Particle Physics Phenomenology: Past and Present

Hai-Yang Cheng

Academia Sinica

May 14, 2015

1. 1992 May 22-24	Kenting (AS)	T. Mannel, J.W. Qiu
2. 1994 May 19-21	Kenting (AS)	M. Neubert, S. Pakvasa, W. Busza, L.F. Li
3. 1996 Nov 14-17	Jinshan (NTHU)	B. Grinstein. E. Braaten; L.N. Chang, E. Ma, John Ng, T. Inagaki, K. F. Liu, Y. Kuno, X.G. He, D. S. Hwang, P. Depommier
4. 1998 June 18-21	Kaohsiung (NCTU,AS)	C. Sachrajda, J. Soffer, A. Soni, S. Stone, H. Yamamoto, R. Fleischer, E.J. Chun, M. Bisset, Y.Q. Chen, S. Donati, D.S. Hwang, S.K. Kang. T. Morozumi, Y. Okada, P. Ko, B. H. Lee
5. 2000 Nov 8-11	Chi-Pen (NCKU)	M. Neubert, S. Pakvasa, S. Brodsky, D. Pirjol, J. Chay, M. Burkhardt, P. Vogel, J. Huston,…
6. 2005 June 5-9	Lo-Tung (NTHU)	Meissner, L. Dixon, S. Fleming, D. Adams, Babu, S. Mathur, P. Ko, X.D. Ji,…

2004 Eastern Formosa Summer School on Particles & Fields, NDHU, Hualien, July 5-10, 2004: D. Chang, P.M. Ho, W.S. Hou, W.Y. Keung, T.K. Kuo, J.W. Qiu

7. 2007 June 7-10	Taipei (NTU)	A. Suzuki, C. S. Kim, Z. J. Xiao, S. Scopel, S. Olsen, J. Gunion, S. Matsumoto, J. Song, P. Poulose, P. Drechsel, G. Kribs
8. 2009 May 20-23	Tainan (NCKU)	M.C. Chen, L.F. Li, K.B. Luk; T.N. Pham, C.S. Kim, Y. Yamamoto, J. Park, T. Kikuchi, H.S. Cheon, T. Asaka, S. Kanemura
9. 2011 June 3-6	Chung-li (NCU)	T. Han, D. Marfatia, G. Roland; N. Kawamoto, T. Kamon, R. Kitano, W.Y. Keung, C. Kao, E. Lanene, S. Fleming, S.F. Su, N. Gaur, K. Hagiwara
10. 2013 June 18-21	Chung-li (CYCU)	P. Ko, D. Soper, J. Zupan; C.S. Kim, C. Kao, Y. Koike, M. Wakamatsu, M. Tanimoto, S.C. Park
11. 2015 May 12-15	Tamsui (AS)	M. Endres, M. Sasaki, W.Y. Keung; A. Soni, J.C. Peng, M. Wakamatsu, T.N. Pham, W. Wang, C.S. Lam, E. Ma, R. Shrock, R. Sinha, S. Matsumoto, S. Mishima, Y.Y. Keum

1. Proceedings of the Third International Workshop ``Particle Physics Phenomenology'', Ed. by D. Chang, H. Y. Cheng, C. Q. Geng and Wei-Min Zhang, (World Scientific, 1997).

2. Proceedings of the Fourth International Workshop ``Particle Physics Phenomenology'', Ed. by H. Y. Cheng, W.S. Hou, H.-n. Li and G.L. Lin, (World Scientific, 1999).

3. Proceedings of the Fifth International Workshop ``Particle Physics Phenomenology'', Ed. by H.-n. Li, G. L. Lin, and Wei-Min Zhang, (World Scientific, 2001).

First PPP Workshop, May 22-24, 1992


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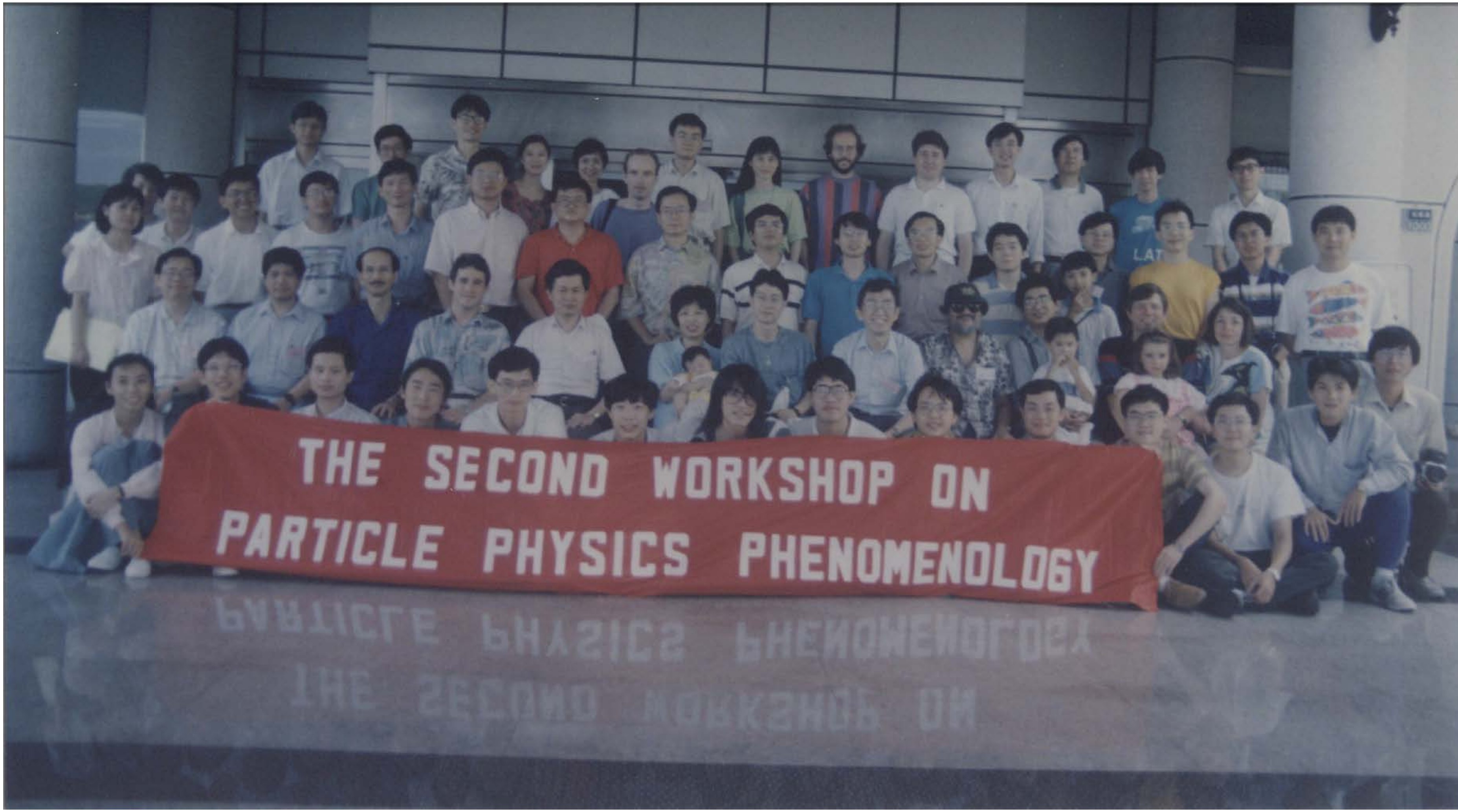
Second PPP Workshop, May 19-21, 1994



