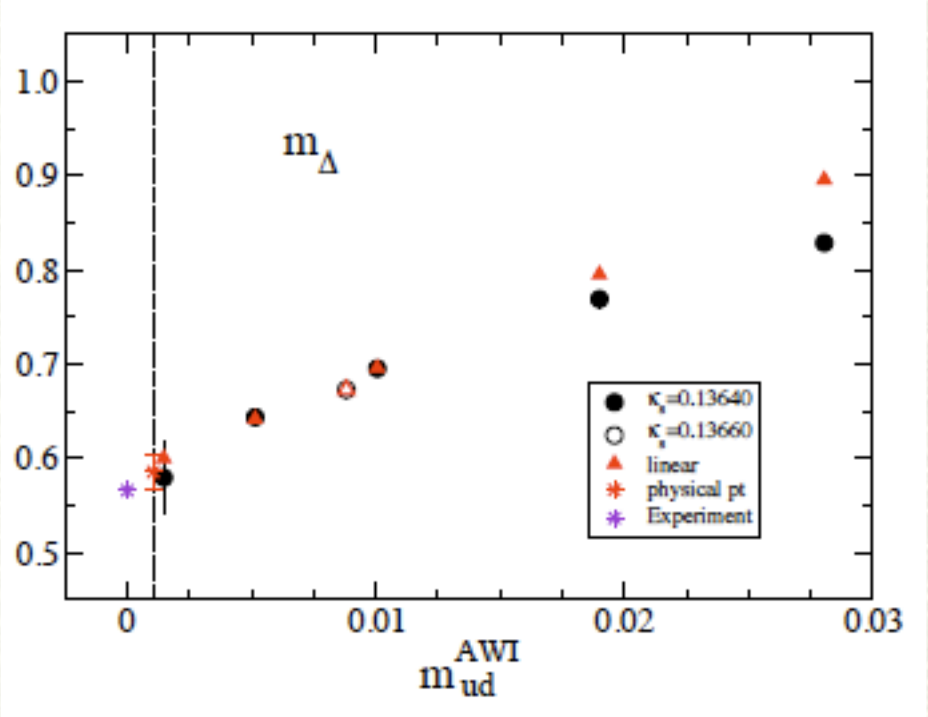
  QCD sum rules, Large Nc, Effective theories

QCDから原子核へ

- Lattice QCD
  - unquenched QCD with $N_f = 2+1$ flavors
    almost physical quark mass

