Luciano Maiani:

Lezione Fermi 15

A fourth quark makes everybody happy; Kobayashi and Maskawa add two more

Sommario

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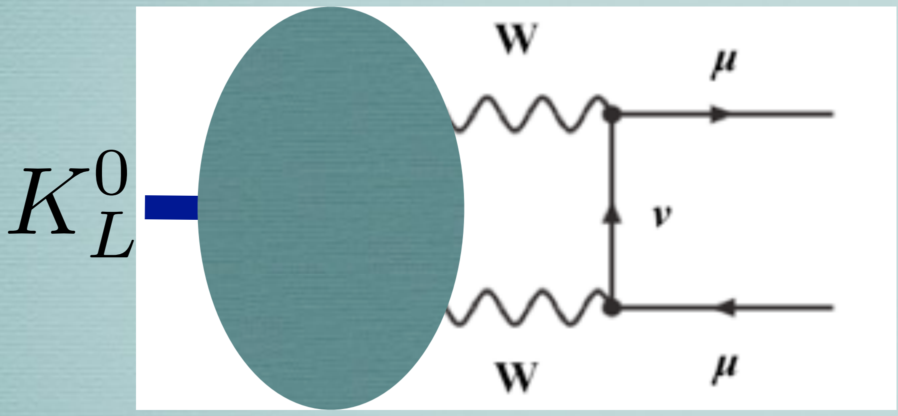
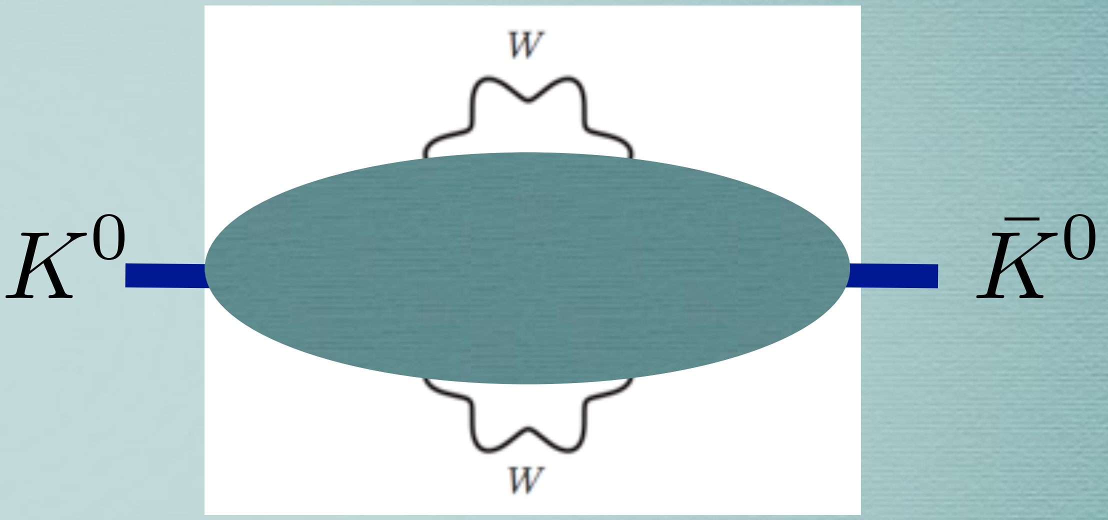
1. THE $G\Lambda^2$ PUZZLE (1968)

- The discussion on higher order weak interactions was opened in 1968 by a calculation by Boris Ioffe and Evgeny Shabalin at Moscow, indicating that $\Delta S = \pm 1$ neutral currents and $\Delta S=2$ amplitudes would result from higher order weak interactions, ***even in a theory with only the charged W***



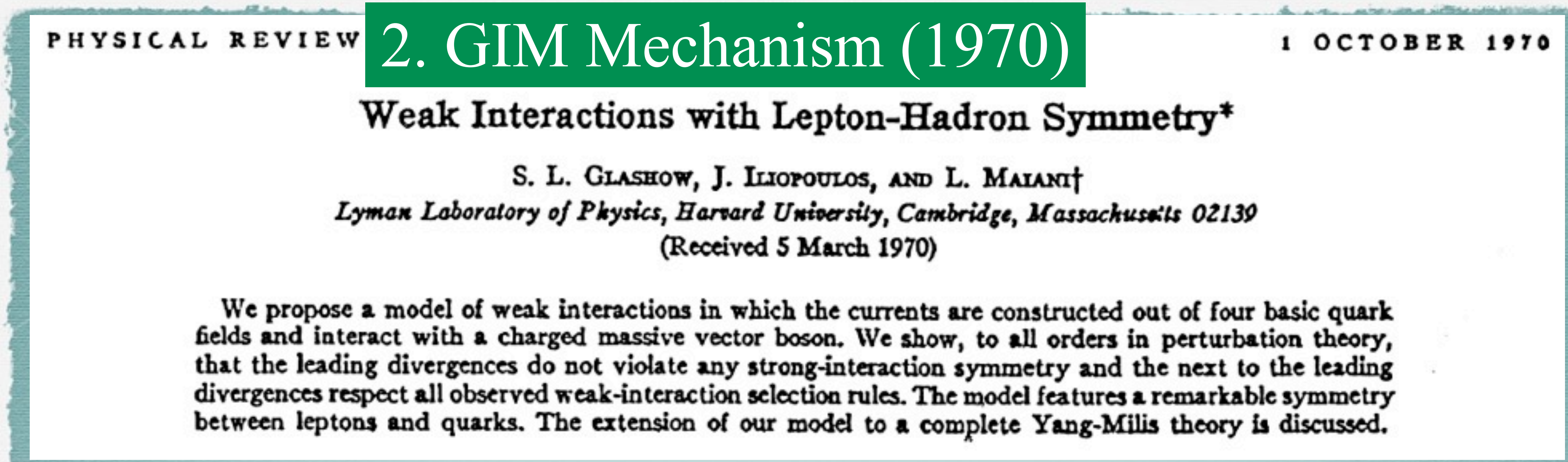


- the amplitudes were found to be divergent, of order $G(G\Lambda^2)$, and in disagreement with experiments, unless limited by an ultraviolet cut-off $\Lambda \approx$ 3-4 GeV (from Δm_K);
- result is based on current algebra commutators and shows that hadron form factors are irrelevant: ***current commutators imply hard constituents***;
- Similar results were found by R. Marshak and coll. and by F. Low in the US.