My collaborators

Ephraim Fischbach, Sam Aronson
Ling-Lie Chau
Stanley Deser, Stefano Bellucci

--------------------- 1987--------------------------------------
Tung-Mow Yan, Chi-Yee Cheung, Hoi-Lai Yu, Guey-Lin Lin, Y.C. Lin
Chi-Yee Cheung, Wei-Min Zhang
Benjamin Tseng
Kwei-Chou Yang
Chun-Khiang Chua
Amarjit Soni
Cheng-Wei Chiang
Keh-Fei Liu
Yu-Kuo Hsiao
Sechul Oh
Yang Hwan Yang
George Wei-Shu Hou
Chung Kao
Rahul Sinha
Jen-Chieh Peng
Robert Shrock
…

Ephraim Fischbach

My adviser at Purdue (1976-1980)

Ephraim Fischbach et al. "Reanalysis of the Eötvös experiment",
Physical Review Letters **56** 3 (1986).   1/6/86

5/22/82

ARE ALL i's CREATED EQUAL?

We wish to explore in more detail Al Overhauser's idea of keeping separate factors of i which arise in different spaces. One example to work is the regeneration (c by rederiving Eq. (1) of our letter PRL 48, 1306 (1982). However, an easier example may be the strangeness-oscillation method for measuring ϕ_{+-}. This is discussed in COMMINS, Weak Interactions p. 257 ff. We first derive the usual result in the usual way and then return to more carefully to keep track of various factors of i.

Suppose we begin with a pure $|K^\circ\rangle$ state at $t=0$. In our conventions

$$|K_L\rangle = [|p|^2+|q|^2]^{-1/2}\,[p|K^\circ\rangle + q|\bar{K}^\circ\rangle] \qquad (1a)$$

$$|K_S\rangle = [|p|^2+|q|^2]^{-1/2}\,[p|K^\circ\rangle - q|\bar{K}^\circ\rangle] \qquad (1b)$$

$$\therefore\quad |K_L\rangle + |K_S\rangle = 2p\,[|p|^2+|q|^2]^{-1/2}\,|K^\circ\rangle \qquad (2a)$$

$$|K_L\rangle - |K_S\rangle = 2q\,[|p|^2+|q|^2]\,|\bar{K}^\circ\rangle \qquad (2b)$$

Hence

$$\boxed{\begin{aligned} |K^\circ\rangle &= \tfrac{1}{2p}[|p|^2+|q|^2]^{1/2}\,[|K_L\rangle+|K_S\rangle] \equiv N_0\,[|K_L\rangle+|K_S\rangle] && (3a)\\ |\bar{K}^\circ\rangle &= \tfrac{1}{2q}[|p|^2+|q|^2]^{1/2}\,[|K_L\rangle-|K_S\rangle] \equiv \bar{N}_0\,[|K_L\rangle-|K_S\rangle] && (3b)\end{aligned}}$$

Hence the wavefunction at $t=0$ is given by

$$|\psi(0)\rangle = N_0\,[|K_L\rangle + |K_S\rangle] \qquad (4)$$

Hence,

$$|\psi(t)\rangle = N_0\left[|K_L\rangle e^{-im_L t-\Gamma_L\frac{t}{2}} + |K_S\rangle e^{-im_S-\Gamma_S\frac{t}{2}}\right] \qquad (5)$$

Having derived the correct standard result, we now return to Eqs. (8) and (9) and treat the factors of i more carefully. Basically there are two sources of such factors which are clearly distinct: In (7) i represents a space-time phase which ultimately comes from the Schrodinger equation $i\,\partial\psi/\partial t = H\psi$. In (9) i represents the relative $|K^\circ\rangle$ and $|\bar{K}^\circ\rangle$ phase in $|K_L\rangle$ and $|K_S\rangle$ and is clearly a phase in a charge space. To keep these distinct we define

$$\boxed{\begin{aligned} |\psi(t)\rangle &= |\psi(0)\rangle\, e^{-i_\mu mt-\Gamma_L t/2} && \text{defines } i_\mu\\ \eta_{+-} &= |\eta_{+-}|\, e^{i_\eta \phi_{+-}} && \text{defines } i_\eta \end{aligned}} \qquad (12)$$

We assume the following rules:

$$i_\eta i_\eta^* = +1 \qquad i_\eta i_\eta = -1 \;\Leftrightarrow\; i_\eta^* = -i_\eta \qquad (13a)$$

$$i_\mu i_\mu^* = +1 \qquad i_\mu i_\mu = -1 \;\Leftrightarrow\; i_\mu^* = -i_\mu \qquad (13b)$$

$$i_\mu i_\eta = i_\eta i_\mu \;=\; \text{unspecified} \qquad (13c)$$

We now return to (10) and write

$$N'_{+-}(t) \propto \left|\, |\eta_{+-}|\, e^{-i_\mu \Delta m t + i_\eta \phi_{+-} - \Gamma_L t/2} + e^{-\Gamma_S t/2}\right|^2$$

$$= \left|\, |\eta_{+-}|\,(\cos\Delta mt - i_\mu \sin\Delta mt)(\cos\phi_{+-} + i_\eta \sin\phi_{+-})\, e^{-\Gamma_L t/2} + e^{-\Gamma_S t/2}\right|^2$$

$$= \left|\, |\eta_{+-}|\,[\cos\Delta mt\cos\phi_{+-} - i_\mu \sin\Delta mt\cos\phi_{+-} + i_\eta\cos\Delta mt\sin\phi_{+-} - i_\mu i_\eta \sin\Delta mt\sin\phi_{+-}]\, e^{-}\right.$$

$$= \left|\left(|\eta_{+-}|\cos\Delta mt\cos\phi_{+-}\, e^{-\Gamma_L\frac{t}{2}} + e^{-\Gamma_S\frac{t}{2}}\right) - i_\mu \underbrace{\sin\Delta mt\cos\phi_{+-}}_{}\, + i_\eta \cos\Delta mt\sin\phi_{+-} - i_\mu i_\eta \sin\Delta mt\sin\phi_{+-}\right|$$

$|\eta_{+-}|e^{-\Gamma_L t/2}$ $\quad |\eta_{+-}|e^{-\Gamma_L t/2}$ $\quad |\eta_{+-}|e^{-\Gamma_L t/2}$

