Models of the Nonmesonic Weak Decay

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- □*I* =1/2 v.s. 3/2
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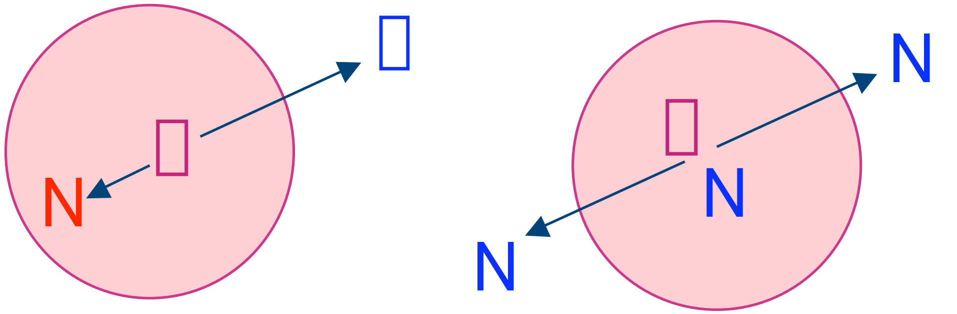
Nonmesonic weak decay

- mesonic decay *v.s.* nonmesonic decay



two modes
□p □ pn
□n □ nn

$p_{\mathrm{N}} \sim 100$ MeV/c

Pauli blocked

$p_{\mathrm{N}} \sim 400$ MeV/c

Short distance

What we knew in 1990?

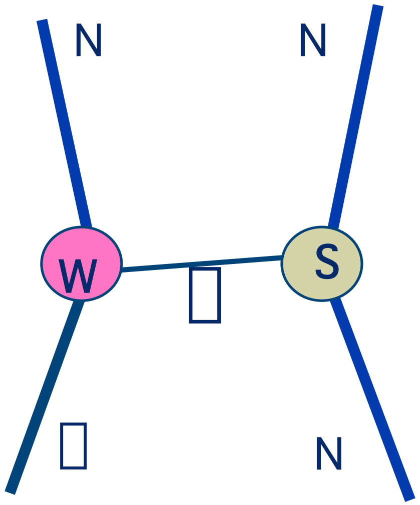
	Exp	Theory
$\square_{NM}$ or $\square$	mostly A □ 16	□+□+.. mostly nucl. matt
$\square_{nn}/\square_{pn}$	~1 or larger	not good
N spectrum	only fast protons	N/A
$\square_{p}^{NM}$	N/A	N/A
$\square I = 1/2$	N/A	assumed

O P E

- One-pion exchange

M. Ruderman, R. Karplus 1956

M.M. Block, R.H. Dalitz 1963



- Strong tensor interaction
  □p ($^3S_1$) □ np ($^3S_1$, $^3D_1$)
  no □n □ nn tensor transition
- $□_{pn}$ >> $□_{nn}$ □ $□_{pn}$ □ $□_{nn}$ (exp)

OPE

PHYSICAL REVIEW VOLUME 102, NUMBER 1 APRIL 1, 1956

Spin of the Λ^0 Particle

MALVIN RUDERMAN AND ROBERT KARPLUS
Physics Department, University of California, Berkeley, California
(Received December 7, 1955)

An analysis of the mesonic and nonmesonic decay of hyperfragments shows that the spin of the Λ^0 particle is 1/2 or 3/2. If the spin is 3/2, the parity is that of the proton.

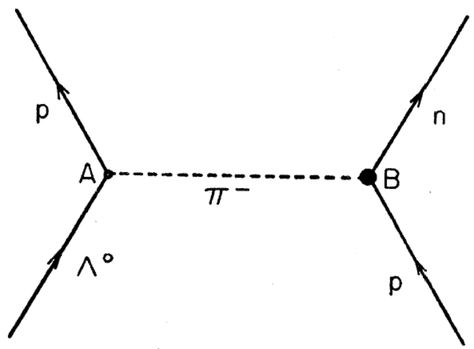


FIG. 1. Feynman diagram for internal conversion of π meson emitted by Λ^0.

Ratio (Nonmesonic / Mesonic) in nuclear matter is calculated. Conclude that the spin of □ is 1/2 or 3/2.

□ exchange

- □ + □
  - **B.M.J. McKellar, B.F. Gibson** (84)

    nuclear matter, tensor only

    □□N coupling by factorization (+pole diagram)
  - **K.Takeuchi, H.Takaki, H.Bando** (85)

    A=4, 5, tensor only

    factorization
  - **A. Parreno, A. Ramos, C. Bennhold** (95)

    significance of the central part

    coupling *a la* de la Torre

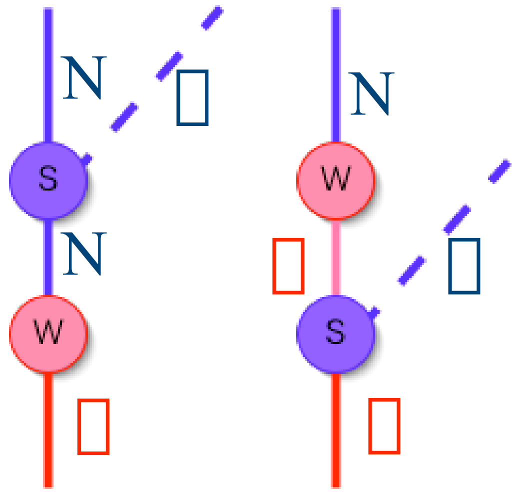
Weak couplings

- **J.F. Dubach, G.B. Feldman, B.R. Holstein, L. de la Torre (1996)**
  Weak coupling constants for pseudoscalar and vector mesons

  PV: SU(3) (PS) and $SU(6)_W$ (V)
  (+ a free parameter)

  PC: pole diagrams

PC part



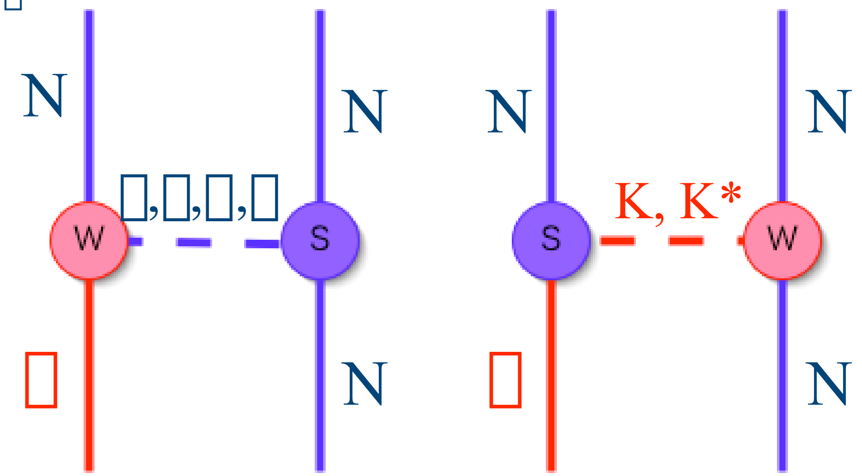
- need confirmation
  standard theory +QCD

More mesons

- + K+ □ + □ + K* (OBE)
  - **J.F. Dubach, et al.** (1996)

    Weak coupling constants for PS and Vector mesons
  - **A. Parreno, A. Ramos, C. Bennhold** (1997)

