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Flavour Dynamics & ~~C~~P in the SM*: A Tale of Great Successes, Little Understanding -- and Promise for the Future!

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Presentation of my lecture series guided by two general predictions

- While the case for New Physics at ~ TeV scale is as strong as ever, we cannot count on NP having a massive impact on B decays.

- I will emphasize general principles for designing strategies over specific & detailed examples

The central goal for this school as for any --
we want you to do your own thinking
rather than `out-source' it!

➥ raise/ask questions !!!

Outline of Lectures

I. Introduction of the SM* -- Renormalizibility, Neutral Currents, Mass Generation, GIM Mechanism, ~~CP~~ a la CKM

II. CKM Phenomenology

III. ~~CP~~ in B Decays -- the `Expected' Triumph of a Peculiar Theory

IV. Adding High Accuracy to High Sensitivity

V. "I have come to praise Charm, not bury it!"

VI. Searching for a New Paradigm 2005 & Beyond Following Samuel Beckett's Dictum

Lecture I (6)

Introduction of the SM* --

Renormalizibility, Neutral Currents, Mass Generation, GIM Mechanism, ~~CP~~ a la CKM

A famous coach once declared:

"Winning is not the greatest thing -- it is the only thing!"

The `SM *' =

$SU(3)_c \times SU(2)_L \times U(1)$ + CKM + PMNS

the `only' thing

not even the greatest thing

an accidental miracle

general considerations	renormalizability+ Adler anomaly + data	data

The Menu for Lecture I

I QCD -- the `Only' Thing

II $SU(2)_L xU(1)$ -- not even the Greatest Thing

- 😐 Higgs-Kibble mechanism
- 😐 Adler-Bell-Jackiw anomaly
- ☹ charge quantization
- ☹ `partial' unification
- ☺ but it works!

III CKM -- an `Accidental' Miracle

- ☹ family structure & replication
- 😐 GIM mechanism
- ☹ ~~CP~~ hard & explicit
- ☺ but it works miraculously!

I QCD -- the `Only' Thing

1.1 `Derivation' of QCD

- chiral symmetry (π Goldstone bosons, soft π theorems, etc.)
  - ➥ need vector couplings for gluons
- $R(e^+e^- \rightarrow$ had.), $\pi^0 \rightarrow \gamma\gamma$, etc. etc.
  - ➥ need three colours
- unbroken symmetry: local gauge theory only known way to couple to m=0, j=1 fields in Lorentz invariant way: $4 \neq 2$!
- confinement → asymtptotic freedom
  - ➥ non-abelian gauge theory

✍ QCD -- unique choice among local quantum field theories

1.2 `Fly-in-the-ointment':the Strong CP Problem of QCD

QCD does not automatically conserve P & T & CP:

$$\mathcal{L}_{eff} = \mathcal{L}_{QCD} + \theta\,(g_s^2/32\pi^2) G_{\mu\nu}\tilde{G}^{\mu\nu}\ ,\ \tilde{G}_{\mu\nu} = (1/2) i \varepsilon_{\mu\nu\rho\sigma} G^{\rho\sigma}$$

$$G_{\mu\nu}\tilde{G}^{\mu\nu} \xrightarrow{\ P,T\ } - G_{\mu\nu}\tilde{G}^{\mu\nu}$$

flavour diagonal ⟶ EDM of neutron

$d_N \longrightarrow \theta < 10^{-9}$ `unnatural'!

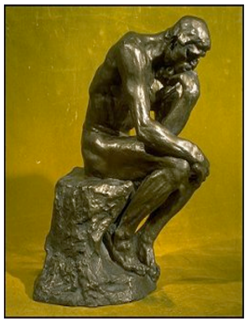
Peccei-Quinn symmetry would make it natural

- requires existence of axions -- which have not been observed yet despite great efforts.

1.3 Theoretical Technologies of QCD

\`theory' = Lagrangian $\mathcal{L}$

yet



$\mathcal{L}$

Observables

theoretical technology !

