Six lectures in the Standard Theory of Elementary Particle Physics

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Lecture 5
GIM Mechanism, Charm, Beauty and CP violation

1. Late nineteen-sixties

...hopes of a basic theory for strong, e.m. and weak interactions

$$\mathcal{L}_F = \frac{G_F}{\sqrt{2}} J^\lambda J^+_\lambda$$
$$J^\lambda = \bar{\nu}_e \gamma^\lambda (1-\gamma_5) e + \bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu + \bar{u}\gamma^\lambda(1-\gamma_5) d_C$$
$$d_C = \cos\theta d + \sin\theta s$$

$$q = \begin{bmatrix} u \\ d \\ s \end{bmatrix}$$

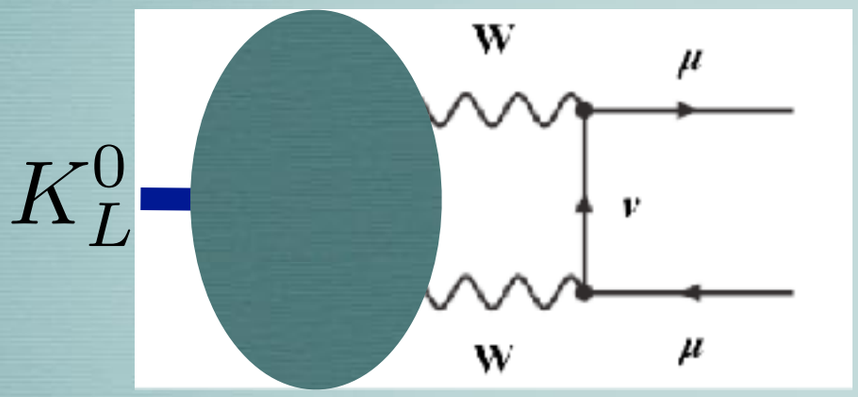
- well established results: one weak doublet:
  - -Gell-Mann-Zweig quarks in 3 flavours (baryons=qqq, etc.)
  - -Cabibbo theory of semileptonic decays, ΔS=0,1, with Fermi interaction:

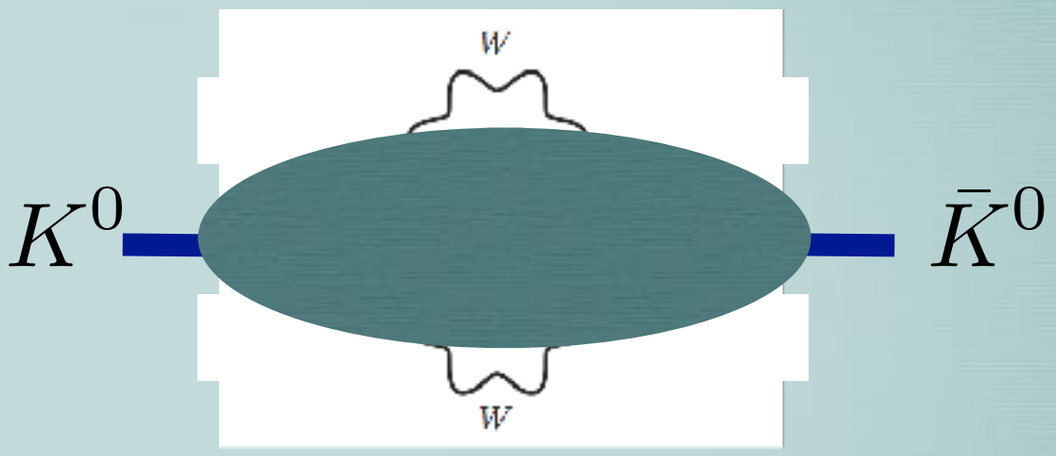
$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; (s_C)_L ; d_R ; u_R ; s_R$$

- clouds:
  - -do quark clash with Fermi-Dirac statistics? first ideas about color (Han-Nambu)
  - -basic strong interactions: are they gluon (abelian) mediated? or string-like ?
  - -Fermi theory not renormalizable. W boson? strong interaction form factors?
- Schwinger ideas about EW unification+Yang-Mills
  - - Glashow's SU(2)⊗U(1)
  - - Brout-Englert-Higgs Mechanism (1965) -> Weinberg-Salam (1967)
- embedding Cabibbo theory in SU(2) ⊗ U(1) leads to unobserved Flavor Changing Neutral Currents (e.g. $K_0 \to \mu^+\mu^-$) : does EW unification work for leptons only ???.

