Baryon Spectroscopy : Concluding remarks

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Hadron Spectroscopy, Chiral Symmetry and Relativistic Description of Bound Systems

Nihon Univ., KEK February 26, 2003

Contents

- Summary of Baryon Sessions
  - Lattice QCD
  - Chiral Symmetry
  - Models and Symmetry
- $U_A(1)$ symmetry breaking in baryon spectrum
- Conclusion

Baryon spectroscopy

- History
  - Symmetry and Quarks

    Strangeness (1947) and SU(3) (1956)

    Quark Model (1964) and SU(6) (1964)
  - QCD and dynamics of quarks

    Charm (1974) and QCD (1973)

    Confinement

    Spin dependent forces (hyperfine and spin-orbit interactions)

    Chiral symmetry
  - QCD motivated quark models

    bag model, potential model, Skyrmion

- New developments
  - lattice QCD

    S. Sasaki
  - chiral symmetry

    D. Jido
  - covariance and new symmetry

    M. Ishida
  - new experiments and data

B.S. Zou (BESS)	J/ψ decay selective production
J. Kasagi (LNS, Tohoku)	□ production
JLab, SPring8	high precision data, coincidence

Lattice QCD for baryons

- baryon as 3-quark states
  - confinement Takahashi et al.

    shape of confinement -> Y shape

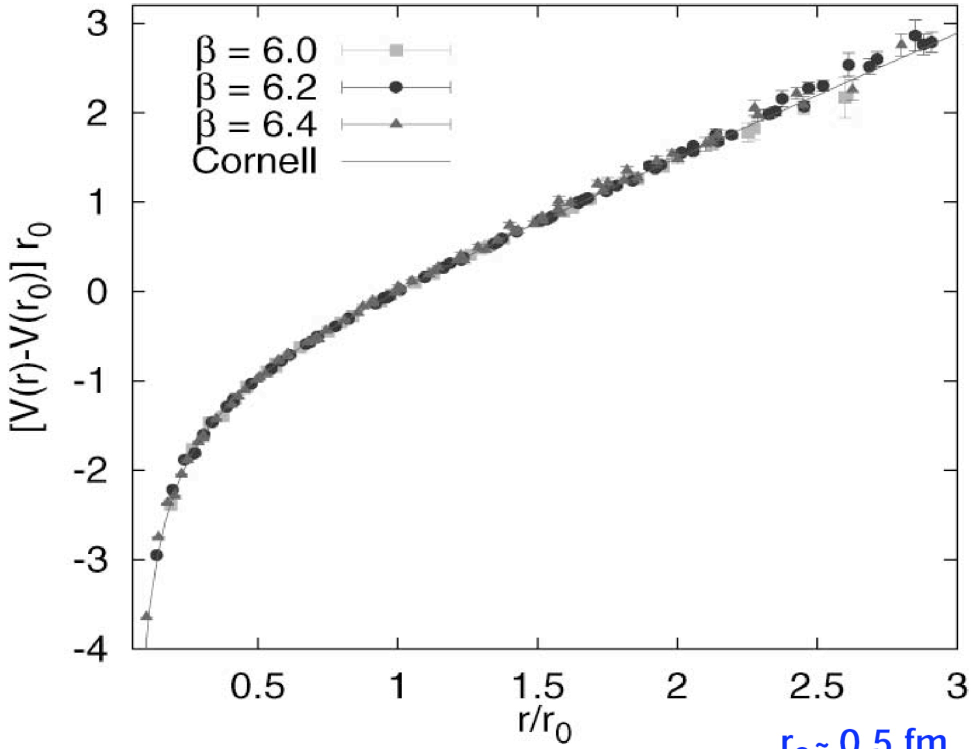
    heavy quark systems *i.e. ccc*
  - excited baryons S. Sasaki et al.

    ordering of excitations N*(1440) <=> N*(1535)

    maximal entropy method (MEM)
- baryon decay widths *real challenge*
  - meson-baryon coupling strengths
  - coupled channel

Confinement potential for the meson

G.S. Bali / Physics Reports 343 (2001) 1–136

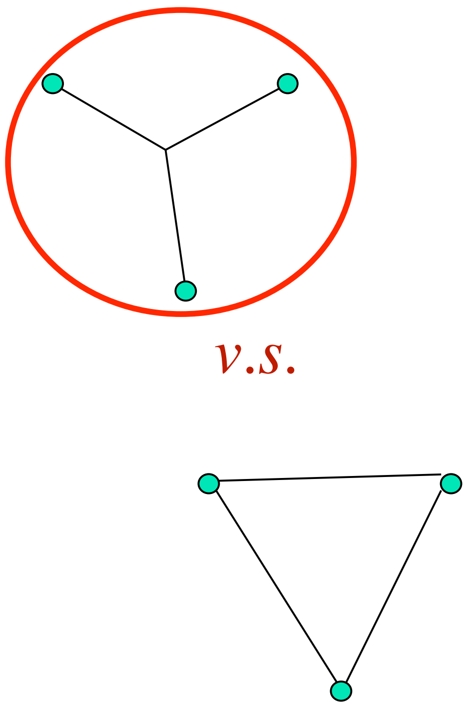


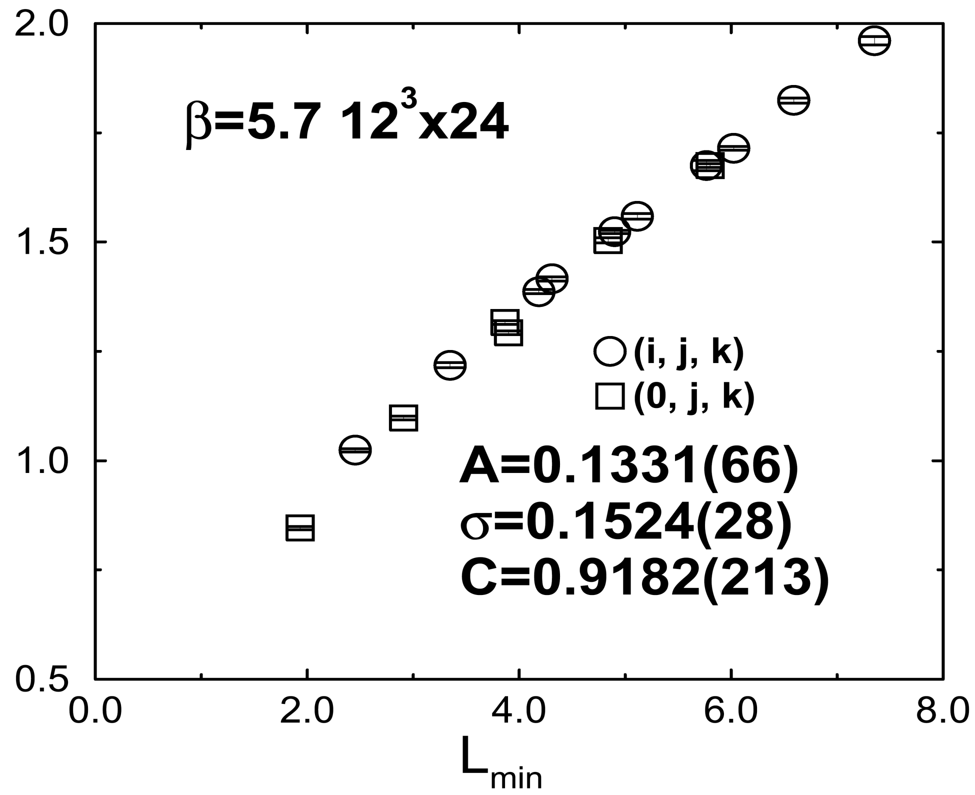
$r_0 \sim 0.5$ fm

Fig. 4.2. The quenched Wilson action $SU(3)$ potential, normalised to $V(r_0) = 0$.