    A full careful calculation $^{12}_{\square}C$



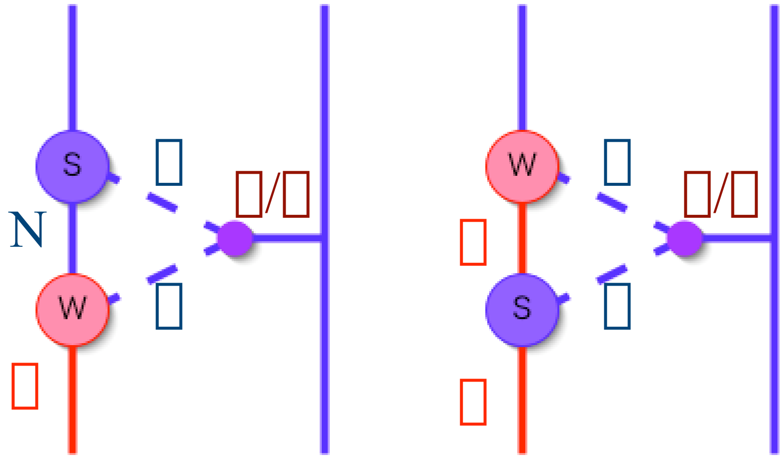
More

- correlated 2□/□ and 2□/□
  - **M.Shmatikov** (1994)

    N + □ cancellation, significant J =0
  - **K. Itonaga, T. Ueda, T. Motoba** (1994, 2002)

    □ -- strong central

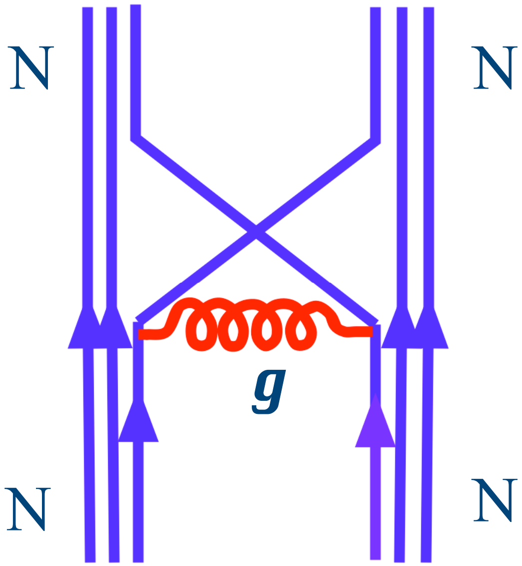
    □ -- strong tensor

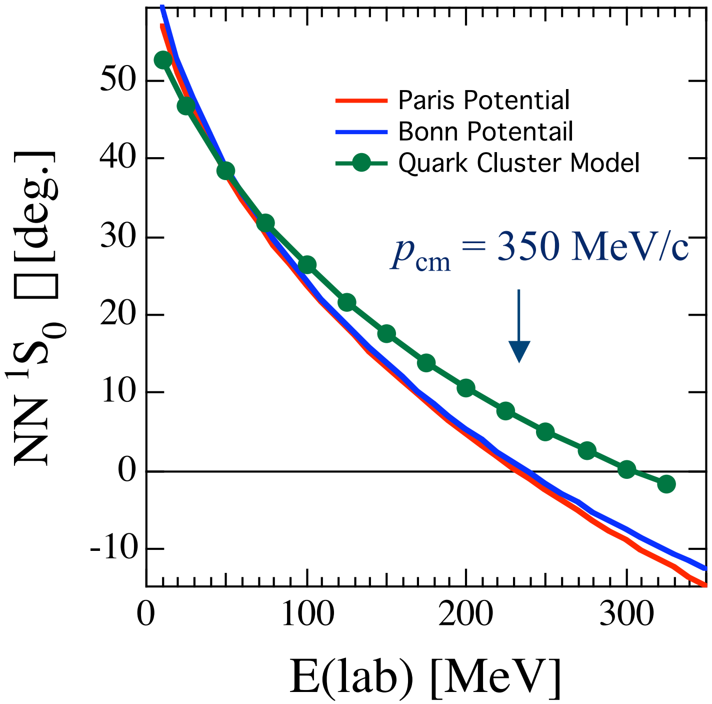


Short range BB interaction

- NN: Quark exchange force

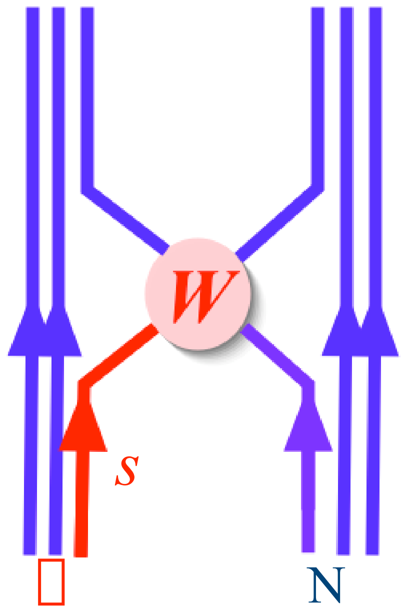
NN Short-range repulsion **(Oka–Yazaki, 1980)**





Direct Quark

- Direct quark weak process



W effective hamiltonian for weak interactions of quarks

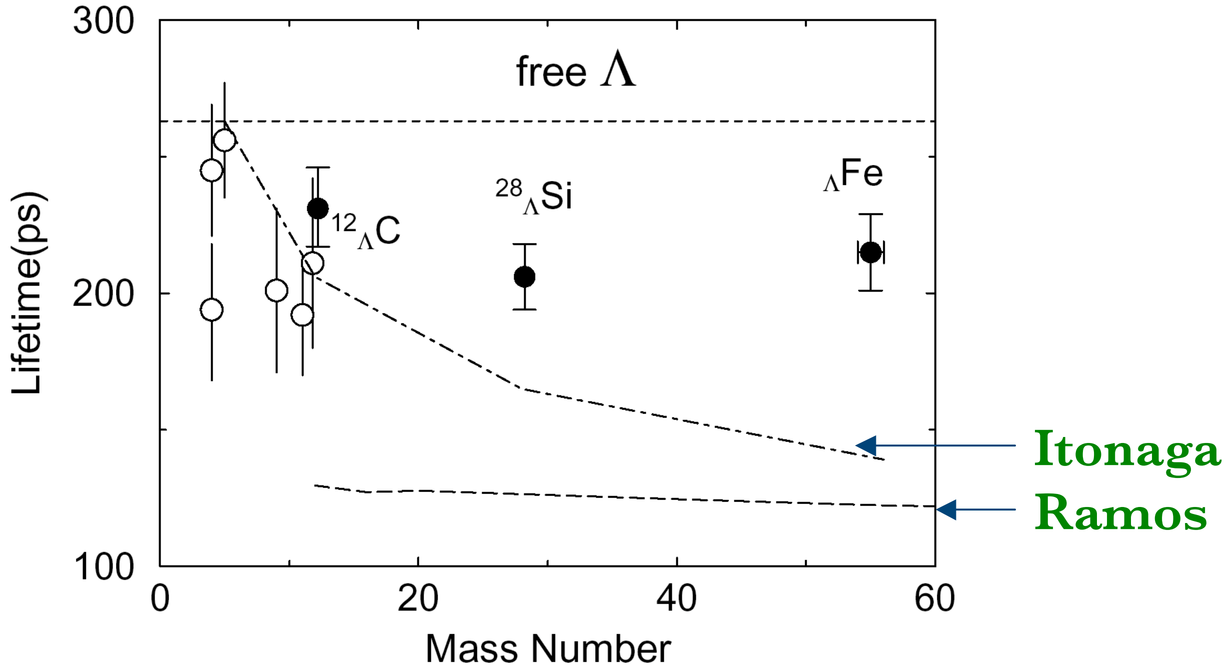
s u → d u
s d → d d

DQ describes short-range part of the baryonic weak interactions.
→ vector meson exchanges