2. The GΛ² puzzle, 1968

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





- the amplitudes were found to be divergent, of order G(GΛ²), and in disagreement with experiments, unless limited by an ultraviolet cut-off ***Λ ≈ 3-4 GeV*** (from Δm_K);
- result from current algebra commutators, 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.

A reminder: vector boson, $W^{\pm}$

- A complex field, W^{μ} : destroys W^{+}, creates W^{-}:

$$W = \frac{W^1 + iW^2}{\sqrt{2}},\ W^{1,2} = \text{ real fields}$$

- The free Lagrangian is: $L = -\frac{1}{2} W_{\mu\nu} W^{\dagger\mu\nu} + M_W^2\ W^{\mu} W^{\dagger\mu}$

$$= \sum_{i=1,2} -\frac{1}{4} W_{i\mu\nu} W_i^{\mu\nu} + \frac{1}{2} M_W^2\ W_{i\mu} W_i^{\mu}.$$

$$W^{\mu\nu} = \partial^{\nu} W^{\mu} - \partial^{\mu} W^{\nu}$$

- and the W propagator in momentum space (see Lecture 1)

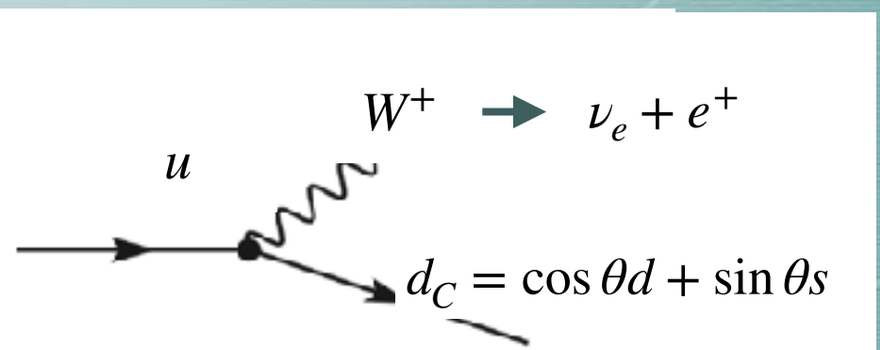
$$D_{W\,\mu\nu}(p) = \frac{1}{p^2 - M_W^2} \left(-g_{\mu\nu} + \frac{p_{\mu} p_{\nu}}{M_W^2} \right)$$

- unlike photon, W propagator does not vanish for large p: D→ O(1) for p→∞.
- To reproduce the Cabibbo theory, the quark-W interaction is:

$$L_{int} = \frac{g}{2\sqrt{2}} W^{\mu} \left[\bar{u} \gamma_{\mu} (1 - \gamma_5) d_C \right] = \frac{g}{\sqrt{2}} W^{\mu}\ \bar{u}_L \gamma_{\mu} d_{CL};\ \left(\frac{G}{\sqrt{2}} = \frac{g^2}{8 M_W^2} \right)$$

Orders of Magnitudes

- Fermi Constant $G_F \simeq 10^{-5} M_P^2$
- $BR(K_S^0 \rightarrow \mu + \mu^-) \simeq 10^{-10}$: ~Second Order Weak?
- Unitarity Limit: $G_F \Lambda^2 = 1;\ \Lambda \simeq 300$ GeV.



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 ≃ Λ!

•another line was to try to cancel the quadratic divergence in correspondence to a specific value of the angle, i.e. “computing” the Cabibbo angle (Gatto, Sartori, Tonin).

- The Ioffe-Shabalin problem was still on the table in November 1969, when I moved to Harvard and met with John Iliopoulos and Shelly Glashow, at work on the $G(G\Lambda^2)$ result.