Confinement potential for the baryon

Three-Quark Potential in SU(3) Lattice QCD
T. T. Takahashi, H. Matsufuru, Y. Nemoto, and H.Suganuma
Phys.Rev.Lett. 86 (2001) 18-21





Chiral symmetry of baryons

- Linear realization of chiral symmetry
  - high T and/or density □ QCD

    chiral symmetry restoration and hadron spectrum
  - mirror baryons D. Jido

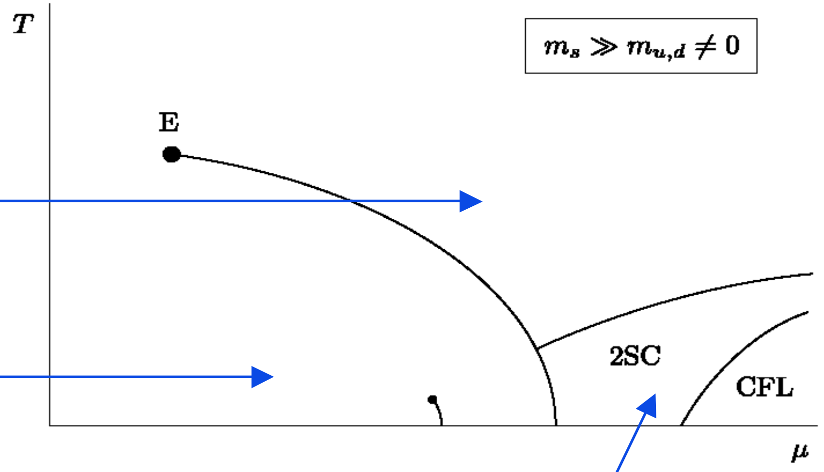
    baryon mass splitting due to the chiral symmetry breaking

    axial-vector coupling constant
- photoproduction experiments
  - □ photoproduction J. Kasagi

    No mass shift has been seen in nuclei, □ production enhanced
  - □ □ photoproduction for the mirror signature D. Jido

Chiral symmetry at high *T* and/or μ

- QCD phase diagram



Quark-gluon phase
Wigner phase

Hadron phase
NG phase

color supercond

- Chiral symmetry restoration

NG phase ⇨ Wigner phase

$\langle \bar{q} q \rangle \neq 0$ $\langle \bar{q} q \rangle = 0$

Hadron spectrum in the Wigner phase
belongs to a definite chiral irrep.
and consists of degenerate parity partners

Chiral irreducible representation

- Mesons

	SU(2)xSU(2)		SU(3)xSU(3)
(□, □)	= (1/2, 1/2)	(PS, S) =	(3, 3*) + (3*, 3)
(□, a_1)	= (1, 0) + (0, 1)	(V, A) =	(8, 1) + (1, 8)

□ meson as the chiral partner of □

Higgs particle of chiral symmetry breaking

softening of □ modes towards chiral symmetry restoration

Hatsuda, Kunihiro, Shimizu, PRL 82 (1999)

- Baryons

N(940 or 1440) ⇔ N(1535 or 1650) (1/2, 0) + (0, 1/2)

$1/2^+$ $1/2^-$

Are they chiral partners with each other?

Linear representation of N

- Linear representation of N $(N_f = 2)$

$$[Q_5^a, N] = \frac{1}{2}\gamma_5\tau^a N \qquad (1/2, 0) + (0, 1/2)$$

Chiral transform

$$N(x) = N_L(x) + N_R(x) \qquad N_{R,L} = \frac{1 \pm \gamma_5}{2} N$$

$$N_L(x) \to L\, N_L(x) \qquad L \in SU(N_f)_L$$
$$N_R(x) \to R\, N_R(x) \qquad R \in SU(N_f)_R$$

$\bar{N}N$ is not chiral invariant =>
N becomes massless in the Wigner phase.

Linear realization for N and N*

- Chiral representation with two baryons

- Naive assignment

$$N_{1R} \to RN_{1R} \qquad N_{1L} \to LN_{1L}$$
$$N_{2R} \to RN_{2R} \qquad N_{2L} \to LN_{2L}$$

- Mirror assignment

$$N_{1R} \to RN_{1R} \qquad N_{1L} \to LN_{1L}$$
$$N_{2R} \to LN_{2R} \qquad N_{2L} \to RN_{2L}$$

B. W. Lee
C. DeTar, T. Kunihiro

Mirror realization

- Linear model for mirror baryon

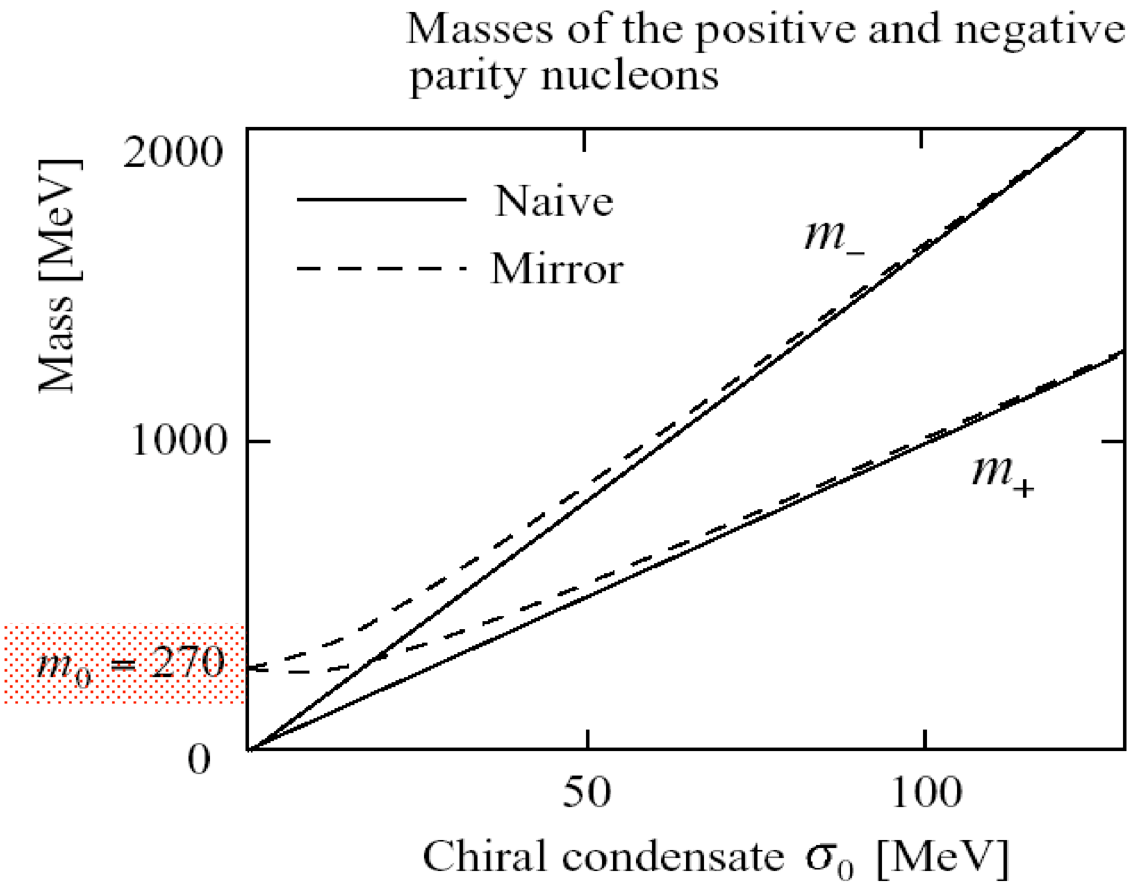
$$L_{\rm mirror} = \bar{N}_1 i\partial\!\!\!/ N_1 - g_1\bar{N}_1(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})N_1 + \bar{N}_2 i\partial\!\!\!/ N_2 - g_2\bar{N}_2(\sigma - i\gamma_5\vec{\tau}\cdot\vec{\pi})N_2$$
$$- m_0(\bar{N}_1\gamma_5 N_2 - \bar{N}_2\gamma_5 N_1) + L_{\rm mes}$$

- diagonalize the mass matrix

$$m_\pm = \frac{1}{2}\left(\sqrt{(g_1+g_2)^2\sigma_0^2 + 4m_0^2} \pm (g_1 - g_2)\sigma_0\right)$$

