

# CHARM

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*Seminar in honour of Romano Bizzarri*

*Roma La Sapienza*

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# SUMMARY

- Prehistory
- Why GIM ?
- Octet enhancement
- Charm as a probe of QCD
- What did we learn
- Conclusions

# Prehistory

- The picture in the early sixties:
  - The Cabibbo theory had given a basis to the Universal Fermi Interaction for both  $\Delta S = 0$  and  $\Delta S = \pm 1$  decays
  - The weak hadronic current selects an SU2 direction inside SU3 (weak isospin)
- Quarks (Gell-Mann, Zweig, 1964):
  - u, d, s, hence broken SU3, *baryons* =  $qqq (= 1, 8, \text{or } 10)$ ; *mesons* =  $q\bar{q} (= 1, 8)$
  - The weak hadronic current takes a very simple form:

$$\bar{u}\gamma_{\mu}(1-\gamma_5)(\cos\theta d + \sin\theta s) \equiv \bar{u}\gamma_{\mu}(1-\gamma_5)d_{\theta}$$

- With respect to the “weak SU2” the other combination remains alone:

$$s_{\theta} = -\sin\theta d + \cos\theta s = \text{SU2}_{\text{Weak}} \text{ singlet}$$

## Prehistory (cont'd)

- In his classic 1964 paper, Gell-Mann starts with a 4-quark model (in modern notation):
  - $c^+, u^+, d^0, s^0$
  - A funny spectroscopy, because of the integral quark charges;
  - weak current now uses both  $d_\theta$  and  $s_\theta$  and displays lepton-quark symmetry:

$$J_\mu = \bar{u}\gamma_\mu(1-\gamma_5)d_\theta + \bar{c}\gamma_\mu(1-\gamma_5)s_\theta = \bar{q}\gamma_\mu(1-\gamma_5)Cq \quad C = \begin{pmatrix} 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

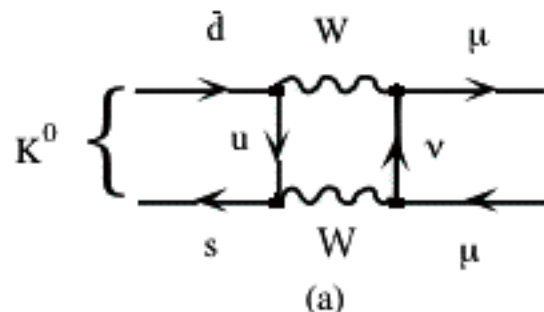
- Gell-Mann has become famous because he did choose the second model: 3 fractionally charged quarks,  $u^{2/3}, d^{-1/3}, s^{-1/3}$
- The four quark model was considered by Toeplitz and Tarjanne and by Hara (1964)
- Bjorken and Glashow (1964) introduced the name *charm* and related the mass scale of charmed particles ( $D^0, D^+, S^+$ ) to the mass of  $\eta'(956)$ ...which definitely killed the model.
- The idea remained, in search of a better framework.

# Prehistory (cont'd)

- The idea that  $s_\theta$  was a weak singlet had some attraction (particularly in Roma), which could make one to forget about lepton-quark universality:
  - Medium strong forces (the SU3 breaking) select the quark  $s$  as a strong isospin sing, similarly weak forces would select  $s_\theta$  as a weak isosinglet;
  - The Cabibbo angle,  $\theta$ , is defined by the mutual relations of medium strong and weak interactions;
  - One could hope to compute the value of  $\theta$  from some consistency condition between these two forces;
- Following a seminal paper by Gatto, Sartori and Tonin (1969), Nicola and I “almost made it ” in 1969...but then...

# Why GIM ?

- A paper by Ioffe and Shabalin had shown that  $\Delta S = \pm 1$  neutral currents would result from higher order weak interactions, in disagreement with experiments, unless limited by an ultraviolet cut-off of 3-4 GeV!!



- Attempts were made during '68-69 to make the amplitude more convergent, thus avoiding the problem, by introducing:
  - (too) many Intermediate Vector Bosons (Gell-Mann, Low, Kroll, Ruderman)
  - ghost states (T.D.Lee and G.C. Wick).