S. Aoki, et al., (PACS-CS Collaboration), arXiv:0807.1661





QCDから原子核へ

- Lattice QCD
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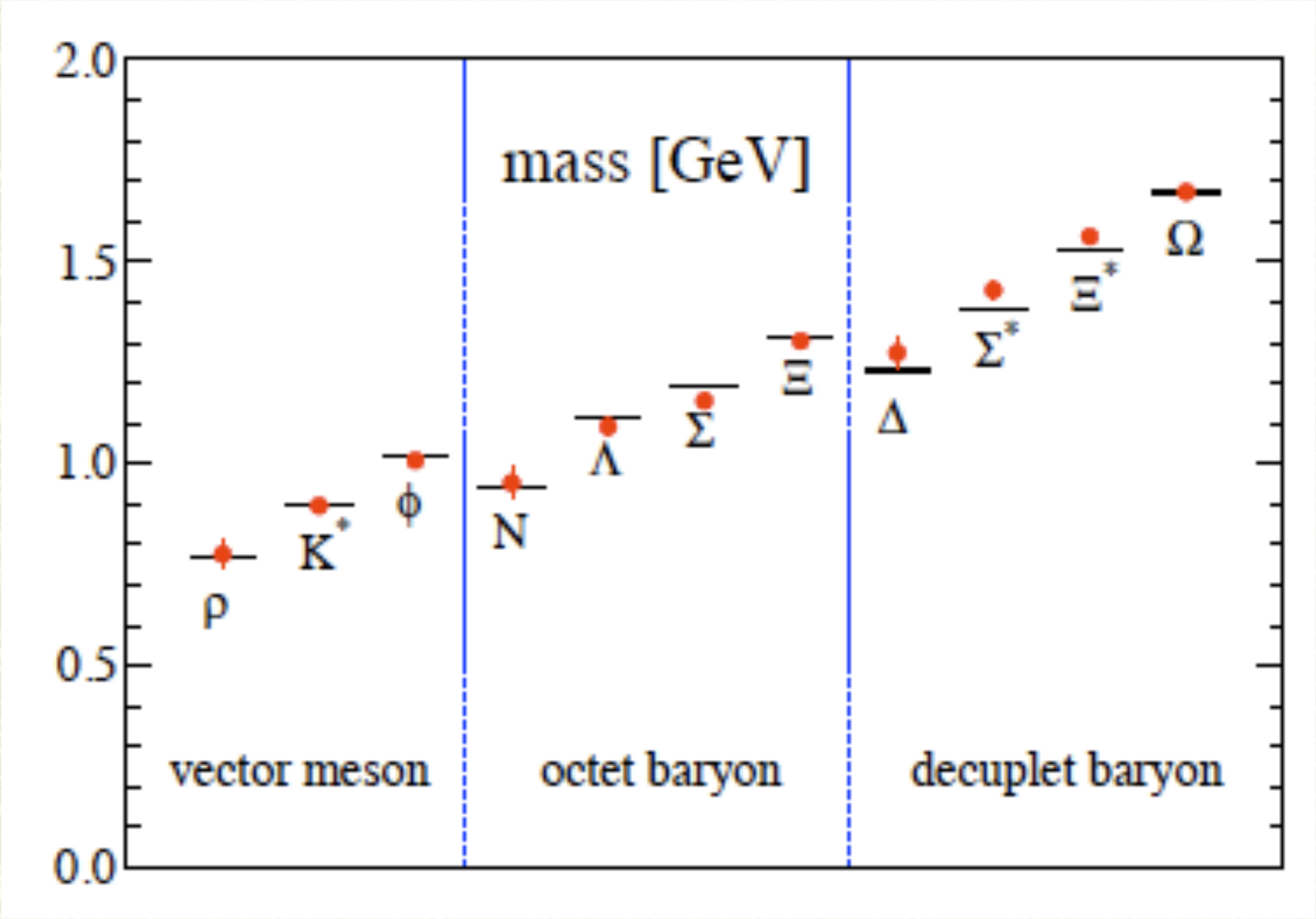
    S. Aoki, et al., (PACS-CS Collaboration), arXiv:0807.1661



QCD calculation of coupling constants

- The meson-baryon coupling constants and form factors are the most fundamental quantities describing hadronic interactions in QCD. Serious QCD-based calculations have just started.
- The SU(3) invariance for the coupling constants is not established, although the phenomenological models often assume the invariance. The F/D ratios of the coupling constants are the fitting parameters in the models.
- How strong is the SU(3) violation in the coupling constants?
- What does QCD predict for F/D ratio, if SU(3) is valid?

QCD Sum rules for coupling constants

πNN coupling constant

T. Doi, H. Kim, M.O., **PR C52 (2000)**

$$\Pi^{\alpha\beta}(q,p) = i\int d^4x\, e^{iq\cdot x}\langle 0|\mathrm{T}\left[J_N^\alpha(x)\bar{J}_N^\beta(0)\right]|\pi(p)\rangle$$

tensor

$$\Pi(q,p) \;=\; i\gamma_5 \not{p}\,\Pi^{\mathrm{PV}} + i\gamma_5\,\Pi^{\mathrm{PS}} + \gamma_5\sigma^{\mu\nu}q_\mu p_\nu\,\Pi^{\mathrm{T}} + \boxed{i\gamma_5\not{q}\,\tilde{\Pi}^{\mathrm{PV}}}$$

$$\boxed{J_N(x;t) \;=\; 2\epsilon_{abc}[\,(u_a^T(x)Cd_b(x))\gamma_5 u_c(x) + t\,(u_a^T(x)C\gamma_5 d_b(x))u_c(x)\,]}$$

$$\begin{aligned}
&g_{\pi N}\lambda_N^2(1 + A_{\pi N}^{\mathrm{T}}M^2)e^{-m_N^2/M^2} \\
&= \frac{1}{96\pi^2 f_\pi}(10+4t-14t^2)\langle\bar{q}q\rangle M^4 E_0(x) - \frac{f_\pi}{3}(-1-2t+3t^2)\langle\bar{q}q\rangle M^2 \\
&\quad -\frac{1}{54}f_\pi\delta^2(-1-26t+27t^2)\langle\bar{q}q\rangle + \frac{1}{72\cdot 12 f_\pi}(17+2t-19t^2)\langle\bar{q}q\rangle\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle \\
&\quad +\frac{f_\pi}{72}(-5-6t+11t^2)m_0^2\langle\bar{q}q\rangle
\end{aligned}$$