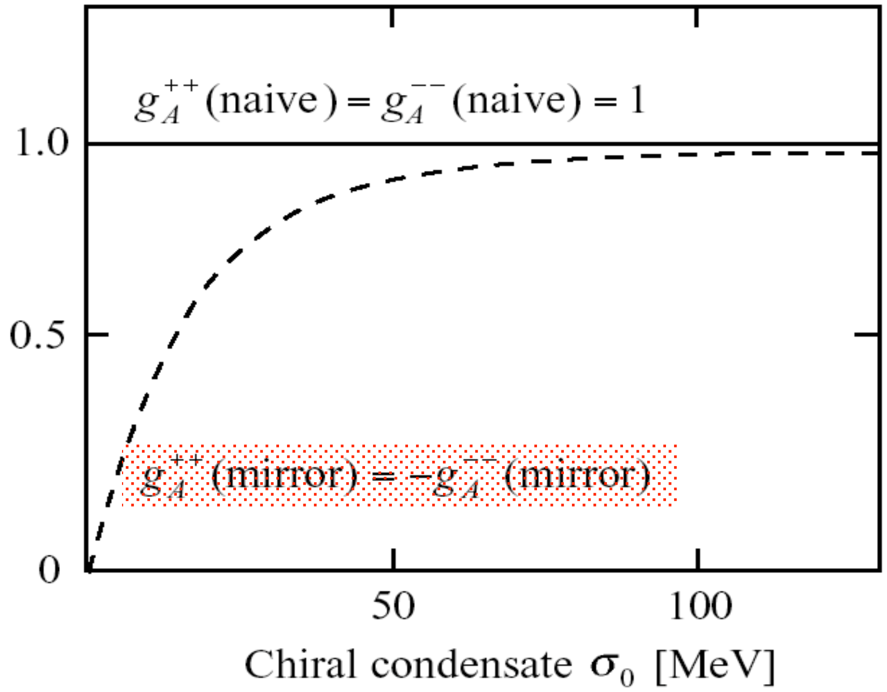
m_0 :"bare" baryon mass
independent of chiral
condensate

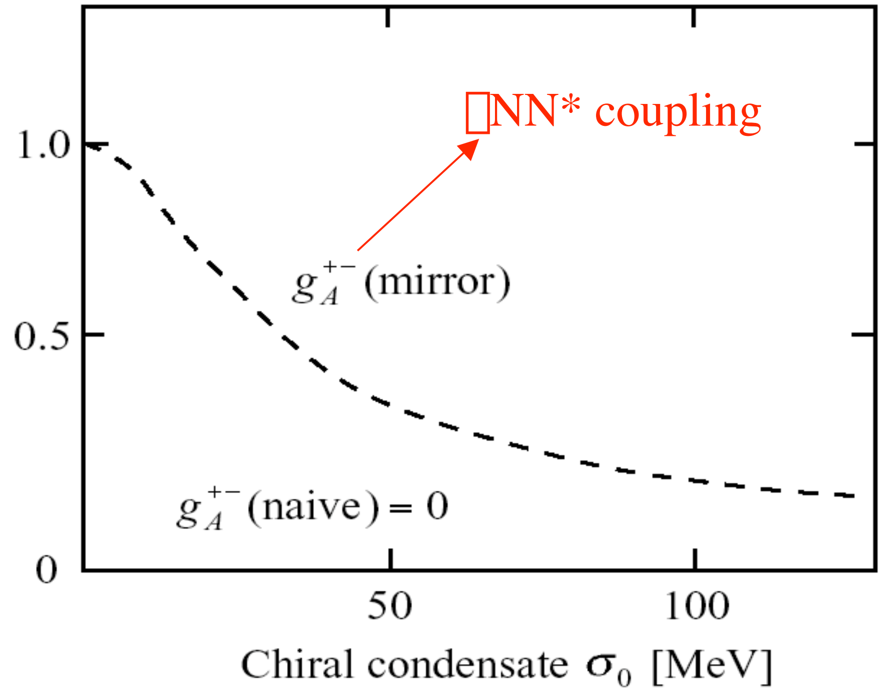
Masses of the mirror baryons vs σ_0



Jido, Hosaka, Oka
Prog. Theor. Phys. (2002)

Axial charges of baryons





Quartet model for N and Δ

Jido-Hatsuda-Kunihiro
Phys.Rev.Lett. 84 (2000) 3252

(1/2, 1) + (1, 1/2) irrep.
contains
N^+, N^-, $Δ^+$, $Δ^-$ quartet

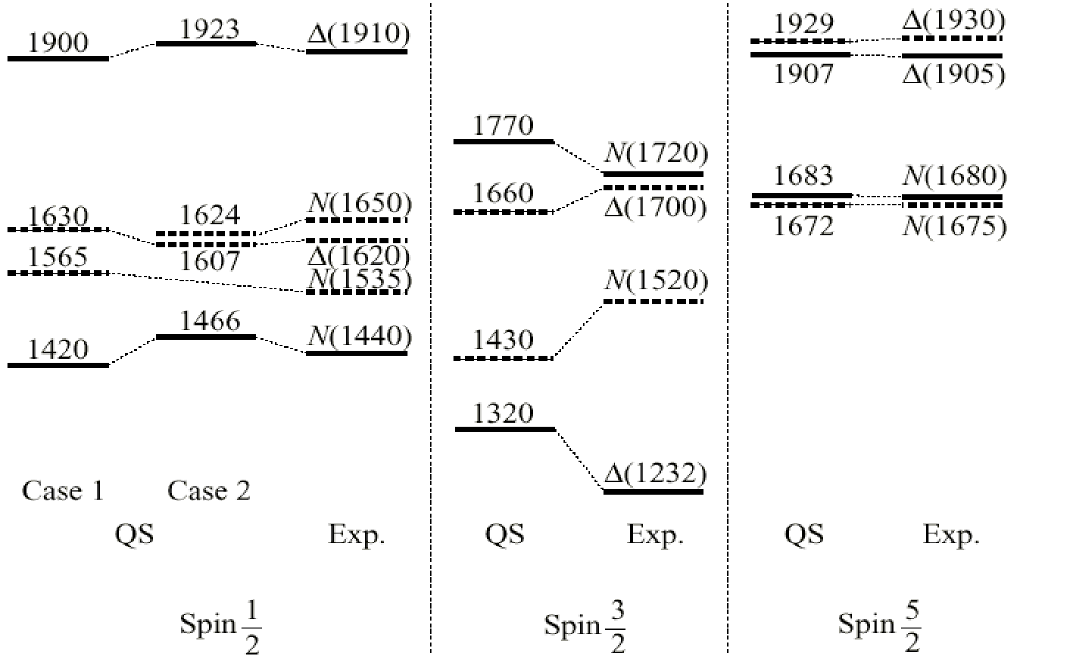


FIG. 1. The quartet members with $J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$. The right (left) hand side for each spin is the observed (quartet scheme) masses. The solid (dashed) lines denote the even (odd) parity baryons. The reproduced masses in our scheme agree with the experimental values within 10 %.

Signature for the mirror baryon pair

- In chiral symmetry restoration, the (N, N*) form a parity doublet with nonzero mass m_0 .
- Mirror baryons have opposite axial charges $g_A^{++} = -g_A^{--}$
- According to the Goldberger-Treiman relation, the sign of □*N***N** coupling constant is opposite to □*NN*.
- Suppose N*(1535) - N(940) form a mirror pair, then □*N* –> □□*N* reaction will be used to determine the sign of the □*N***N** coupling constants,

Models and Symmetry

- $U(12)_{SF}$ symmetry Ishida
  - new symmetry based on the extra degrees of freedom due to the small components of the quark fields
  - new interpretation of baryon resonances

    N(1440) : $56'^{+}$

    Λ(1405) : 70^{-}

- Collective Models of Baryons
  - deformed harmonic oscillator Hosaka, Koma, Toki
  - vibron model of baryons Bijker, Iachello, Leviatan