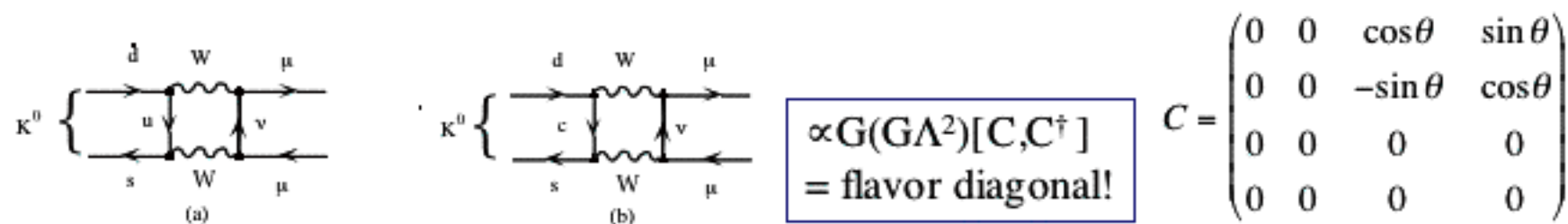
## Weak Interactions with Lepton-Hadron Symmetry\*

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(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-Mills theory is discussed.



- the charmed quark makes possible *a gauge theory of electro-weak interactions for quarks*;

-Hadronic neutral currents predicted:  $\bar{\nu} + Nucleous \rightarrow \bar{\nu} + anything$  ;

-The role of the Joffe & Shabalin cut-off is taken by the mass scale of charmed particles, thereby fixed at  $\approx 3-4$  GeV, thus avoiding the problems of the old Bjorken-Glashow model;

-...and the full power of the quark model shows up.

# GIM, some decades after



Romano'sFest, 10/02/04



GIM at J. Iliopoulos's 60th birthday, ENS, Paris (2001)

L. Maiani. Charm



Iliopoulos: John & Alexandros

## AN ANOMALY-FREE VERSION OF WEINBERG'S MODEL

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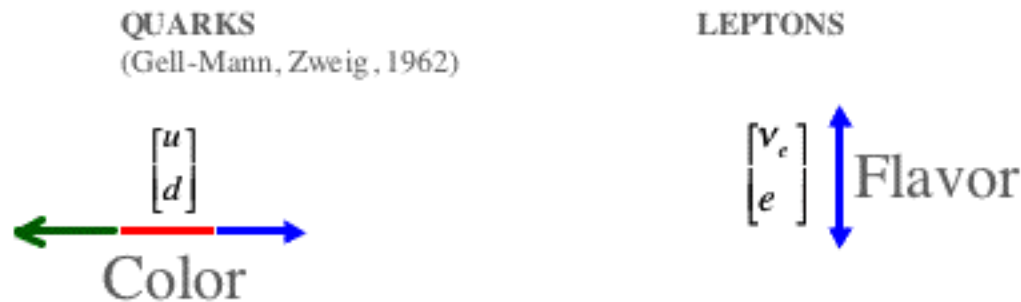
Received 11 February 1972

We discuss the difficulties of carrying the renormalization program in a theory containing Adler anomalies. We present some models of weak and electromagnetic interactions, involving both lepton and quark fields, in which the troublesome anomalies cancel.

- Anomaly cancellation in  $SU(2) \times U(1)$ : the last obstacle towards a renormalizable electroweak theory
- why quarks **and** leptons

# The Standard Theory

## 1. Ordinary Matter (Galaxy, Earth, us...) :



Proton = [uud]

Neutron = [ddu]

$N \rightarrow P + e^- + \nu_e$  ( Pauli, Fermi,  $\approx 1930$ )

## 2. Analogous Structures at Higher Energy:

$\begin{bmatrix} c(1974) \\ s \end{bmatrix}$

$\begin{bmatrix} t(1994) \\ b(1976) \end{bmatrix}$

$\begin{bmatrix} \nu_\mu(1962) \\ \mu \end{bmatrix}$

$\begin{bmatrix} \nu_\tau(2000) \\ \tau(1975) \end{bmatrix}$

## 3. Forces:

Gravity  $\rightarrow$

Electromagnetic  $\rightarrow$

Strong ( Nuclear)  $\rightarrow$

Weak  $\rightarrow$

Mass generation  $\rightarrow$

GRAVITON (Not yet seen)

PHOTON (Einstein, 1905)

GLUONS (Not seen in isolation)

INTERMEDIATE BOSONS (CERN, 1983)

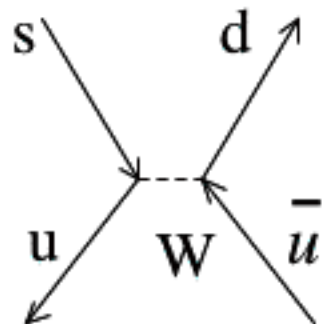
HIGGS BOSON (?)

