Lecture about the Recent Nobel Prize

From B Factory to the Large Hadron Collider

George W.S. Hou (侯維恕)
National Taiwan University

June 1, 2009, FPCP @ Lake Placid, NY

臺灣大學

National Taiwan University

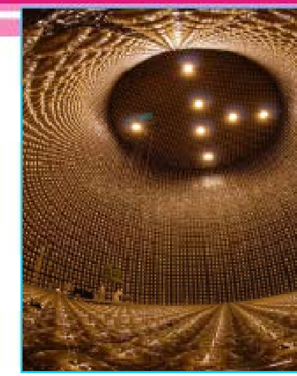
Predicting 2008 Prize

9/30/2008

Ling-Fong Li gave first colloquium of Fall semester @ NTU, on “Higgs Particle”. At the end, I commented on Higgs Mechanism ..., that SBGT is already verified, and that it does not require a physical Higgs boson. Then I said (abbreviated),

“There should be enhanced chance for Japanese receiving the Prize this year, because former KEK Director General, Totsuka, passed away in July.”

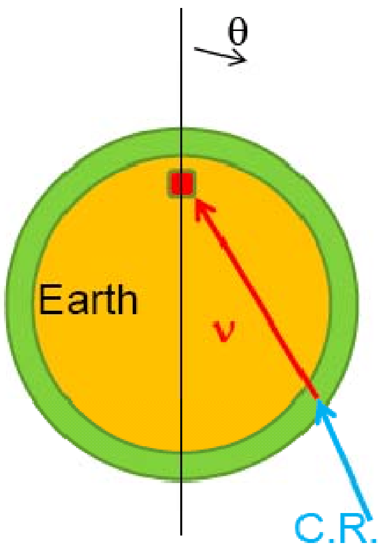
Lepton Flavor Mixing



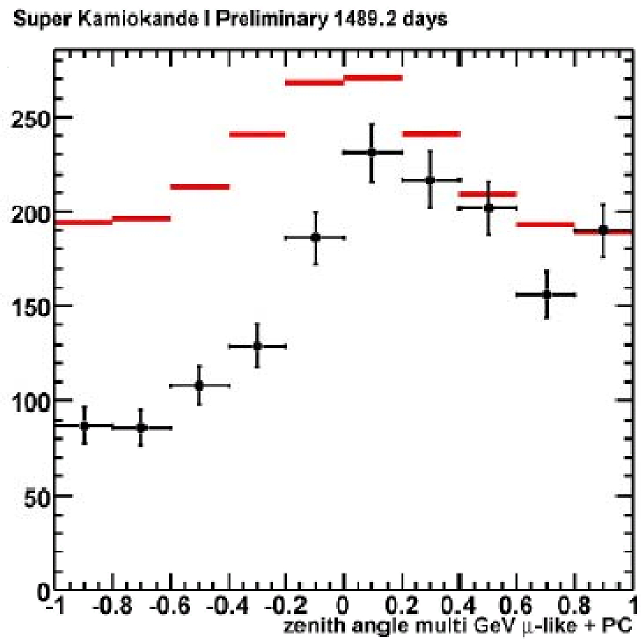
Discovery of neutrino oscillation
at Super-Kamiokande
using atmospheric neutrinos

Super-K 1996～

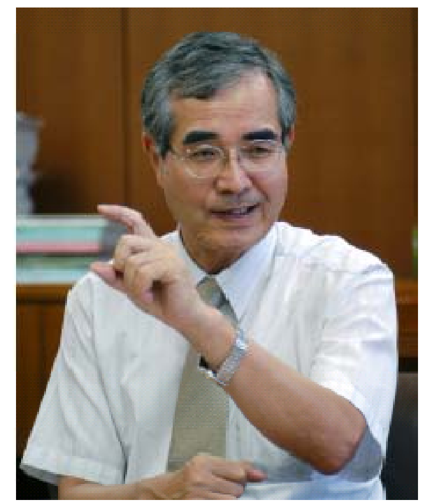
Atmospheric Neutrino



Multi-GeV μ-like + PC



J.Raaf, Talk at Neutrino 2008



Courtesy of KEK

Yoji Totsuka
1942-2008

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Turning around to my colleague, Yeong-Chuan Kao, a Nambu fan, I said to him,

"Could it be Nambu and Goldstone ?! Nambu well deserves, and he's *really* old !"

Nambu was already an old guy over 20 years ago !

Progress of Theoretical Physics Supplement No. 86, 1986 i

Preface

To honor Yoichiro Nambu on the occasion of his 65th birthday, January 18, 1986, some of his friends, colleagues and students have contributed the papers contained in this volume.

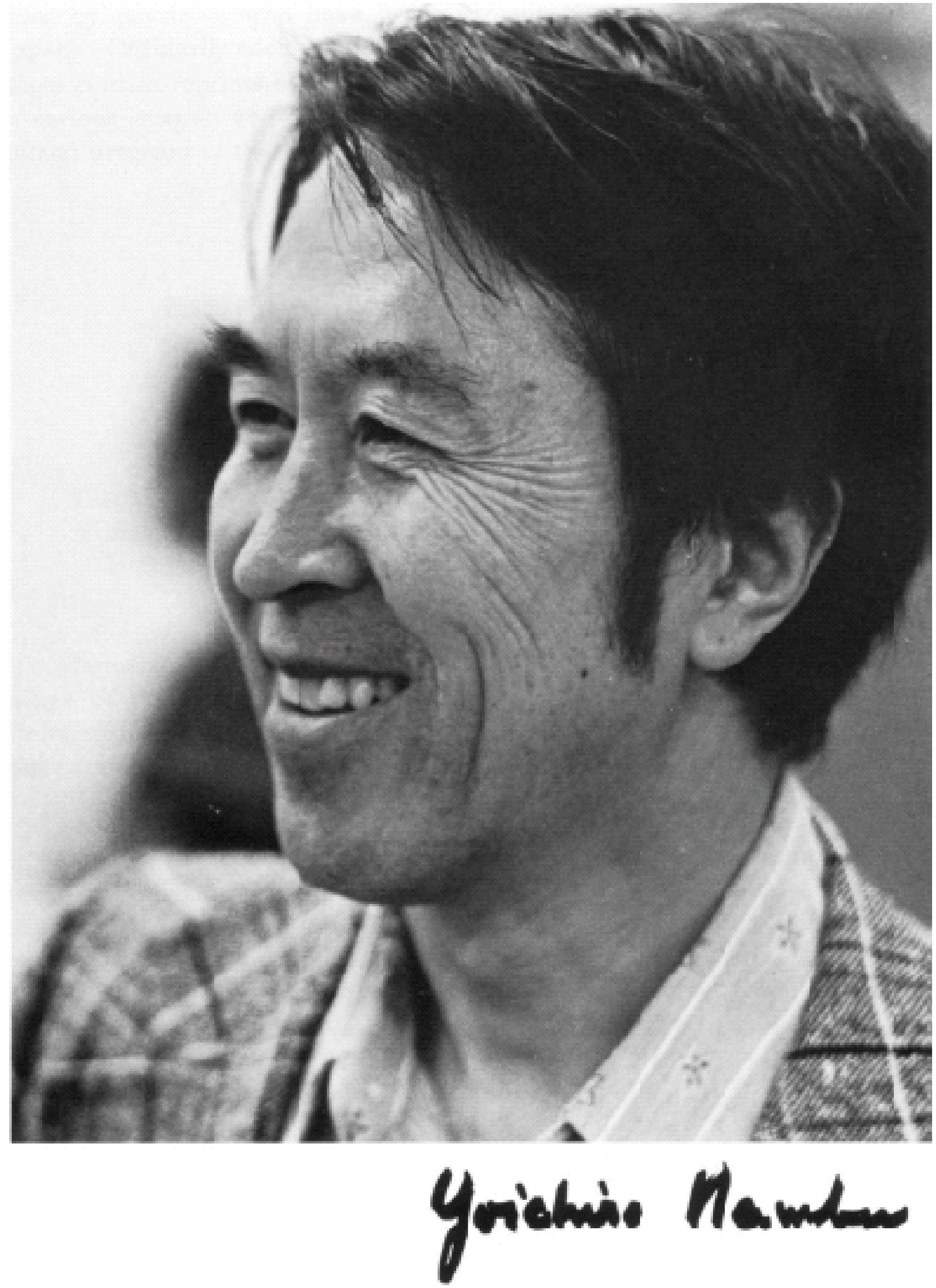
Nambu is one of the major figures in postwar theoretical physics. Fundamental ideas such as spontaneous symmetry breaking, color, relativistic strings and many others are connected with his name. In many instances, his thinking was years ahead of its time. Beyond his manifest brilliance, he has consistently behaved with dignified modesty.

Nambu's activity has always provided a sturdy bridge connecting two major traditions in theoretical physics. We find it therefore most appropriate that this volume is being published in Japan, where his scientific personality was formed, while a Symposium in his honor was held in Chicago, where he has worked for over thirty years.

Along with our sincere admiration, we ask him to accept our very best wishes for many more productive years.

Chicago, January 1986

Peter G. O. Freund and Reinhard Oehme



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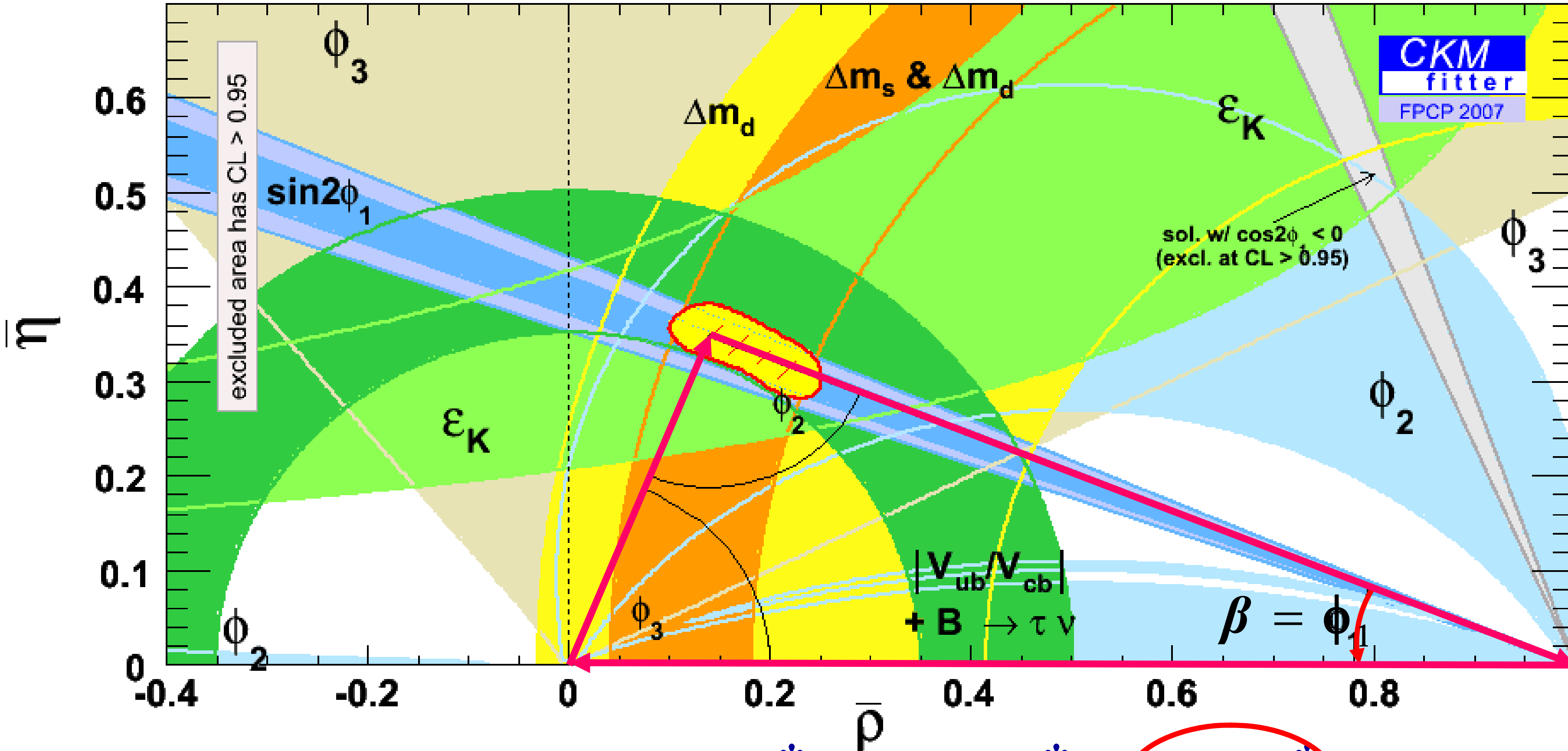
10/2/2008

I gave seminar at Murayama's Institute (IPMU), and stated after showing CKM fit

"*Could this be the Year of CKM ?* "

b → d transitions consistent with SM

Could this be the Year of CKM ?