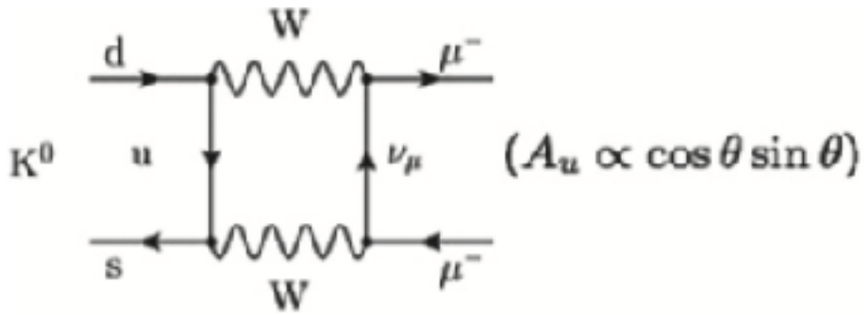
•So, we discussed for long, usually two of us arguing against the one at the blackboard, apparently getting nowhere.

L.Bonolis, L. Maiani, Eur. Phys. J. H **42** (2017) 611

3. *Discussions at Harvard (1969-70)*

- But during our discussions a change in paradigm occurred.
- Previous works had been done in the framework of the "algebra of currents", but slowly we began to phrase more and more our discussion in terms of quarks.

- In quark language, the Ioffe-Shabalin problem for $K_L \to \mu^+\mu^-$ is represented by the box diagram in the Figure. The divergent amplitude is proportional to the product (sin θ cos θ) of the couplings of quarks d and s to the u quark, as required by the Cabibbo theory



(a)

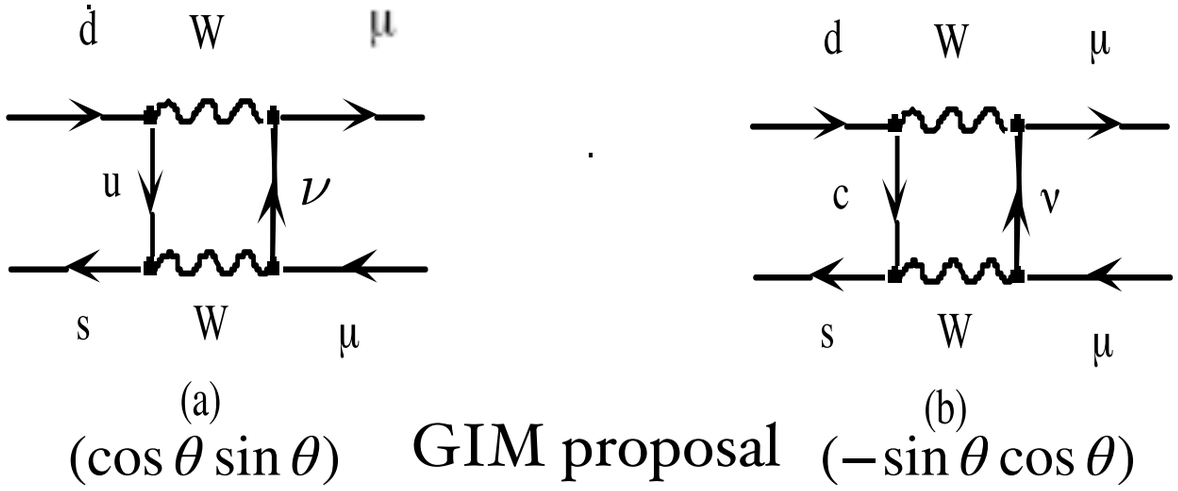
- By January 1970 we got convinced that the only possibility was to modify the weak interaction theory.
- ***Once we realised that, the solution was just under our eyes.***
- A fourth quark of charge +2/3, called the *charm* quark, had been introduced few years before by Bjorken and Glashow (and by others), for entirely different reasons.
- In the weak interaction, the charm quark was coupled in a doublet to the s_C quark left out in the Cabibbo theory.

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.