"plumbers"

"thinkers"

perturbation theory
chiral perturbation theory
QCD sum rules
heavy quark expansions

} no universal claim of validity

i.e., all \`protestant' in nature

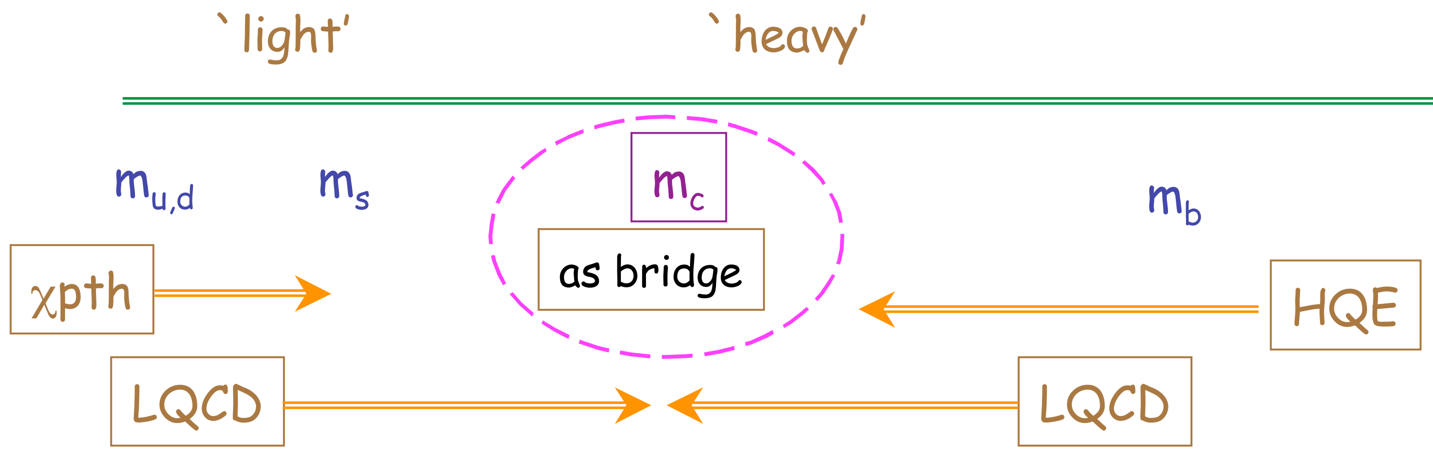
describe later

∃ only 1 `catholic' * technology -- lattice gauge theory

* `catholic' in substance, `protestant' in sociology!

Lattice gauge theory

- can be applied to nonperturb. dynamics in all domains -- with the possible practical exception of strong FSI --,
- with a theoretical uncertainty that can be reduced in a systematic way



II $SU(2)_L \times U(1)$ -- not even the Greatest Thing

2.1 Prehistory

- 4-fermion-coupling
  - ~~unitarity~~ ~ 250 GeV
  - non-renormalizable
- intermediate vector bosons (IVB) soften problem

  need massive charged vector bosons

  longitudinal W create problem

  propagator $$\frac{g_{\mu\nu} - k_\mu k_\nu / M_W^2}{k^2 - M_W^2}$$

  - need non-abelian gauge theory

    $[J^+, J^-] \propto J^0$, i.e. requires neutral currents (NC)

2.2 Strong points

renormalizibility (+unitarity) severely restrict possible theories (problem of mass -- later)

- ☺ single $SU(2)_L$ ⟶ weak universality due to self coupling of gauge bosons
- ☺ predicted
  - ❑ existence of NC parametrized by 1 parameter $\sin\theta_W$
  - ❑ M_W, M_Z
- ☺ most remarkable: combines
  - QED -- pure V coupling (P √) with $m_\gamma = 0$ --
  - with weak interactions -- V-A CC coupling (P̸ maximal) & V,A NC coupling $M_Z > M_W \neq 0$