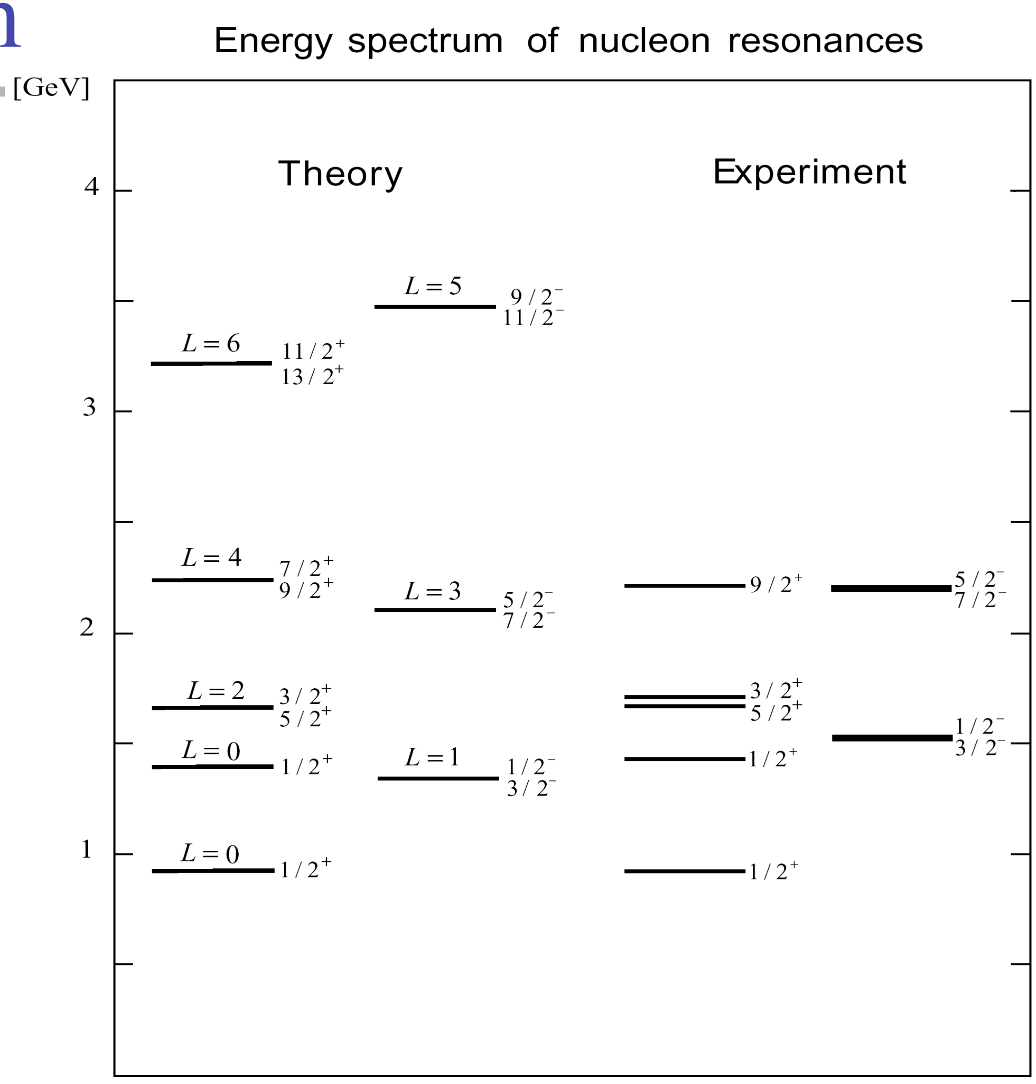
$\tilde{U}(12)_{SF}$ baryons

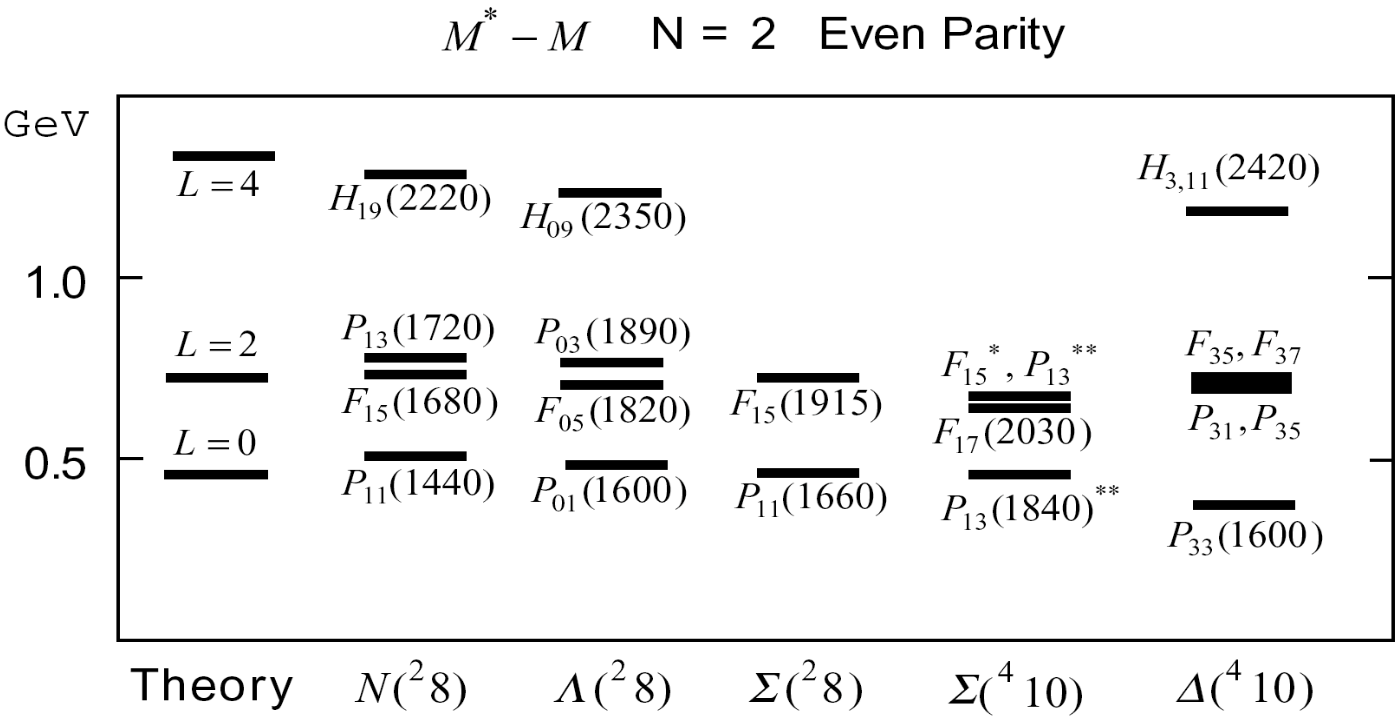
Ishida et al.

- 56^{+}(NR) *N*, □, □, □ □, □*, □*. □
- 56$^{'+}$ *N*(1440), □(1600), □(1660), .
  □(1600), …
- 70^{-} □(1405), …

Rotational band in baryon spectrum

Baryon Spectra in
Deformed Oscillator Quark Model
Hosaka, Takayama, Toki
Mod.Phys.Lett. A13 (1998) 1699





M* – M N = 2 Even Parity
GeV
1.0
0.5
L = 4
L = 2
L = 0
H19(2220)
P13(1720)
F15(1680)
P11(1440)
H09(2350)
P03(1890)
F05(1820)
P01(1600)
F15(1915)
P11(1660)
F15*, P13**
F17(2030)
P13(1840)**
H3,11(2420)
F35, F37
P31, P35
P33(1600)
Theory
N(²8)
Λ(²8)
Σ(²8)
Σ(⁴10)
Δ(⁴10)