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

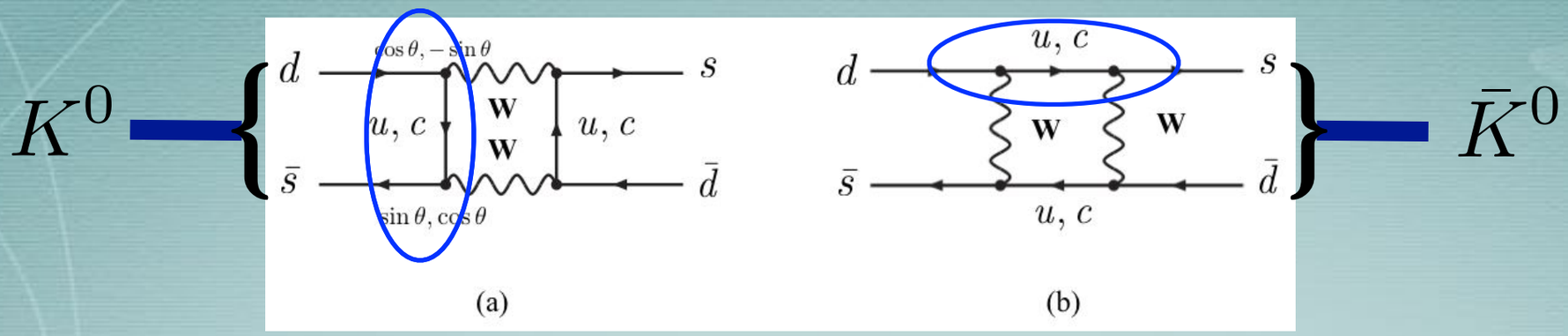
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ; \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L ; e_R ; \mu_R$$

$$J_\mu^W(quark) = \bar{q} C \gamma_\mu q_L$$

$$C = \begin{pmatrix} 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

finite amplitude: $\propto G[G(m_c - m_u)^2][C, C\dagger]$

[C,C†] = flavor diagonal!



- each quark line, which leads to $\Delta F \neq 0$, carries a factor

$$\Sigma_{i=u,c} U^*_{si} S_i(p) U_{di} = \sin\theta\cos\theta\,[S_c(p) - S_u(p)] \simeq \sin\theta\cos\theta\,[\frac{\hat{p} + m_c}{p^2 - m_c^2} - \frac{\hat{p} + m_u}{p^2 - m_u^2}] \simeq$$

quark propagator

$$\simeq \sin\theta\cos\theta\,\frac{m_c - m_u}{p^2}, \quad (p^2 >> m_{c,u})$$

- the subtraction makes the integral convergent
- The result has to vanish for $m_c = m_u$
- the upshot is that one finds an amplitude of order $G[G(m_c - m_u)^2]$

The limit on the cutoff Λ is replaced by a limit on Δ, the parameter measuring SU(4) breaking; and from the observed K_1K_2 mass difference we now conclude that Δ must be not larger than 3—4 GeV (GIM, PRD 1970)

Ioffe&Shabalin's result has turned into a prediction of the charm quark mass.

Predictions and facts following GIM

- ***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 GIM 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 (1972, fractionally charged and $SU(3)_{color}$ triplet quarks required).

- ***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 (see later) .

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 (the charmed particles) 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.*

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 (1968): the universality relations of weak interactions are preserved if strong interactions are 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 P&W 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.

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.