2.3 Generating Mass

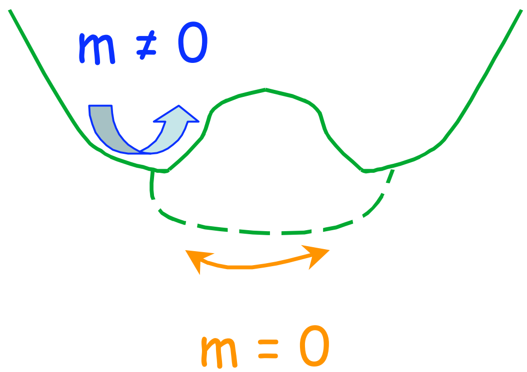
Higgs-Brout-Englert-Guralnik-Hagen-Kibble

$M \neq 0$, $J=1$: 3 phys. d.o.f vs. 4 components

- $k_\mu s_\mu = 0$ √

$M = 0$, $J=1$: 2 phys. d.o.f vs. 4 components

Spontaneous realization of a symmetry (SSB)



m=0 scalar transmogrified into longitudinal component of VB

non-pert. quantity $\langle 0|\phi|0\rangle$

SM:

- M_W, M_Z ← SU(2) triplet: no!
  ← SU(2) doublet: yes!
- m_f ← SU(2) doublet

$m_f \propto g_f^{Yuk} \langle 0|\phi|0\rangle$

1 complex doublet scalar field

$\Phi = (\phi^0{}_{1,2})$; $\langle\phi^0\rangle \neq 0$, $\langle\phi^\pm\rangle = 0$

Single VEV

$\phi^+ \to W^+{}_{long}$

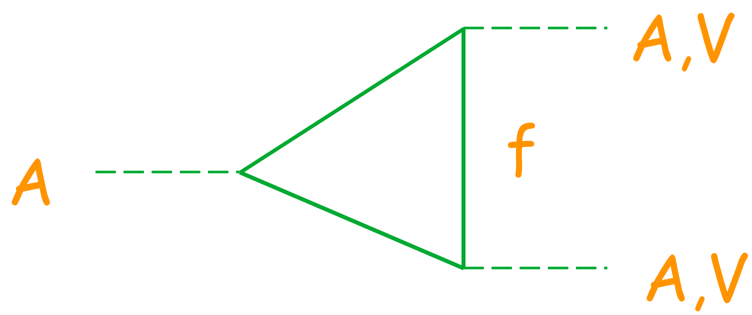
$\phi^- \to W^-{}_{long}$

$\phi^0{}_1 \to Z^0{}_{long}$

$\phi^0{}_2 \to H^0{}_{phys}$

2.4 Triangle Anomaly

Adler-Bell-Jackiw



`quantum anomaly':

classical conservation law vitiated due to quantum correction

$$\partial_\mu J^5_\mu \neq 0 \text{ even for } m_f=0$$

- destroys renormalizibility
- can be neutralized within SM by

$\Sigma_f Q_f = 0$, f = fermions within given family

lepton-quark connection

2.5 Theoretical Deficiencies

With all these amazing successes --
what is the fuss, why not be happy?

- ☹ $SU(2)_L \times U(1)$ -- partial unification only
- ☹ HBEGHK mechanism:
  - only `engineering' solution -- at least till Higgs is found
  - scalar couplings `unnatural' (quadratic mass renormal. !)
  - ➥ justification for LHC & motivation for ILC
- ☹ maximal $\not{P}$ (for CC) `par ordre du mufti'
- ☹ $m_\nu = 0$ (up to Majorana) `par ordre du mufti'
- ☹ charge quantization

why $Q_e = 3\ Q_d$?

... and then the whole issue of family replication!

III CKM -- an `Accidental' Miracle

3.1 Overview

3 families

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \Big| \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \Big| \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

- Why > 1 family? Why 3? ?? M theory ??
- Is N_{fam} a fundamental quantity?

Evidence for us being `dense'/`blind' is even stronger!