Decay rates

- large *A*

KEK-PS E307



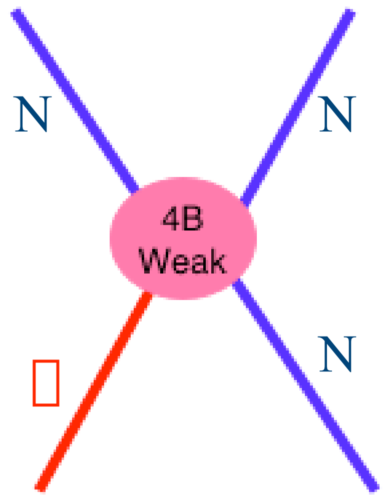
Quarks

- Direct quark mechanism
  - **C.Y. Cheung, D.P. Heddle, L.S. Kisslinger** (1983)
    The weak vertex was *not correct.*
  - **K. Maltman, M. Shmatikov** (1994) quark + π, K
    ΔI =1/2 violation
  - **T. Inoue, S. Takeuchi, M.O.** (1994) DQ, DQ + π
    DQ gives a large n/p ratio
    Strong ΔI =3/2 in J = 0 amplitudes
  - **K. Sasaki, T. Inoue, M.O.** (2000) π+K, DQ+π+K
    n/p ratio improved ~ 0.5 or larger

4-baryon vertex

- effective interaction approach
  - **M.M. Block, R.H. Dalitz** (1963)
  - **J.-H. Jun, H. C. Bhang** (1998, 2001) phenomenology
  - **A. Parreno, C. Bennhold, B.R. Holstein** (2003) talk

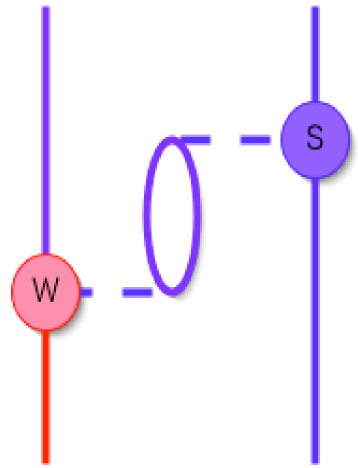
    Chiral effective theory of the weak interaction



Nuclear effects

- medium effects on OPE and OBE
  - **E. Oset, L.L. Salcedo** (1985)
  - **A. Parreno, A. Ramos, E. Oset** (1995, 2001)

    Short-range correlation and Final state interactions



- 2N induced decay
  - **A. Ramos, E. Oset. L.L. Salcedo** (1994)

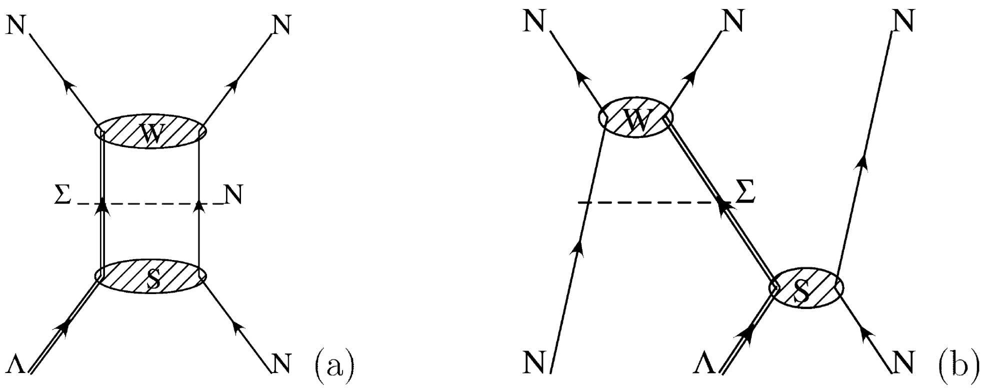
    importance in extracting n/p ratio
  - **W.M. Alberico, A. De Pace, G. Garbarino, A. Ramos** (2000)

Roles of □

- □□□ coupling
  - **H. Bando, Y. Shono, H. Takaki** (1988)
  - **K. Sasaki, T. Inoue, M. O.** (2002)

coherent mixing of □

10% effects on A=4 hypernuclei



Data

- Observables
  - NM decay rates Γ_{NM} or lifetimes
  - Partial rates Γ_{pn} , Γ_{nn} and the **n/p** ratio
  - Proton asymmetry parameter α_{p}^{NM}
  - Nucleon spectrum and 2N induced mode Γ_{2N}

n/p ratio : $\Gamma_{nn} / \Gamma_{pn}$

- Theory

1963	OPE	~ 0.1	too small
1997	OBE (all mesons)	~ 0.1	no improvement
1998	π+DQ	0.49	
1999	π+K+DQ	0.20	for $^{5}_{\Lambda}He$

2000 Sasaki et al. f_p(K) and f_n(K) sign corrected

π+K 0.45 f_N : $^3S_1 \rightarrow {}^3P_1$ (I =0)

π+K+DQ 0.70 for $^{5}_{\Lambda}He$

NP A678 (2000) 455-456

n/p Status

$^{5}_{□}$He	$□_{NM}$	$□_{nn}/□_{pn}$	$□_{p}^{NM}$
□+K+DQ (Sasaki et al., 2000)	0.52	0.70	- 0.68
OBE (all) (Parreno et al., 2001)	0.32	0.46	- 0.68
□+K+□+2□/□, □ (Itonaga et al., 2002)	0.42	0.39	-0.33 or 0.12
Exp	0.41 ± 0.14	0.44 ± 0.11 (KEK E462)	0.09 ± 0.08 (KEK E462)