$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Predicting 2008 Prize

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Murayama responded that announcement should be tomorrow. He was wrong, but it did prompt me to check the date ...

In evening of 10/7, a little tired and bored, I recalled the date and went on line, and was exhilarated to witness the announcement. And the genius of Nobel Committee.

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: Universtity of Chicago

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute,
University of Chicago
Chicago, IL, USA

b. 1921
(in Tokyo, Japan)

Photo: KEK

Makoto Kobayashi

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK)
Tsukuba, Japan

b. 1944

Photo: Kyoto University

Toshihide Maskawa

1/4 of the prize

Japan

Kyoto Sangyo University;
Yukawa Institute for Theoretical Physics (YITP),
Kyoto University
Kyoto, Japan

b. 1940

CP Violation in SM

naturenews
7 October 2008

The Belle detector in Japan helped to confirm the symmetry breaking effects predicted by theoretical physicists.

KEK

B Factories (BaBar & Belle)

The Nobel Prize in Physics 2008

SSB

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SSB

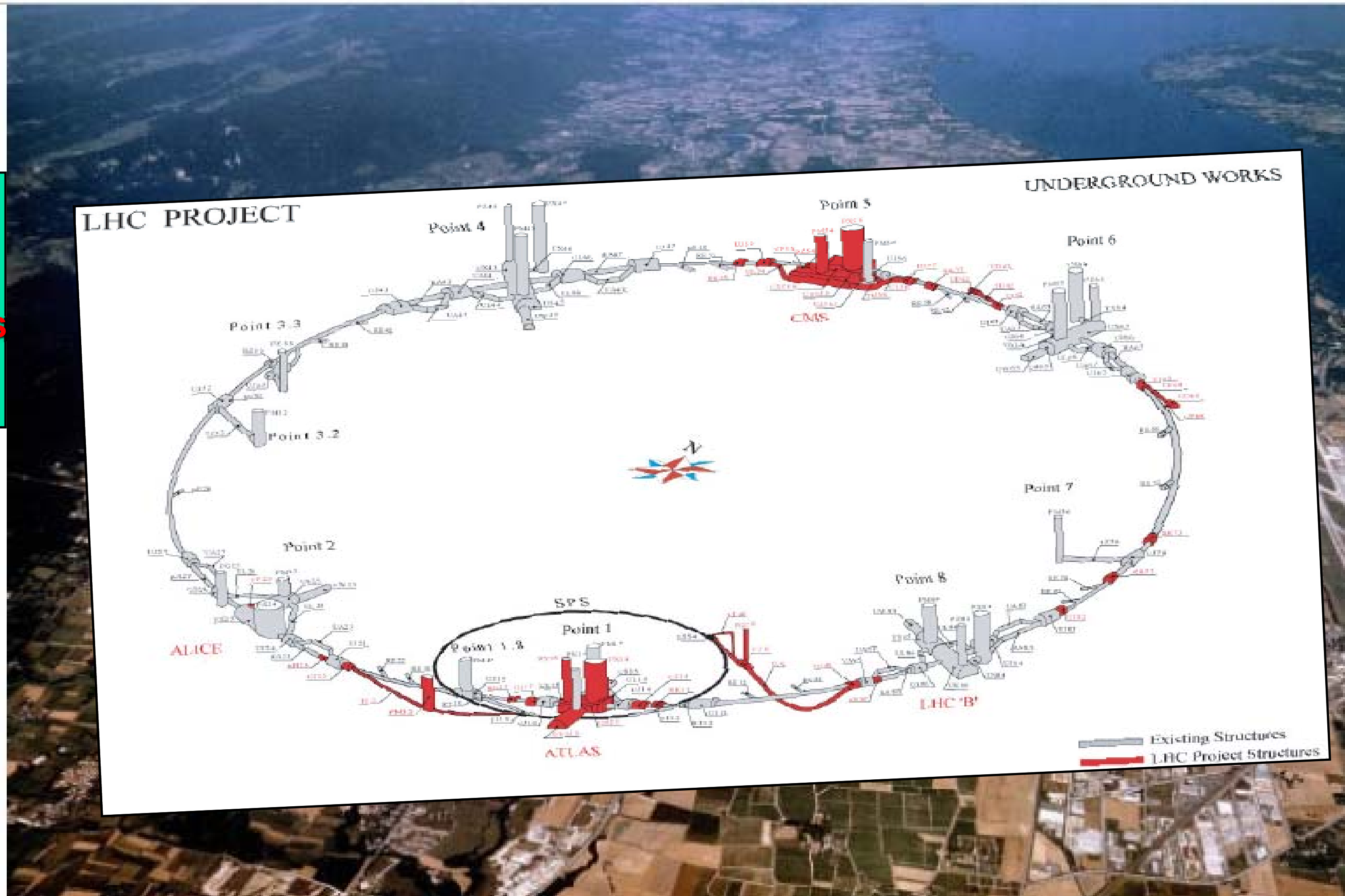
Aim: "Higgs"

SSB

***Origin* of Mass**

[SUSY]

@ LHC



Kungliga
Svenska Vetenskapsakademien
har den 7 oktober 2008 beslutat
att med det
NOBELPRIS
som detta år tillerkännes den
som inom fysikens område gjort den
viktigaste upptäckten eller uppfinningen
belöna
Yoichiro Nambu
för upptäckten av mekanismen för
spontant symmetribrott inom den
subatomära fysiken

STOCKHOLM DEN 10 DECEMBER 2008

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måste ha minst tre familjer av kvarkar

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STOCKHOLM DEN 10 DECEMBER 2008

the Charge

... a talk describing the theoretical insights of those honored (and the one who wasn't) and how this has led to all the physics we have been doing over the last couple of decades etc...

Sources
* phyadv.pdf of Nobel webpage
* Nambu and Kobayashi Nobel Lecture slides
* "*From Yukawa's Pion to Spontaneous Symmetry Breaking*" by Nambu, J. Phys. Soc. Japan (2007)
* "*From BCS to the LHC*" by Weinberg at BCS@50 (published in CERN Courier)

Outline

0. Prologue: Predicting 2008 Prize

I. Intro: the Trouble of Mass[es]

N, π, and Fermi-Yang/Sakata; Quark Model

II. Squalid State to the Rescue — Nambu's Insight

m_N as BCS Energy Gap
π as Nambu-Goldstone Boson
} χSB and NJL Model

III. Spont. Symm. Breaking and SU(3)xSU(2)xU(1)

(Ginzburg-Landau-)Higgs Mechanism; χPT and QCD

IV. Gell-Mann-Lévy-Cabibbo and GIM 3 → 4 Quarks

V. Insight of Kobayashi-Maskawa: 6 Quarks for CPV

VI. Richness of KM: from tau to top; FPCP

VII. Epilogue: KM-N Redux? A Perspective

I. Intro: the Trouble of Mass[es]

N ~ isospin doublet ($m_n \sim m_p$, why?)

π ~ isospin triplet ($m_\pi \ll m_N$, why?)

Chadwick; Heisenberg; Yukawa; Powell ...

Fermi-Yang Suggestion

THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 76, NO. 12 DECEMBER 15, 1949

$\pi \sim N\bar{N}$?

E. FERMI AND C. N. YANG*

Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

but $m_\pi \ll 2m_N$!

I. INTRODUCTION

IN recent years several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

We assume that the π-meson is a pair of nucleon and anti-nucleon bound in this way. Since the mass of the π-meson is much smaller than twice the mass of a nucleon, it is necessary to assume that the binding energy is so great that its mass equivalent is equal to the difference between twice the mass of the nucleon and the mass of the meson.

Sakata Model: p, n, Λ

Prog. Theor. Phys. 16 (1956) 686

On a Composite Model for the New Particles*

Shoichi Sakata

Institute for Theoretical Physics, Nagoya University, Nagoya

September 3, 1956

Recently, Nishijima-Gell-Mann's rule[1] for the systematization of new particles has achieved a great success to account for various facts obtained from the experiments with cosmic rays and with high energy accelerators. Nevertheless, it would

Name	Model	Isotopic Spin	Strangeness	Ordinary Spin
$\mathfrak{N}$		1/2	0	1/2
$\bar{\mathfrak{N}}$		1/2	0	1/2
Λ		0	−1	1/2 ?
$\bar{\Lambda}$		0	1	1/2 ?
π	$\mathfrak{N}+\bar{\mathfrak{N}}$	1	0	0
$\theta(\tau)$	$\mathfrak{N}+\bar{\Lambda}$	1/2	1	0 ?
$\bar{\theta}(\bar{\tau})$	$\bar{\mathfrak{N}}+\Lambda$	1/2	−1	0 ?
Σ	$\mathfrak{N}+\bar{\mathfrak{N}}+\Lambda$	1	−1	1/2 ?
Ξ	$\bar{\mathfrak{N}}+\Lambda+\Lambda$	1/2	−2	1/2 ?

Here $\mathfrak{N}$ and $\bar{\mathfrak{N}}$ denote nucleon and antinucleon respectively, whereas Λ and $\bar{\Lambda}$ denote Λ^0 and anti-Λ^0 respectively[3].

So far as the internal structure is not concerned, our model for new particles is identical with that of Nishijima and Gell-

3) Markov (Rep. Acad. Sci. USSR, 1955) proposed also a composite model which is very similar to ours. It should be remarked that our model may be considered as a generalization of the π-meson model proposed by Fermi and Yang (Phys. Rev. 76 (1948), 1739), and that

N.B. Early indicator of nucleon structure is 1933 measurement of anomalous magnetic moment of proton by Otto Stern. At time of Sakata paper, Hofstadter was uncovering nucleon structure at Stanford w/ e-beam.

copied from Kobayashi's
Nobel Lecture slides

Courtesy of Sakata Memorial
Archival Library

Shoichi Sakata
1911-1970

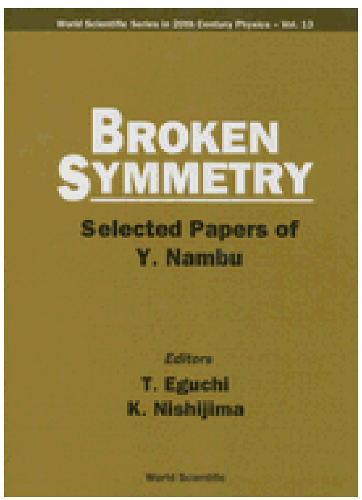
PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

Can one understand $m_\pi \ll 2m_N$?

Where Does Proton Mass Come From ?



— Where does *Mass* come from !?

Nambu Guided the Way.

II. Squalid State to the Rescue — Nambu’s Insight

quip by Gell-Mann

Nambu's background

from Nambu's Nobel Lecture slides

Y. Nambu, preliminary Notes for the Nobel Lecture

I will begin by a short story about my background. I studied physics at the University of Tokyo. I was attracted to particle physics because of the three famous names, Nishina, Tomonaga and Yukawa, who were the founders of particle physics in Japan. But these people were at different institutions than mine. On the other hand, condensed matter physics was pretty good at Tokyo. I got into particle physics only when I came back to Tokyo after the war. In hindsight, though, I must say that my early exposure to condensed matter physics has been quite beneficial to me.