Ling-Lie Chau

- Quark-diagrammatic approach
  “Quark Mixing in Weak Interaction”
  Phys. Rep. **95**, 1 (1983)
- Chau-Keung parametrization of quark mixing matrix

CP Violation in Standard Model

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{CKM} is the only source of CPV in flavor-changing process in the SM. Only charged current interactions can change flavor

Kobayashi & Maskawa ('72) pointed out that one needs at least six quarks in order to accommodate CPV in SM with one Higgs doublet

$$V_{KM} = \begin{pmatrix} c_1 & c_3 s_1 & s_1 s_3 \\ -c_2 s_1 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + c_3 s_2 e^{i\delta} \\ s_1 s_2 & -c_1 c_3 s_2 - c_2 s_3 e^{i\delta} & -c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{pmatrix}$$

$$c_i \equiv \cos\theta_i$$
$$s_i \equiv \sin\theta_i$$
$$1 >> \theta_1 >> \theta_2 >> \theta_3$$

Physics is independent of a particular parameterization of CKM matrix, but V_{KM} has some disadvantages :

- Determination of θ_2 & θ_3 is not very accurate
- Some elements have comparable real & imaginary parts

$$V_{Maiani} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\phi} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\phi} & s_{23}c_{13}e^{i\phi} \\ s_{12}s_{23}e^{-i\phi} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{-i\phi} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

Maiani ('77)

advocated by PDG ('86) as a standard parametrization.

However, the coefficient of the imaginary part of V_{cb} and V_{ts} is $O(10^{-2})$ rather than $O(10^{-3})$ as $s_{23} \sim 10^{-2}$

In 1984 Ling-Lie Chau and Wai-Yee Keung proposed a new parametrization

$$V_{CK} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\phi} \\ 0 & 1 & 0 \\ -s_{13}e^{i\phi} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\phi} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\phi} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\phi} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\phi} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\phi} & c_{23}c_{13} \end{pmatrix}$$

$1 >> \theta_{12} >> \theta_{23} >> \theta_{13}$

$s_{13} \sim 10^{-3}$

For general N $\times$ N case, see L.L. Chau, PLB 651, 293 (2007).

The imaginary part is O(10^{-3}) ! This new matrix is adapted by PDG as a standard parametrization since 1988.

- Charmless nonleptonic rare decays of *B* mesons ('91) citation: 246
- CP violation in rare B decay ('92)

Chau, Cheng, Wah-Keung Sze, Herng Yao, Benjamin Tseng

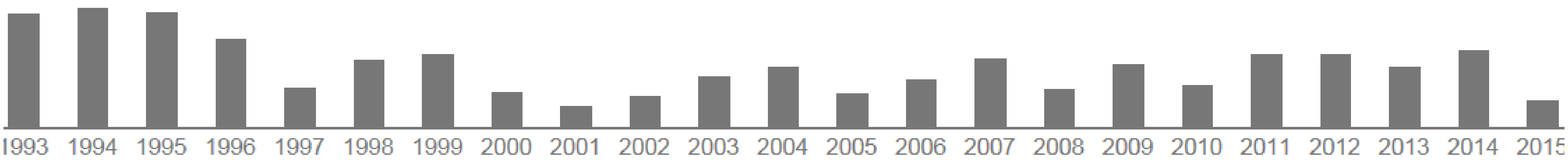
Tung-Mow Yan

Heavy quark symmetry and chiral dynamics (1992)

Tung-Mow Yan, Cheng, Chi-Yee Cheung, Guey-Lin Lin, Yeu-Chung Lin and Hoi-Lai Yu =(CLY)^2

Wise ('92)
Burdman, Donoghue ('92) } heavy meson sector only

# of citation as of today = 502 (INSPIRES)
668 (Google Scholar)



50 53 51 33 33 28 34 12

Collaboration period: 1991-1996, 8 papers

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Comments on the momentum parametrization.

Objective: The intermediate particle is sufficiently off shell. So we would like to reduce the two step process into an effective local interaction which is gauge invariant.

Requirements

1. Both light quark and heavy quark are close to mass shell.
2. Invariant mass $(p_q + p_Q)^2 = (m_Q + m_q)^2 \pm \Lambda_{QCD}^2$ and it should be independent of outside kinematics. Otherwise, it is not a bound state.

Implications

1. For the light quark, $m_q \sim \Lambda_{QCD}$, and the off-shellness is also of order Λ_{QCD}. So it is either exactly on the mass shell or it is off-shell a lot. So we choose to have it exactly on shell:

$$p_q = m_q v. \qquad v^2 = 1.$$

$$(e) = -\frac{g^2}{64\pi^2} \ln\frac{|k|^2}{\mu^2} K_d \cdot 4 \{ -2(\tilde{F}^{\alpha\beta} + iF^{\alpha\beta}) \bar{u}_c \tfrac{1}{2}\lambda_a \gamma_\alpha (1-\gamma_5) u_b \times \bar{v}_d \tfrac{1}{2}\lambda_a \gamma_\beta (1-\gamma_5) v_u$$
$$+ 2(\tilde{F}^{\mu\kappa} + iF^{\mu\kappa}) \bar{u}_c \tfrac{1}{2}\lambda_a \gamma_\kappa (1-\gamma_5) u_b \cdot \bar{v}_d \tfrac{1}{2}\lambda_a \gamma_\kappa (1-\gamma_5) v_u \}$$

$$\boxed{(e) = 0}$$

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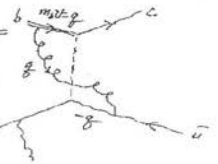
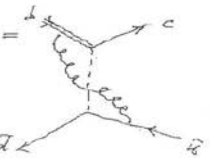
We almost forgot to include diagram (j) on p. 26.

$(j) =$ 

$(\bar{j}) =$ 

We can first compute the correction factor to 4-point vertex first

$$(\bar{j}) = \int\frac{d^4q}{(2\pi)^4} \bar{u}_c \gamma^\mu (1-\gamma_5) \frac{i}{m_b \not{v} - \not{q} - m_b} \left(-ig\frac{\lambda_a}{2}\gamma^\nu\right) u_b$$
$$\times \bar{v}_d \gamma_\mu (1-\gamma_5) \frac{i}{\not{q}} \left(-ig\frac{\lambda_a}{2}\gamma_\nu\right) v_u \frac{-i}{q^2}$$
$$= +ig^2 \int\frac{d^4q}{(2\pi)^4} \frac{q^\lambda}{(q^2)^2 v\cdot q} \bar{u}_c \gamma^\mu (1-\gamma_5) \frac{\lambda_a}{2} u_b \bar{v}_d \gamma_\mu (1-\gamma_5) \gamma_\lambda \not{v} \frac{\lambda_a}{2} v_u$$
$$= -\frac{g^2}{16\pi^2} \ln\frac{|k|^2}{\mu^2} \bar{u}_c \gamma^\mu (1-\gamma_5) \frac{\lambda_a}{2} u_b \bar{v}_d \gamma_\mu (1-\gamma_5) \frac{\lambda_a}{2} v_u$$

$$\therefore \boxed{(j) = -\frac{g^2}{16\pi^2} \ln\frac{|k|^2}{\mu^2} K_d (\tilde{F}_{\mu\nu} + iF_{\mu\nu}) \left(\bar{u}_c \gamma^\mu (1-\gamma_5) \frac{\lambda_a}{2} u_b\right) \left[\bar{v}_d \gamma^\nu (1-\gamma_5) \frac{\lambda_a}{2} v_u\right]}$$