FIRST ATTEMPTS

- Attempts were made during 1968-69 to make the amplitude more convergent:
  - introducing more than one Intermediate Vector Boson (Gell-Mann, Low, Kroll, Ruderman) (too many were needed);
  - introducing negative metrics (ghost) states (T.D.Lee and G.C. Wick), of mass $\simeq \Lambda$!
- another line was to cancel the quadratic divergence, in correspondence to a specific value of the angle, i.e. “computing” the Cabibbo angle (Gatto, Sartori, Tonin; Cabibbo, Maiani);
- it was realised that quadratic divergent amplitudes at order $G\Lambda^2$ would also arise, in the IVB theory, with potential violations of strong interaction symmetries (parity, isospin, SU(3) and strangeness).
- C. Bouchiat, J. Iliopoulos and J. Prentki observed that, with chiral $SU(3) \otimes SU(3)$ breaking described by quark masses, the leading divergences give only diagonal contributions (no parity and strangeness violations).
- ...but the small cutoff in the $G(G\Lambda^2)$ terms still called for an explanation.

2. GIM Mechanism (1970)



PHYSICAL REVIEW 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

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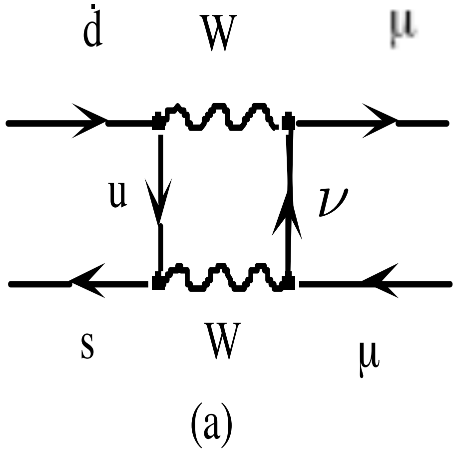
We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the 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.

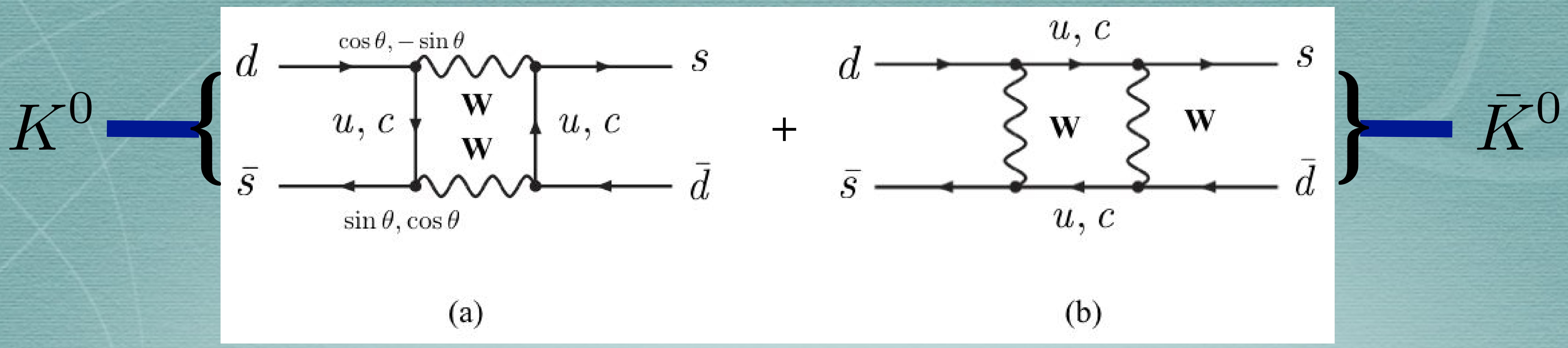


$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; \begin{pmatrix} c \\ s_C \end{pmatrix}_L ; (d)_R ; (s)_R ; u_R ; c_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ; \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L ; e_R ; \mu_R$$

Esperimento delle due fenditure:

- pensate che ce ne sia una sola aperta e vi aspettate che certi punti dello schermo siano illuminati
- se questo non avviene, l'ipotesi piu' semplice e' che ci sia un'altra fenditura e che l' interferenza porti l'ombra la' dove ci si apettava la luce
- ma allora ci devono essere zone dove le due fenditure interferiscono costruttivamente
- questi sono i processi dove i numeri quantici non cambiano, es: $\nu + q \to \nu + q$



(a) (b)

- each u or c line carries a Cabibbo factor: +/- sinθ cosθ
- if masses of u and c equal: result=0, perfect distructive interference
- the subtraction makes the integral convergent
- for $m_c \neq m_u$ one finds an amplitude of order $G[G(m^2_c - m^2_u)]$, i.e. Ioffe&Shabalin’s result with:

$$\Lambda^2 \to m_c^2 - m_u^2 \approx (3 - 4 \text{ GeV})^2$$

Ioffe&Shabalin’s result has turned into a prediction of the charm quark mass, m_c=1.5-2 GeV !!

FACTS AND PREDICTIONS FOLLOWING GIM

- c quark must exist
- Neutrino neutral current processes must exist

-Flavour conserving, neutral current processes are indeed predicted, in W boson theory, or in Yang-Mills theory, to order G $[C,C^\dagger]$ = flavor diagonal;

-in the unified theory, they appear in lowest order, mediated by Z^0

- In 1973, the Gargamelle bubble chamber collaboration at CERN observed muonless or electronless neutrino events soon recognised to be neutrino processes of the type: $\nu(\bar{\nu}) + \text{Nucleous} \rightarrow \nu(\bar{\nu}) + \text{hadrons}$

-strange particles (and, at higher energy, charmed particles) are pair produced, indicating flavour conservation in these abundant neutral current reactions.

- Quark-lepton symmetry.

-Restoring quark-lepton symmetry was one of the basic motivations of the GIM paper and is at the basis of the partial cancellation of FCNC amplitudes.

-quark-lepton symmetry is ***mandatory*** in the unified electroweak theory for the cancellation of the Adler-Bell-Jackiw anomalies, the last obstacle towards a renormalizable theory, as shown by C. Bouchiat, J. Iliopoulos and P. Meyer (fractionally charged and $SU(3)_{\text{color}}$ triplet quarks).

- CP violation ?

-with 4 quarks in 2 doublets the weak coupling matrix U can be made real

- already worried by the charm quark, GIM did not ask what would happen with even more quarks and failed to discover a simple theory of CP violation.

CAN GIM MECHANISM SURVIVE IN THE PRESENCE OF STRONG INTERACTIONS ?