Sc.D., 1952
(age:31)

SCIENTIFIC AMERICAN

Features - October 7, 2008

Profile: Yoichiro Nambu in 1995

Strings and gluons--The seer, this year's physics Nobel laureate, saw them all

Edward Witten of the Institute for Advanced Study in Princeton, N.J., "People don't understand him, because he is so farsighted."

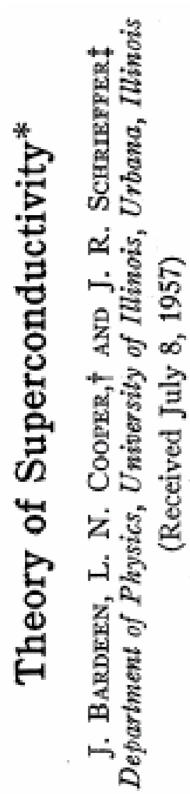
"Over the years," remarks Murray Gell-Mann of the Santa Fe Institute, "you could rely on Yoichiro to provide deep and penetrating insights on very many questions."

In 1952 Nambu was invited to visit the Institute for Advanced Study. There he found many brilliant and aggressive young men. "**Everyone seemed smarter than I. I could not accomplish what I wanted to and had a nervous breakdown**." Nambu wrote decades later.

In 1957, after having moved to Chicago, he proposed a new particle and met with ridicule. ("In a pig's eye!", Richard Feynman shouted at the conference, Laurie Brown recalls. The omega was discovered the next year, in an accelerator.)

"Give it another month, or a month and a half. Wait 'til I get back and keep working. Maybe something'll happen."

With these parting words to Bob Schrieffer, John Bardeen left for Sweden in late November of 1956 to accept the Nobel Prize in Physics, his first,


Theory of Superconductivity*

J. Bardeen, L. N. Cooper,† and J. R. Schrieffer‡

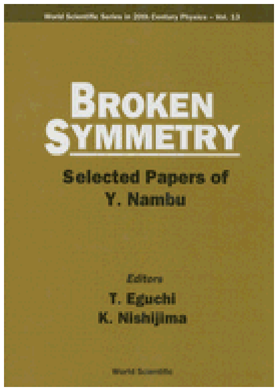
Department of Physics, University of Illinois, Urbana, Illinois

(Received July 8, 1957)

Triumf of Squalid State Physics !

BCS, Spontaneous Symmetry Breaking, and Gauge Inv.

Autobiography in



One day before publication of the BCS paper, Bob Schrieffer, still a student, came to Chicago to give a seminar on the BCS theory in progress. . . . I was very much disturbed by the fact that their wave function did not conserve electron number. It did not make sense. . . . At the same time I was impressed by their boldness and tried to understand the problem.

Schriefer joined Chicago faculty

PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

Quasi-Particles and Gauge Invariance in the Theory of Superconductivity*

YOICHIRO NAMBU
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois
(Received July 23, 1959)

The gauge invariance, to the first order in the external electromagnetic field, can be maintained in the quasi-particle picture by taking into account a certain class of corrections to the charge-current operator due to the phonon and Coulomb interaction. In fact, generalized forms of the Ward identity are obtained between certain vertex parts and the self-energy. The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.

6. THE COLLECTIVE EXCITATIONS

In order to understand the mechanism by which gauge invariance was restored in the calculation of the Meissner effect, and also to solve the integral equations

. . .

We interpret this as describing a pair of a particle and an antiparticle interacting with each other to form a bound state with zero energy and momentum $q=p'-p=0$.

ACKNOWLEDGMENT

We wish to thank Dr. R. Schrieffer for extremely helpful discussions throughout the entire course of the

Nambu-Goldstone Boson and Higgs Mechanism

From Yukawa's Pion to Spontaneous Symmetry Breaking

Y. Nambu, J. Phys. Soc. Japan **76**, 111002 (2007)

The BCS theory assumed a condensate of charged pairs of electrons or holes, hence the medium was not gauge invariant. There were found intrinsically massless collective excitations of pairs (Nambu-Goldstone modes) that restored broken symmetries, and they turned into the plasmons by mixing with the Coulomb field.

Meissner Effect

~ Higgs Mechanism

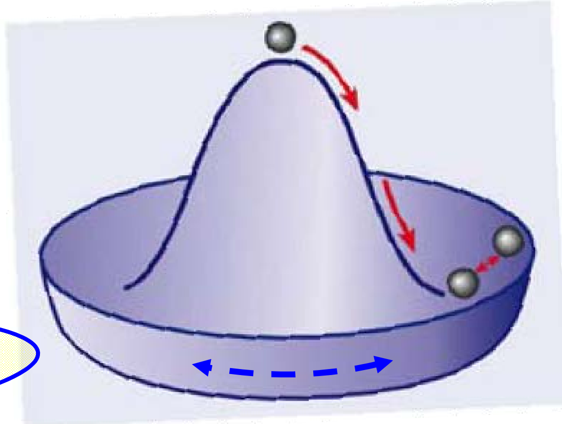
NR — Anderson (1958; 1963)

Englert & Brout (1964)
Higgs (1964; 1966)
} Wolf Prize

[Guralnik, Hagen, Kibble (1964)

Ginzburg & Landau (1950)

Nambu uses the term Ginzburg-Landau-Higgs "effective" field



A Mexican hat illustrates the Goldstone theorem. Though the hat is invariant under rotations about a vertical axis, a small ball will come to rest off the axis of symmetry, somewhere on the brim of the hat, but it can move freely with no restoring force around the brim. Broken approximate symmetry is illustrated by slightly tilting the hat; this produces a small restoring force, analogous to the small mass of the pion.

Nambu;
Goldstone (1961);
Goldstone, Salam & Weinberg (1962)

Nambu's comment

Y. Nambu, preliminary Notes for the Nobel Lecture

In hindsight I regret that I should have explored in more detail the general mechanism of mass generation for the gauge field. But I thought the plasma and the Meissner effect had already established it. I also should have paid more attention to the Ginzburg-Landau theory which was a forerunner of the present Higgs description.

Other examples of BCS type SSB

- ^3He superfluidity
- Nuleon pairing in nuclei
- Fermion mass generation in the electro-weak sector of the standard model

Nambu calls the last entry

my biased opinion, there being other interpretations as to the nature of the Higgs field

m_N as "BCS Energy Gap"
π as Nambu-Goldstone Boson

VOLUME 4, NUMBER 7 PHYSICAL REVIEW LETTERS APRIL 1, 1960

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

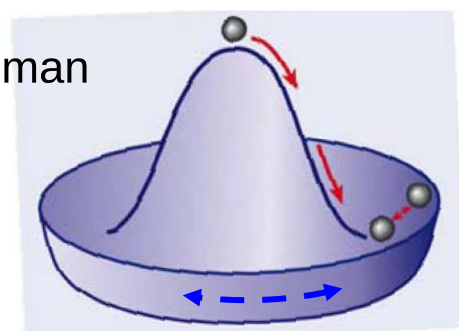
V – A 1958

In analogy to the conserved vector current interaction in the beta decay suggested by Feynman and Gell-Mann, some speculations have been made about a possible conserved axial vector current.[1-3] One can formally construct an axial vector nucleon current, which satisfies a continuity equation,

$$\Gamma_\mu^A(p',p) = i\gamma_5\gamma_\mu - 2M\gamma_5 q_\mu/q^2, \quad q = p' - p, \qquad (1)$$

where p and p' are the initial and final nucleon

Goldberger-Treiman Relation



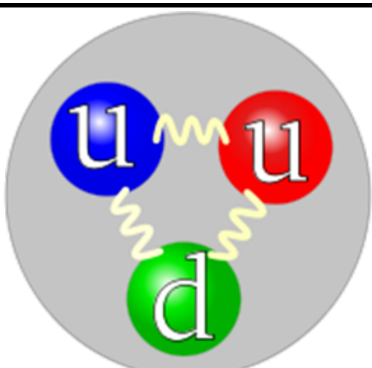
This situation may be understood by making an analogy to the theory of superconductivity originated by Bardeen, Cooper, and Schrieffer,[9] and refined by Bogoliubov.[10] There gauge invariance, the energy gap, and the collective excitations are logically related to each other as was shown by the author.[11] In the present case we have only to replace them by γ_5 invariance, baryon mass, and the mesons. In fact, the mathematical method used in superconductivity may be taken over to study the self-energy problem of elementary particles. It is interesting that pseudoscalar mesons automatically emerge in this theory as bound states of baryon pairs. The nonzero meson masses and baryon mass splitting would indicate that the γ_5 invariance of the bare baryon field is not rigorous, possibly because of a small bare mass of the order of the pion mass.

π

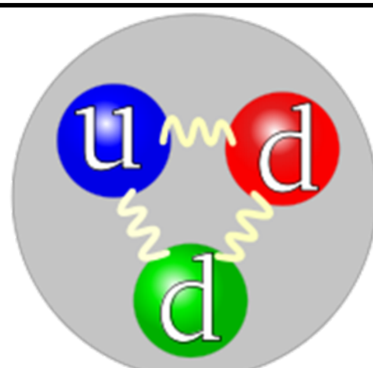
The Penetrating Analogy

ca. 1960

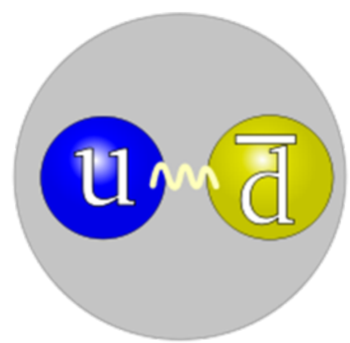
Superconductivity	Strong Interactions	
free electrons	hypothetical fermions with small mass	u, d quarks
phonon interaction	unknown interaction	QCD
energy gap	observed nucleon mass	m_N
collective excitations	mesons, bound states	π
charge	chirality	
gauge invariance	chiral invariance, possibly approximate	



proton



neutron



pion

Yukawa's pion as NG boson of Spontaneous Chiral Symmetry Breaking

Beyond Analogy: Dynamical χSB, NJL Model, χPT

electrons and holes
coherent mixture near the Fermi surface:

$$E\psi_{p+} = \epsilon_p \psi_{p+} + \phi \psi_{-p-}^*,$$
$$E\psi_{-p-}^* = -\epsilon_p \psi_{-p-}^* + \phi \psi_{p+},$$
$$\Rightarrow \quad E_p = \pm(\epsilon_p^2 + \phi^2)^{\frac{1}{2}}$$

ϵ_p is the kinetic energy (from Fermi surface)
ϕ is the gap parameter

ψ_1 and ψ_2 eigenstates of
chirality operator γ_5

$$E\psi_1 = \sigma \cdot p\psi_1 + m\psi_2,$$
$$E\psi_2 = -\sigma \cdot p\psi_2 + m\psi_1,$$
$$E_p = \pm(p^2 + m^2)^{\frac{1}{2}},$$

Dirac mass m

As the energy gap ϕ in a superconductor is created by the interaction, let us assume that the mass of a Dirac particle is also due to some interaction between massless bare fermions.

⇒ **Nambu-Jona-Lasinio Model**

It is perhaps not a coincidence that there exists such an entity in the form of the pion. For this reason, we would like to regard our theory as dealing with nucleons and mesons. The implication would be that the nucleon mass is a manifestation of some unknown primary interaction between originally massless fermions, the same interaction also being responsible for the binding of nucleon pairs into pions.

⇒ χPT

Works when QCD doesn't

Cutoff takes place of Fermi Surface

III. Spont. Symm. Breaking and SU(3)xSU(2)xU(1)

— SSB *is* integral part of SM !

SSB Phenomena in Standard Model Dynamics

$SU(2)xU(1) \xrightarrow{SSB} U_Q(1)$

Weinberg (1967)

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation

Breakthru: SBNAGT renormalizable
'’t Hooft (1971); ’t Hooft & Veltman (1972)

N.B. Need only G-L-H effective field,
Does not require fundamental H.
[Longitudinal W, Z are NG bosons]

$SU_C(3)$

Han & Nambu (1965)
argument of statistics
used integer quark charges

Asymptotic Freedom ...