Missing

# The octet enhancement of non-leptonic weak interactions

- Two “octet dominance” cases are invariably mentioned in the papers of the sixties:
  - Octet SU3 breaking
  - Octet dominance in non leptonic decays of strange particles (i.e.  $\Delta I=1/2$ ).
- It was tempting to associate them to the same mechanism (e.g. the “tadpoles” of Coleman and Glashow)
- “Occam razor” did not work:
  - SU3 breaking is associated to quark masses (8 of SU3,  $(3, \bar{3})$  of SU3xSU3)
  - The  $\Delta I=1/2$  rule results from renormalization of the weak hamiltonian from the W mass scale to the QCD scale (first proposed by K. Wilson).

$$s \rightarrow \bar{u}ud$$



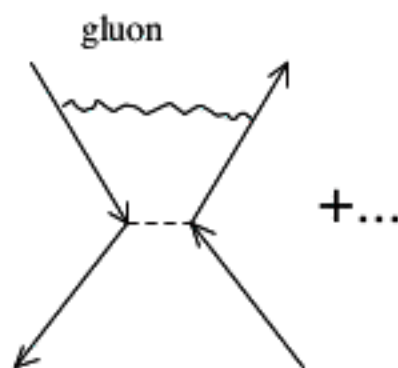
$$J \times J = O^{(+)} + O^{(-)}$$

+/- refer to symmetry or antisymmetry in u-d exchange

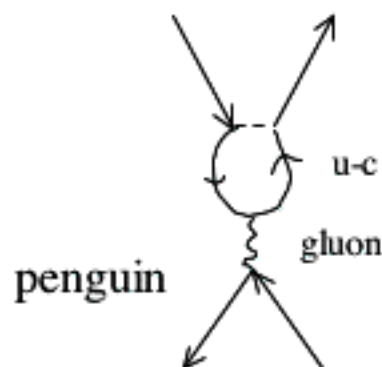
$O^{(-)}$  has  $I=0$  and is pure  $\Delta I=1/2$

*This applies at momentum scales  $\sim M_W$*

QCD corrections down to GeV scale do renormalize the operators (B.W. Lee & M.K. Gaillard; G. Altarelli & L. Maiani, 1974) and enhance the coefficient of  $O^{(-)}$  !!!



+...



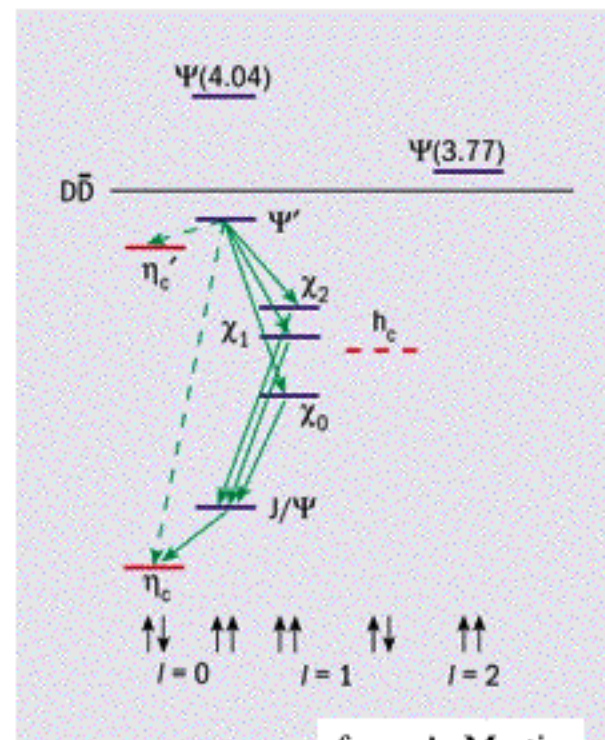
- Penguin diagrams enhance further the octet operators, when scaling down from  $m_c$  to  $\Lambda_{\text{QCD}}$  (Shifman, Veinshtein and Zakharov, 1977)

- Perturbative calculation is not reliable for the last part;

- Lattice calculation would give crucial answer... But still in the future !!!

# Charm as a probe of QCD

- The charmed quark was the first example of a “very heavy quark”, for which  $m_c \gg \Lambda_{\text{QCD}}$ ;
- It provides tests of the “Asymptotic freedom” of QCD, independent from deep inelastic phenomena;
- The spectrum of charmonia bound states and its similarity to the spectrum of positronium, as first proposed by Glashow and De Rujula, gives an impressive example;
- Next followed the calculation of the semileptonic rate and electron spectrum in charm decay ( Cabibbo, Maiani, 1978, and following papers by with Altarelli, Corbo’ and Martinelli, for c and b decay)
- The c-quark can propagate in possible lattice simulations,
  - to provide tests of non-perturbative QCD, like the value of e.g.  $f_D$ ;
  - to test the  $m \rightarrow \infty$ , approximation done for the b-quark.



from A. Martin

# Conclusions

- Discovering that a fourth quark was required by data has been a great fun..
- ... and a fundamental step towards a unified electroweak theory
- The c quark was found surprisingly close to what was advertised;
- The study of the c quark can give very important insights to QCD in the strong regime.
- It is so good that it was there!