Double pole term

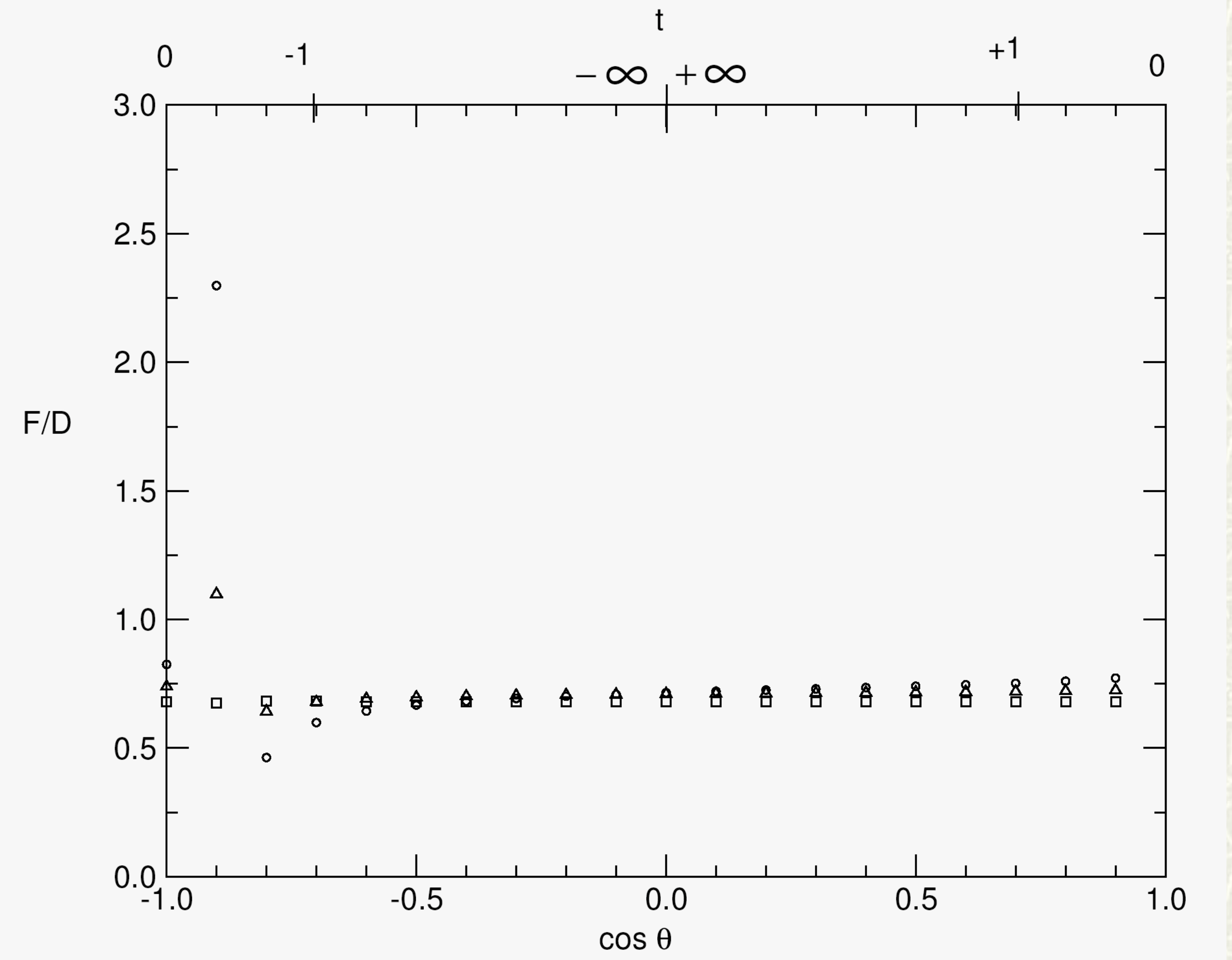
F/D ratio *v.s.* cosθ for T sum rule

- **Tensor sum rule** T. Doi, H. Kim, M.O., PR C52 (2000)