Gross & Wilczek (1973)
[also Fritzsch and Gell-Mann (1972)]

⇒ QCD

$SU_L(3)xSU_R(3) \xrightarrow[(QCD)]{D\chi SB} SU_V(3)$

χPT as effective FT

used in conjunction w/ LQCD etc.

IV. Gell-Mann-Lévy-Cabibbo and GIM)

3 $\longrightarrow$ 4 quarks

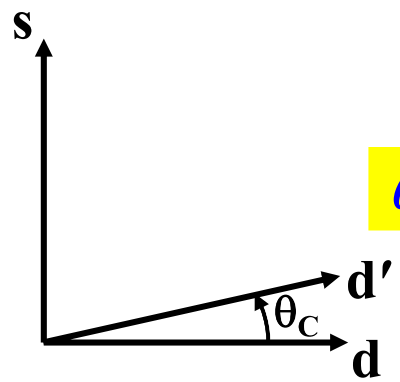
... (and the one who wasn't)

Cabibbo Theory

VOLUME 10, NUMBER 12 PHYSICAL REVIEW LETTERS 15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)



$\theta_c \cong 13°$

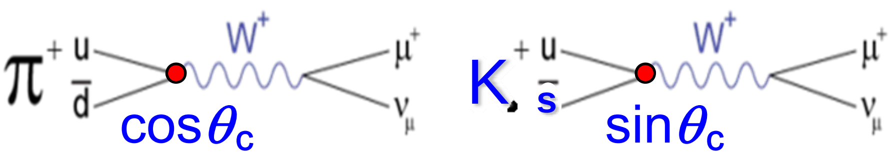
We then rewrite J_μ as[4]

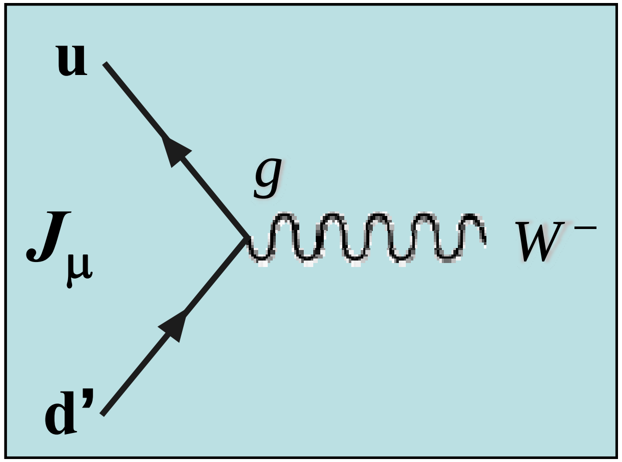
$$J_\mu = \cos\theta(j_\mu^{(0)} + g_\mu^{(0)}) + \sin\theta(j_\mu^{(1)} + g_\mu^{(1)}), \quad (2)$$

where $\tan\theta = b/a$. Since J_μ, as well as the baryons and the pseudoscalar mesons, belongs to the octet representation of SU_3, we have relations (in which θ enters as a parameter) between processes with $\Delta S = 0$ and processes with $\Delta S = 1$.

$$d' = d\cos\theta_C + s\sin\theta_C$$

Strangeness conserving changing





To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$
$$= \tan^2\theta M_K(1 - M_\mu^2/M_K^2)^2/M_\pi(1 - M_\mu^2/M_\pi^2)^2. \quad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$

Cabibbo Theory

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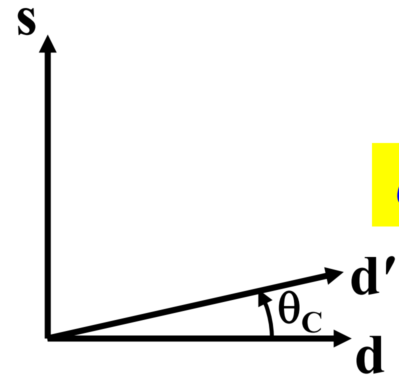

$\theta_c \cong 13°$

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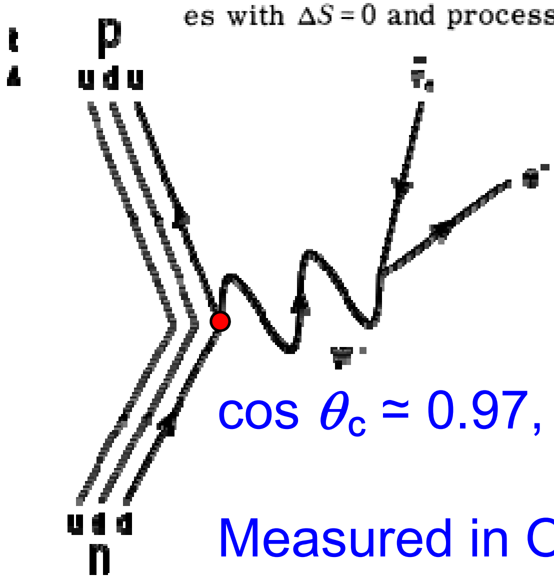
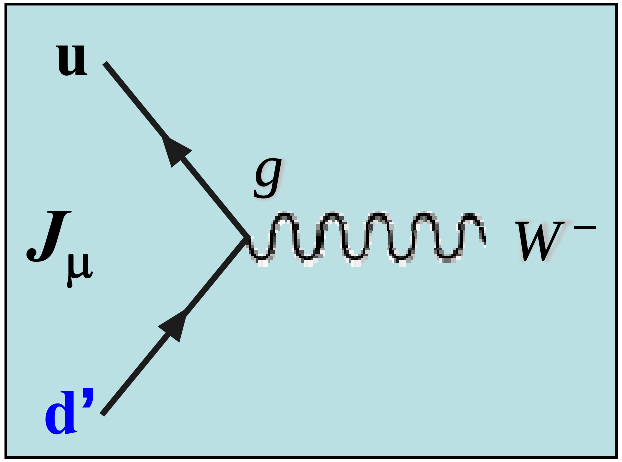


cos θ_c ≃ 0.97, slight reduction in amplitude

Measured in $O^{14} \rightarrow F^{14} + e + \nu$



What may have done Cabibbo in ...

VOLUME 10, NUMBER 12 PHYSICAL REVIEW LETTERS 15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

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CERN, Geneva, Switzerland
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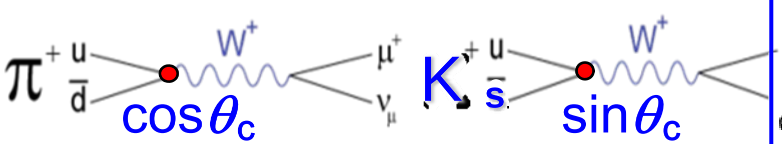

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From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$

[4] Similar considerations are forwarded in M. Gell-Mann and M. Lévy, Nuovo Cimento 16, 705 (1960).

IL NUOVO CIMENTO VOL. XVI, N. 4 16 Maggio 1960

The Axial Vector Current in Beta Decay

this number, the experimental value, and the conserved vector current hypothesis, we obtain $G/G_\mu = 0.97 \pm 0.01$ rather than unity (*).

(*) *Note added in proof.* – Should this discrepancy be real, it would probably indicate a total or partial failure of the conserved vector current idea. It might also mean, however, that the current is conserved but with $G/G_\mu<1$. Such a situation is consistent with universality if we consider the vector current for $\Delta S=0$ and $\Delta S=1$ together to be something like:

Already Unitary Form

$$GV_\alpha + GV_\alpha^{(\Delta S=1)} = G_\mu \bar{p}\gamma_\alpha(n+\varepsilon\Lambda)(1+\varepsilon^2)^{-\frac{1}{2}} + \ldots,$$

and likewise for the axial vector current. If $(1+\varepsilon^2)^{-\frac{1}{2}} = 0.97$, then $\varepsilon^2 = .06$, which is of the right order of magnitude for explaining the low rate of β decay of the Λ particle. There is, of course, a renormalization factor for that decay, so we cannot be sure that the low rate really fits in with such a picture.

What may have done Cabibbo in ...

VOLUME 10, NUMBER 12 PHYSICAL REVIEW LETTERS 15 JUNE 1963

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"Gell-Mann-Lévy-Cabibbo"

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Gell-Mann remembers in Quark Model paper

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

M. GELL-MANN

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q $\bar{q}$), etc., while mesons are made out of (q $\bar{q}$), (q q $\bar{q}$ $\bar{q}$), etc. It is assuming that the lowest baryon configuration (q q q) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration (q $\bar{q}$) similarly gives just **1** and **8**.

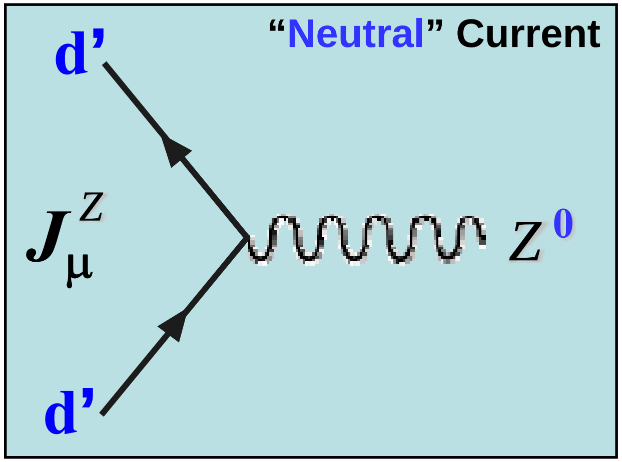
A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model, for example 3) with all strong interactions ascribed to a neutral vector meson field interacting symmetrically with the three particles. Within such a framework, the electromagnetic current (in units of e) is just

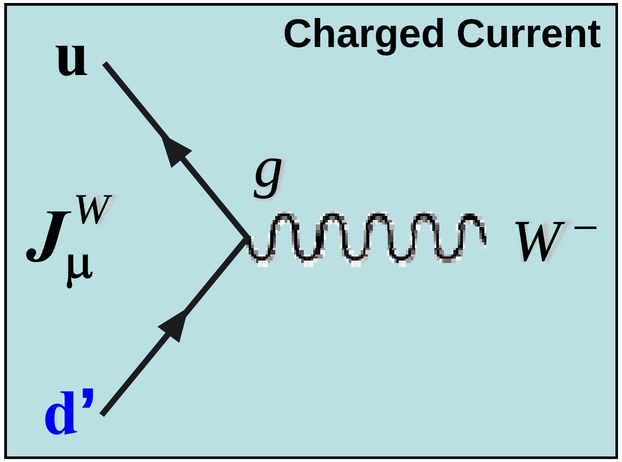
$$i\{\tfrac{2}{3}\,\bar{u}\,\gamma_\alpha\,u - \tfrac{1}{3}\,\bar{d}\,\gamma_\alpha\,d - \tfrac{1}{3}\,\bar{s}\,\gamma_\alpha\,s\}$$

or $\mathcal{F}_{3\alpha} + \mathcal{F}_{8\alpha}/\sqrt{3}$ in the notation of ref. 3). For the weak current, we can take over from the Sakata model the form suggested by Gell-Mann and Lévy 7), namely $i\,\bar{p}\,\gamma_\alpha(1+\gamma_5)(n\cos\theta + \Lambda\sin\theta)$, which gives in the quark scheme the expression ***

$$i\,\bar{u}\,\gamma_\alpha(1+\gamma_5)(d\cos\theta + s\sin\theta)$$

We thus obtain all the features of Cabibbo's picture 8)