We note that $(d) + (\bar{j}) = 0$, $(e) = 0$, $(g) + (h) + (i) = 0$

So
$$\boxed{\begin{aligned}(a) + (b) + \dots + (j) &= (a) + (b) + (c) + (f) \\ &= \frac{3g^2}{64\pi^2} \cdot \frac{N_c^2 - 1}{N_c} \ln\frac{|k|^2}{\mu^2} K_d (\tilde{F}_{\mu\nu} + iF_{\mu\nu}) \bar{u}_c \gamma^\mu (1-\gamma_5) u_b \cdot \bar{v}_d \gamma^\nu (1-\gamma_5) v_u \\ &+ \frac{g^2}{16\pi^2} \ln\frac{|k|^2}{\mu^2} K_d (\tilde{F}_{\mu\nu} + iF_{\mu\nu}) \bar{u}_c \gamma^\mu (1-\gamma_5) \frac{\lambda_a}{2} u_b \cdot \bar{v}_d \gamma^\nu (1-\gamma_5) \frac{\lambda_a}{2} v_u\end{aligned}}$$

Let's define
$$\boxed{\begin{aligned} O_{1\mu\nu} &= \bar{c} \gamma^\mu (1-\gamma_5) b \cdot \bar{d} \gamma^\nu (1-\gamma_5) u. \\ O_{2\mu\nu} &= \bar{c} \gamma^\mu (1-\gamma_5) u \cdot \bar{d} \gamma^\nu (1-\gamma_5) b \end{aligned}}$$

Then
$$\boxed{\begin{aligned} &(\tilde{F}_{\mu\nu} + iF_{\mu\nu}) O_1^{\mu\nu} \xrightarrow[\text{1-loop}]{QCD} (\tilde{F}_{\mu\nu} + iF_{\mu\nu}) O_1'^{\mu\nu} \\ &(\tilde{F}_{\mu\nu} + iF_{\mu\nu}) O_1'^{\mu\nu} = (\tilde{F}_{\mu\nu} + iF_{\mu\nu}) \Big\{ \Big[1 + \frac{3g^2}{64\pi^2} \cdot \frac{N_c^2 - 1}{N_c} \ln\frac{|k|^2}{\mu^2}\Big] O_1^{\mu\nu} \\ &\qquad + \frac{g^2}{16\pi^2} \ln\frac{|k|^2}{\mu^2} \bar{c} \gamma^\mu (1-\gamma_5) \frac{\lambda_a}{2} b \cdot \bar{d} \gamma^\nu (1-\gamma_5) \frac{\lambda_a}{2} u \Big\} \end{aligned}}$$

$$\bar{c} \gamma^\mu (1-\gamma_5) \frac{\lambda_a}{2} b \cdot \bar{d} \gamma^\nu (1-\gamma_5) \frac{\lambda_a}{2} u$$
$$= \bar{c}^\alpha \gamma^\mu (1-\gamma_5) b^\beta \cdot \bar{d}^{\alpha'} \gamma^\nu (1-\gamma_5) u^{\beta'} \cdot \frac{1}{2} \left[\delta_{\alpha\beta'} \delta_{\alpha'\beta} - \frac{1}{N_c} \delta_{\alpha\beta} \delta_{\alpha'\beta'}\right]$$
$$= \frac{1}{2} \bar{c}^\alpha \gamma^\mu (1-\gamma_5) b^\beta \cdot \bar{d}^\beta \gamma^\nu (1-\gamma_5) u^\alpha - \frac{1}{2N_c} O_1^{\mu\nu}$$

$$\boxed{\begin{aligned} &\bar{c} \gamma^\mu (1-\gamma_5) \frac{\lambda_a}{2} b \cdot \bar{d} \gamma^\nu (1-\gamma_5) \frac{\lambda_a}{2} u \\ &\quad = \frac{1}{2} \bar{c}^\alpha \gamma^\mu (1-\gamma_5) b^\beta \cdot \bar{d}^\beta \gamma^\nu (1-\gamma_5) u^\alpha - \frac{1}{2N_c} O_1^{\mu\nu} \end{aligned}}$$

$$\therefore \boxed{\begin{aligned} (\tilde{F}_{\mu\nu} + iF_{\mu\nu}) O_1'^{\mu\nu} &= (\tilde{F}_{\mu\nu} + iF_{\mu\nu}) \Big\{ \Big[1 + \frac{g^2}{64\pi^2} \Big(\frac{3(N_c^2 - 1)}{N_c} \mp \frac{2}{N_c}\Big) \ln\frac{|k|^2}{\mu^2}\Big] O_1^{\mu\nu} \\ &+ \frac{g^2}{32\pi^2} \ln\frac{|k|^2}{\mu^2} \bar{c}^i \gamma^\mu (1-\gamma_5) b^j \cdot \bar{d}^j \gamma^\nu (1-\gamma_5) u^i \Big\} \end{aligned}}$$

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...tion operators $1-\gamma_5$ simplify things somewhat.

...k at $\bar{3} \to \bar{3}$ first.

$...) | O_{1\mu\nu} | \Xi_b^0(v) \rangle$

$... \gamma_\mu (1-\gamma_5) u_b(v) [A v_\nu + B v'_\nu]$

$$= \frac{1}{2} \gamma_\mu \{\not{v}, \gamma_\nu\} = \frac{1}{2} [\gamma_\mu \gamma_\nu \not{v} + \gamma_\mu \not{v} \gamma_\nu]$$
$$\frac{1}{2} \{ g_{\mu\nu} \not{v} + \frac{1}{2} [\gamma_\mu, \gamma_\nu] \not{v} \} + \frac{1}{2} \gamma_\mu \not{v} \gamma_\nu$$
$$-\frac{i}{2} \sigma_{\mu\nu} \not{v} + \frac{1}{2} g_{\mu\nu} \not{v} + \frac{1}{2} \gamma_\mu \not{v} \gamma_\nu$$
$$= -\not{v} \gamma_\mu \gamma_\nu + 2 v_\mu \gamma_\nu$$
$$\gamma_\nu = -\frac{1}{2} \not{v} \gamma_\mu \gamma_\nu + v_\mu \gamma_\nu$$
$$= -\frac{1}{2} \not{v} \{ g_{\mu\nu} + \frac{1}{2} [\gamma_\mu, \gamma_\nu] \} + v_\mu \gamma_\nu$$
$$= -\frac{1}{2} g_{\mu\nu} \not{v} + \frac{1}{2} i \not{v} \sigma_{\mu\nu} + v_\mu \gamma_\nu$$
$$\boxed{- \gamma_\nu v_\mu = -\frac{i}{2} \sigma_{\mu\nu} \not{v} + \frac{i}{2} \not{v} \sigma_{\mu\nu}}$$