F/D = 0.65 ± 0.10

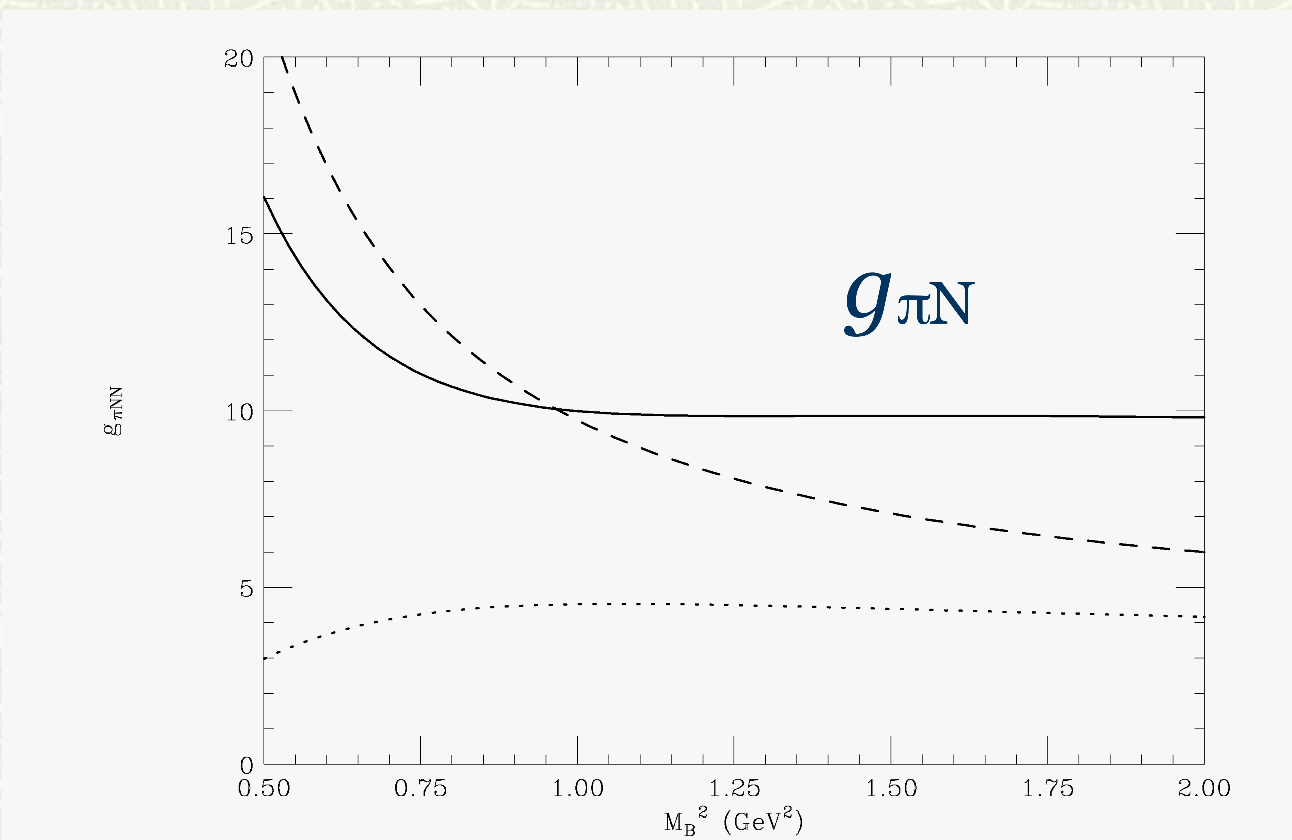
2/3 for SU(6)

0.57 from g_A (exp)



Projected correlation function

- **The most reliable estimate of the absolute value of the pi-N-N coupling is by the projected correlated function method: Kondo-Morimatsu/ Nucl. Phys. A717 (2003)**