Glashow-Weinberg-Salam Electroweak Theory

GIM Mechanism

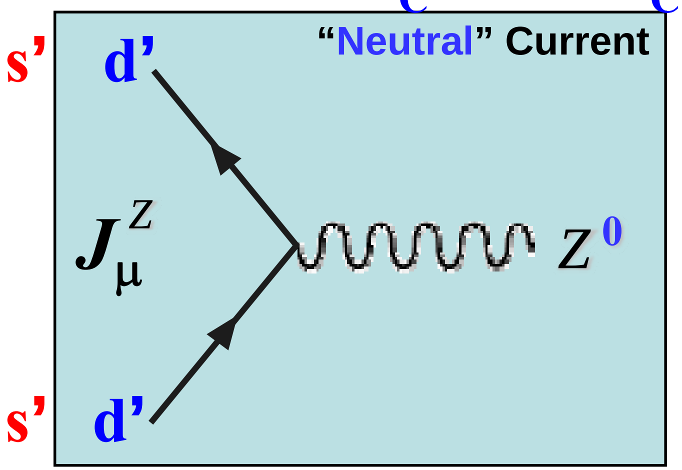
PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

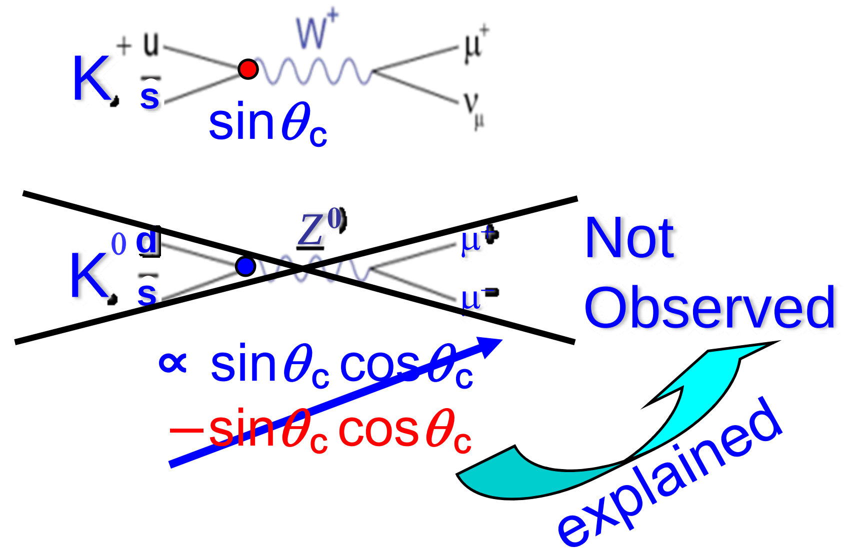
S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

$$d' = d\cos\theta_C + s\sin\theta_C$$



$$s' = -d\sin\theta_C + s\cos\theta_C$$



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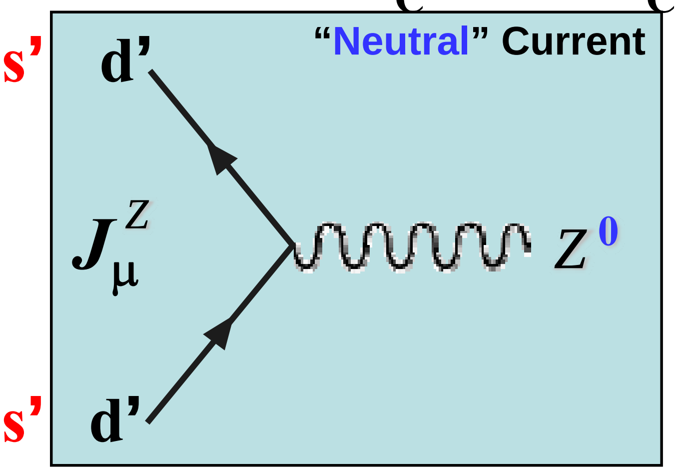
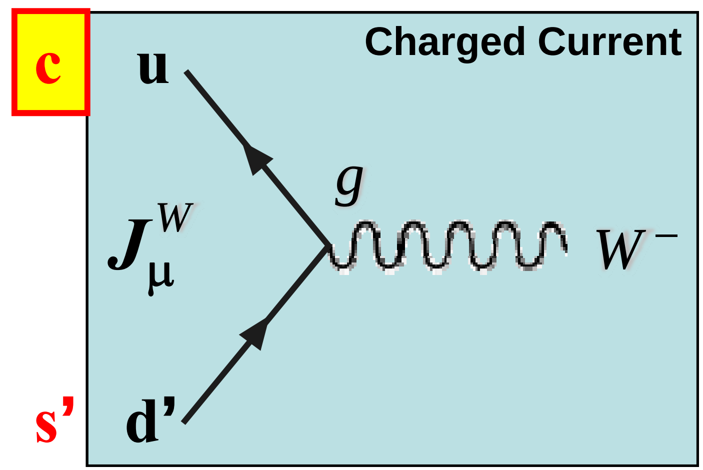
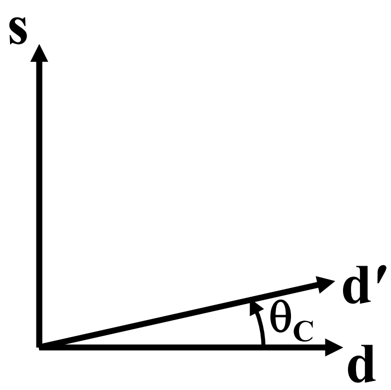


$$\mathbf{s'} = -\mathbf{d}\sin\theta_C + \mathbf{s}\cos\theta_C$$

A Fourth Charge +2/3 Quark !

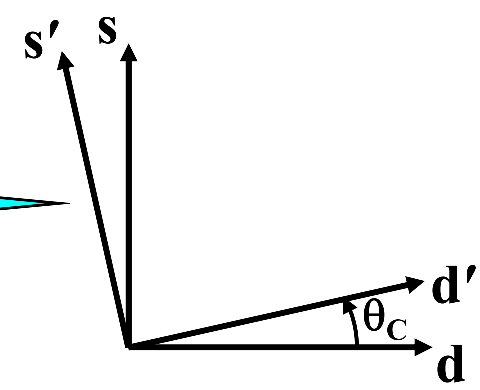


GIM Mechanism Completes 2 x 2



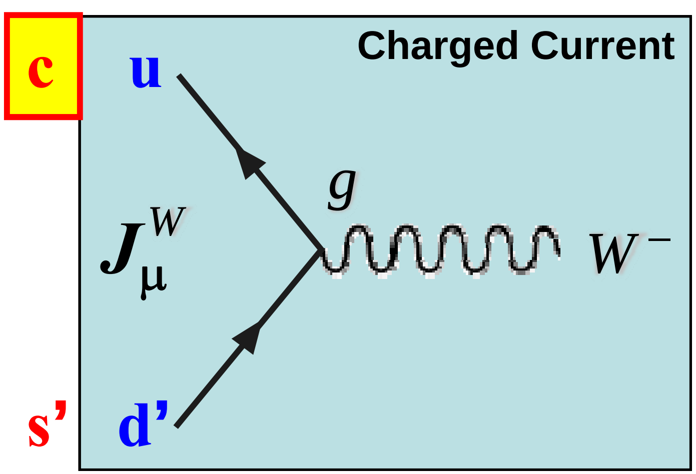
$$\mathbf{d' = \ \ d\cos\theta_C + s\sin\theta_C}$$

$$\mathbf{s' = -d\sin\theta_C + s\cos\theta_C}$$



$$\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}$$

2x2 Rotation !



V. Insight of Kobayashi-Maskawa: 6 Quarks for CPV

Experimental Discovery of CP Violation

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$48-in. collimator at an average distance of 14.5 ft. from

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu3}$, from 280 to ~516; and the $K_{\pi3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This

2×10^{-3} : *Too Small .... for Sakharov !*

(1967)

CPV & BAU (& U): The Sakharov View

- *Baryon Number Violation*
- *CP Violation*
- Deviation from Equilibrium

GIM 2x2

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

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theless, suitable redefinitions of the relative phases of the quarks may be performed in order to make U real and orthogonal, so without loss of generality we write

$$U=\begin{bmatrix} -\sin\theta & \cos\theta \\ \cos\theta & \sin\theta \end{bmatrix}. \qquad (5)$$

Did not pursue CPV

tribute to Sakata

We begin by introducing four quark fields.[10] The three quarks $\mathcal{P}$, $\mathcal{N}$, and λ form an $SU(3)$ triplet, and the fourth, $\mathcal{P}'$, has the same electric charge as $\mathcal{P}$ but differs from the triplet by one unit of a new quantum number $\mathcal{C}$ for charm. The strong-interaction Lagrangian

Kobayashi-Maskawa

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

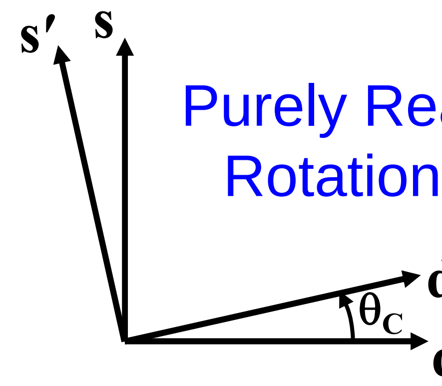
CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.



consider the quartet model v
or p, n, λ and ζ, respectively

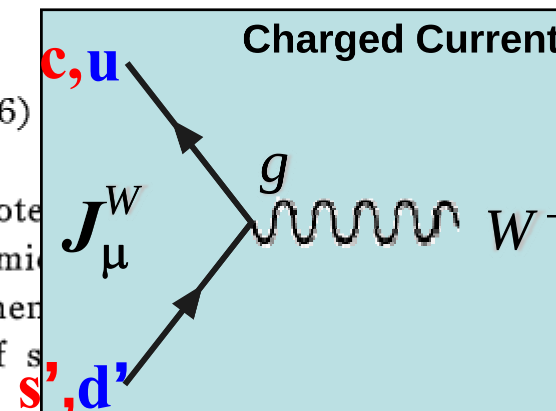
Sakata

did not refer GIM

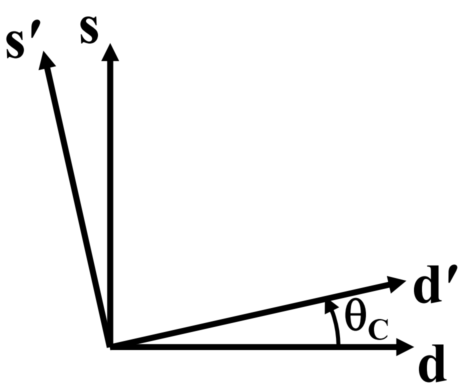
field corresponding to $U(1)$ which is irrelevant to our discussion. With an appropriate phase convention of the quartet field we can take U as

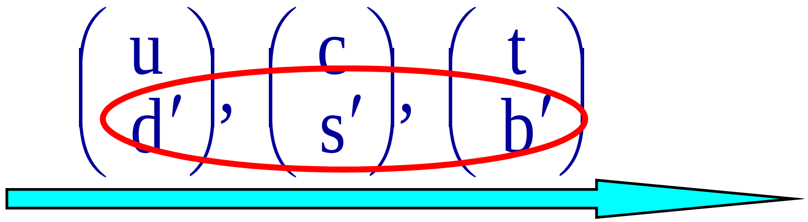
$$U=\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}. \tag{6}$$

Therefore, if $\mathcal{L}'=0$, no *CP*-violations occur in this case. It should be note however, that this argument does not hold when we introduce one more fermi doublet with the same charge assignment. This is because all phases of elemen of a 3×3 unitary matrix cannot be absorbed into the phase convention of s fields. This possibility of *CP*-violation will be discussed later on.



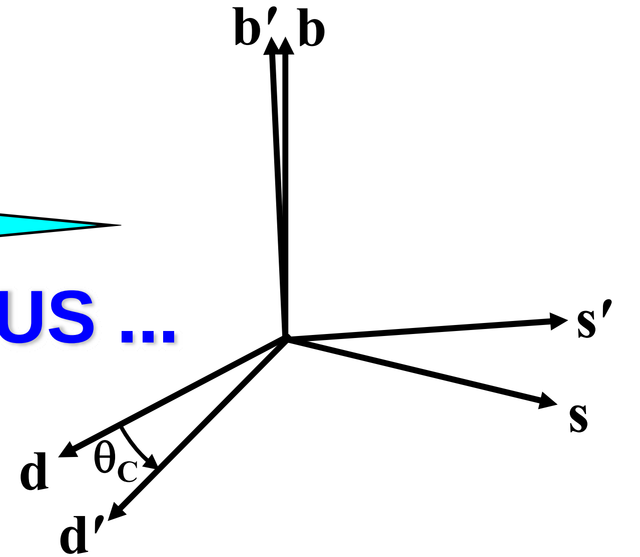
KM Development : from 2 x 2 to 3 x 3





3x3 Rotation !