$$= \langle 0 | \bar{B}_\lambda(v') \phi_{v'}^\lambda \bar{c}_{v'} \bar{c}_{v'} \gamma_\mu (1-\gamma_5) u \bar{d} \gamma_\nu (1-\gamma_5) b_v \bar{b}_v \phi_v^\dagger u_\Xi(v) | 0 \rangle$$
$$= \bar{B}_\lambda(v') \frac{1+\not{v}'}{2} \gamma_\mu (1-\gamma_5) \langle 0 | \phi_{v'}^\lambda u \bar{d} \phi_v^\dagger | 0 \rangle \gamma_\nu (1-\gamma_5) \frac{1+\not{v}}{2} u_\Xi(v)$$

$$\boxed{\begin{aligned} &\langle 0 | \underset{1^+}{\phi_{v'}^\lambda} \; u \bar{d} \; \underset{0^+}{\phi_v^\dagger} | 0 \rangle = v^\lambda \gamma_5 (G_1 + G_2 \not{v} + G_3 \not{v}' + G_4 \not{v}' \not{v}) \\ &\qquad + \gamma^\lambda \gamma_5 (H_1 + H_2 \not{v} + H_3 \not{v}' + H_4 \not{v}' \not{v}) \end{aligned}}$$

$$\therefore \boxed{\begin{aligned} &\langle B_6(v') | O_{2\mu\nu} | \Xi_b(v) \rangle \\ &= \bar{B}_\lambda(v') \gamma_\mu (1-\gamma_5) [v^\lambda \gamma_5 (G_1 + G_2 \not{v} + G_3 \not{v}' + G_4 \not{v}' \not{v}) \\ &\quad + \gamma^\lambda \gamma_5 (H_1 + H_2 \not{v} + H_3 \not{v}' + H_4 \not{v}' \not{v})] \gamma_\nu (1-\gamma_5) u_\Xi(v) \end{aligned}}$$

Now
$$(\gamma_\mu v_\nu - \gamma_\nu v_\mu)(1-\gamma_5) = -\frac{i}{2} \sigma_{\mu\nu} (1+\gamma_5) \underset{\downarrow\, 1}{\not{v}} + \frac{i}{2} \not{v} \sigma_{\mu\nu} (1-\gamma_5)$$
$$= -\frac{i}{2} \sigma_{\mu\nu} (1+\gamma_5) + \frac{i}{2} \not{v} \sigma_{\mu\nu} (1-\gamma_5)$$

$$m_{\Xi_b} v = m_{\Xi_c} v' + k \qquad \text{in} \quad \Xi_b \to \Xi_c + \gamma(k)$$

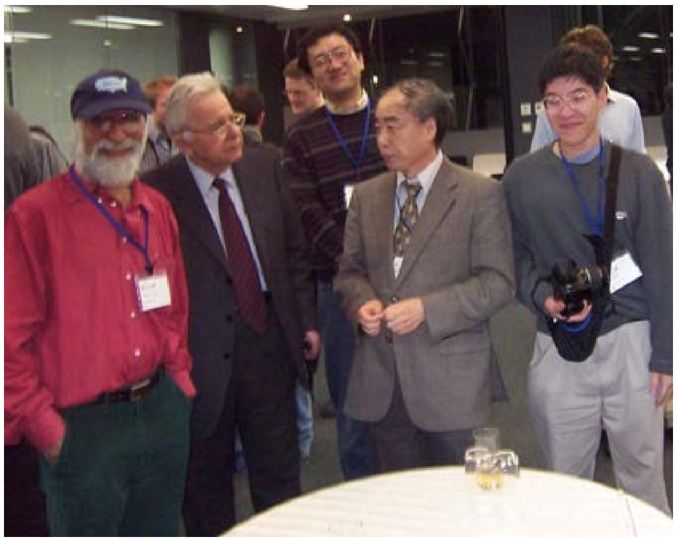
$$\therefore \boxed{\not{v} = \frac{m_{\Xi_c}}{m_{\Xi_b}} \not{v}' + \frac{\not{k}}{m_{\Xi_b}}}$$

$$\therefore \quad \not{v} \sigma_{\mu\nu} (1-\gamma_5) = \frac{m_{\Xi_c}}{m_{\Xi_b}} \not{v}' \sigma_{\mu\nu} (1-\gamma_5) + \frac{1}{m_{\Xi_b}} \not{k} \sigma_{\mu\nu} (1-\gamma_5).$$

Amarjit Soni

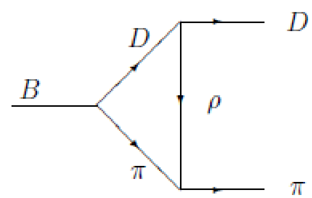
First collaboration in 2001 on semi-inclusive B decays

Then Chun-Khiang and I had intensive collaboration with with Soni during 2004-2007



Final state interactions in hadronic B decays ('05)

(citation : 269)



$$F(t,m) = \left(\frac{\Lambda^2 - m^2}{\Lambda^2 - t}\right)^n$$

$$\Lambda = m + \eta \Lambda_{QCD}$$

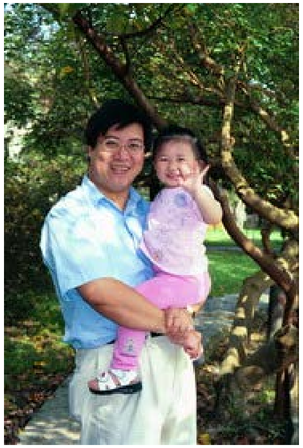
widely used in the XYZ community

Kwei-Chou Yang (at AS: 1996-1999)

1998-2013: 26 papers

QCD factorization
Baryonic B decays
$B \to (S,A,T)\ M$

Chun-Khiang Chua (at AS: 2003-2006)