- One may suspect that strong interactions will spoil the cancellations at the basis of GIM;
- Preparata & Weisberger: the universality relations of weak interactions are preserved by strong interactions mediated by a neutral gluon
- ... but at that time people believed that strong interactions had to be described by dual models (introduced by G. Veneziano in 1968), there was room for suspicion.
- what seemed a simple curiosity (the Preparata-Weisberger theorem for the abelian gluon) became reality after the discovery of $SU(3)_{color}$ commuting with the EW group (eight gluons, all electrically neutral, anyway) and asymptotic freedom
- strong interactions, in leading order, renormalize quark EW parameters, i.e. masses and gauge couplings, and the strenght of non leptonic processes in a calculable way.

3. CHARM PRECURSORS

- Elementary particles in the Sakata model:

$$\begin{pmatrix} & p & \\ n & & \Lambda \end{pmatrix} \begin{pmatrix} & \nu & \\ e & & \mu \end{pmatrix}$$

- In 1962, after the discovery of the two neutrinos, Sakata et al. (Nagoya) and Katayama et al. (Tokyo) proposed to extend the model to a fourth baryon, called V^+:

$$\begin{pmatrix} p & V^+ \\ n & \Lambda \end{pmatrix} \quad \begin{pmatrix} \nu_1 & \nu_2 \\ e & \mu \end{pmatrix}$$

a possible mixing among ν_e and ν_μ was paralleled by n-Λ mixing a-la Cabibbo, giving rise to weak couplings of p and V^+ similar to the ones we have assumed for u and c.

- In 1964, Glashow and Bjorken proposed a 4th quark and invented the name "charm". The motivation was again lepton-quark symmetry and, in addition, they speculated that the charm quark was related to the meson φ(1020) and that it could give rise to hadrons below 1 GeV; weak couplings: u -> d_C and c -> s_C were assumed.

4. THE DISCOVERY OF CHARMED PARTICLES

•In 1970 there was no experimental evidence of weakly decaying hadrons beyond the lowest lying strange baryons and mesons.

•GIM's explanation: ...*Suppose they are all relatively heavy, say 2 GeV.*

-..*will decay rapidly* (10^{-13} *sec) by weak interactions....into a very wide variety of uncharmed final states*

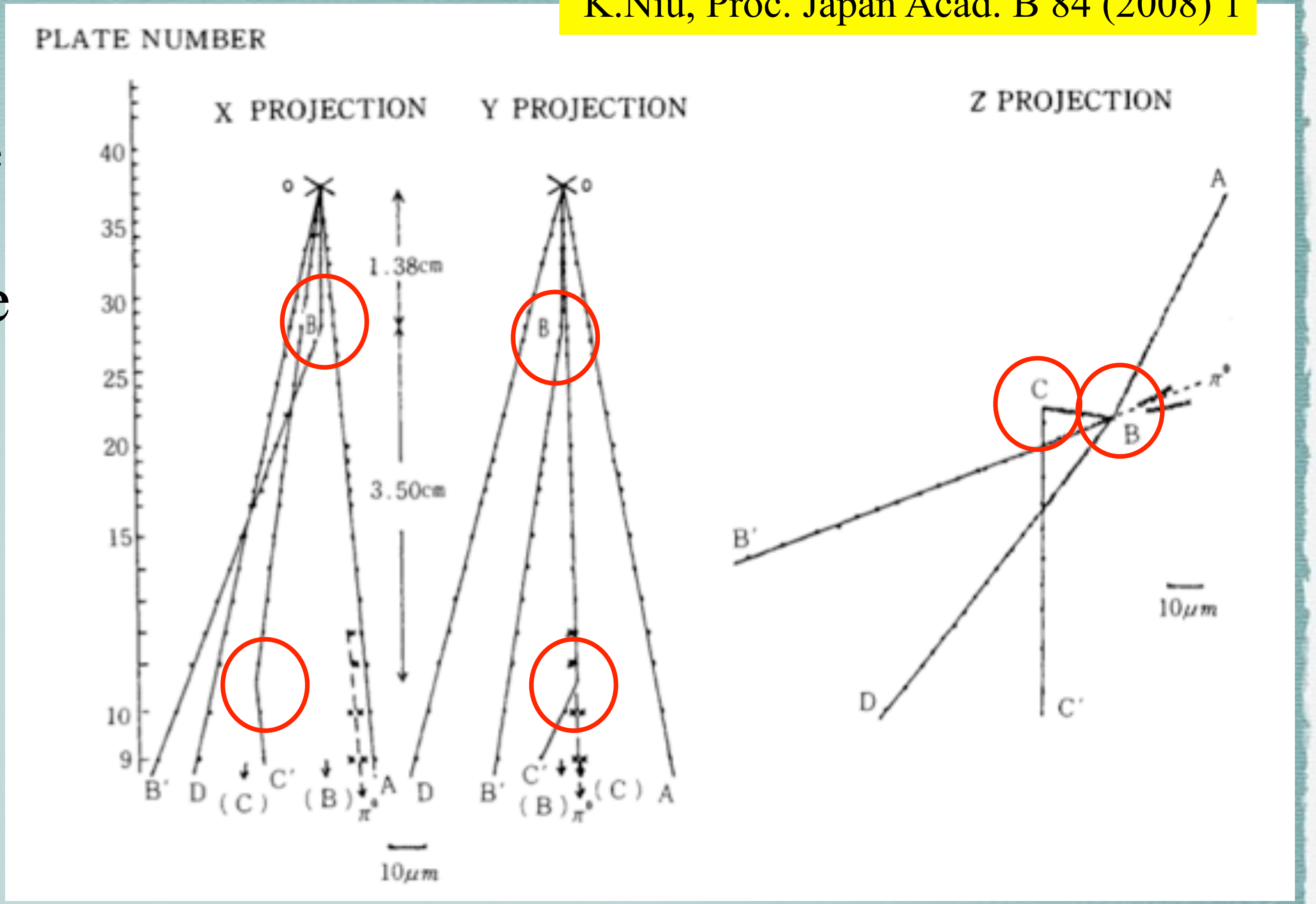
-.....*are copiously produced only in associated production, such events will necessarily be of very complex topology*

-...*Charmed particles could easily have escaped notice.*

CHARMED PARTICLES OBSERVATION

- In 1971, K. Niu and collaborators observed ***kinks*** in cosmic ray emulsion events, indicating unstable particles with lifetimes of order of 10^{-12} to 10^{-13} sec. These lifetimes are in the right ballpark for charmed particles and indeed they were identified as such in Japan.

- But cosmic rays events were paid not much attention in western countries.



K.Niu, Proc. Japan Acad. B 84 (2008) 1

The November Revolution

$$J/\Psi = c\bar{c}\ (3097\ \mathrm{MeV})$$

is discovered in 1974 by C. C. Ting and coll. (Brookhaven) and by B. Richter and coll. (SLAC); immediately after, was observed in Frascati.