Borel Mass M_B^2

$g_{\pi N} = 9.6 \pm 1.6$

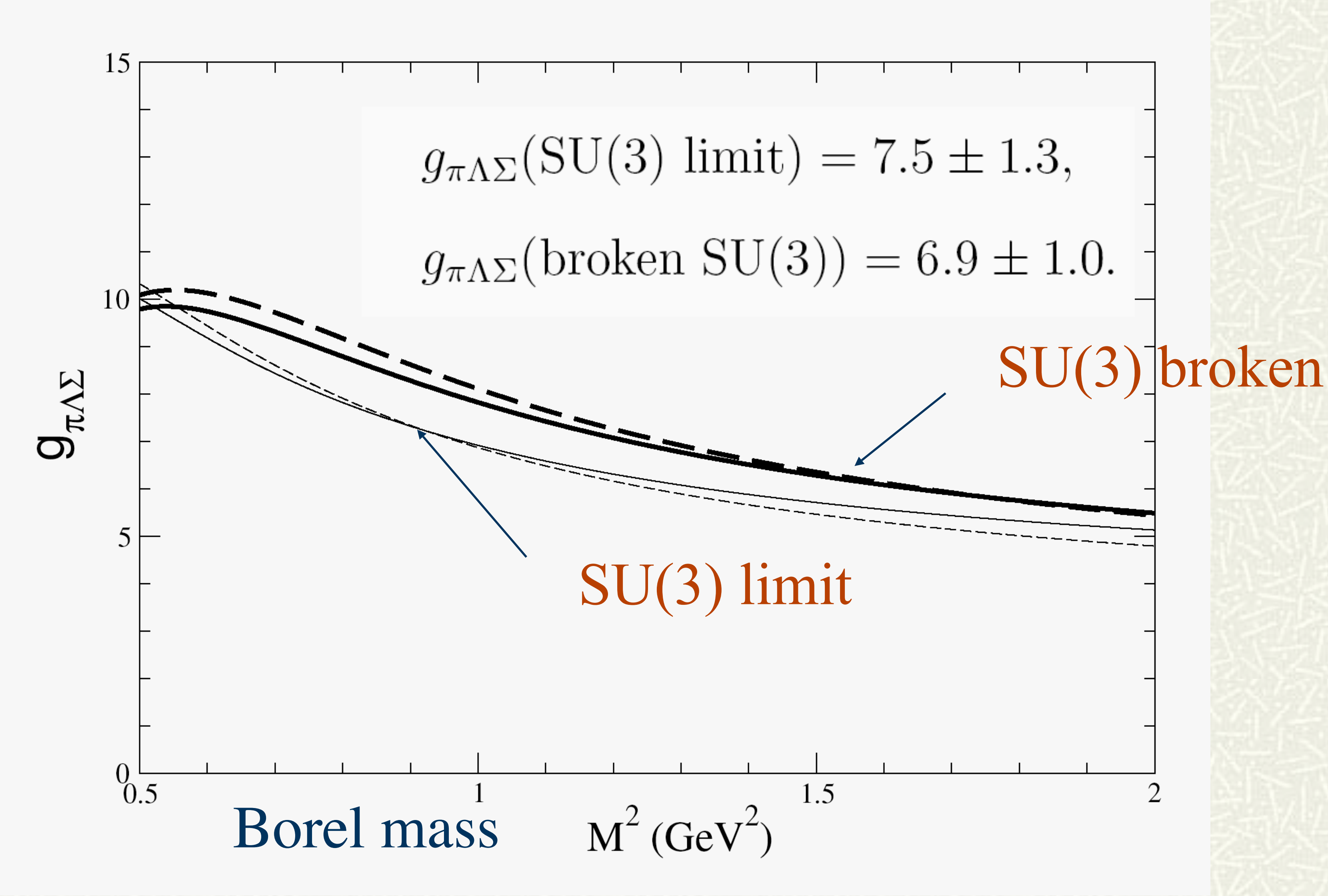
v.s.