Proton asymmetry

- Theory **H.Nabetani, T.Ogaito, T.Sato, T.Kishimoto (1999)**

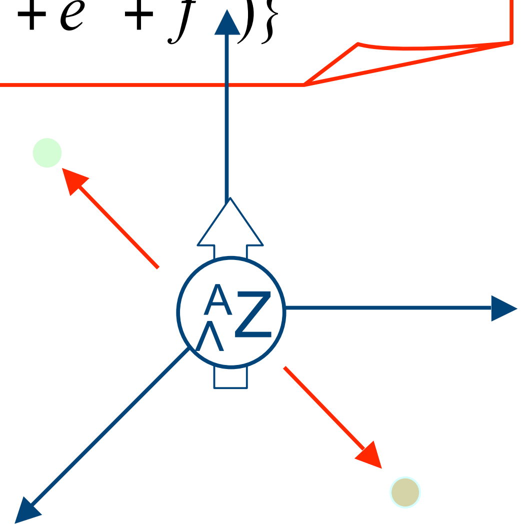
asymmetry parameter

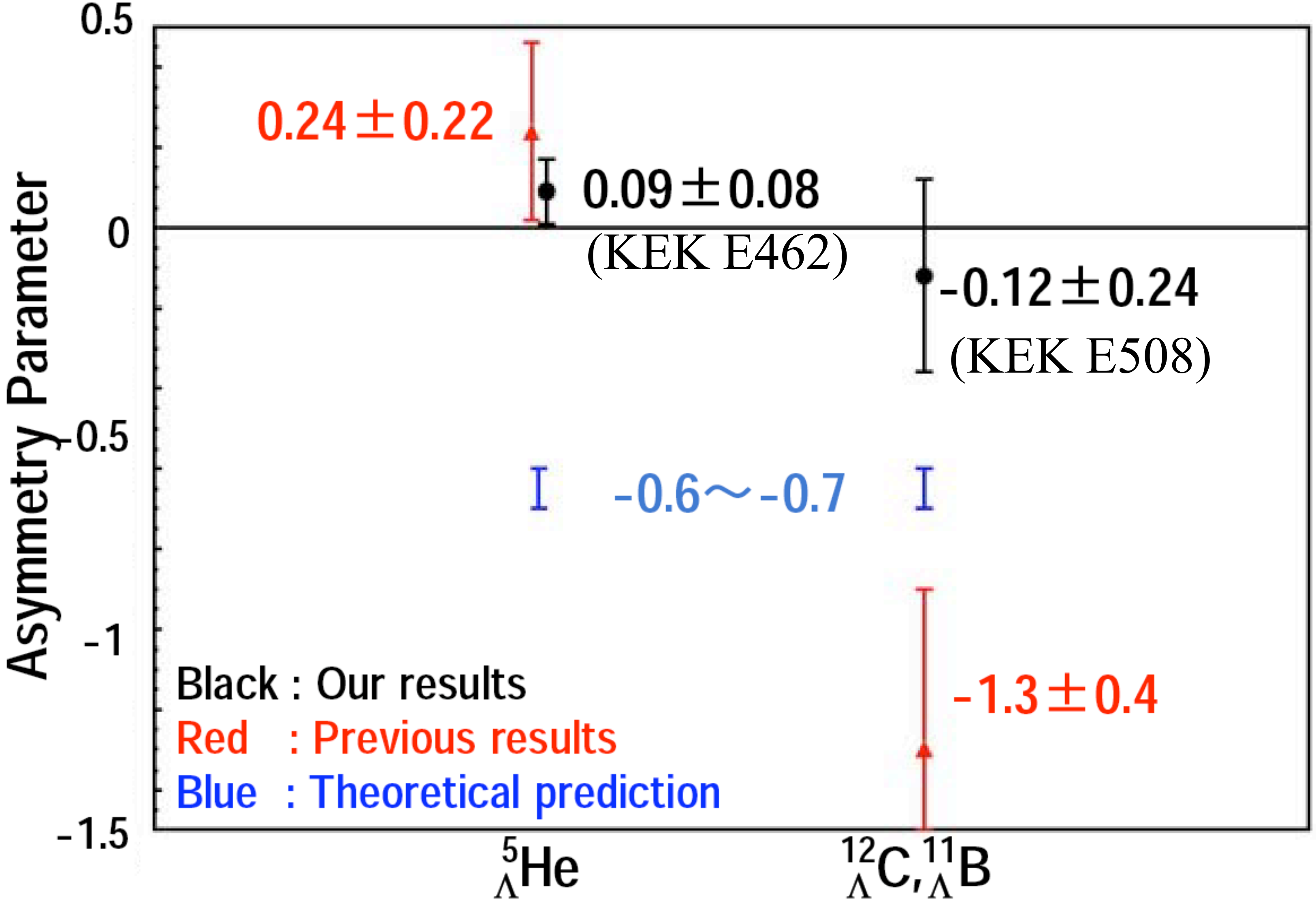
$$\alpha_p^{NM} = \frac{\sqrt{3}/2\,[-ae + b(c - \sqrt{2}d)/\sqrt{3} + (\sqrt{2}c + d)f]}{1/4\,\{a^2 + b^2 + 3(c^2 + d^2 + e^2 + f^2)\}}$$

Interference between

PC and PV amplitudes

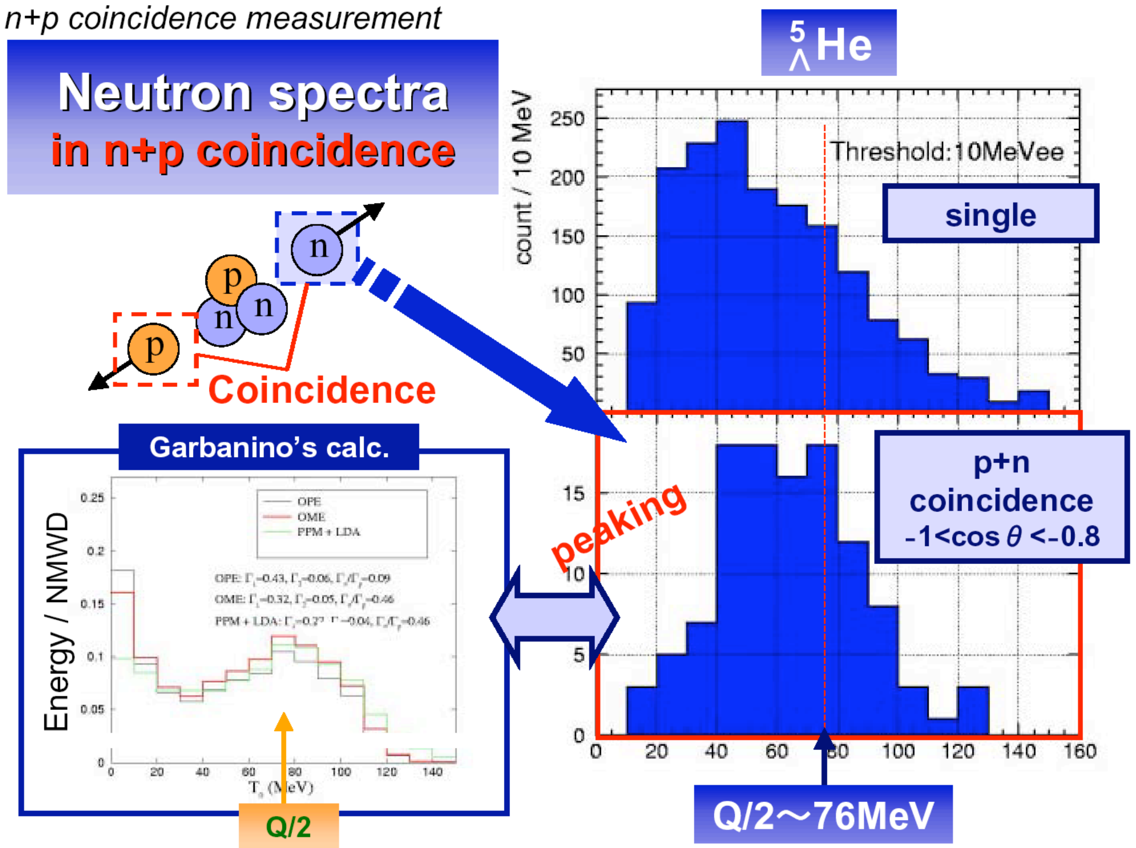
J=0 and J=1 amplitudes





0.5
0
-0.5
-1
-1.5
Asymmetry Parameter
0.24±0.22
0.09±0.08
(KEK E462)
-0.12±0.24
(KEK E508)
-0.6～-0.7
-1.3±0.4
Black : Our results
Red : Previous results
Blue : Theoretical prediction
$^{5}_{\Lambda}$He
$^{12}_{\Lambda}$C, $^{11}_{\Lambda}$B