Vibron model of baryon excitations

Bijker, Iachello, Leviatan

Annals Phys. 284 (2000) 89

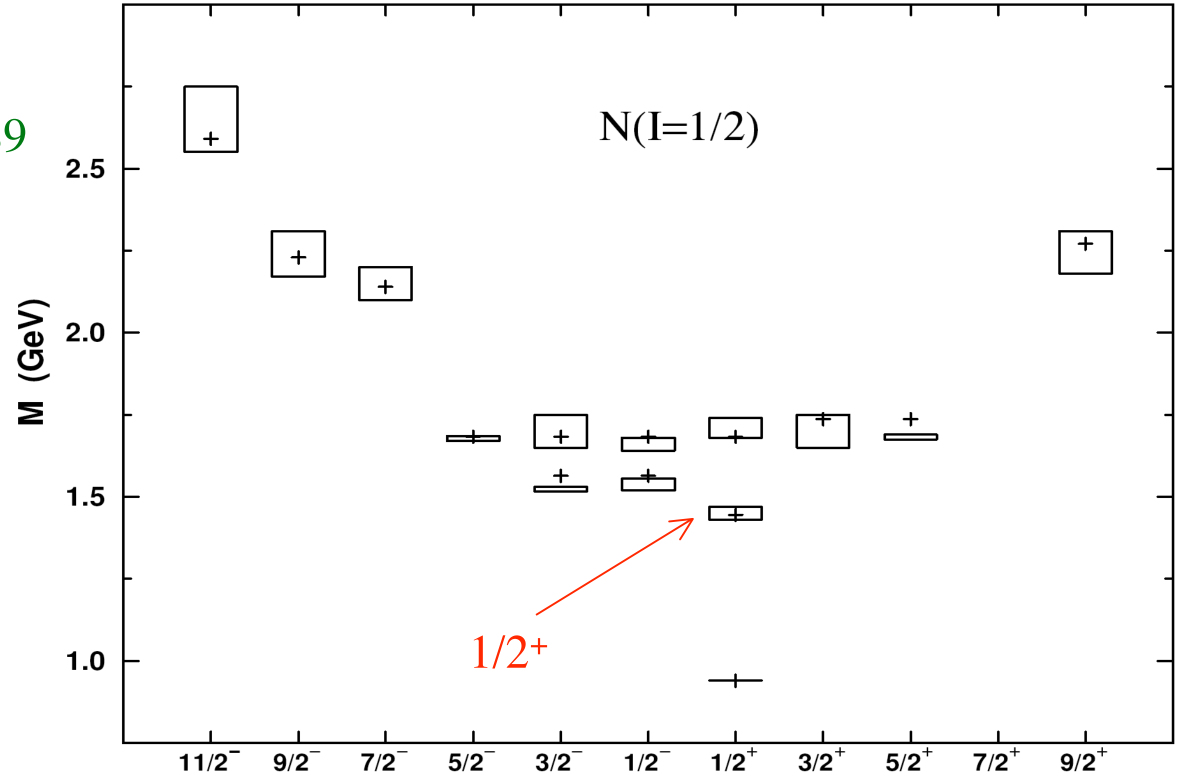


Figure 3: Comparison between the experimental mass spectrum of three and four star nucleon resonances (boxes) and the calculated masses (+).

$U_A(1)$ problem

- Symmetry of QCD Lagrangian ($m_{u,d,s} = 0$)

$$
\begin{array}{ccccc}
U(N_f)_R & \times & U(N_f)_L & \rightarrow & U(N_f)_V \\
Q_R & & Q_L & & Q_V \\
N_f^2 & & N_f^2 & & N_f^2
\end{array}
$$

We expect $N_f^2 (= 9)$ NG bosons

Weinberg limit on the η' mass

$$
\begin{array}{ccc}
m(\eta') & < & \sqrt{\frac{3}{2}} m_8 \\
985\text{MeV} & & \sim 700\text{MeV}
\end{array}
$$

$U_A(1)$ Anomaly

- $U_A(1)$ symmetry is broken by ANOMALY

$$U_A(1):$$

$$\begin{aligned} J_A^{\mu 0} &= \bar{q}\gamma^\mu\gamma^5 q \\ \partial_\mu J_A^{\mu 0} &= 2im_q\bar{q}\gamma^5 q + \frac{\alpha_s}{2\pi} N_f \,\mathrm{Tr}\{G_{\mu\nu}\tilde{G}^{\mu\nu}\} \end{aligned}$$

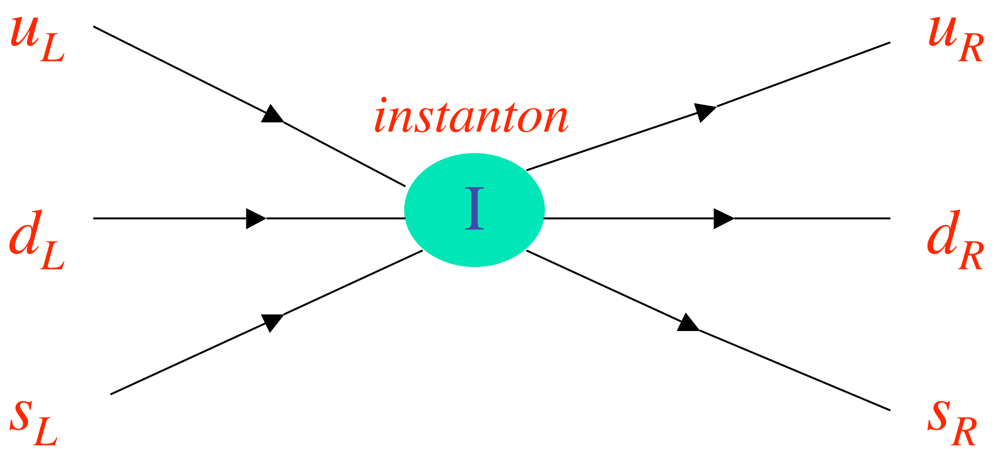
- Chiral Symmetry of QCD

$$\begin{array}{ccccccccc} SU(N_f)_R & \times & SU(N_f)_L & \times & U(1)_V & \rightarrow & SU(N_f)_V & \times & U(1)_V \\ Q_R & & Q_L & & & & Q_V & & \\ N_f^2-1 & & N_f^2-1 & & & & N_f^2-1 & & \end{array}$$

$$N_f^2 - 1 (= 8) \text{ NG bosons}$$

Instanton and KMT interaction

- Kobayashi-Maskawa-'t Hooft interaction
  - instanton-light-quark couplings

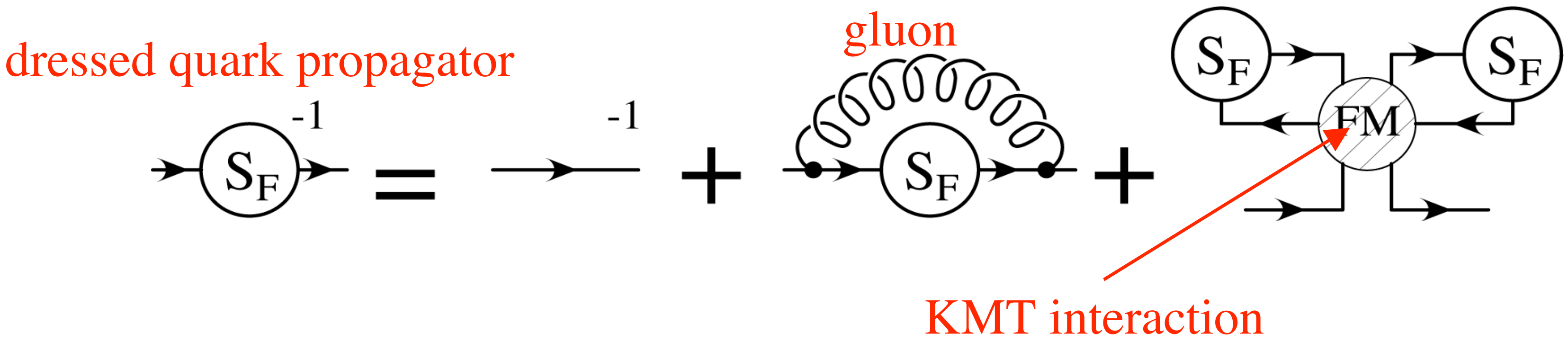


$$\mathcal{L}_6 \quad = \quad G_D \left\{ \det{}_{(i,j)} \left(\bar{q}^i_R q^j_L \right) + (\text{h.c.}) \right\}$$

Effective interaction on flavor singlet 3 quarks causes flavor mixing in $q\bar{q}$ systems