$g_{\pi N}$ (exp.) ~12.8

slightly underestimated

Sum rule result

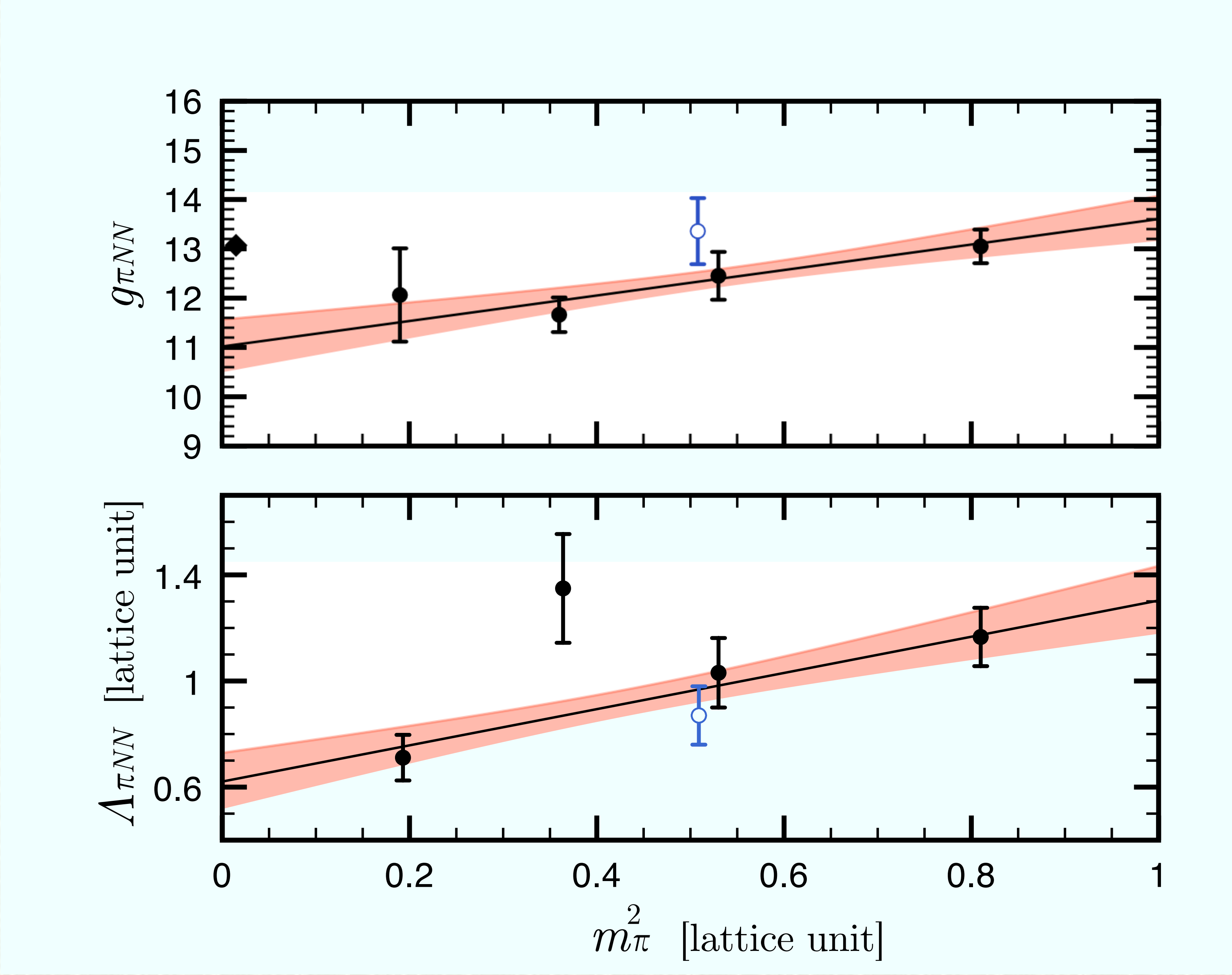
T. Doi, Y. Kondo, M.O. (2003)



LQCD for the meson-baryon couplings

- **Lattice QCD (N_f=2) is applied to the ps-meson-octet-baryon coupling form factors.**
  T.T. Takahashi, G. Erkol, MO (2008)
  - **CP-PACS gauge configuration: 2-flavor dynamical quarks on the 16^3x32 lattice**
  - **RG improved gauge action + the mean-field improved clover quark action**
  - **β=1.95 → a = 0.16 fm a^{-1} = 1.267 GeV**
  - **The ratio and absolute values of the coupling constants are obtained for several quark masses: m_q ~ 150, 100, 65, 35 MeV.**