Nucleon Spectrum



KEK E462
(E508)
S. Okada

G. Garbarino, A. Parreno, A. Ramos (2002)

In this conference

- Plenary
  - **H.C. Bhang** KEK E462, E508 (single particle spectra)
  - **H. Outa** KEK E462, E508 (coincidence exp)
  - **A. Parreno** Effective theory approach
- Parallel Session 8
  - **G. Garbarino** Nucleon spectrum
  - **K. Sasaki** DQ+□+K
  - **T. Maruta** $\square_{p}^{NM}$

More Observables

- Weak production of □ in np □ □p

J. Haidenbauer et al. (1995)	OPE
A. Parreno et al. (1998)	OBE
N. Nabetani et al. (1999)	Spin observables
T. Inoue, K. Sasaki, M. O. (2001)	DQ+□

$J=1$ amplitudes dominant □ $\sim 10^{-39} \sim 10^{-40}$ cm^2

□ Experiments planned at RCNP, COSY

□ **Minami** (S8)

$J = 0$ amplitudes

- Need further study on a_{p}, a_{n}, b_{p}, b_{n}
  - Proton asymmetry $□_{\mathrm{p}}^{\mathrm{NM}}$
  - $□I = 3/2$ in NMWD
- Decays of double hypernuclei
  - □□ □ □N pure $J = 0$ (initial state: $^{1}S_{0}$)

$J = 0$ amplitudes

- □□ □ YN decays of $_{□□}{}^{6}$He

$\Lambda\Lambda \to YN$ decay rates of $_{\Lambda\Lambda}^{\;6}$He in unit of Γ_Λ. The PC and PV denote the $^1S_0 \to {}^1S_0$ parity-violating and $^1S_0 \to {}^3P_0$ parity-conserving transitions, respectively

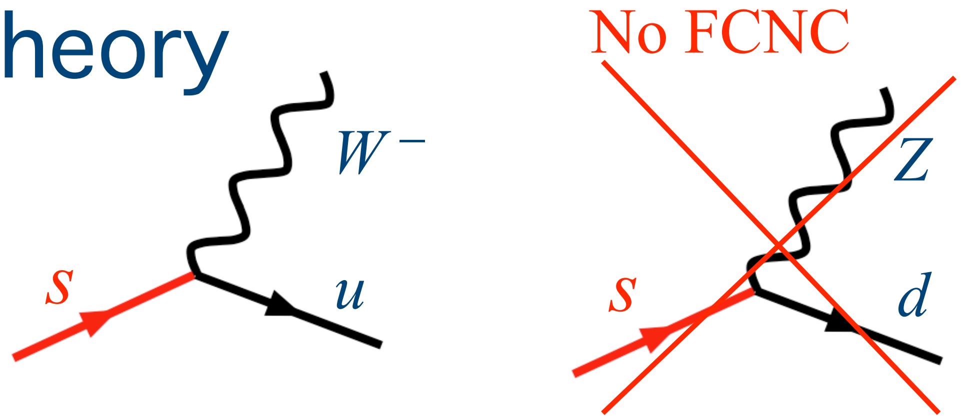
$_{\Lambda\Lambda}^{\;6}$He	$\Gamma_{\Lambda n}$ PC	$\Gamma_{\Lambda n}$ PV	$\Gamma_{\Sigma^0 n}$ PC	$\Gamma_{\Sigma^0 n}$ PV	$\Gamma_{\Sigma^- p}$ PC	$\Gamma_{\Sigma^- p}$ PV
π	–	–	0.0004	0.0030	0.0009	0.0061
$\pi + K$	0.0001	0.0002	0.0011	0.0040	0.0021	0.0079
DQ	0.0001	0.0012	0.0047	0.0037	0.0012	0.0018
$\pi + K +$ DQ	0.0000	0.0024	0.0065	0.0000	0.0064	0.0021
Total	0.0024		0.0065		0.0085	
Ref. [10]	0.025		0.0006		0.0012	
Ref. [11] (E)	0.0044		0.011		0.022	
Ref. [11] (F)	0.036		0.001		0.003	

[10]Itonaga et al (2003), [11]Parreno et al. (2002)

Tiny

Weak Interactions of Quarks ($\Delta S = 1$)

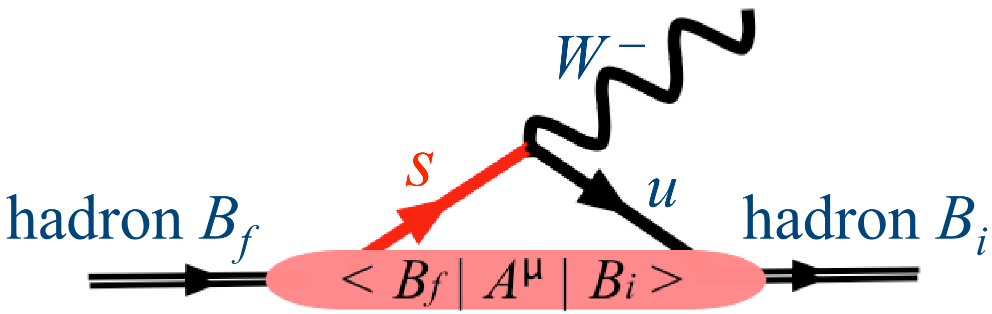
- Standard theory



- semi-leptonic weak interactions

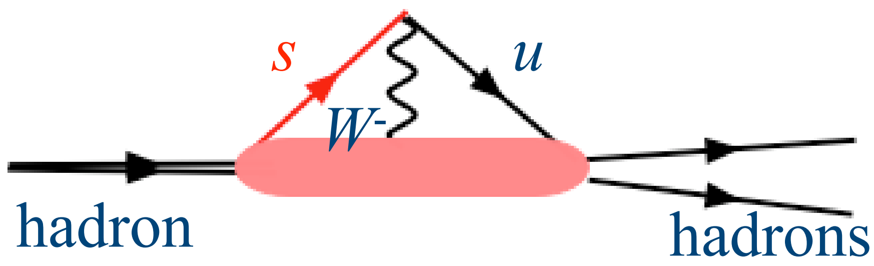
$$K^- \to \mu^- \nu_\mu$$

$$\Lambda \to p e^- \nu_e$$

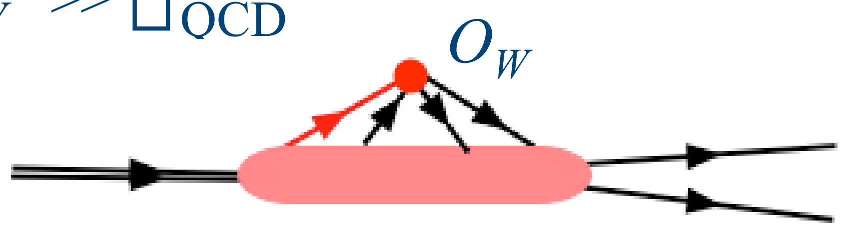


Weak Interactions of Quarks ($\Delta S = 1$)