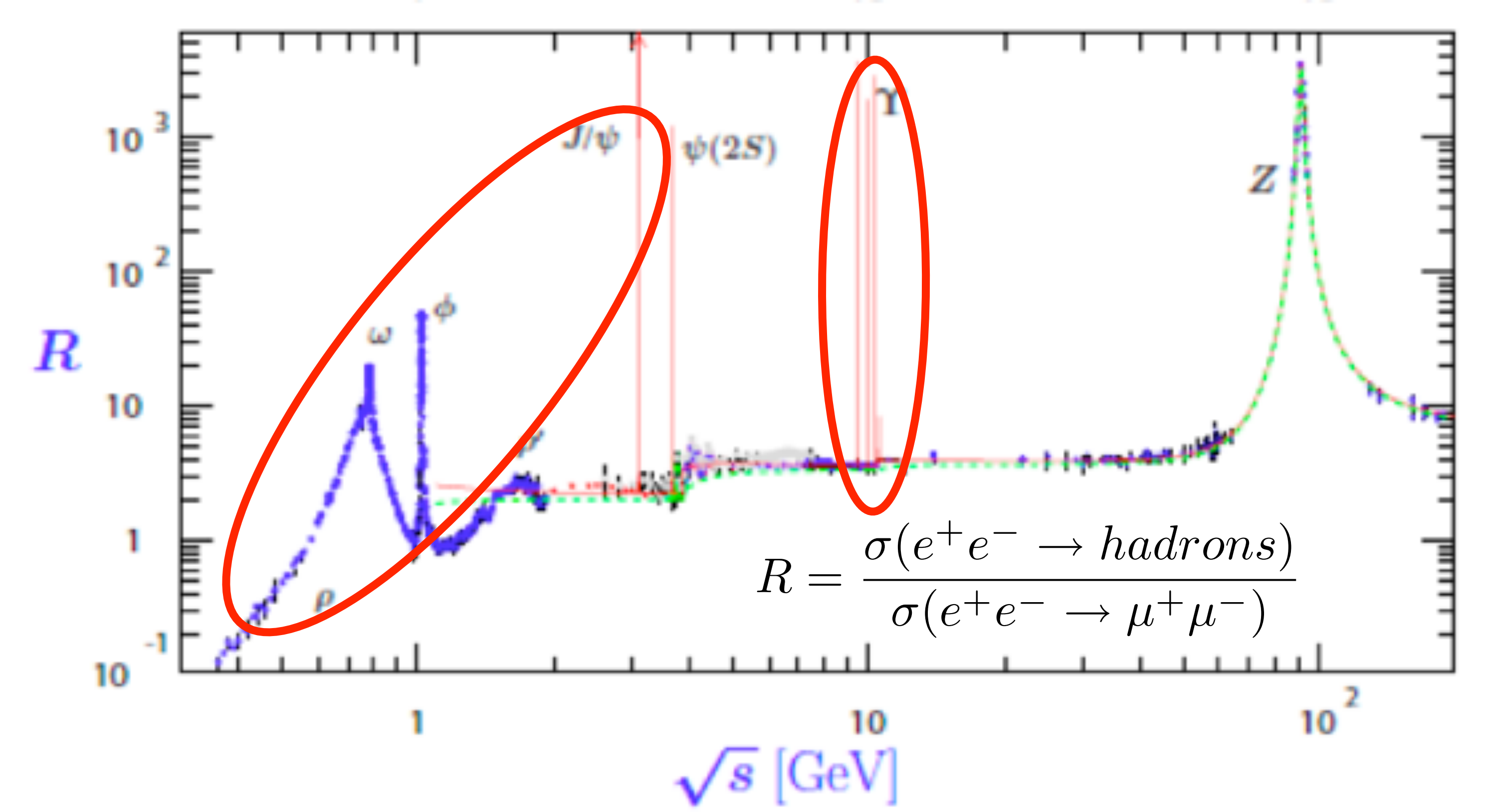
$$D^0 = c\bar{u}\ (1865\ \mathrm{MeV})$$

the lightest weakly decaying charmed meson, D^0, is discovered by the Mark I detector (SLAC) in 1976.

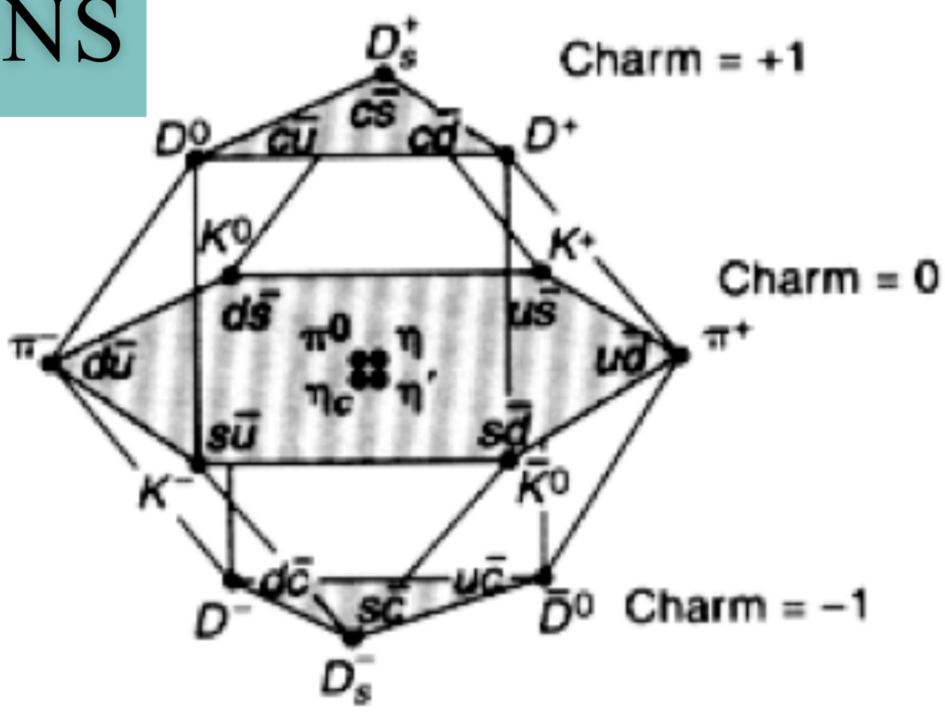
The same year, Lederman and coll. discover the Υ=(b b-bar), the first evidence of the 3rd family