pi-N-N coupling/form factor



★ **The naive chiral extrapolation results in**

$g_{\pi NN} \sim 11.02 \pm 0.55$

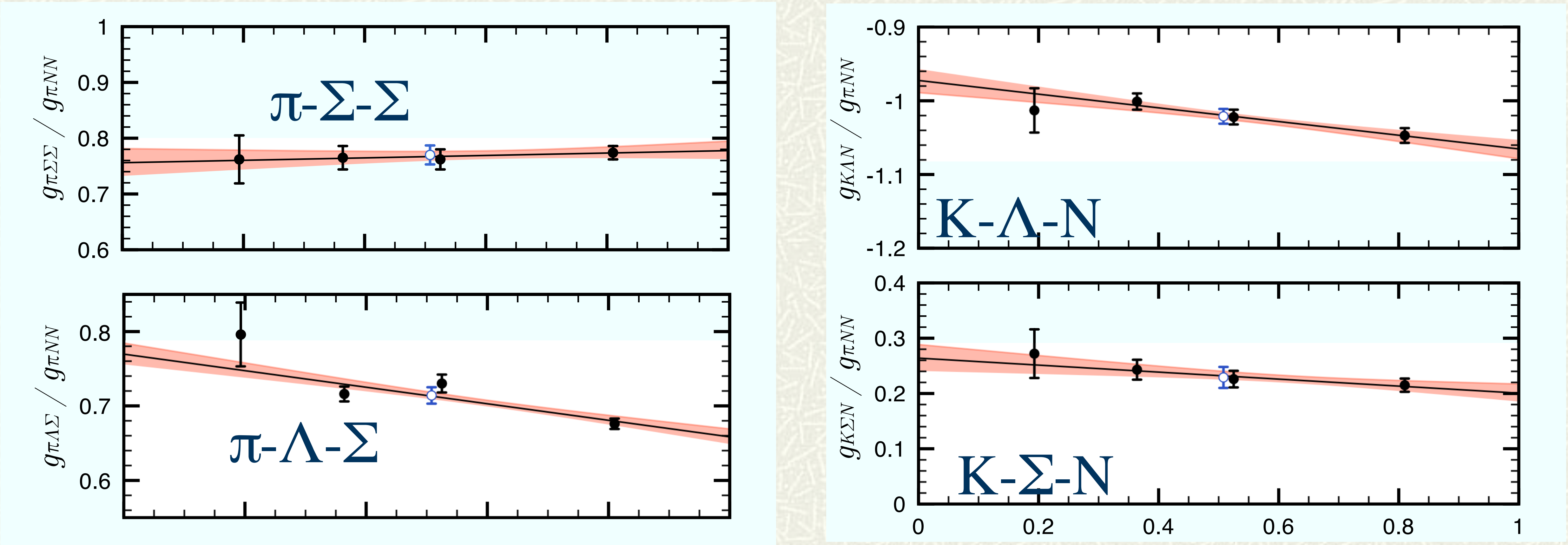
($g_{\pi NN}$ (pheno.) ~ 12.8

★**The monopole form factor is softer than the one used in the meson exchange models.**

$\Lambda_{\pi NN} \sim 0.62 \pm 0.11\ a^{-1}$

~ 0.79 GeV

SU(3) couplings



$$\alpha = \frac{F}{F+D} = 0.384 \qquad v.s.\ \mathrm{SU(6)\ value} \quad \alpha = 0.4$$

SU(3) breaking effect is very small. The deviation δ < 5%

Lattice QCD Summary

- **The two-flavor full-QCD lattice calculation was performed for the ps meson-baryon coupling constants and form factors.**
- **The SU(3) symmetry for the ps meson- octet-baryon couplings happens to be "very" good. The F/(F+D) ~ 0.384 ratio is consistent with SU(6).**
- $g_{\pi NN} \sim 11.02 \pm 0.55$ **vs** $g_{\pi NN}$ **(pheno.)** ~ 12.8
- **The monopole form factor is softer than the one used in the meson exchange models.** $\Lambda_{\pi NN} \sim 0.79$ **GeV.**
- **These results are consistent with the QCDSR.**
- ***Future perspectives***
  Further important predictions, πΞΞ, KΛΞ, KΣΞ, . . .
  Excited baryons, πNΔ, πNN*, πΣΛ(1405), KNΛ(1405) . .
  Other mesons, ρ, ω, K*, σ

結論

- QCDから原子核へ

  QCD = (quark + gluon) カラーゲージ理論

  核子とパイオン = 白色の多クォーク系

  ハドロンの相互作用 = 白色多体系間の相互作用

- カラーを積分して「白色」有効理論を作る

  有効理論のパラメータをQCDから決める

  質量、結合定数

- quark model は復活できるか？

  No! ならハドロンの統一的な物理描像の構築が新しい課題