Ladder approximation of QCD

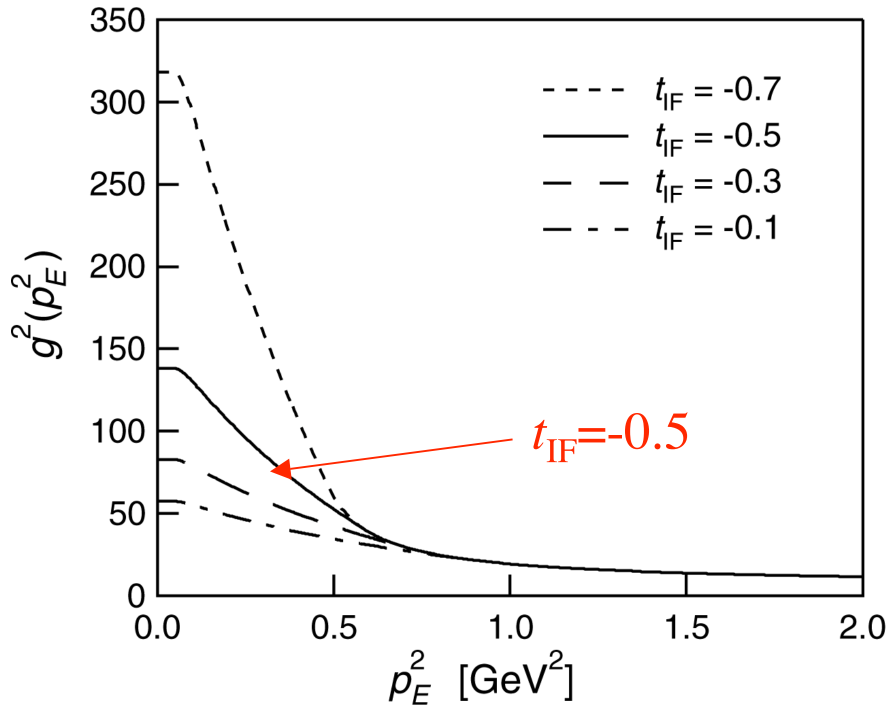
- Improved ladder Schwinger-Dyson equation with instanton induced 6-quark interaction



  - <u>running coupling constant</u> for quark-gluon vertex
  - chiral symmetry breaking -> nonzero mass function

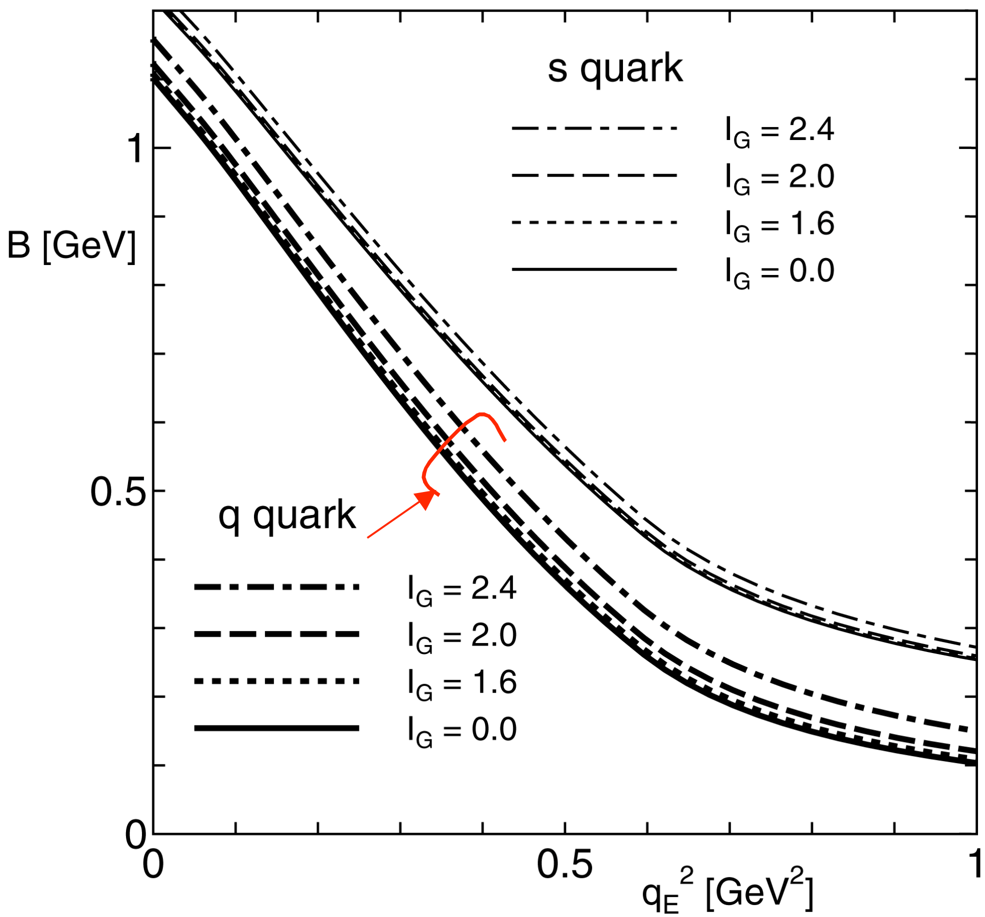
Running coupling constant

- $\bar{g}^2(p,k) = \theta(p_E^2 - k_E^2)g^2(p_E^2) + \theta(k_E^2 - p_E^2)g^2(k_E^2)$