5. CHARMED MESONS AND BARYONS

- mesons are quark-antiquark states and fall in a 15+1 dimensional multiplet, both lowest states (spin 0^-) and first resonances (spin1^-)
- particles made by a pair of the same quark flavor are neutral and fall in the center of the multiplets
- peaks in the ratio of the probability for $e^+ e^-$ to annihilate into hadrons or muon pairs indicate the onset of a new quark "flavor"

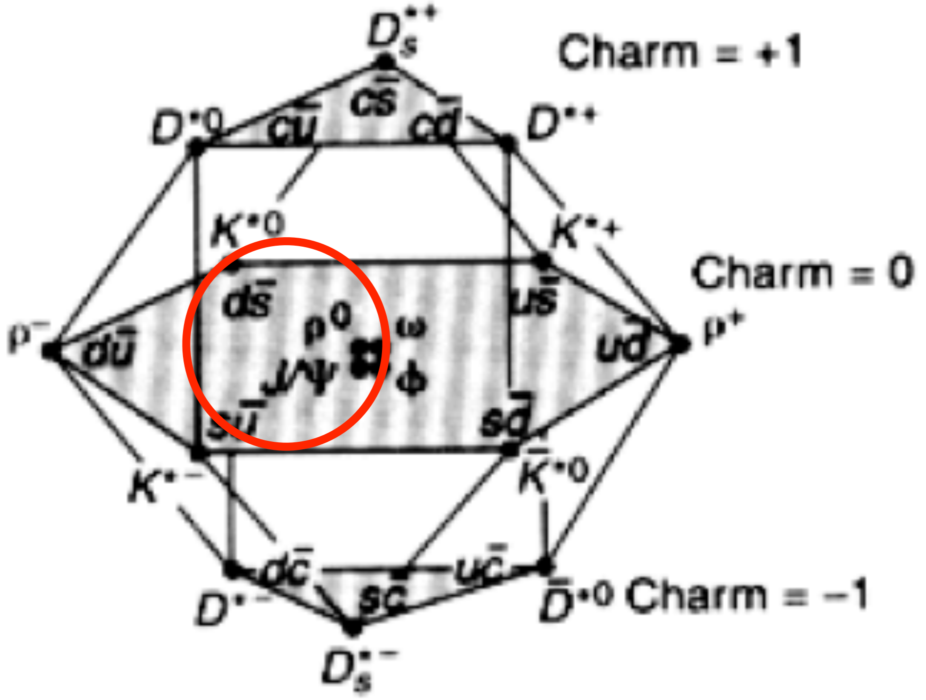


$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



0^- Mesons

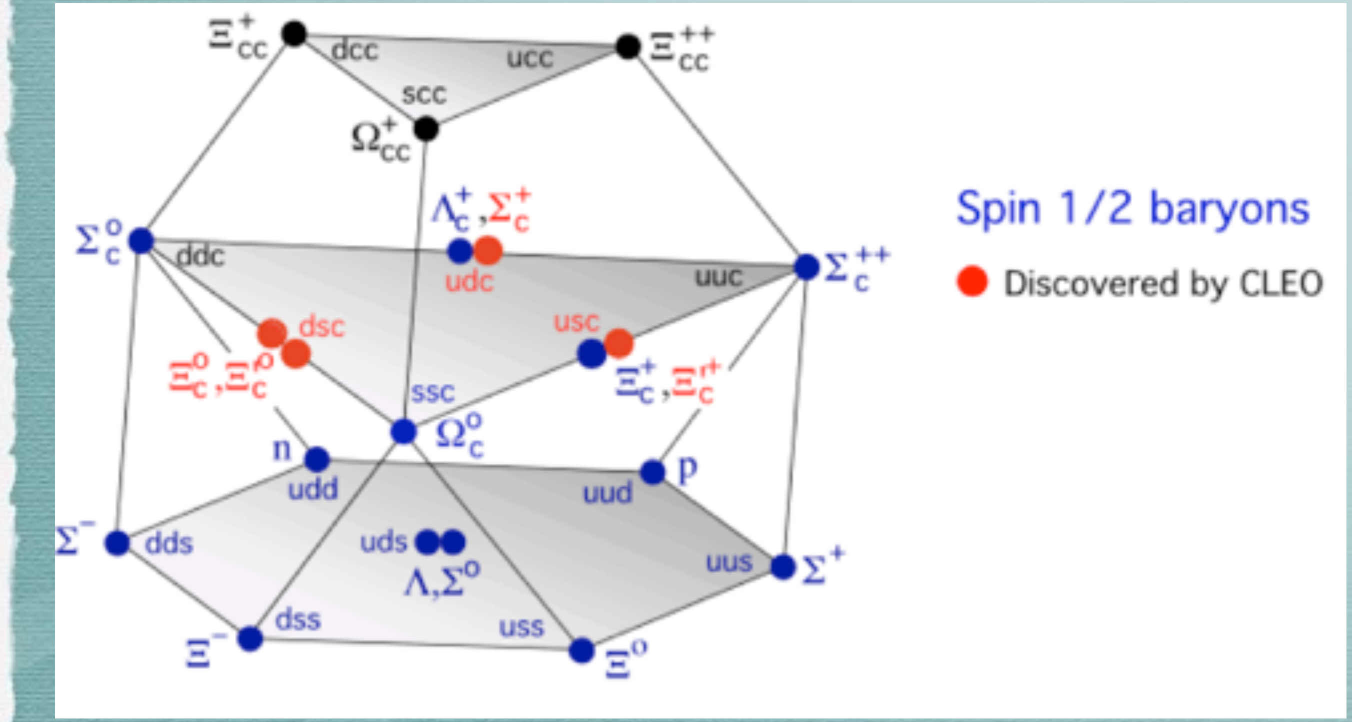
(a)