- nonleptonic weak interactions



  - as $m_W^2 >> \Lambda_{QCD}^2$



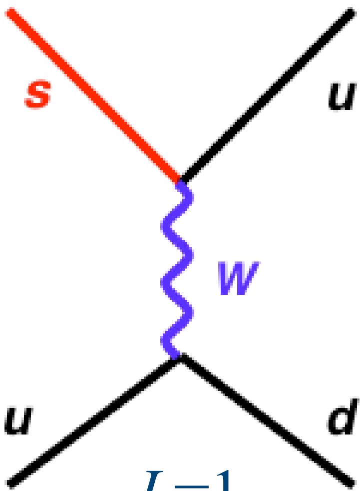
$$O_W = C_W \left(\bar{u}\gamma^{\mu}(1-\gamma^5)s\right)\left(\bar{d}\gamma_{\mu}(1-\gamma^5)u\right)$$

□I =1/2 rule

- standard theory does *NOT* predict
  □I =1/2 dominance

$$s \to \underline{u} + W^- \qquad W^- \to \underline{d + \bar{u}}$$

I =1/2 $\oplus$ □=1



I =1

$$\Delta I = \frac{1}{2} \qquad \left(\frac{1}{2}\,\frac{1}{2}\,1\ -1\middle|\frac{1}{2}\ -\frac{1}{2}\right) = \sqrt{\frac{2}{3}} \qquad \cdots 2$$

$$\Delta I = \frac{3}{2} \qquad \left(\frac{1}{2}\,\frac{1}{2}\,1\ -1\middle|\frac{3}{2}\ -\frac{1}{2}\right) = \sqrt{\frac{1}{3}} \qquad \cdots 1$$

$\Delta I = 1/2$ rule (exp)

- $K \to \pi\pi$
  - $K_s \to \pi^+\pi^-$ (68%), $\pi^0\pi^0$ (32%) $\to$ almost $I = 0$ $\to$ $\Delta I = 1/2$
  - $K^+ \to \pi^+\pi^0$ ($I = 2$, $J = 0$) (21%) $\to$ $I = 2$ $\to$ pure $\Delta I = 3/2$

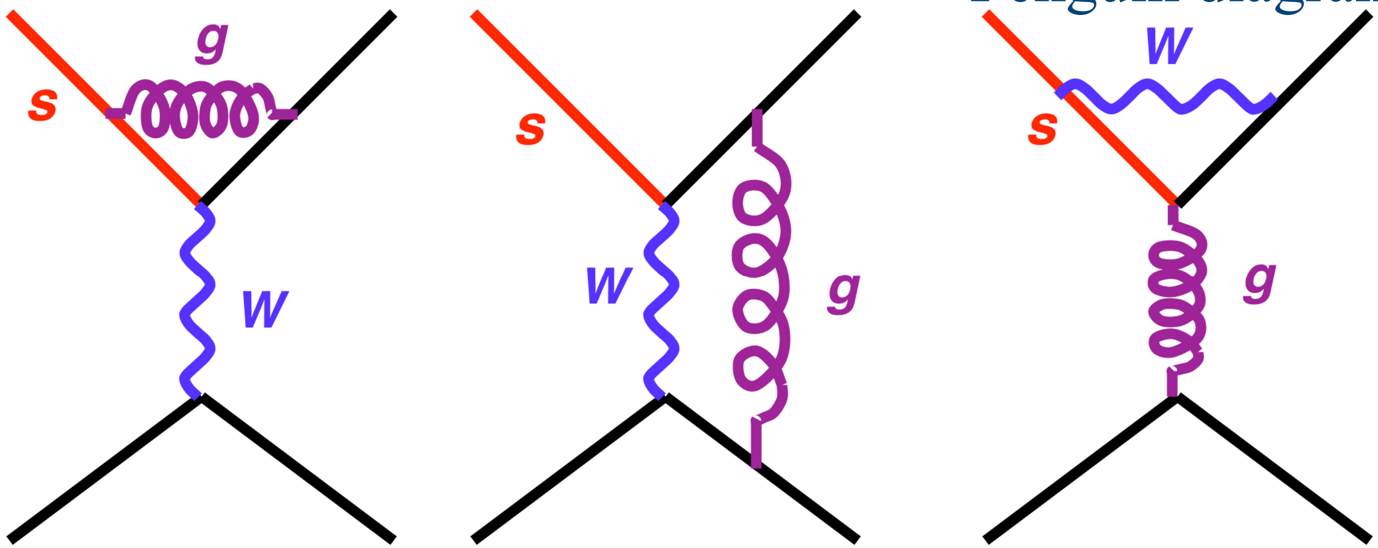
    $A_0 / A_2 \approx 22$
- $\Lambda \to N\pi$
  - $\Lambda \to p\pi^-$ (63.9%): $n\pi^0$ (35.8%) ~ 2 : 1 for $\Delta I = 1/2$

    $A_{\Delta I=1/2} / A_{\Delta I=3/2} \approx 20$

QCD at work

- QCD corrections (one loop)

Penguin diagram



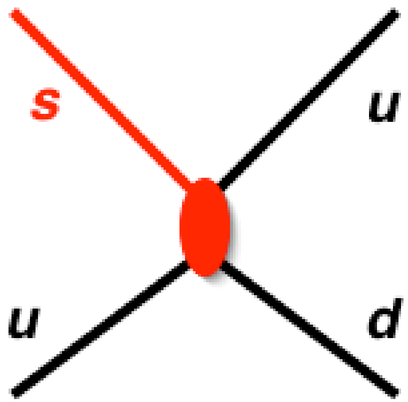
Vainshtein et al, 1977

QCD at work

- isospin structure of the 4-quark operator

$$\hat{O} = (\bar{u}^\alpha s^\alpha)_L (\bar{d}^\beta u^\beta)_L \qquad (\bar{q}q)_L \equiv (\bar{q}\gamma^\mu(1-\gamma^5)q)$$
$$= (\bar{d}^\beta s^\alpha)_L (\bar{u}^\alpha u^\beta)_L$$

Fierz equivalence



symmetric under exchanges

u□ □ *d*□

final states

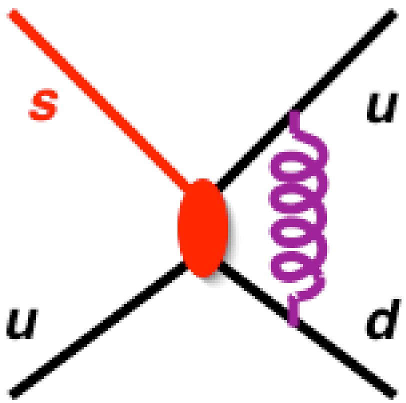
I =0, S =0, C =3* or

I =1, S =0, C =6

QCD at work

- Final state interaction enhances $\Delta I = 1/2$

$$V_{\rm CM} \propto -\alpha_s (\lambda_i \cdot \lambda_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j)$$



attractive for $I=0$, $S=0$, $C=3^*$

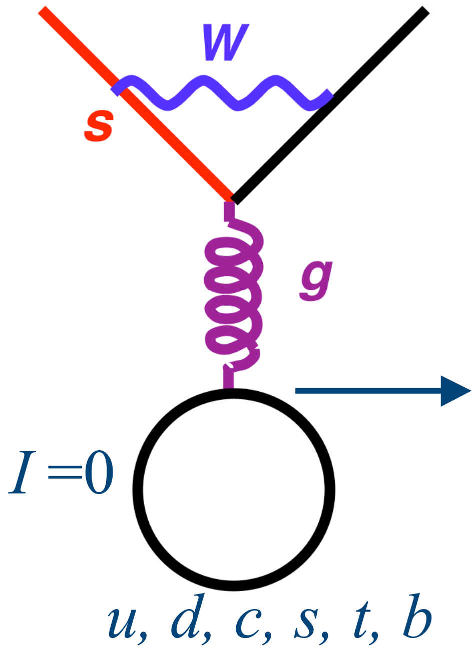
pure $\Delta I = 1/2$

repulsive for $I=1$, $S=0$, $C=6$

$\Delta I = 1/2$, $3/2$ mixed

QCD at work

- Penguin is pure $\Delta I = 1/2$



s → d $\Delta I = 1/2$

Right handed current (flavor singlet)