$m_t \sim 175$ GeV

$m_b \sim 4.6$ GeV ← M_W, M_Z

$m_c \sim 1.2$ GeV

$m_s \sim 0.1$ GeV ← Λ_{QCD}

$m_\tau \sim 1.7$ GeV

$m_\mu \sim 0.1$ GeV

$m_u \sim$ a few MeV

$m_e \sim 0.5$ MeV

$m_d \sim$ a few more MeV

$m_{\nu(\tau)} < 18.2$ MeV

$m_{\nu(\mu)} < 0.19$ MeV

$m_{\nu(e)} < 3$ eV

} direct bounds from kinematics

$\Delta m^2 \sim \mathcal{O}(10^{-3}\ \mathrm{eV}^2),\ \mathcal{O}(10^{-4}\ \mathrm{eV}^2)$ — ν oscillations

3.2 Quark Masses, GIM & ~~CP~~

there is more:

$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

mass eigenstates
≠
interaction eigenstates

$$\mathcal{L}_{CC} \propto \bar{g}_W U_L^F \gamma_\mu D_L^F W_\mu \quad , \mathcal{L}_{NC}^{U[D]} \propto \bar{g}_Z U[D]_L^F \gamma_\mu U[D]_L^F Z_\mu$$

$$\mathcal{L}_M \propto U_L^F \mathcal{M}_U U_R^F + D_L^F \mathcal{M}_D D_R^F \propto U_L^F \mathcal{G}_U^Y U_R^F \Phi_U + D_L^F \mathcal{G}_D^Y D_R^F \Phi_D$$

$$\mathcal{M}_{\dots} = \langle \Phi_{\dots} \rangle \mathcal{G}_{\dots}^{Y}$$

$\mathcal{M}_{\dots}, \mathcal{G}_{\dots}^{Y}$ nondiagonal in general,diagonalized by unitary $\mathcal{T}_{U,L/R}, \mathcal{T}_{D,L/R}$

- EV's of $\mathcal{M}_{U,D} \rightarrow$ physical masses of U, D
- $\mathcal{L}_{NC}^{U[D]} \rightarrow U[D]_L^m \gamma_\mu U[D]_L^m Z_\mu$
- $\mathcal{L}_{CC} \rightarrow U_L^m \gamma_\mu V_{CKM} D_L^m W_\mu$

$$V_{CKM} = \mathcal{T}_{U,L} \mathcal{T}_{D,L}^*$$

➥ weak *neutral* currents couplings unaffected

`generalized GIM' mechanism

$$V_{CKM} = \mathcal{T}_{U,L}\, \mathcal{T}_{D,L}^{\;*}$$

$V_{CKM} = \mathcal{T}_{U,L}\, \mathcal{T}_{D,L}^{\;*}$ nontrivial

(unless high scale dynamics enforces alignment between U & D)

➥ weak *charged* currents couplings affected

N families: N x N matrix that is unitary due to 2 facts

(i) $\mathcal{T}_{U,L/R}$, $\mathcal{T}_{D,L/R}$ unitary by construction

(ii) $\mathcal{L}_{CC} \propto \bar{g}_W U_L^F \gamma_\mu D_L^F W_\mu$

SM: single SU(2) group

➥ gauge coupling $\bar{g}_W$ of W to fermions controlled by single self-coupling of W's

➥ `weak universality' $|V(ud)|^2+|V(us)|^2+|V(ub)|^2=1$ etc.

Can weak universality be violated?

Yes -- it can

✍ horizontal gauge interactions = FlChNC

✍ couple one separate $SU(2)_L$ to each family

-- i.e. gauge group $SU(2)_L^1 \times SU(2)_L^2 \times SU(2)_L^3$ -- while allowing those three sets of gauge bosons to mix; the mass eigenstates of these W_L^i can be such that the lightest couple to all families with universal strength

- ➥ weak universality only approximate
- ➥ induce FlChNC ... & EDM's

N x N unitary matrix

- N (weak) universality relations

$$\Sigma_j |V(ij)|^2 = 1, \quad i=1,\ldots, N$$

important -- yet insensitive to complex phases

➥ tells us nothing directly about $\not{CP}$

- N^2 - N orthogonality relation

$$\Sigma_j V^*(ij)V(jk) = 0, \quad i \neq k$$

very sensitive to complex phases

➥ tells us directly about $\not{CP}$

Caveat:

➼ the phase of a fermion field is not always an observable!