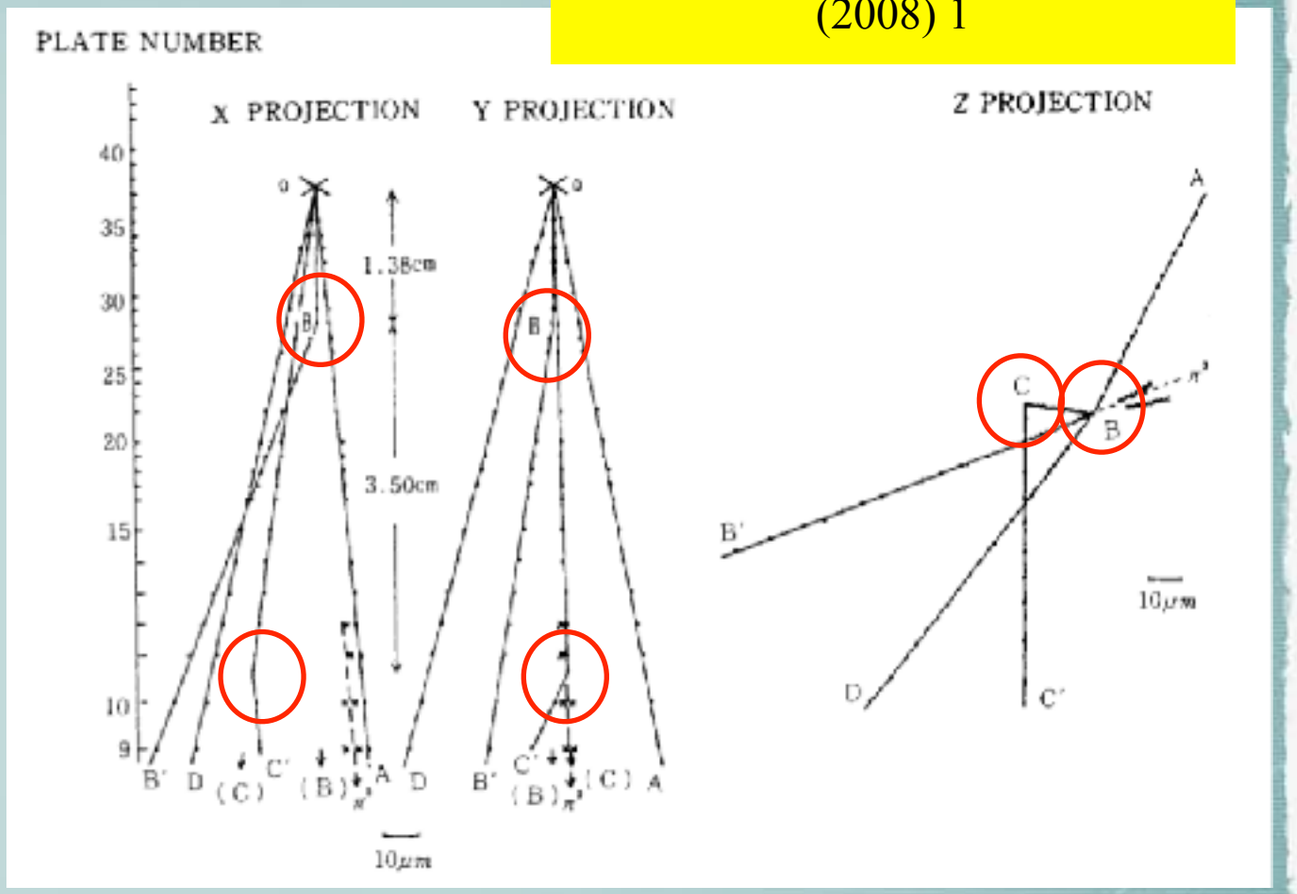
- In 1964, Glashow and Bjorken proposed a 4th quark and invented the name "charm". The motivation was again lepton-quark symmetry and, in addition, they speculated that the charm quark was related to the meson $\varphi(1020)$ and that it could give rise to hadrons below 1 GeV; weak couplings: u -> d_C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

The first observation of charmed particles

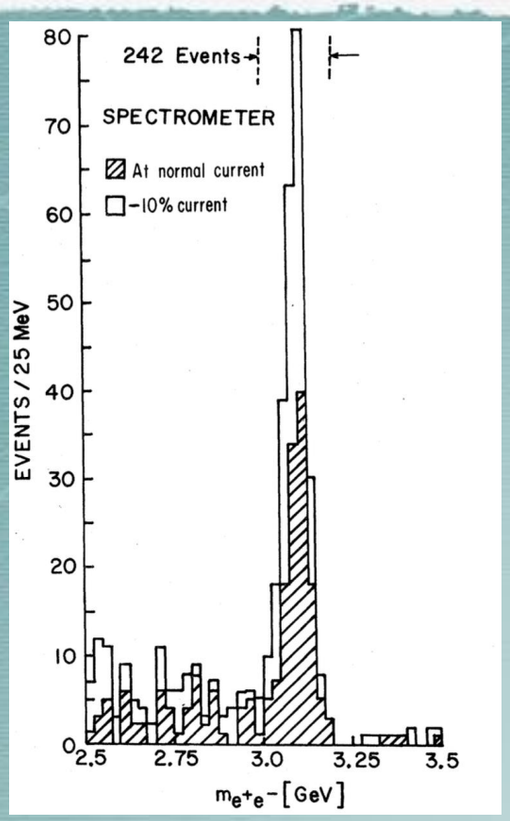
K.Niu, Proc. Japan Acad. B 84 (2008) 1

•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.