Low energy effective interaction

- QCD loop corrections

  renormalized at a scale μ

- factorization (or OPE) $\sum_i c_i(\mu) O_i$

  O_i : 4-quark local operators

- leading log summation

  renormalization group (RG) improvement

  operator mixing

  M.K. Gaillard, B.W. Lee (1974)

  G. Altarelli, L. Maiani (1974)

  A.I. Vainshtein, V.I. Zakharov, M.A. Shifman (1977)

  F.J. Gilman, M.B. Wise (1979)

Effective Hamiltonian

- effective weak Hamiltonian for $\Delta S = 1$

$$H_W = -\frac{G_f}{\sqrt{2}} \sum_i c_i O_i$$

$$O_1 = (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta)_{V-A} - (\bar{u}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta u_\beta)_{V-A}\,,$$

$$O_2 = (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta)_{V-A} + (\bar{u}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta u_\beta)_{V-A} + 2(\bar{d}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta d_\beta)_{V-A} + 2(\bar{d}_\alpha s_\alpha)_{V-A}(\bar{s}_\beta s_\beta)_{V-A}\,,$$

$\Delta I = 3/2$

$$O_3 = 2(\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta)_{V-A} + 2(\bar{u}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta u_\beta)_{V-A} - (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta d_\beta)_{V-A} - (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{s}_\beta s_\beta)_{V-A}\,,$$

Penguin

$$O_5 = (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta + \bar{d}_\beta d_\beta + \bar{s}_\beta s_\beta)_{V+A}\,,$$

$$O_6 = (\bar{d}_\alpha s_\beta)_{V-A}(\bar{u}_\beta u_\alpha + \bar{d}_\beta d_\alpha + \bar{s}_\beta s_\alpha)_{V+A}\,.$$

right handed current

$\Delta I = 1/2$ rule (theory)

- Is the perturbative QCD correction sufficient to explain $\Delta I = 1/2$ dominance?

c_1	c_2	c_3	c_5	c_6
-0.284	0.009	0.026	0.004	-0.021

enhanced (c_1) suppressed (c_3) Penguin (c_5, c_6)

But, it is not enough to explain A_2/A_0 ratio of $K \to 2\pi$ decay.

$A_2/A_0 \sim$ 3-4 (pQCD) $\Leftrightarrow$ $A_2/A_0 \sim 22$ (exp)

$\Delta I = 1/2$ rule (theory)

- Nonperturbative corrections

$$\langle \text{final hadrons} | H_{\text{eff}}^{W} | \text{initial hadrons} \rangle = \sum_i c_i(\mu) \langle f | \mathcal{O}_i | i \rangle_\mu$$

- operators renormalized at scale μ: All physics above μ are included in the Wilson coefficients, $c_i(\mu)$
- matrix element taken with a cutoff μ

How do we calculate the matrix elements?

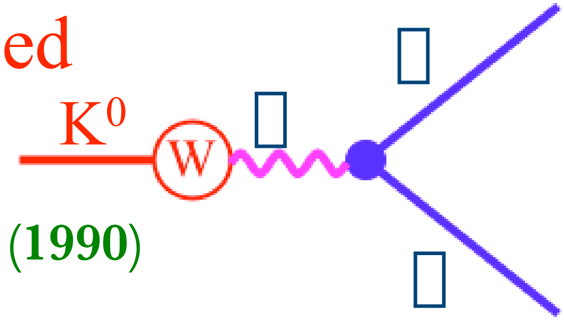
Lattice QCD, Effective theories, Models

$\Delta I = 1/2$ rule (theory)

- $\Delta I = 1/2$ enhancement in K decay
  - K → σ(I=0) → $(\pi\pi)_{I=0}$ enhanced

    as $m_K \sim m_\sigma \sim 600$ MeV

    T. Morozumi, C.S. Lim, A.I. Sanda (1990)



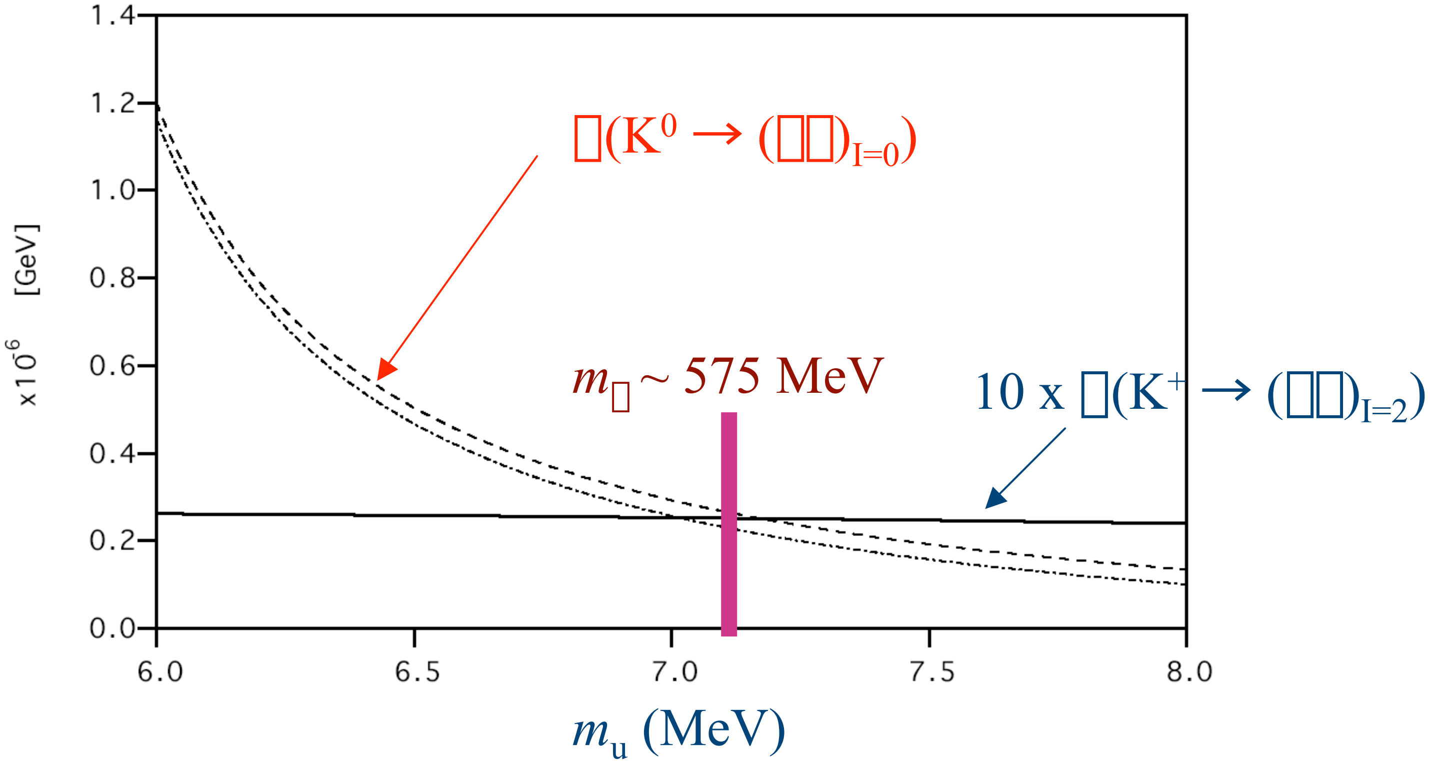
  - model calculation
    - $\Gamma(K^0 \to (\pi\pi)_{I=0})$ v.s. m_σ in NJL model