Observable parameters of N x N unitary matrix

- N x N complex matrix: $2N^2$ real parameters
- unitary reduces it to N^2 independent real parameters
- phases of quark fields can be rotated freely
  - ➥ $2N-1$ phases can be removed (1 overall phase irrelevant)
  - ➥ $(N-1)^2$ independent physical parameters
- N x N orthogonal matrix: $N_{angles} = 1/2\, N(N-1)$
  - ➥ NxN unitary matrix: $N_{physical\ phases} = 1/2(N-1)(N-2)$
- N=2: 1 angle -- Cabibbo angle -- & 0 phases
- N=3: 3 angles & 1 phase
- N=4: 6 angles & 3 phases

} Kobayashi & Maskawa

A graphic representation

N=2 case:

- 2 weak universality relations:

  $|V(ud)|^2 + |V(us)|^2 = 1$

  $|V(cd)|^2 + |V(cs)|^2 = 1$

- 2 orthogonality relations:

  $V(ud)^*V(us) + V(cd)^*V(cs) = 0$

  $V(us)^*V(ud) + V(cs)^*V(cd) = 0$

  ➥ no relative phase

  ➥ no ~~CP~~ with 2 families!

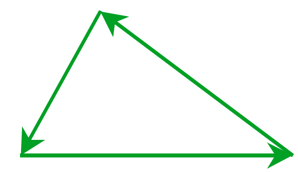
N=3 case:

- 3 weak universality relations:

$$|V(ud)|^2 + |V(us)|^2 + |V(ub)|^2 = 1$$
$$|V(cd)|^2 + |V(cs)|^2 + |V(cb)|^2 = 1$$
$$|V(td)|^2 + |V(ts)|^2 + |V(tb)|^2 = 1$$

- 6 orthogonality relations

$$\Sigma_{j=1}^{\,j=3} V^*(ij)V(jk) = 0, \quad i \neq k$$



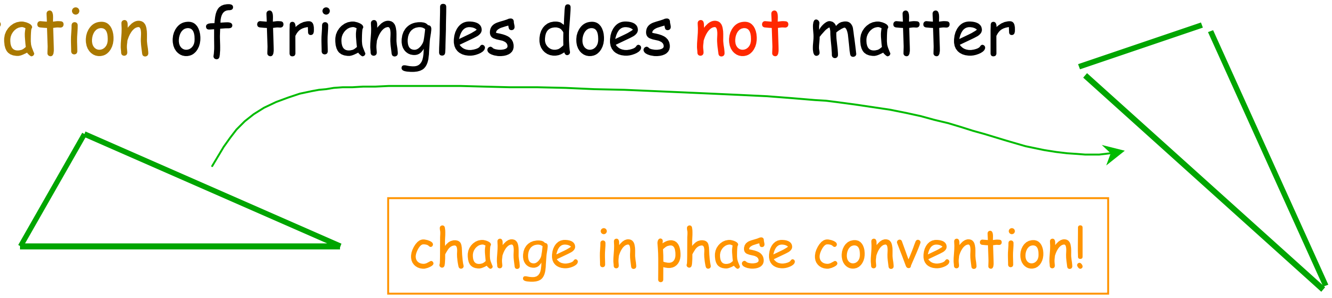
  - triangle relations in the complex plane
  - 6 triangles have equal area ⟸ single complex phase!

area(every triangle) = 1/2 J

Jarlskog variable $J = \mathrm{Im}\,V(ud)V(cs)V^*(us)V^*(cd)$

if $J = 0 \Rightarrow$ no ~~C~~P

  - orientation of triangles does not matter



- if any pair of up- or down-type quarks were mass degenerate, then any linear combination of those two is a mass eigenstate as well, and one can remove their `CKM' parameters
  - ➥ up- & down-type quarks have to possess different masses to allow for $\not{CP}$ with 3 families