1974: The November Revolution



J.J. Aubert *et al.* PRL **33**, 12 Nov.1974

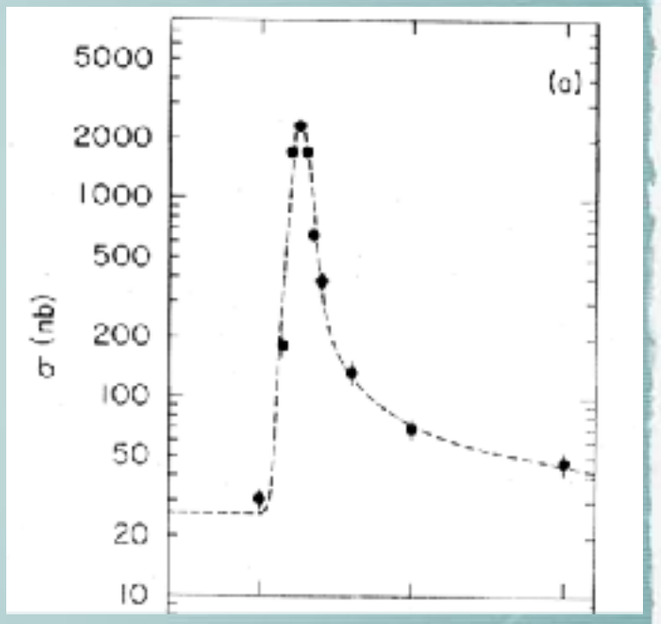
$p + p \rightarrow e^+ + e^- + \ldots.$ $\quad M = 3.1$ GeV, $\Gamma \sim 100$ KeV!!

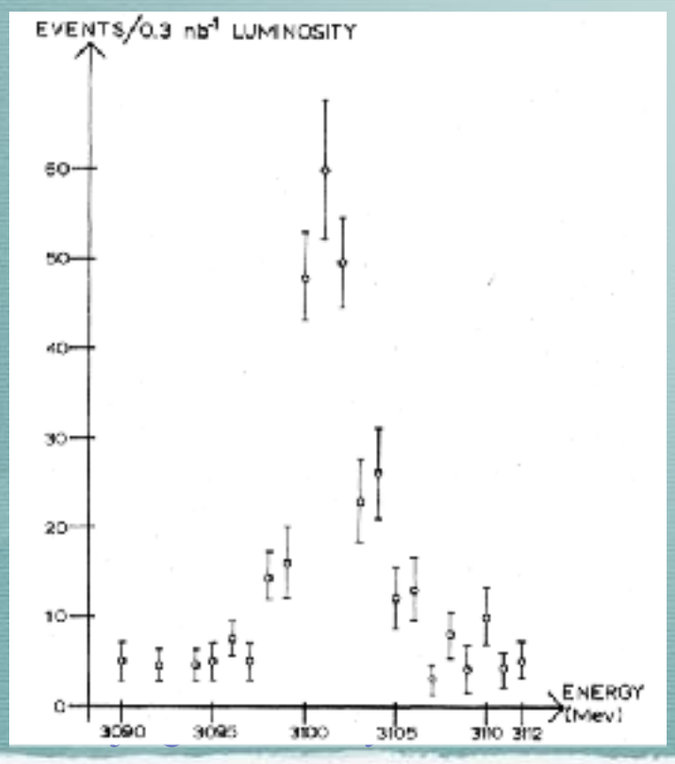
The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles[2] or a's[3] or Z_0's,[4] etc.

J.E. Augustin *et al.* PRL **33**, 13 Nov.1974

$e^+ + e^- + \rightarrow$ hadrons

It is difficult to understand how, without involving new quantum numbers or selection rules, a resonance in this state which decays to hadrons could be so narrow.





Confirmed by Adone (Frascati)

C.Bacci *et al.* PRL **33**, 18 Nov.1974

$e^+ + e^- + \rightarrow$ hadrons

Soon after the news that a particle of 3.1 GeV with a width consistent with zero had been observed at Brookhaven National Laboratory by the Massachusetts Institute of Technology group,[1] it was immediately decided to push ADONE beyond its nominal limit of energy (2×1.5 GeV) to look for this particle.