PLUS ...



ponents, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

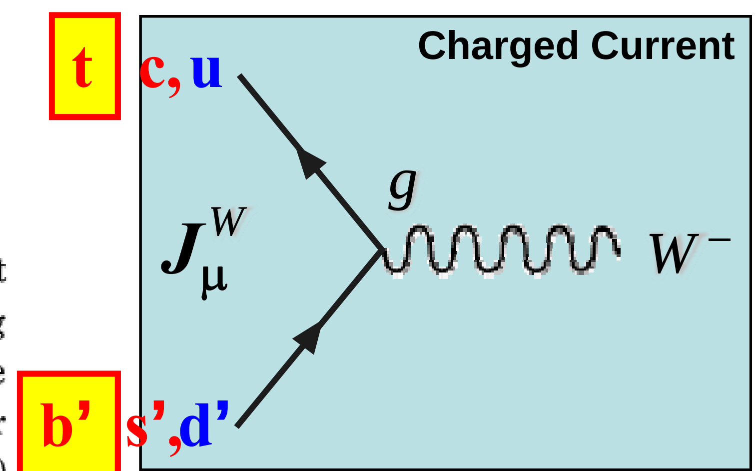
$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

cos

the phase counting is called Iwasawa decomp.

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

3 "Generations"



"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

CP Violation

~ 28

~ 32

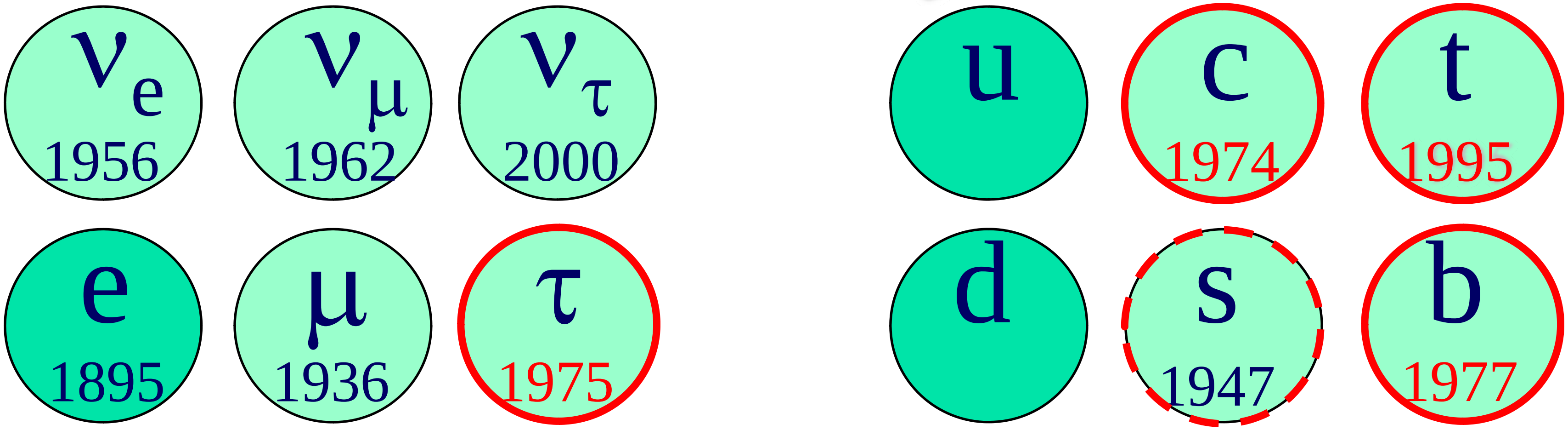
ca. 1973

VI. Richness of KM: from tau to top; FPCP

KM **is** Flavor part of SM !

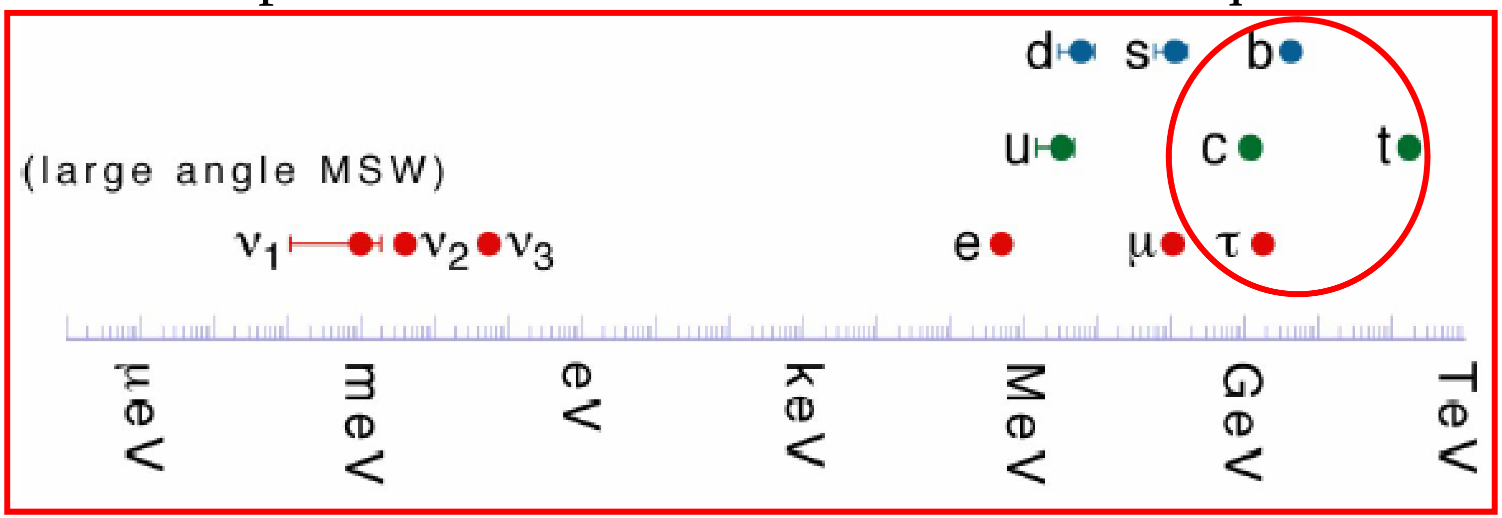
The Fundamental Fermions

Heavy Flavor



six leptons

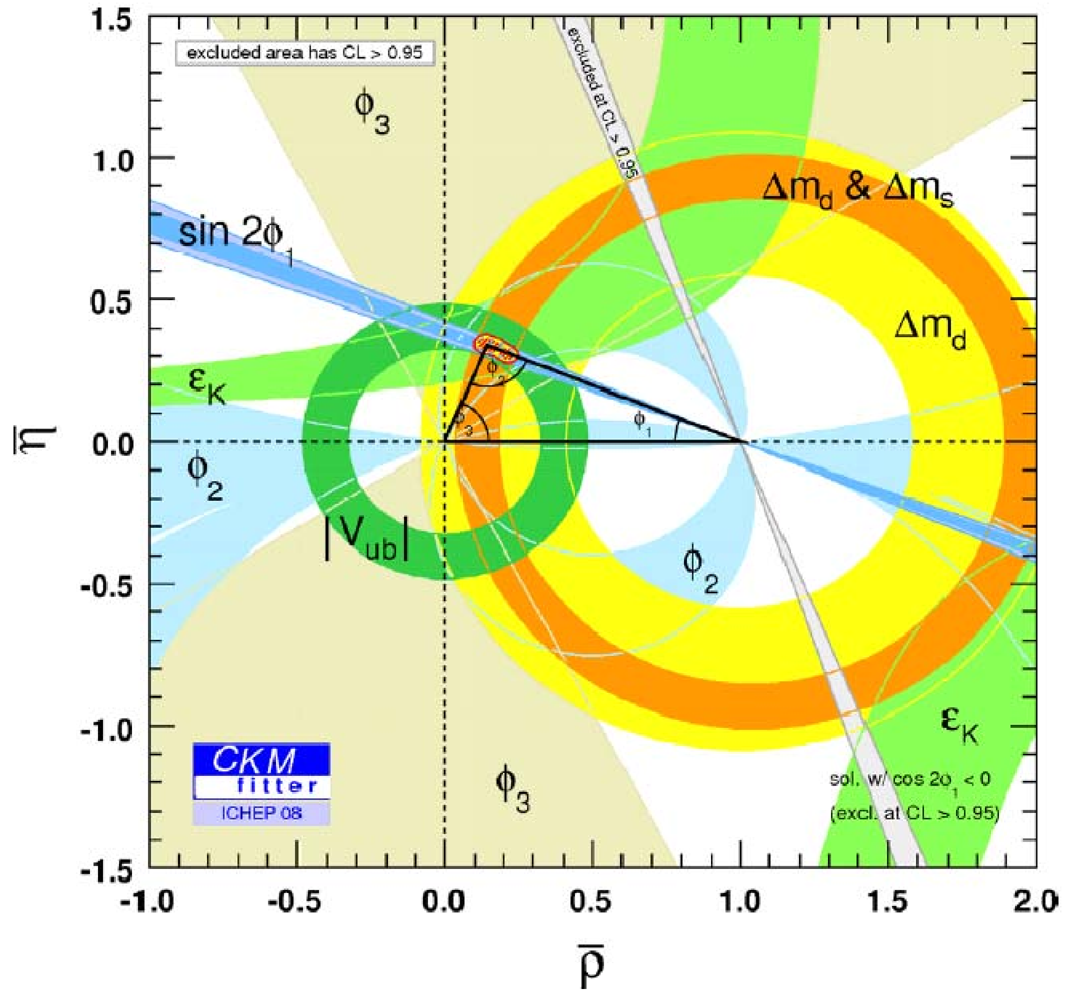
six quarks



KM's Impact, and our pay-back

Experimental Verification at B-Factories

Kobayashi slides



Kobayashi slides

Present Status of CP Violation

B-factory results show that quark mixing is the dominant source of CP violation

B-factory results allow room for additional source from new physics

Matter dominance of the Universe seems requiring new source of CP violation

CPV so far only observed in KM ...

- Nontrivial CPV Phase

  Nontrivial $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

- All like-charge quark pairs nondegenerate,

  Otherwise → Back to 2-gen. and CPV vanish.

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\, A$$

Jarlskog's Invariant for **CPV**

$$\mathrm{Im}\,\det\left[m_u m_u^\dagger,\ \ m_d m_d^\dagger\right]$$

Experimental Verification at B-Factories

Kobayashi slides

Present Status of CP Violation

B-factory results show that quark mixing is the dominant source of CP violation

B-factory results allow room for additional source from new physics

Matter dominance of the Universe seems requiring new source of CP violation

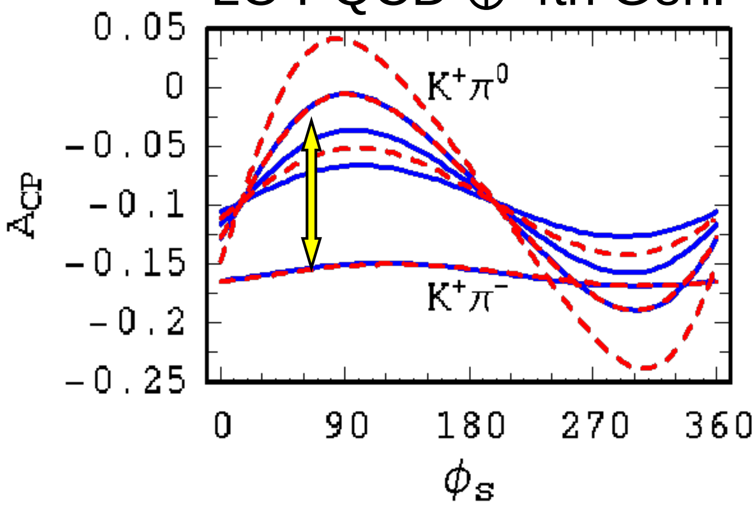
J seems short by at least 10^{-10}

VII. Epilogue: KM-N Redux? A Perspective

I'm a born-again 4th generationist!