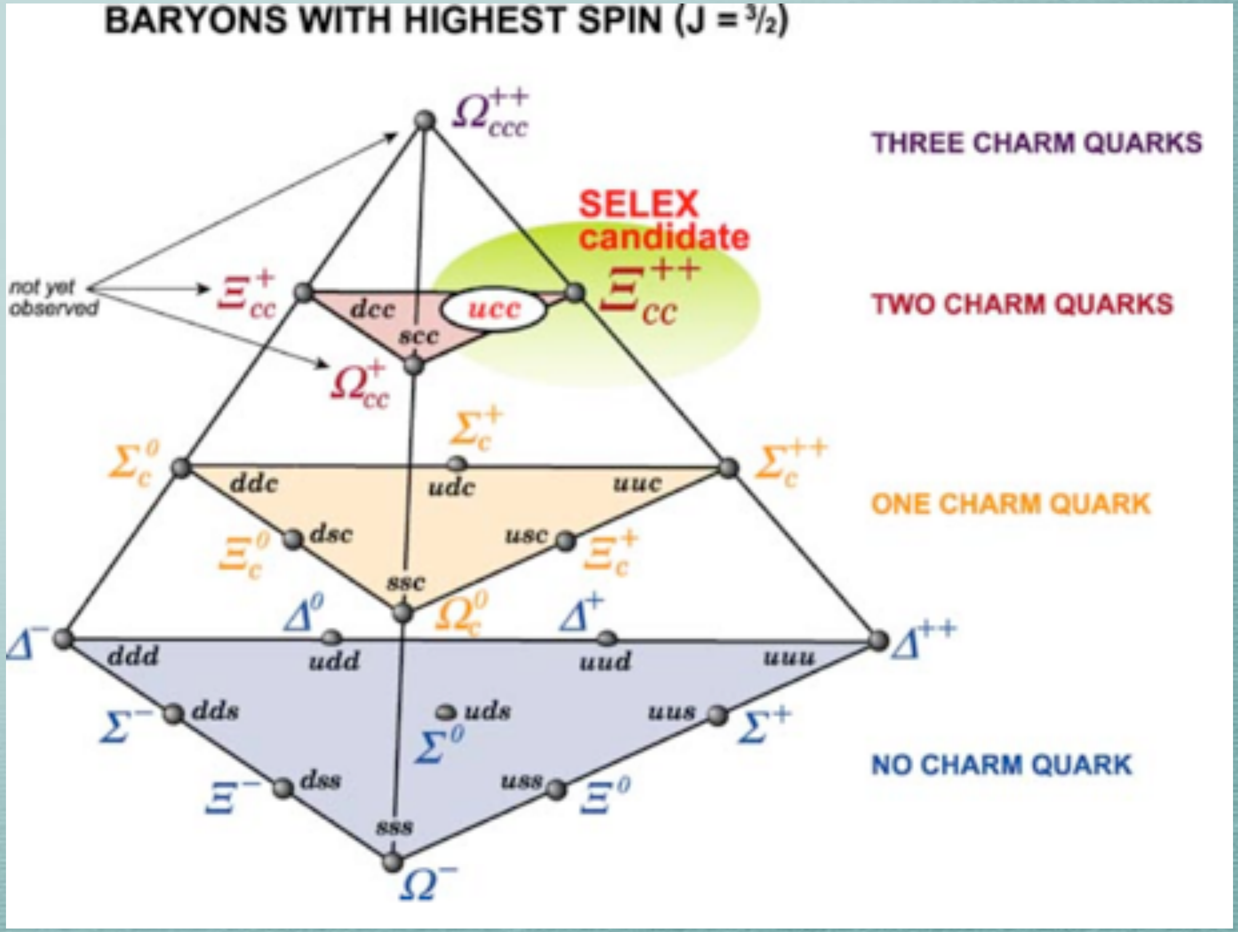


1^- Mesons

CHARMED AND UNCHARMED BARYONS

- Particle states are now displayed in a 3 dimensional space: I_3, Strangeness, Charm
- baryons are still 3 quark states, classified in two different 20-dimensional multiplets
- new resonances are being observed in several different experiments





6. CP VIOLATION, IN BRIEF

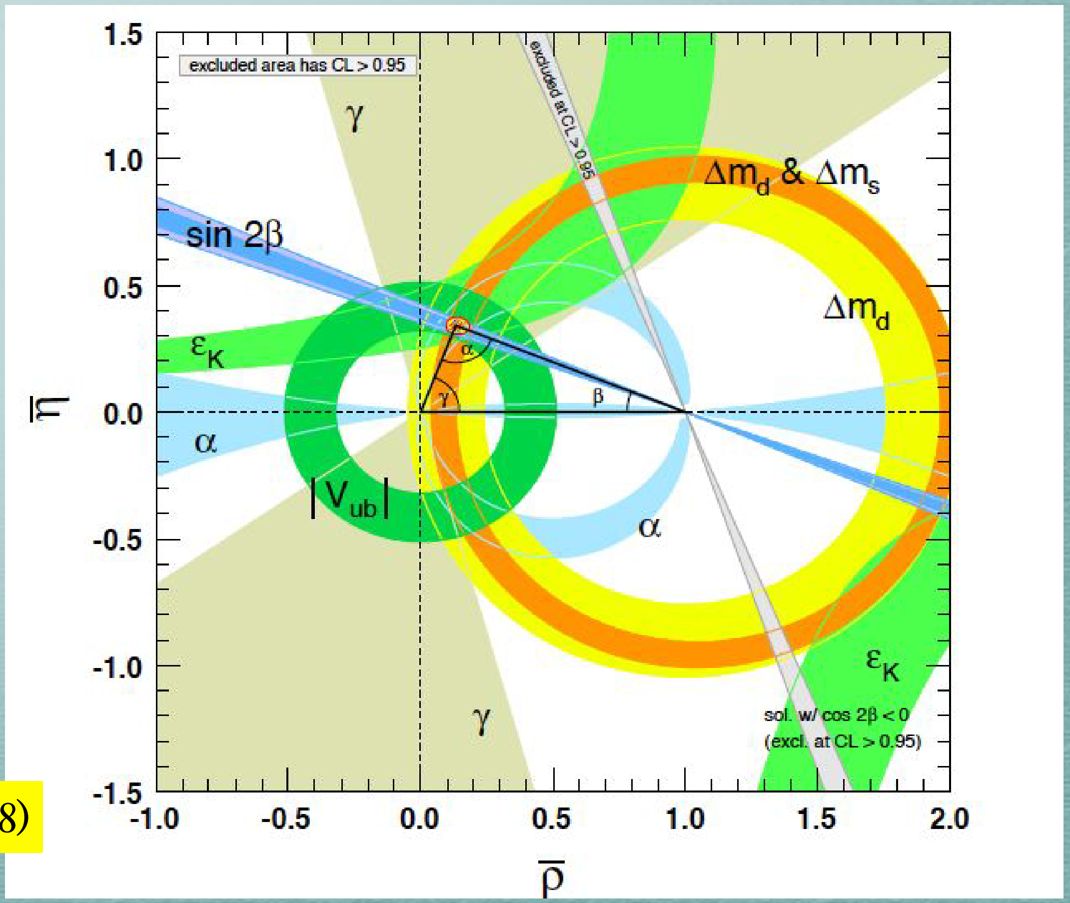
- 1973, Kobayashi and Maskawa: three left-handed quark doublets allow for one CP violating phase in the quark mixing matrix, since known as the Cabibbo-Kobayashi-Maskawa matrix;
- the phase could agree with the observed CP violation in K decays and led to neutron electric dipole vanishing at one loop (Pakvasa & Sugawara, Maiani, 1976);
- 1986, I. Bigi and A. Sanda predict direct CP violation in B decay;
- 2001, Belle and BaBar discover CP violating mixing effects in B-decays.