Compact representation:

$$iC = [\mathcal{M}_U \mathcal{M}_U^*, \mathcal{M}_D \mathcal{M}_D^*]$$

$$\det C = -2J(m_t^2-m_c^2)(m_c^2-m_u^2)(m_u^2-m_t^2)(m_b^2-m_s^2)(m_s^2-m_d^2)(m_d^2-m_b^2)$$

need $\det C \neq 0$ for $\not{CP}$

- CKM implementation of $\not{CP}$ irrespective of mass generation
- with SM mass generation & 1 VEV $\not{CP}$ in Yukawa coupling, i.e. hard $\not{CP}$!

maximal ~~CP~~?

$V_{CKM}=$

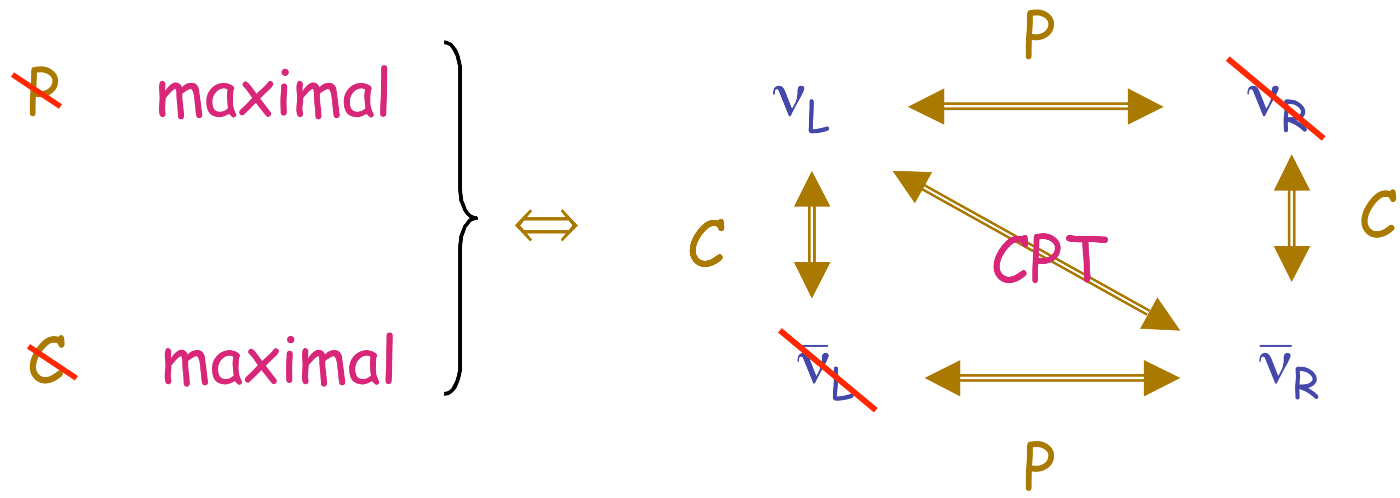
V(ud)	V(us)	V(ub)
V(cd)	V(cs)	V(cb)
V(td)	V(ts)	V(tb)

=

$c_{12}c_{13}$	$s_{12}c_{13}$	$s_{13}e^{-i\delta}$
$-s_{12}c_{23}-c_{12}s_{23}s_{13}\, e^{-i\delta}$	$c_{12}c_{23}-s_{12}s_{23}s_{13}\, e^{-i\delta}$	$s_{23}c_{13}$
$s_{12}s_{23}-c_{12}c_{23}s_{13}\, e^{-i\delta}$	$-c_{12}s_{23}-s_{12}c_{23}s_{13}\, e^{-i\delta}$	$c_{23}c_{13}$

$\delta = 90^o$: `maximal' ~~CP~~?