$\Delta A = A_{K^+\pi^0} - A_{K^+\pi^-} \sim 15\%$ and $P_{EW}^{b\to s}$

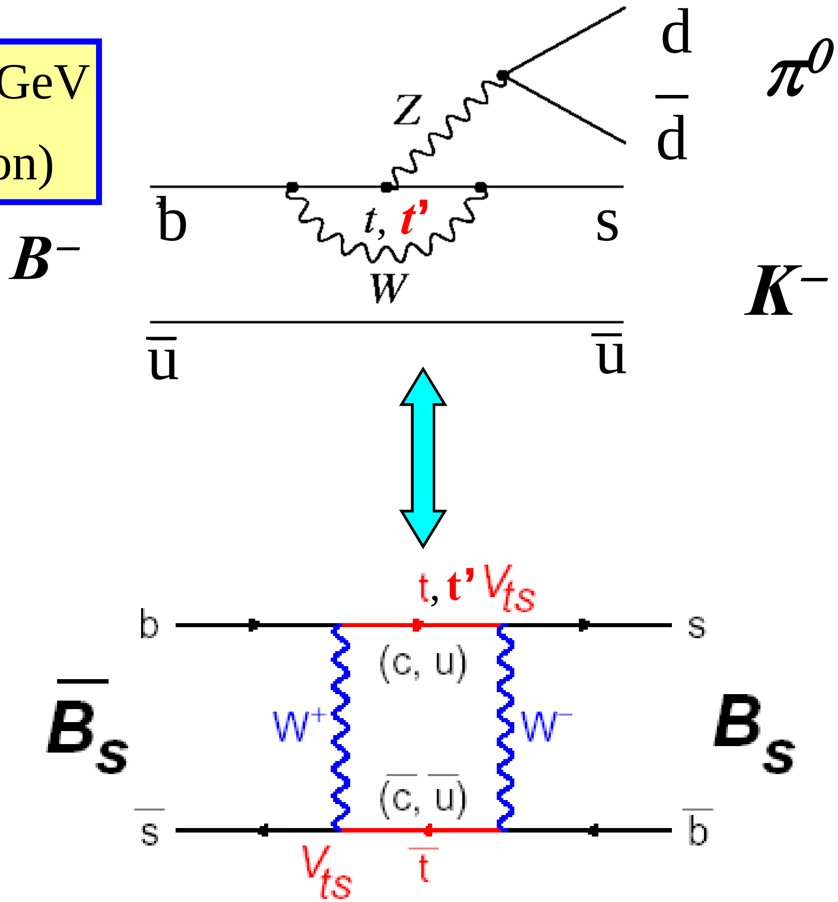
LO PQCD ⊕ 4th Gen.



WSH, Nagashima, Soddu, PRL'05

$\Delta A \approx 12\%$ vs 15% (data)

$m_{t'} = 300$ GeV
(illustration)

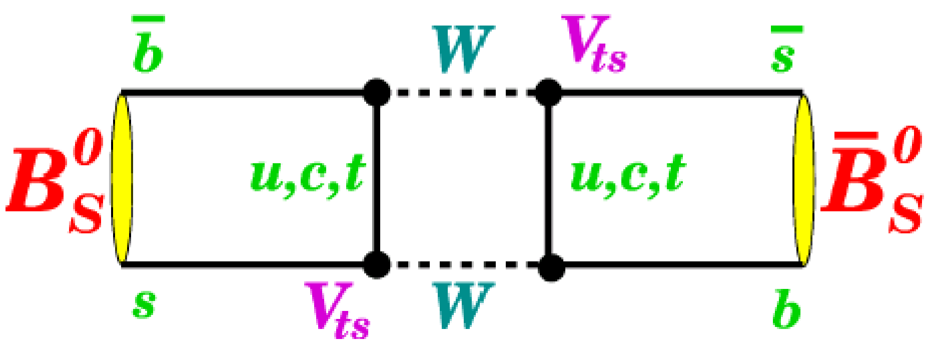


An Updated Measurement of the *CP* Violating Phase $\beta_s^{J/\psi\phi}$

The CDF Collaboration[1]

CDF/ANAL/BOTTOM/PUBLIC/9458
Version 1.0
August 7, 2008

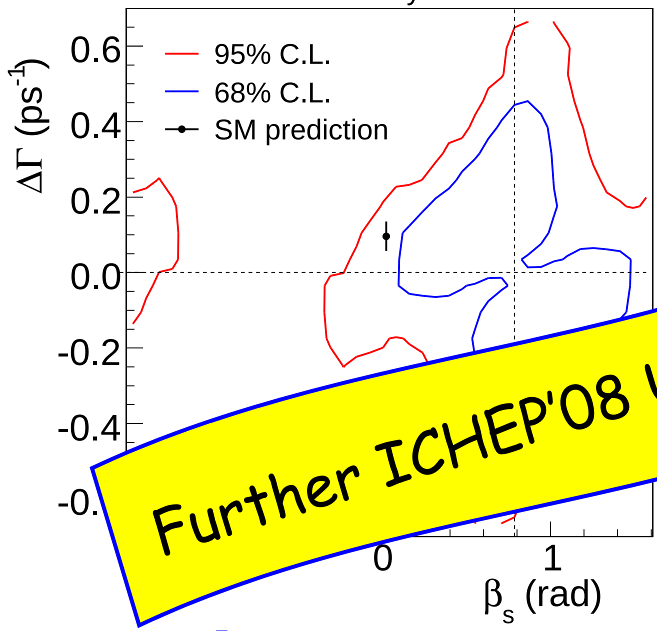
It is interesting to note that the Belle and *BABAR* collaborations have observed an asymmetry between direct *CP* asymmetries of charged and neutral $B \to K\pi$ decays with 5σ significance [5, 6]. In the absence of an under-estimation of the contribution from color-suppressed tree decays, it is difficult to explain this discrepancy without some source of new physics contributing to the electroweak penguin which governs the $b \to s$ transition.In the standard model, this isospin-violating diagram should be highly suppressed, but if a new source of physics is indeed present in these transitions it may be enough to cause the different *CP* asymmetries that have been observed.. In the $B_s^0 \to J/\psi\,\phi$ decay, the $b \to s$ transition occurs through the mixing box diagram shown in Fig. 1. It is possible that new particles could enter this transition through the $b \to s$ quark transition. While there are surely a number of possible sources of new physics that might give rise to such discrepancies, George Hou predicted the presence of a t' quark with mass between ~ 300 and 1,000 GeV/c^2 in order to explain the Belle result and predicted *a priori* the observation of a large *CP*-violating phase in $B_s^0 \to J/\psi\,\phi$ decays [7, 8]. Another result of interest in the context of these measurements is the excess observed at ~ 350 GeV/c^2 in the recent t' search at CDF using 2.3 fb^{-1} of data [9]. In this direct search for a fourth generation up-type quark, a significance of less than 2σ is obtained for the discrepancy between the data and the predicted backgrounds, so that the effect, while intriguing, is presently consistent with a statistical fluctuation. A updated search with more data would also clearly be of interest, particularly if a large value of $\beta_s^{J/\psi\phi}$ persists with the addition of more data.



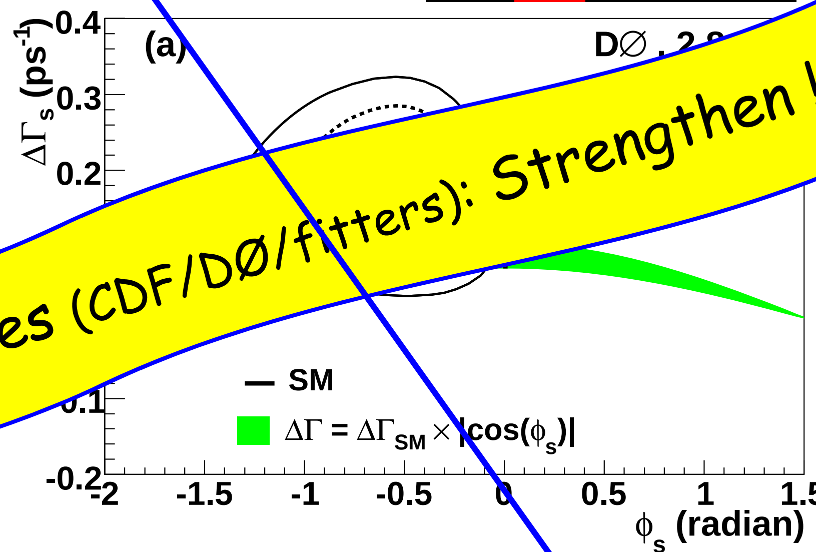
$\sin 2\Phi_{B_s} \sim -0.5$ - -0.7

WSH, Nagashima, Soddu, PRD'07 (already in 05)

PRL'08
arXiv:0712.2397 [hep.ex]



PRL'08
arXiv:0802.2255 [hep.ex]



Further ICHEP'08 Updates (CDF/DØ/fitters): Strengthen !

Observable	68% Prob.	95% Prob.
ϕ_{B_s} [°]	-19.9 ± 5.6	[-30.45, -9.29]
	-68.2 ± 4.9	[-78.45,-58.2]

UT*fit*

arXiv:0803.0659 [hep.ph]

$\sin 2\Phi_{B_s} = -0.64$ ~2.8σ ± ?

Incredible !!!

B.A.U. from *Electroweak Baryogenesis* ?

CPV

$$\frac{n_{\mathcal{B}}}{n_\gamma} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$

WMAP

$$\text{KM} \sim 10^{-20}$$

Too Small in SM

If shift by One Generation in SM4 (need 3 generation in KM)

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\, A$$

WSH, arXiv:0803.1234 [hep/ph]

$$J^{sb}_{(2,3,4)} \simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\, A^{sb}_{234}$$

$$\sim \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\frac{A^{sb}_{234}}{A} J$$

$\sim 10^{+15}$ Gain

Only fac. 30 in CPV per se

Gain mostly in Large Yukawa Couplings !

Nature would likely use this !?

SSB

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Photo: Universtity of Chicago

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute,
University of Chicago
Chicago, IL, USA

b. 1921
(in Tokyo, Japan)

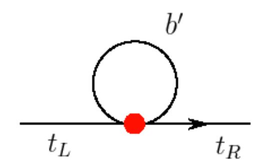
$\langle \bar{Q}Q \rangle$ can Condense

by Large Yukawa !

Could EWSB be
due to b' and t'
above unitarity bound ~ 500-600 GeV ?

Bob Holdom: N–J-L

[Bardeen, Hill, Lindner



Gustavo Burdman: "Holographic" 4th gen.

KM-N Redux

$$J^{sb}_{(2,3,4)} \simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\, A^{sb}_{234}$$

$$\sim \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\frac{A^{sb}_{234}}{A} J$$

$\sim 10^{+15}$ Gain

Even if $O(1)$

$m_{b'}, m_{t'} \cong 300\,\text{GeV}$ 10^{+13}

$\sim 600\,\text{GeV}$ 10^{+15}

Enough CPV for B.A.U.

Maybe there is a 4th Generation !

$\sin 2\Phi_{B_s}$ @ Tevatron by 2010(1)

Will Really Know in ~ 3–5 years !