Wolfenstein's parametrization

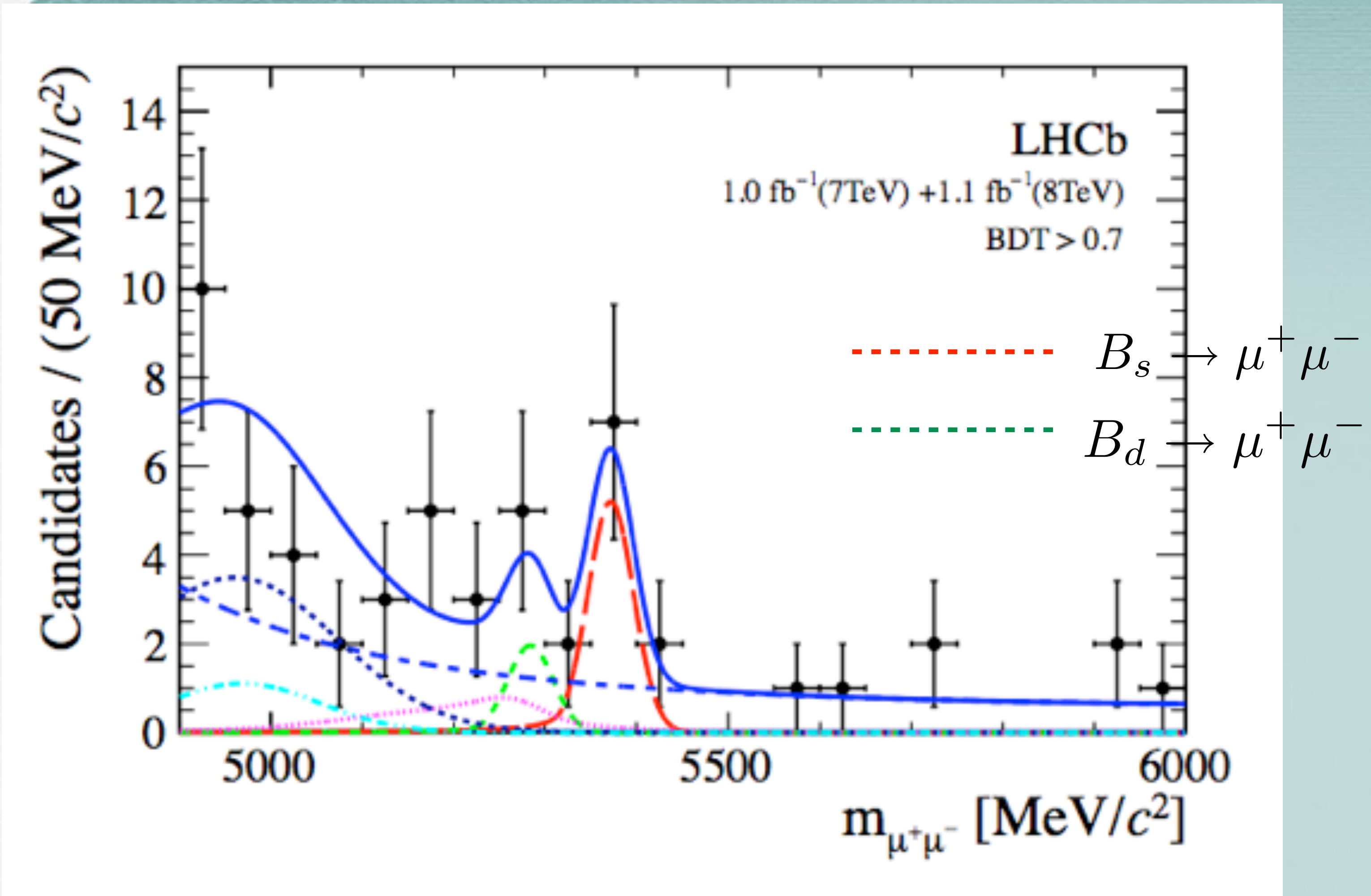
$$U_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix}$$

U_{CKM} is in an extraordinary agreement with data

C.-Amsler *et al.* [Particle Data Group Collaboration], Phys. Lett. B**667**, (2008)

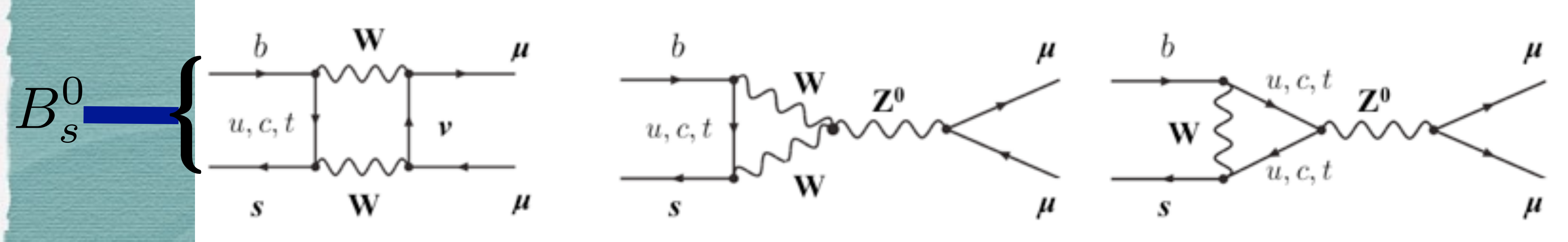


BREAKING NEWS FROM LHCB: $B_s \to \mu^+\mu^-$



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

$$theory: \ 4.3 \times 10^{-10}$$



see e.g. Buchalla, Buras, Lautenbacher, 1995

7. Particelle fondamentali, oggi (in parentesi l'anno della scoperta)

1. Materia ordinaria (Galassie, la Terra, noi...) :

QUARKS
(Gell-Mann, Zweig, 1962)

LEPTONI

$\begin{bmatrix} u \\ d \end{bmatrix}$

Colore

$\begin{bmatrix} \nu_e \\ e \end{bmatrix}$

Sapore

Protone = [uud]
Neutrone = [ddu]