☹ change phase convention for quark fields --
phases of fermions like the `Scarlet Pimpernel'!



i.e., CPT already enforces presence of $\bar{\nu}_R$

`no future generation'

`man without a future -- woman without a past'

Historical Asides

- ~~CP~~ discovered in '64 through $K_L \to \pi\,\pi$ -- yet it was not realized that dynamics known at that time could not generate it.
  - Maybe forgivable since no renormalizable theory for weak interactions yet: when worrying about infinities one can be excused to forget about $BR(K_L \to \pi\,\pi) \approx 2.2 \times 10^{-3}$
  - Yet even after arrival of renormalizable GSW model its phenomenological incompleteness was not realized for a few years -- till the '73 paper by KM! (short comment on it by Mohapatra in '72)
  - In addition to > 2 family source for ~~CP~~ KM in their '73 paper list also non-minimal Higgs dynamics & right-handed currents

- Being at Nagoya University K&M had a `competitive edge'/`insider knowledge'!

for most places outside Nagoya

- 3 quarks: u,d,s
- quarks mathematical entities
- typical attitude: "Nature is smarter than Shelly (Glashow) -- she can do without charm"

Background: in Cabibbo theory

$$J_{...}^{CC} \propto \cos\theta_C\, d_L\gamma\ldots u_L + \sin\theta_C\, s_L\gamma\ldots u_L$$

$\Rightarrow$ $[J_{...}^{+}, J_{...}^{-}] \propto \ldots + \sin\theta_C\, s_L\gamma\ldots d_L$

☹ strangeness (flavour) changing NC !

✍ some even suggested the observed huge suppression of strangeness (flavour) changing NC implied a similar reduction for all NC observation of

- DIS
- $e^+e^- \to$ hadrons
- J/ψ

} caused a huge paradigm shift!

\`Genius loci' of Nagoya University

☞ home of the Sakata School

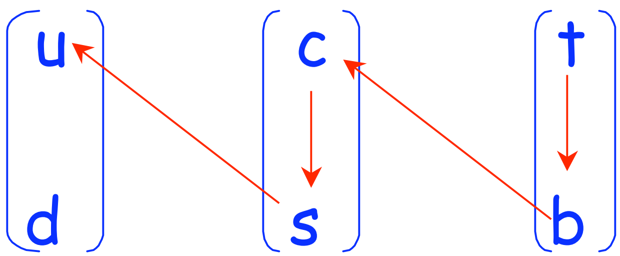
➥ quarks readily accepted as physical objects

☞ home of Prof. Niu -- an expert in cosmic ray experiments with emulsions:

in '71 Niu reported a candidate for charm seen

➥ 2 complete families were \`known'

3.3 Preview of CKM Theory

- V_{CKM} unitary as long as CC described by a single $SU(2)_L$
- 

expectation:
intra- >> inter-family coupl.

inter-fam. ~ $V(us) = \sin\theta_C$ ~ $|V(cb)|$

would imply $\tau(B) \sim$ few x 10^{-14} sec

yet actually observed: $\tau(B) \sim 10^{-12}$ sec

➥ $|V(cb)| \sim \lambda^2$, $\lambda = \sin\theta_C$

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

✍ the CKM matrix -- with this apparently highly non-accidental pattern -- describes successfully very diverse processes on vastly different scales (see later)

✍ Schlaeft ein Lied in allen Dingen,	There sleeps a song in all things
Die da traeumen fort und fort,	That dream on and on,
Und die Welt hebt an zu singen,	And the world will start to sing,
Findst Du nur das Zauberwort.	If only you find the magic word.

J. v. Eichendorff

IV Summary of Lecture I

The `SM *' = $SU(3)_C \times SU(2)_L \times U(1)$ + CKM + PMNS

- $SU(3)_C$ -- the unique solution among local field theories for the strong interactions

- $SU(2)_L \times U(1)$ --
  - gauge structure restricted by renormalizability & data
  - with `theoretical engineering' for generating masses for the gauge bosons and
  - quite a whiff of incompleteness

- CKM dynamics
  - `all it does, it works in describing electroweak decays'
  - for no understood deeper reason
  - yet the strong suspicion that such deeper reason has to exist

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

  - it is intrinsically connected with central mysteries of the SM: family replication and fermion mass generation