2004-now : 25 papers

$$= \frac{-\alpha_s}{4\pi} \times \frac{C_F}{N_c} \times \frac{4\pi^2}{N_c} \times \frac{1}{16} \times i f_B \times \frac{1}{16} \times \left(f_{V_1} - f_{V_1}^T \frac{m_1^{V_1} + m_2^{V_1}}{m_{V_1}}\right)\left(f_{V_2} - f_{V_2}^T \frac{m_1^{V_2} \mp m_2^{V_2}}{m_{V_2}}\right) m_{V_1} m_{V_2}$$

$$\times \varepsilon_{\mu\nu\alpha\beta}\, \epsilon_{V_1}^{\perp * \nu} P_{V_1}^{\alpha}\, \varepsilon_{\omega\rho\eta\delta}\, \epsilon_{V_2}^{\perp * \rho} P_{V_2}^{\eta}\, \partial_{P_{V_1}}^{\beta}$$

$$\times \int \frac{d\xi}{\xi} \frac{d\Xi}{\Xi} d\bar{\xi}\; \varphi^{B_1}(\bar{\xi})\, g_\perp^{V_2(a)}(\xi)\, g_\perp^{V_1(a)}(\Xi) \times \mathrm{Tr}\{\gamma^\mu \gamma^\lambda \not{P}_B \gamma^\sigma (1-\gamma_5)\}$$

$$\times 2 \Big\{ \mathrm{Tr}[\gamma^\omega \gamma_\sigma (\xi) \gamma^\delta \gamma_\lambda] \times \frac{1}{(\Xi P_{V_1} - \bar{\xi} P_B)^2 [(\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]}$$

γ_5 部份為零

$$- \mathrm{Tr}[\gamma^\omega \gamma_\sigma (\xi \not{P}_{V_2} + \Xi \not{P}_{V_1} - \bar{\xi} \not{P}_B) \gamma_\lambda] \times \frac{2\xi (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^\delta}{(\Xi P_{V_1} - \bar{\xi} P_B)^2 [(\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]^2} \Big\}$$

$$= -\frac{\alpha_s}{4\pi} \times \frac{C_F}{N_c} \times \frac{4\pi^2}{N_c} \times \frac{1}{16} \times i f_B \times \frac{1}{16} \times \left(f_{V_1} - f_{V_1}^T \frac{m_1^{V_1} + m_2^{V_1}}{m_{V_1}}\right)\left(f_{V_2} - f_{V_2}^T \frac{m_1^{V_2} + m_2^{V_2}}{m_{V_2}}\right) m_{V_1} m_{V_2}$$

$$\times \varepsilon_{\mu\nu\alpha\beta}\, \epsilon_{V_1}^{\perp * \nu} P_{V_1}^{\alpha}\, \varepsilon_{\omega\rho\eta\delta}\, \epsilon_{V_2}^{\perp * \rho} P_{V_2}^{\eta}$$

$$\times \int \frac{d\xi}{\xi} \times \frac{d\Xi}{\Xi} d\bar{\xi}\; \varphi^{B_1}(\bar{\xi})\, g_\perp^{V_2(a)}(\xi)\, g_\perp^{V_1(a)}(\Xi) \times \mathrm{Tr}\{\gamma^\mu \gamma^\lambda \not{P}_B \gamma^\sigma (1-\gamma_5)\}$$

$$\times 2 \Big\{ \mathrm{Tr}[\gamma^\omega \gamma_\sigma \cdot \xi \gamma^\delta \gamma_\lambda] \times \left[\frac{\ominus 2\Xi (\Xi P_{V_1} - \bar{\xi} P_B)^\beta}{(\Xi P_{V_1} - \bar{\xi} P_B)^4 [(\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]} + \frac{\ominus 2\Xi (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^\beta}{(\Xi P_{V_1} - \bar{\xi} P_B)^2 (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]^2} \right]$$

$$- \mathrm{Tr}[\Xi \gamma^\omega \gamma_\sigma \gamma^\beta \gamma_\lambda] \times \frac{2\xi (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^\delta}{(\Xi P_{V_1} - \bar{\xi} P_B)^2 [(\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]^2}$$

$$+ \mathrm{Tr}[\gamma^\omega \gamma_\sigma (\xi \not{P}_{V_2} + \Xi \not{P}_{V_1} - \bar{\xi} \not{P}_B) \gamma_\lambda] \times \Big\{ \frac{4\xi\Xi (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^\delta (\Xi P_{V_1} - \bar{\xi} P_B)^\beta}{(\Xi P_{V_1} - \bar{\xi} P_B)^4 [(\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]^2}$$

$$- \frac{2\xi\Xi\, g^{\beta\delta}}{(\Xi P_{V_1} - \bar{\xi} P_B)^2 [(\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]^2} + \frac{8\xi\Xi (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^\delta (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^\beta}{(\Xi P_{V_1} - \bar{\xi} P_B)^2 [(\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^2 - m_q^2]^3} \Big\}$$

$$= -\frac{\alpha_s}{4\pi} \times \frac{C_F}{N_c} \times \frac{4\pi^2}{N_c} \times \frac{1}{16} \times i f_B \times \frac{1}{16} \times \left(f_{V_1} - f_{V_1}^T \frac{m_1^{V_1} + m_2^{V_2}}{m_{V_1}}\right)\left(f_{V_2} - f_{V_2}^T \frac{m_1^{V_2} + m_2^{2}}{m_{V_2}}\right) m_{V_1} m_{V_2}$$

$$\times \int \frac{d\xi}{\xi} \frac{d\Xi}{\Xi} d\bar{\xi}\, \varphi^{B_1}(\bar{\xi})\, g_\perp^{V_2(a)}(\xi)\, g_\perp^{V_1(a)}(\Xi) \times \varepsilon_{\mu\nu\alpha\beta}\, \epsilon_{V_1}^{\perp * \nu} P_{V_1}^{\alpha}\, \varepsilon_{\omega\rho\eta\delta}\, \epsilon_{V_2}^{\perp * \rho} P_{V_2}^{\eta}$$

$$\times 4 \left(g^{\mu\lambda} P_B^\sigma - g^{\lambda\sigma} P_B^\mu + g^{\mu\sigma} P_B^\lambda - i \varepsilon^{\mu\lambda\xi\sigma} P_{B\xi}\right)$$

$$\times 2 \Big\{ 4 (g^\omega{}_\sigma g^\delta{}_\lambda + g^\omega{}_\lambda g^\delta{}_\sigma) \times \left[\frac{-2\xi\Xi(-\bar{\xi} P_B^\beta)}{\bar{\xi}^2 \Xi^3 \xi^2} - \frac{2\xi\Xi(\xi - \bar{\xi}) P_B^\beta}{\bar{\xi}\, \Xi^3 \xi^2} \right] \frac{1}{m_B^6}$$

$$- 4 (g^\omega{}_\sigma g^\beta{}_\lambda - g^{\omega\beta} g_{\sigma\lambda} + g^\omega{}_\lambda g_\sigma{}^\beta) \times \frac{-2\Xi\xi(\Xi - \bar{\xi}) P_B^\delta}{\bar{\xi}\, \Xi^3 \xi^2} \times \frac{1}{m_B^6}$$

$$+ 4 [g^\omega{}_\sigma (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)_\lambda - g_{\sigma\lambda} (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)^\omega + g^\omega{}_\lambda (\xi P_{V_2} + \Xi P_{V_1} - \bar{\xi} P_B)_\sigma]$$

$$\times \left[\frac{4\xi\Xi (\Xi - \bar{\xi}) P_B^\delta (-\bar{\xi}) P_B^\beta}{\bar{\xi}^2 \Xi^4 \xi^2} - \frac{8\xi\Xi (\Xi - \bar{\xi}) P_B^\delta (\xi - \bar{\xi}) P_B^\beta}{\bar{\xi}\, \Xi^4 \xi^3} \right] \times \frac{1}{m_B^8} + \frac{2\xi\Xi\, g^{\beta\delta}}{\bar{\xi}\, \Xi^3 \xi^2 m_B^6} \Big\}$$