N → P + e⁻ +ν_e (Pauli, Fermi, ≈ 1

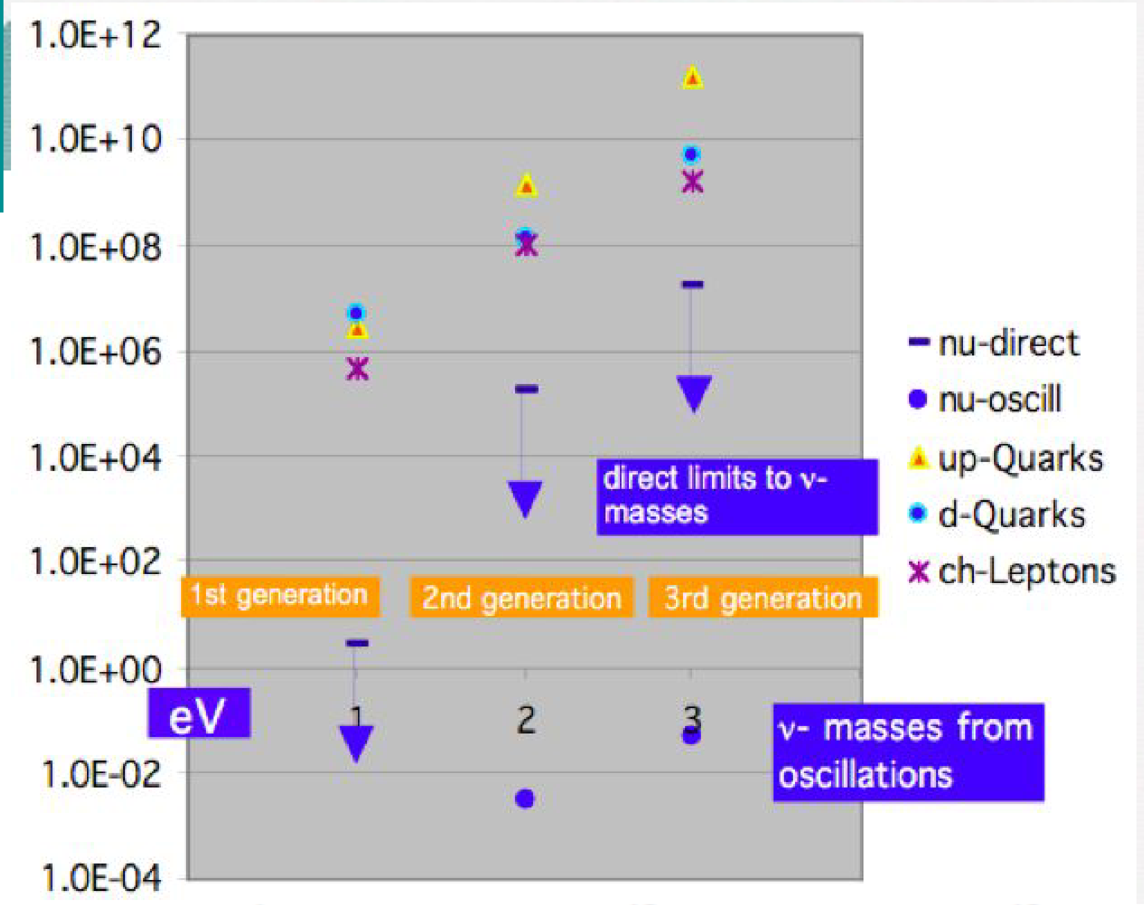
2. Strutture analoghe a piu' alta energia:

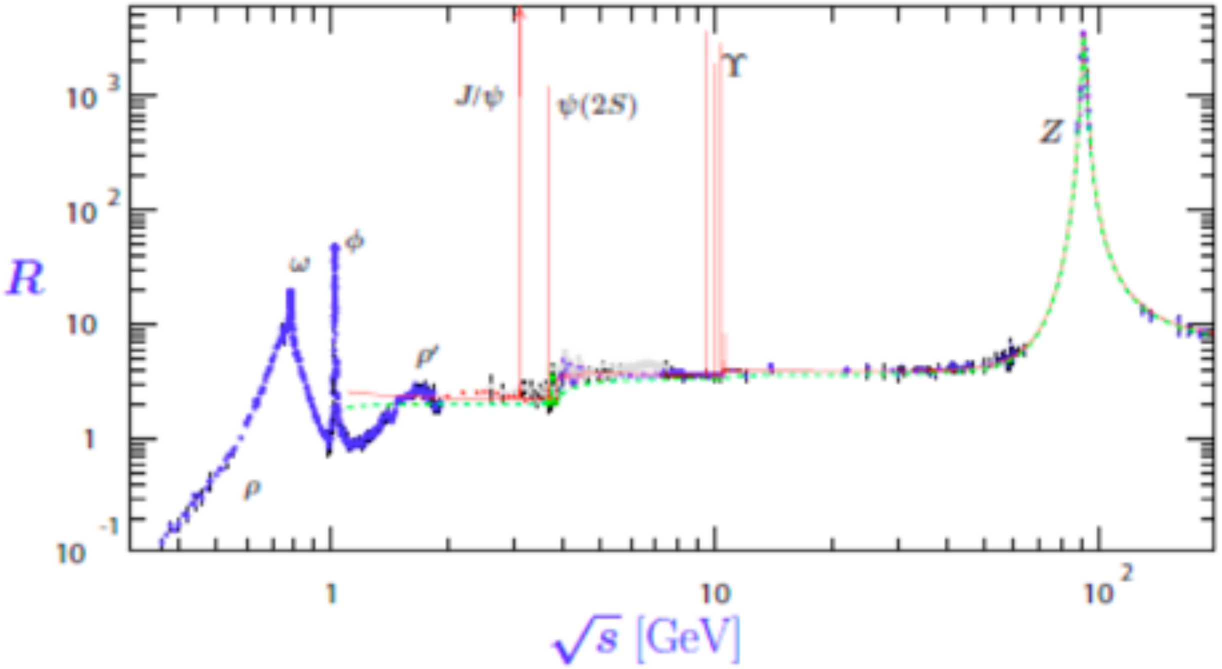
$\begin{bmatrix} c(1974) \\ s \end{bmatrix}$ $\begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}$

$\begin{bmatrix} t(1994) \\ b(1976) \end{bmatrix}$ $\begin{bmatrix} \nu_\tau \\ \tau(1975) \end{bmatrix}$

3. Forze :

Gravita' → GRAVITONE (non ancora osservato)
Elettromagnetiche → FOTONE (Einstein, 1905)
Forti (Nucleari) → GLUONI (non osservati allo stato libero)
Deboli → BOSONI INTERMEDI (CERN, 1983)
Generazione della massa → BOSONE DI HIGGS (?)





Colore= interazioni forti
Sapore= interazioni elettrodeboli
Ma la simmetria richiede M=0, per tutte !!??!!