      T. Inoue, M. Takizawa, M.O. (1995)

□I =1/2 rule (theory)

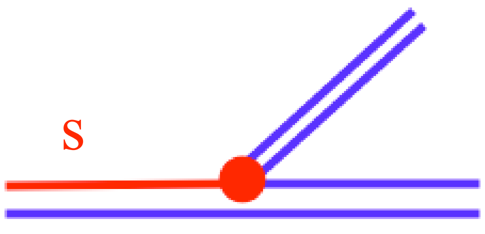
NJL model calculation with □

T. Inoue, M. Takizawa, M.O. (1995)

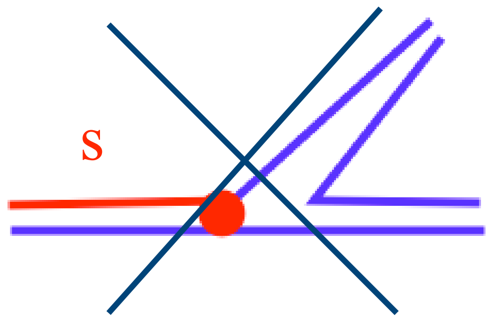


□I =1/2 rule (theory)

- K → (□□)$_{I=2}$ □I =3/2 is suppressed
  - no internal diagrams

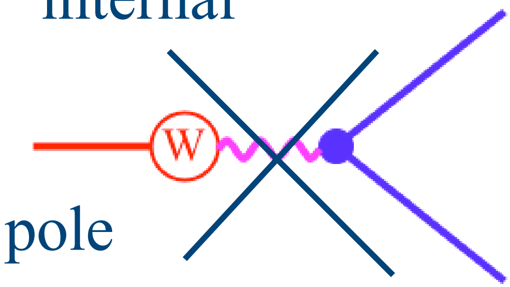


external



internal

  - no q$\bar{\text{q}}$ intermediate state



no I=2 pole

$\Delta I = 1/2$ rule (theory)

- $\Delta I = 1/2$ in Baryon decays
  - □ $\rightarrow$ N □ etc

    PV part: soft pion decay/ reduced to $\langle B' | H^{PC} | B \rangle$

    PC part: pole dominance given by $\langle B' | H^{PC} | B \rangle$

  - *MMPW* mechanism

    Miura-Minamikawa (1967), Pati-Woo (1971)

    no $\Delta I = 3/2$ contribution to $\langle B' | H^{PC} | B \rangle$

    due to the color structure of H_{W}

□I =1/2 rule (theory)

- soft pion theorem for PV amplitudes

$$\langle n\pi^0(q)|H^{\rm PV}|\Lambda\rangle \to -\frac{i}{f_\pi}\langle n|[Q_5^0, H^{\rm PV}]|\Lambda\rangle = -\frac{i}{2f_\pi}\langle n|H^{\rm PC}|\Lambda\rangle$$

$$\begin{aligned} [Q_R^a, H_W] &= 0 \\ [Q_5^a, H^{\rm PV}] &= -[I^a, H^{\rm PC}] \end{aligned}$$

PC ME for B □ B'
+ *MMPW* mechanism
□
□□ □□=3/2

Baryon matrix elements

- Is $\langle B'|H^{PC}|B\rangle$ large enough to explain baryon decays?

  The matrix elements are sensitive to the baryon size.
- In the DQ calculation, the NRQM wave function with $b = 0.5$ fm is used. This gives a large enough matrix element for the □ □ N□ decay.
- The MIT bag model tends to underestimate.

□*I* in NMWD

- Is □*I* a half in NMWD?
  - *No enhancement mechanism for □I =1/2*
  - *No suppression mechanism of □I =3/2*
- □*I* =3/2 comparable to □*I* =1/2 in NMWD?
  - Direct quark mechanism

    Maltman-Shmatikov (94)

    Inoue-Takeuchi-Oka (94)
  - □, □ → N □ couplings may contain □*I* =3/2

    Maltman-Shmatikov (95)

    Parreno-Ramos-Bennhold-Maltman (98)

ΔI in *S*-shell NMWD

- *S* -shell hypernuclei A=4 and 5

C. Dover (1987), R.A. Schumacher (1992)

  - A simple relation among Γ_{NJ}'s

$$x = \frac{\Gamma_{n0}}{\Gamma_{p0}} \qquad = 2 \quad \text{for } \Delta I = \tfrac{1}{2} \qquad = \frac{1}{2} \quad \text{for } \Delta I = \tfrac{3}{2}$$

$$\alpha \equiv \frac{\Gamma_{NM}({}^4_\Lambda H)}{\Gamma_{NM}({}^4_\Lambda He)} \qquad \beta \equiv \frac{\Gamma_{nn}({}^5_\Lambda He)}{\Gamma_{pn}({}^5_\Lambda He)}$$

Theorem: If □ > □ then $x < 1/$□

Data (Outa) $\alpha = \frac{0.17 \pm 0.11}{0.17 \pm 0.05}$ $\overset{>}{?}$ $\beta = 0.48 \pm 0.10$

□+ decay of Hypernuclei

- soft □+ decay **M.O (1999)**
  - thru p□ □ n□+ □ nn□+ is strongly hindered in the soft pion (*S* wave) limit.
  - □*I* =3/2 is the only allowed matrix element in the soft pion limit.

$$[I_-, H_W(\Delta I = 1/2, \Delta I_z = -1/2)] = 0$$

$$[I_-, H_W(\Delta I = 3/2, \Delta I_z = -1/2)] = \sqrt{3} H_W(\Delta I = 3/2, \Delta I_z = -3/2)$$

$$\lim_{q\to 0}\langle nn\pi^+(q)|H_W|\Lambda p\rangle = \frac{i\sqrt{3}}{\sqrt{2} f_\pi}\langle nn|H_W(\Delta I = 3/2, \Delta I_z = -3/2)|\Lambda p\rangle$$

Where Are We ?

- What we know in 2003?

$□_{NM}$	weak A dependence > suggest SR int.
$□_{nn}/□_{pn}$	~ 0.5 (exp)□ long battle□ ~0.5 (theory)
N spectrum	consistent > suggest strong FSI
$□_p^{NM}$	New battle, $J = 0$ amplitudes
$□I = 1/2$	Violation indicated: Coming soon
np□ □p	Coming soon

And the battles continue ...

- Future problems
  - □I =1/2 violation

    □$_{NM}$(^{4}□H) is critical.

    □$^+$ decay is discriminative.
  - □ mixing □N → □N ⇒ NN

    □ mixing □□ → □N, H ⇒ YN
  - □$_{YY}$ / □$_{YN}$ ratio $J = 0$ amplitude

    Are they really small and negligible?

And Finally

- Theoretical goal

QCD □ Hyperon nonleptonic decays

YN □ NN, YY □ YN interactions

Parity-violating NN interaction

Nonperturbative QCD renormalization of weak interactions of the standard theory