$\Lambda_{QCD} = 0.6\,\text{GeV}$

Quark mass function



I_G [GeV^{-1}]: the strength of $U_A(1)$ breaking interaction

$$m_{u,d\,R} = 0$$

$$m_{s\,R}(\mu = 2\,\mathrm{GeV}) = 100\,\mathrm{MeV}$$

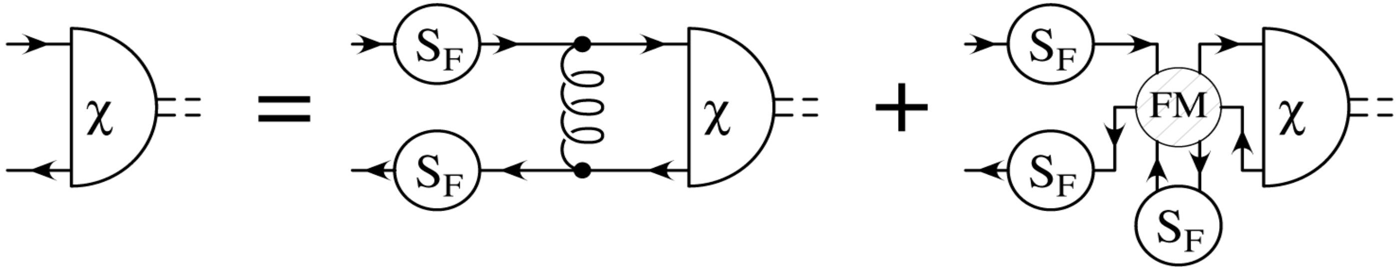
$$\Lambda_{QCD} = 600\,\mathrm{MeV}$$

$$t_{IF} = -0.5$$

Naito et al. PRC61 (2000) 065201

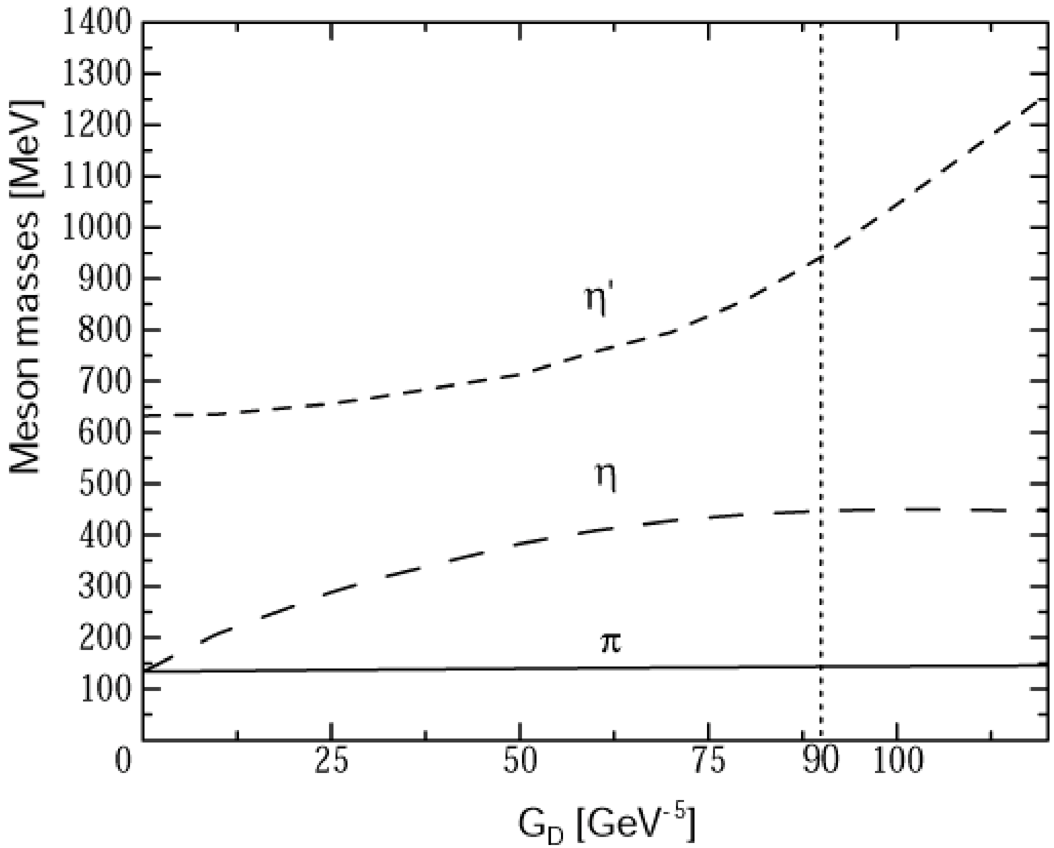
Ladder QCD

- Bethe-Salpeter equation for the $q\bar{q}$ mesons



  - pseudoscalar meson (NG boson)
  - scalar meson (Higgs of chiral symmetry)

Pseudoscalar meson masses



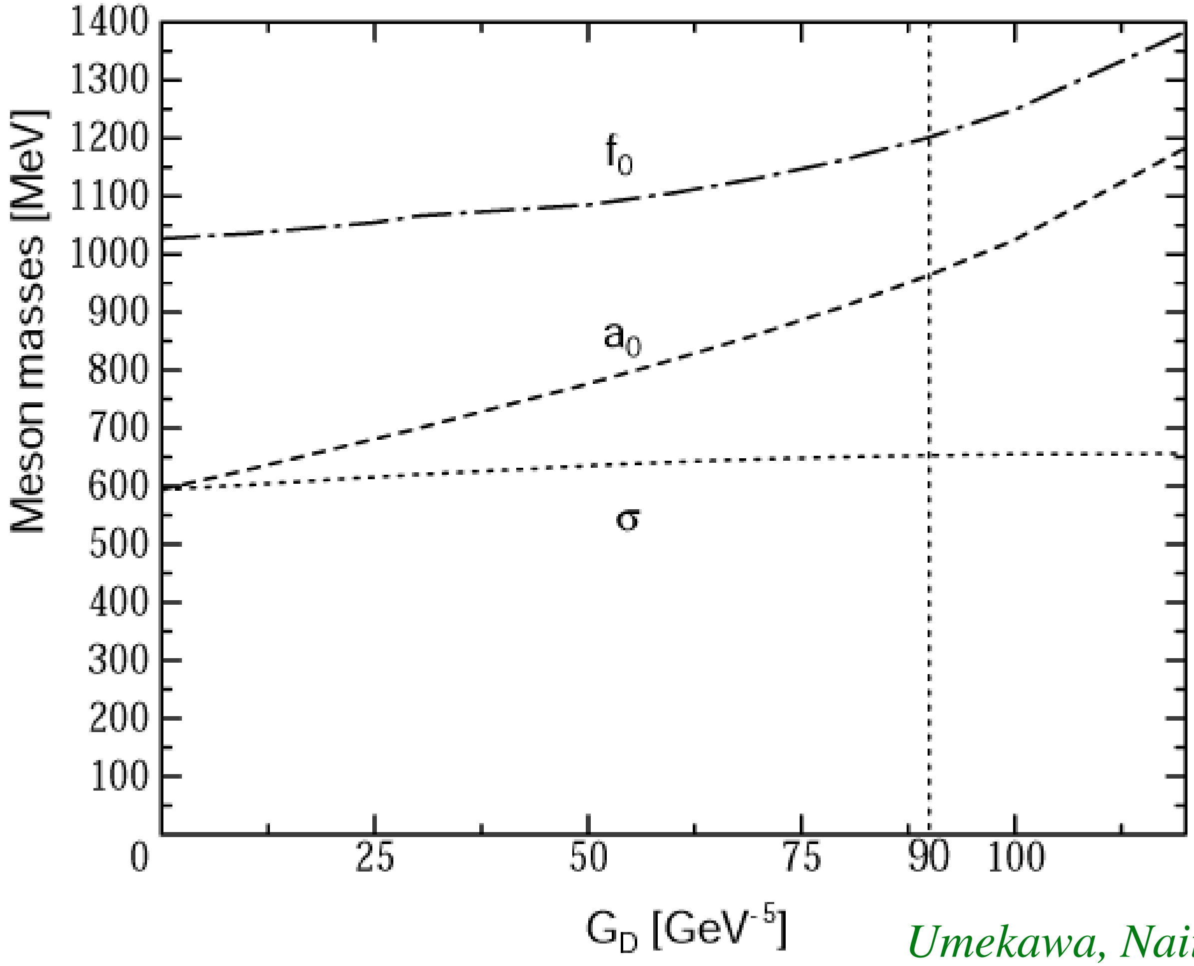
$$M_{\pi} = 144\,(138) \quad \text{[MeV]}$$

$$M_{\eta} = 447\,(547) \quad \text{[MeV]}$$

$$M_{\eta'} = 942\,(958) \quad \text{[MeV]}$$

Naito et al. PRC61 (2000) 065201

Scalar meson masses



[MeV]

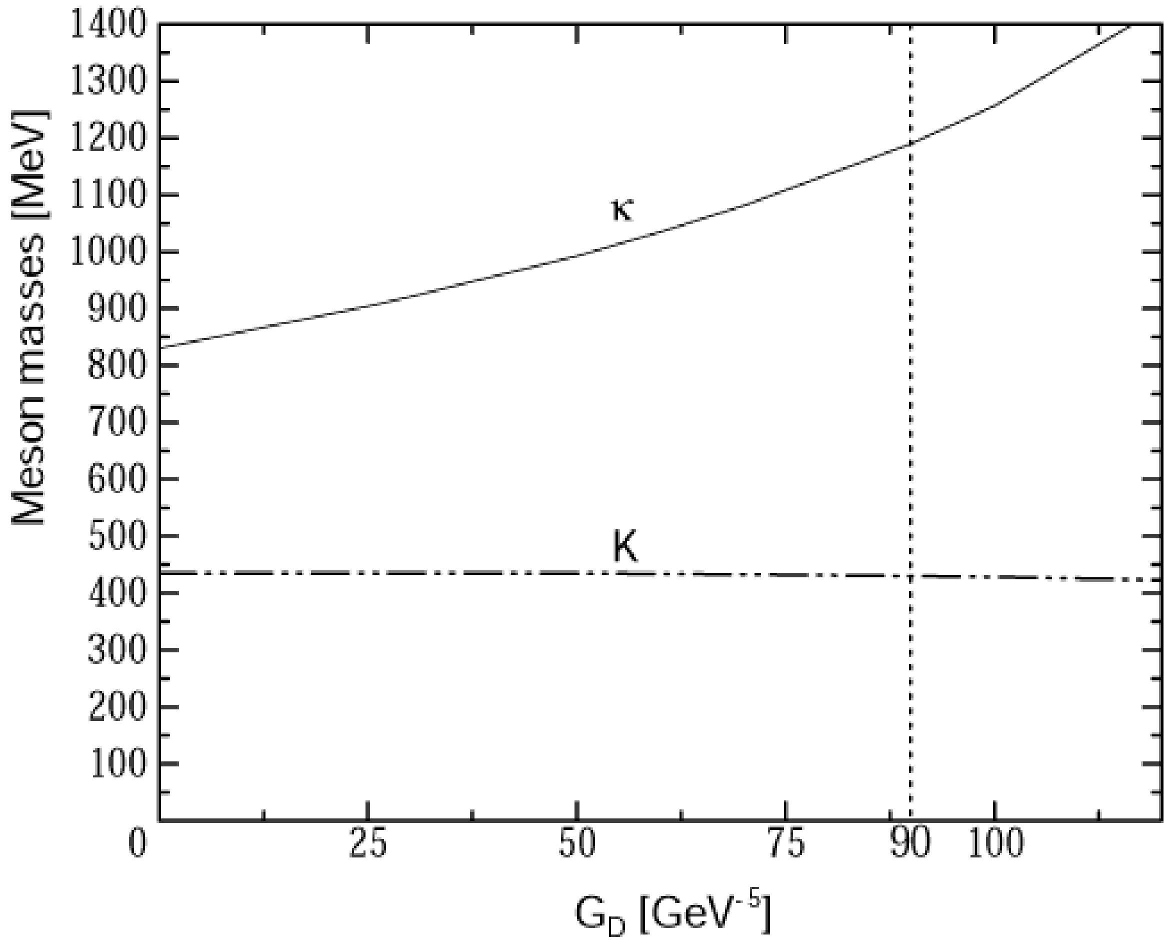
$M_{\sigma} = 653$

$M_{a_0} = 964$

$M_{f_0} = 1201$

Umekawa, Naito, Oka, Takizawa (2003)