K.C. Yang's note around 2001

m 8.7.8-3

C.K. Chua's note in 2008

Consider $\begin{cases} J = 0 \\ L = 0 \\ S = 0 \end{cases}$ first.

$$\langle \tfrac{1}{2}\, \tfrac{1}{2} ; s_2\, s_3 \,|\, \tfrac{1}{2}\, \tfrac{1}{2} ; S\, n \rangle$$

$$= \langle \tfrac{1}{2}\, \tfrac{1}{2} ; s_2\, s_3 \,|\, \tfrac{1}{2}\, \tfrac{1}{2} ; 0\,0 \rangle$$

$$= \frac{1}{\sqrt{2}} \chi^{\dagger}_{s_2}\, i\sigma_2\, \chi^{*}_{s_3}$$

$$\bar{u}_D(p_2, s_2)\, \frac{\bar{\not p} + M_0}{2M_0}\, \gamma_5\, V_D(p_3, s_3)$$

$\bar{p} = (M_0, \vec{0})$ in frame

$$= \bar{u}_D(e_2, \vec{k}_2, s_2)\, \frac{\gamma^0 + 1}{2}\, \gamma_5\, V_D(e_3, \vec{k}_3, s_3)$$

Dirac rep.

$$\frac{(\chi^{\dagger}_{s_2}\ 0)}{\sqrt{e_2+m_2}} \begin{pmatrix} e_2+m_2 & \cdots \\ \cdots & -e_2+m_2 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} -e_3+M_3 & \cdots \\ \cdots & +e_3+M_3 \end{pmatrix} \frac{\begin{pmatrix} 0 \\ i\sigma_2 \chi_{s_3} \end{pmatrix}}{\sqrt{e_3+m}}$$

$$= \frac{1}{\sqrt{e_2+m_2}\,\sqrt{e_3+m_3}} (e_2+m_2)(+e_3+m_3)\, \chi^{\dagger}_{s_2}\, i\sigma_2\, \chi^{*}_{s_3}$$

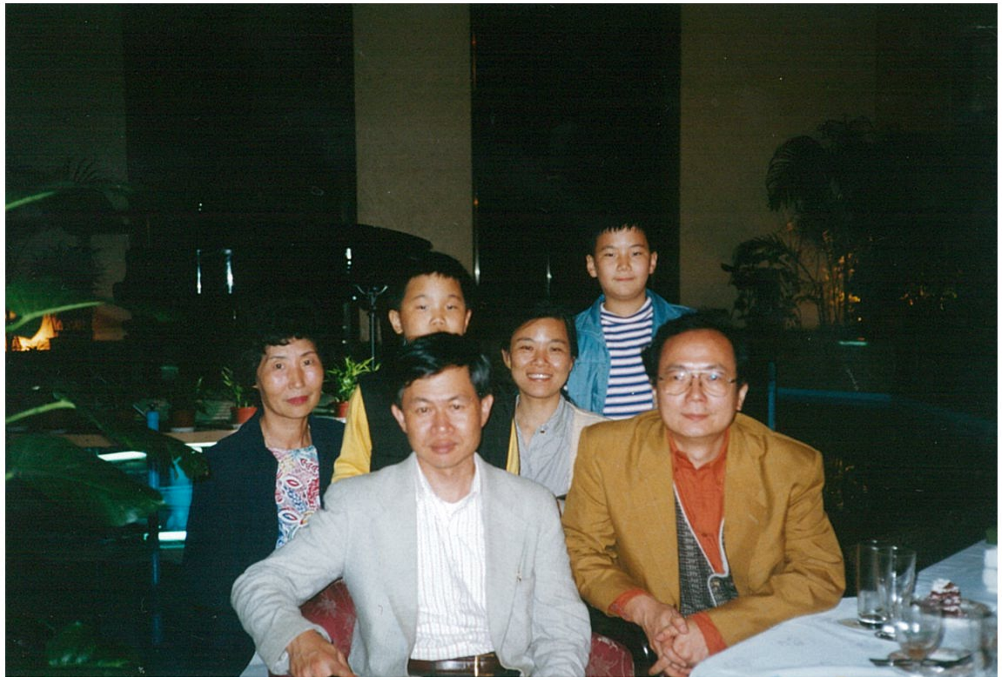
$$= +\sqrt{2(e_2+m_2)(e_3+m_3)}\, \langle \tfrac{1}{2}\, \tfrac{1}{2} ; s_2\, s_3 \,|\, \tfrac{1}{2}\, \tfrac{1}{2} ; 0\,0 \rangle$$

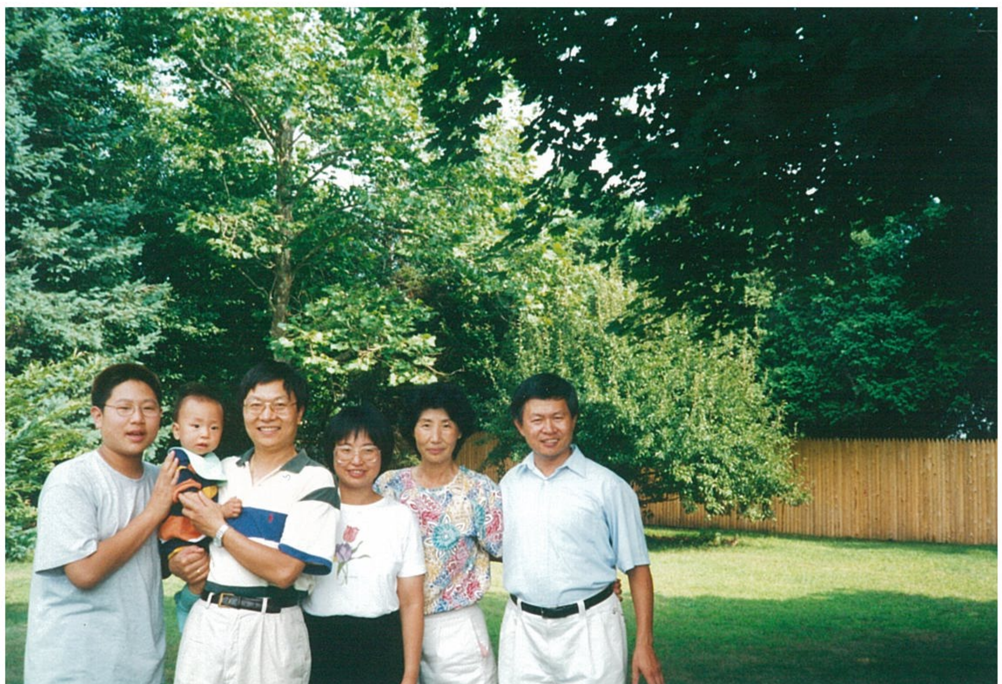
$$\therefore\ \langle \lambda_2 | R_M^{\dagger} | s_2 \rangle \langle \lambda_3 | R_M^{\dagger} | s_3 \rangle \langle \tfrac{1}{2}\, \tfrac{1}{2} ; s_2\, s_3 \,|\, \tfrac{1}{2}\, \tfrac{1}{2} ; 0\,0 \rangle$$