@ LHC

⇒ *Heaven on Earth?*

Backup

My first B paper

WSH, Willey, Soni

VOLUME 58, NUMBER 16 PHYSICAL REVIEW LETTERS 20 APRIL 1987

an by Inami and Lim,[9] and we follow their notation. The effective Lagrangean arising from Fig. 1 is

$$\mathcal{L}_{\rm eff}^{b\bar{s}\to l^+l^-} = 2\sqrt{2}G_{\rm F}\chi v_i\{\bar{C}_i(\bar{s}\gamma_\mu Lb)(\bar{l}\gamma_\mu Ll) - s_W^2(F_1^i + 2\bar{C}_i^Z)(\bar{s}\gamma_\mu Lb)(\bar{l}\gamma_\mu l) - s_W^4 F_2^i[\bar{s}i\sigma_{\mu\nu}(q_\nu/q^2)(m_sL + m_bR)b](\bar{l}\gamma_\mu l)\}, \quad (1)$$

$$\mathcal{L}_{\rm eff}^{b\bar{s}\to \nu\bar{\nu}} = -2\sqrt{2}G_{\rm F}\chi v_i\bar{D}_i(\bar{s}\gamma_\mu Lb)(\bar{\nu}\gamma_\mu L\nu), \quad (2)$$

where $\chi = g^2/16\pi^2$, $v_i \equiv V_{is}^* V_{ib}$, i is summed from 2 to n (where n is the number of generations),[10] s_W is the sine of the Weinberg angle, and we exhibit[11]

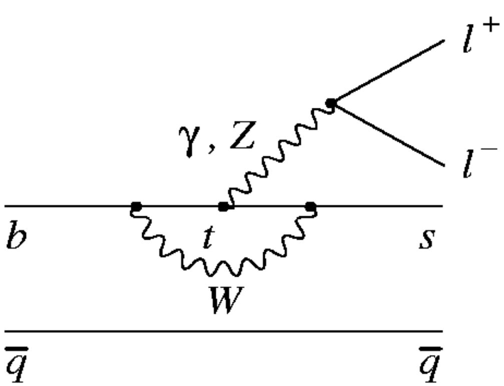
$$\bar{C}_i \equiv \bar{C}_i^Z + \bar{C}_i^{\rm box} = \tfrac{1}{4}x_i + \frac{3}{4}\left(\frac{x_i}{x_i - 1}\right)^2 \ln x_i - \frac{3}{4}\frac{x_i}{x_i - 1}, \quad (3)$$

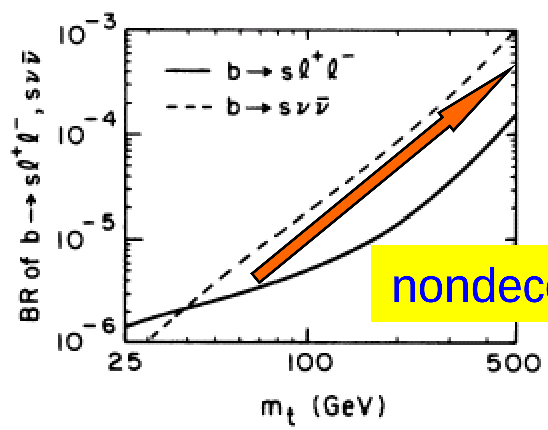
$$\bar{D}_i \equiv \bar{D}_i^Z + \bar{D}_i^{\rm box} = \tfrac{1}{4}x_i + \frac{3}{4}\frac{x_i(x_i - 2)}{(x_i - 1)^2}\ln x_i + \frac{3}{4}\frac{x_i}{x_i - 1}, \quad (4)$$

dimensions

γ		Z
αG_F	<	$G_F^2 m_t^2$

where $x_i = m_i^2/M_W^2$, and m_i is the internal quark mass. The important feature of Eqs. (3) and (4) is the term $x_i/4$,[8]





Nondecoupling

Decoupling Thm: Heavy Masses are decoupled in QED/QCD
∵ Appear in Propagator

Nondecoupling: Yukawa Couplings λ_Q Appear in Numerator

dynamical

Subtlety of Spont. Broken Gauge Theory

B.A.U. from CPV in KM ? The Lore.

$$\frac{n_{\bar{\mathcal{B}}}}{n_\gamma} \cong 0$$

$$\frac{n_{\mathcal{B}}}{n_\gamma} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$

WMAP

$$\text{KM} \sim 10^{-20}$$

Too Small in SM

Jarlskog Invariant in SM3 (need 3 generation in KM)

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

Normalize by T ~ 100 GeV

$$J/T^{12} \sim 10^{-20}$$

EW Phase Transition Temperature

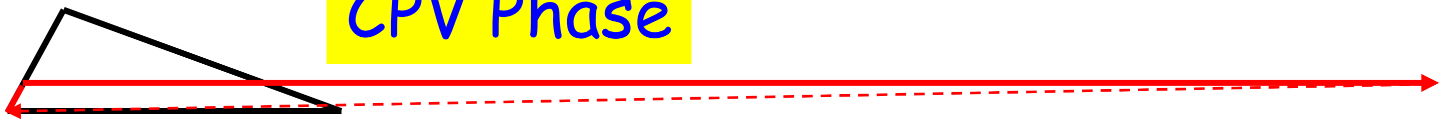
~ v.e.v.

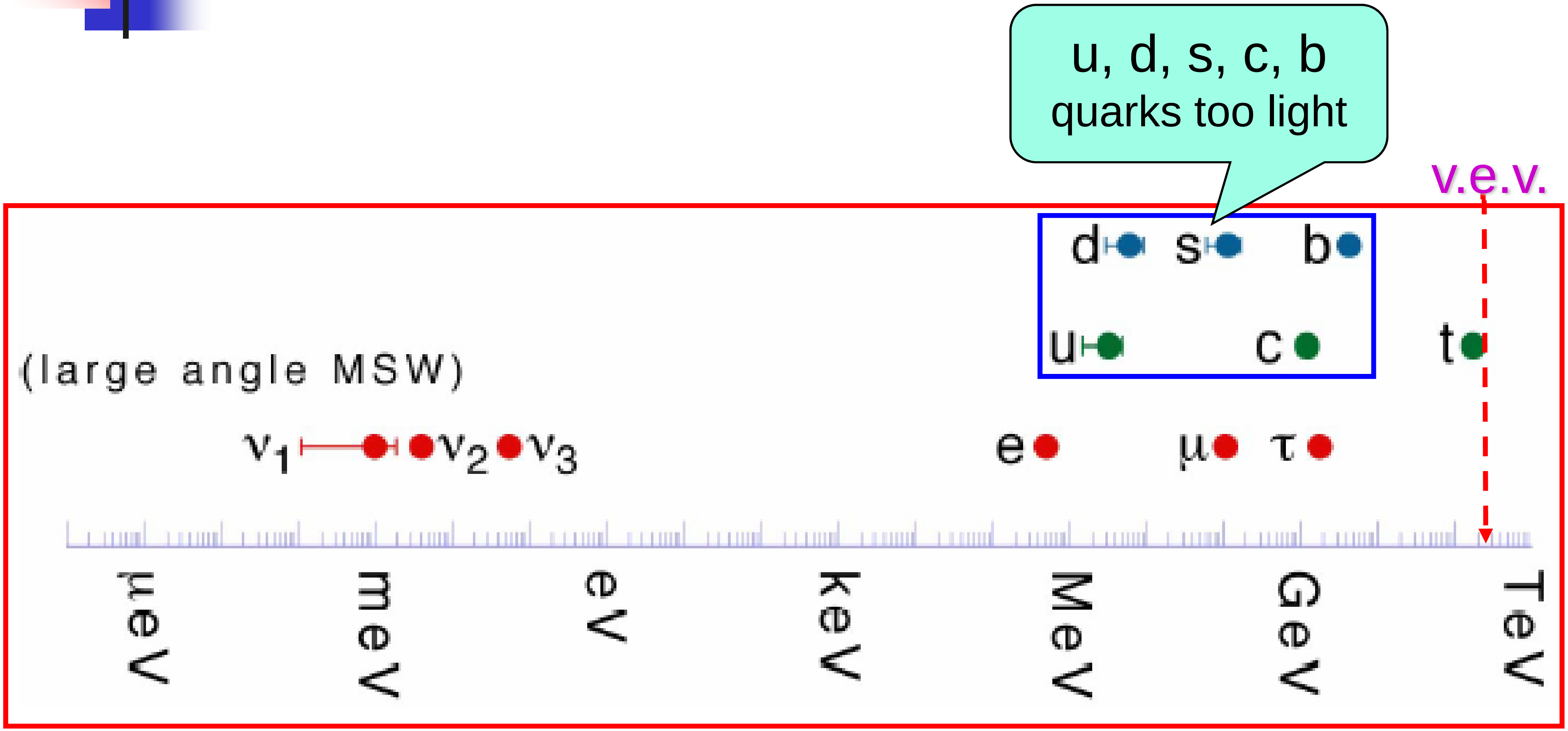
Masses too Small !

Small, but *not Too* small

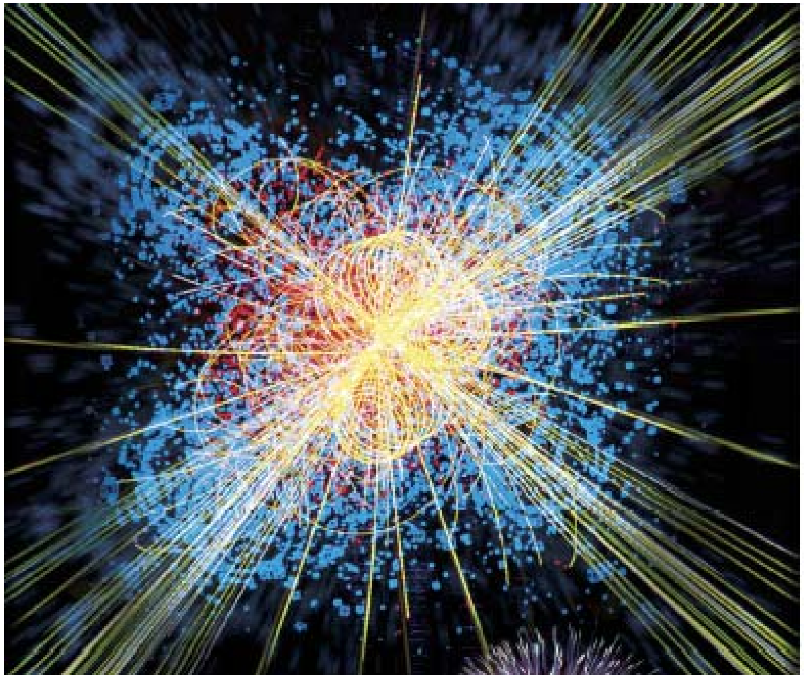
$A \sim 3\times 10^{-5}$ is common (unique) area of triangle in SM

CPV Phase



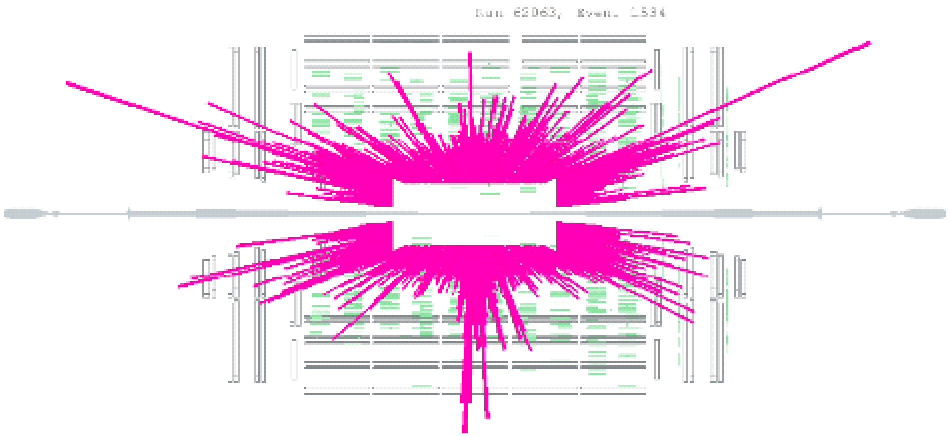

u, d, s, c, b
quarks too light
v.e.v.
d
s
b
u
c
t
(large angle MSW)
ν1
ν2
ν3
e
μ
τ
μeV
meV
eV
keV
MeV
GeV
TeV

Universe (Genesis)



CPV

BAU



Earth (EW + KM4)