Strange mesons



$m_{s,R} = 50$ MeV

$$M_K = 430 \quad \text{[MeV]}$$

$$M_{K_0^*} = 1190$$

Ladder QCD summary

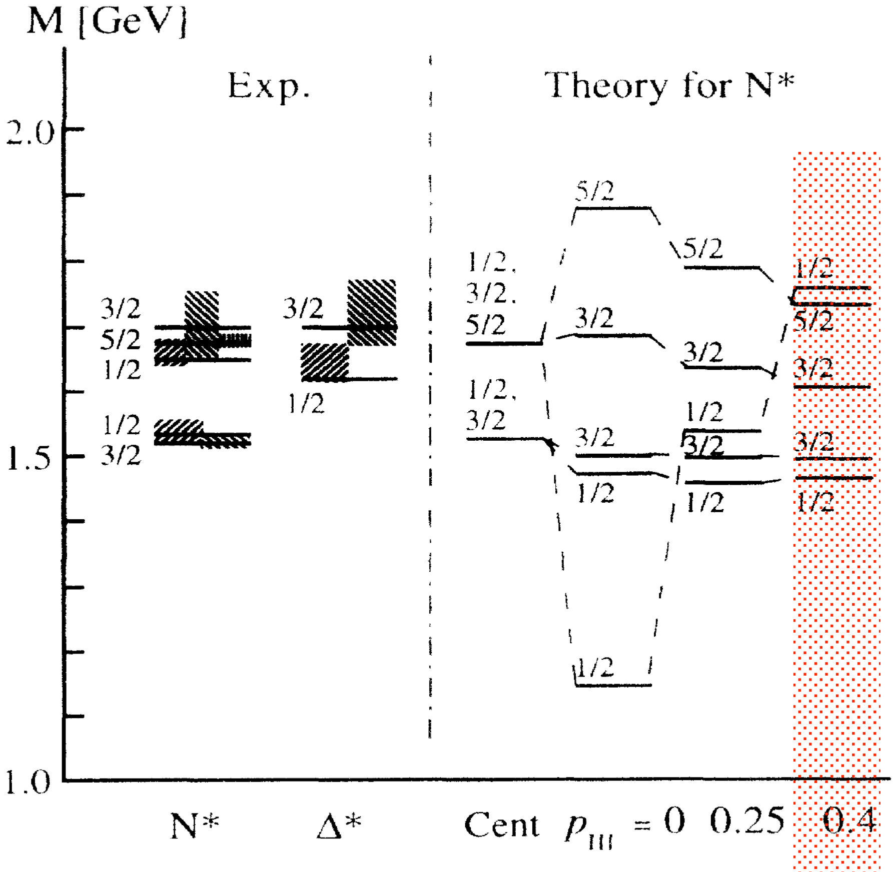
- The ladder QCD accounts for chiral symmetry breaking, the Nambu-Goldstone bosons, and the scalar partners.

- The $U_A(1)$ breaking KMT interaction explains the □' mass.

- The □ meson mass is predicted to be $M_{□} = 653$ MeV.
- The KMT interaction induces the □ and a_0 mass difference ~ 300 MeV : $M_{a0} = 964$ MeV
- □(~900) and f_0 (980) may not be chiral partners of the PS mesons K and □.

KMT in the baryon spectrum

$$H_{quark} = K + (1 - p_{III}) V_{OGE} + p_{III} V_{III} + V_{conf}$$



p_{III} = part of III (KMT) in the hyperfine splitting

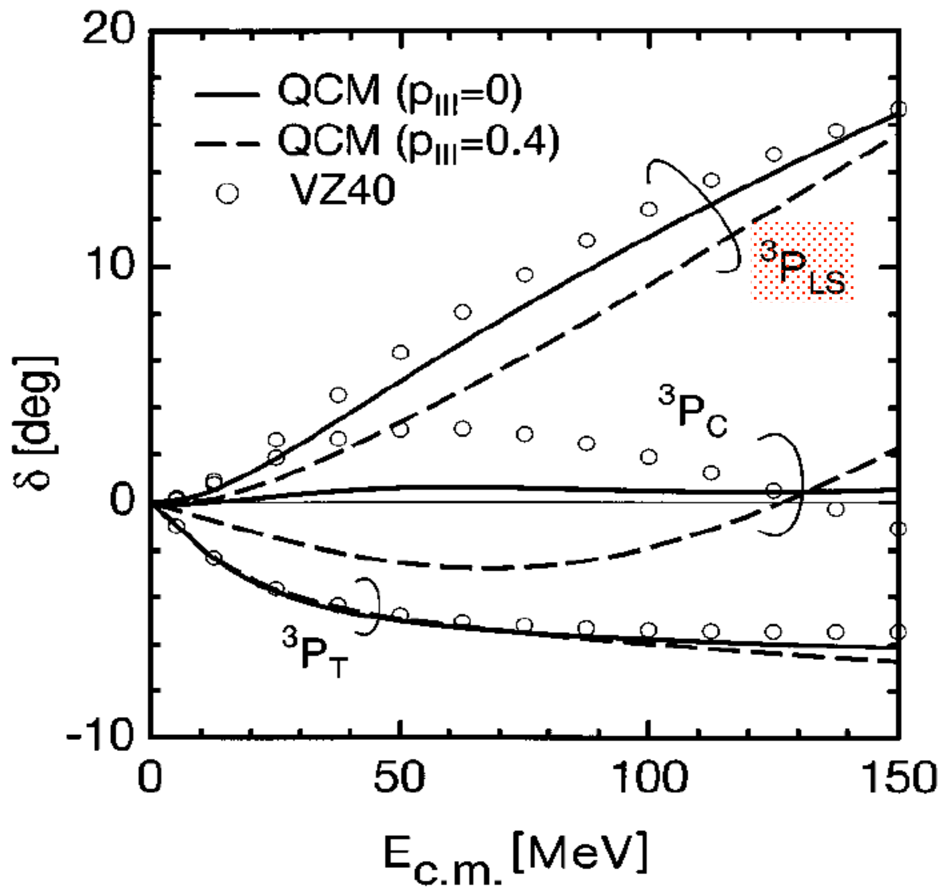
S. Takeuchi, PRL 73 (1994)

Weak LS force
in the P wave baryon spectrum

LS force in the *NN* P-wave interaction

Strong LS force
in NN P-wave scattering

S. Takeuchi, PR D53 (1996)



Conclusion

- Baryon spectrum is as interesting as the meson spectrum. More data are coming!

  JLab, SPring8, Tohoku

  BESS, ELSA, GRAAL, DAFNE, J-PARC (50GeV PS)
- Realistic lattice QCD calculations for the excited baryons have just begun.
- Chiral symmetry aspects of baryon and baryon resonances are yet to be studied.
- Roles of $U_A(1)$ breaking interaction should be explored in the baryon sector more.

Immediate future subject

- N*(1440) (Roper) $1/2^+$
  - Why is it lighter than N*(1535) $1/2^-$?
- Λ (1405) singlet? hybrid?
  - Is this f_0 in the baryon? $N\bar{K}$ bound state?

    If so, K^- may have a deeply bound nuclear state.
- Exotic
  - Z^+ (S=+1 baryon) reported in the nK^+ spectrum

    at SPring8 and JLab