$$= +\frac{1}{2M_0\sqrt{2(e_2+m_2)(e_3+m_3)}}\, \bar{u}(p_2, \lambda_2)(\bar{\not p} + M_0)\gamma_5 \underbrace{V(p_3, \lambda_3)}_{C\bar{u}_3^T}$$

5

Cheng-Wei Chiang






ROOTS
MATHEMATICA 4
Quantum Field Theory
Electroweak Theory
String Cosmology
GRAVITATION
SPACETIME
RANDOM MATRICES
High Energy Astrophysics
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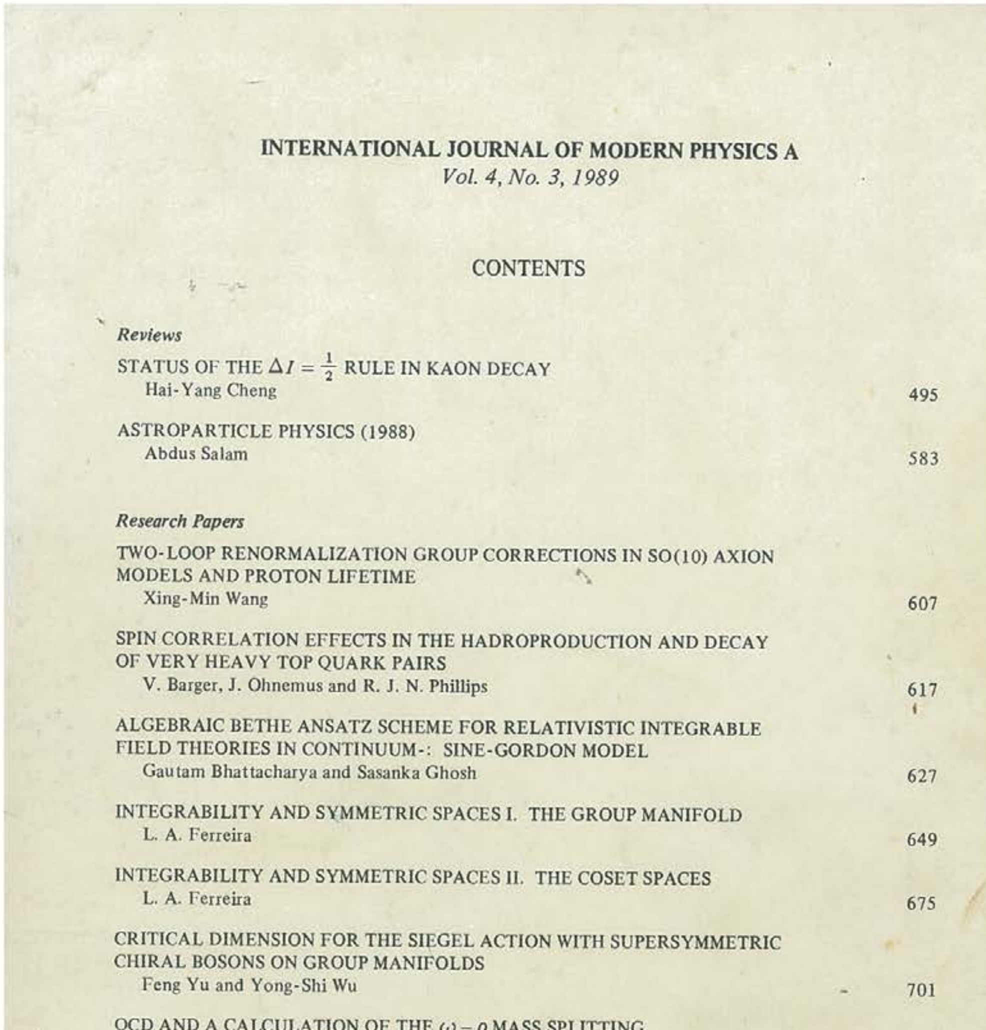
Review Articles

1. The Strong CP Problem Revisited, Phys. Rept. ('88)
2. Status of the ΔI=1/2 Rule in Kaon Decay, Int. J. Mod. Phys. ('89)
3. Topics
4. Status
5. Exclus
6. Charm



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CONTENTS

DFSZ & KSVZ invisible axions

PHYSICAL REVIEW D VOLUME 36, NUMBER 6 15 SEPTEMBER 1987

Tabulation of astrophysical constraints on axions and Nambu-Goldstone bosons

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(Received 3 March 1987)

Astrophysical constraints on the couplings of light and weakly coupled pseudoscalar particles (axions, Majorons, familons, . . .) from considerations of various stellar objects are summarized. We tabulate the astrophysical bounds on the mass and the decay constant of Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) axions and Kim-Shifman-Vainshtein-Zakharov (KSVZ) axions, on the triplet Majoron vacuum expectation value v_T, and on the familon breaking scale. The lower bound of the Peccei-Quinn breaking scale in the KSVZ model is generally one order of magnitude weaker than that in the DFSZ model. The most stringent limit on $v_T < 2$ keV is obtained from considerations of Majoron emission from the cores of neutron stars. Bounds on the strength of the $1/r$ potential mediated by Gelmini-Roncadelli Majorons are also given.

Phys. Rept.

a. This type of invisible axion was first proposed by Zhitnitsky [60] (unfortunately, the work of Zhitnitsky was largely overlooked in the literature), and then independently by Dine, Fischler and Srednicki [63] that the breaking of $U_{PQ}(1)$ symmetry can occur at a large scale if there is an additional $SU(2) \times U(1)$-singlet scalar field χ which develops an arbitrary large VEV. Since in section 3.3 we already discuss the DFSZ model in some detail, here we merely mention two salient features: (1) The χ field couples to quarks by first coupling to the Higgs fields ϕ_1 and ϕ_2 [eqs. (3.22), (3.23)]. (2) For

- My warmest thanks to the organizers: T.C. Yuan, Hsiang-nan Li