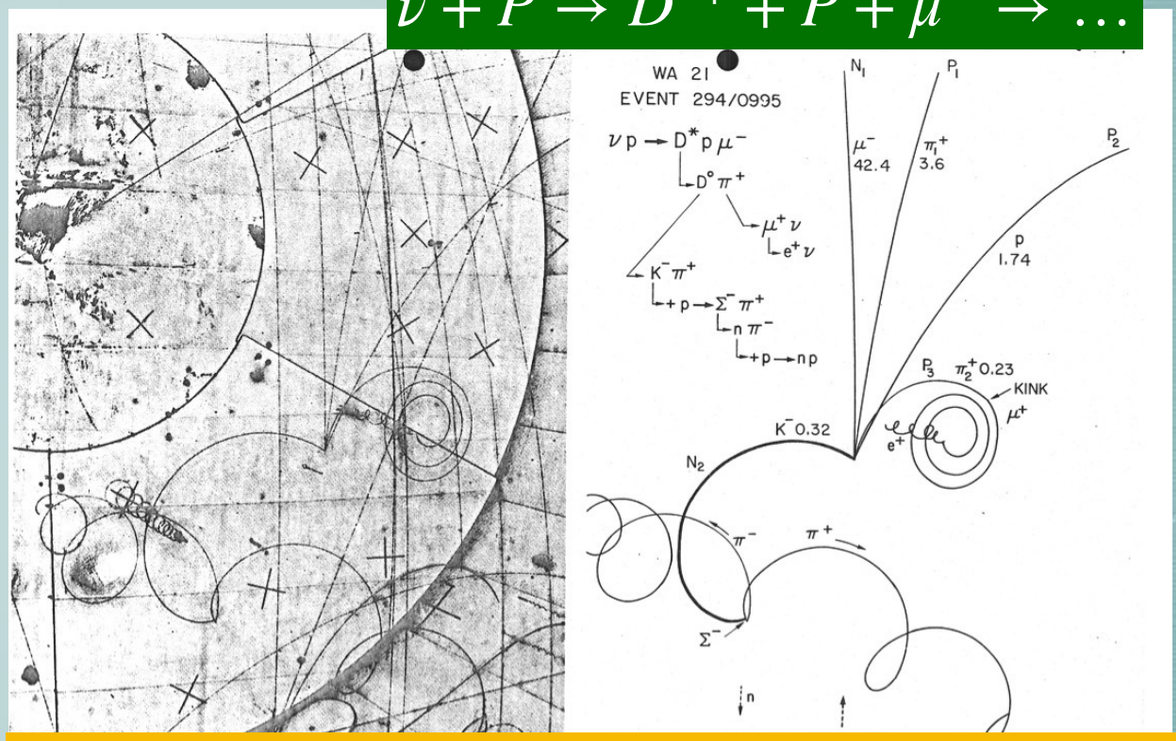
- $c\bar{c}$ interpretation of the rise of $e^+e^- \rightarrow$ hadrons in the J/Psi was not so obvious, due to the presence of problematic $e - \mu$ events.
- 1975-1977. M. Perl and coll. at SLAC: a new sequential lepton, ***the τ lepton***, is the origin of the $e - \mu$ events

M. L. Perl *The Discovery of the Tau Lepton,* 3rd International Symposium on the History of Particle Physics: *The Rise of the Standard Model*, SLAC-PUB-5937

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

Charmed particle production and decay shows very complicated decay pattern indeed….

$\nu + P \rightarrow D^{*+} + P + \mu^- \rightarrow \ldots$



Blietschau, J., et al. Physics Letters B 86 (1979)108

1976. L. Lederman and coll. discover the $\Upsilon = b\bar{b}$, evidence of the 3rd generation

- the 3rd quark-lepton generation was completed in 1994 with the discovery of the top quark at FermiLab.

5. Yukawa couplings, quark masses and CP violation

Left -handed doublets

Right-handed singlets

- consider N generations and define $Q_L = \begin{pmatrix} q_L^{(1)} \\ \cdot \\ \cdot \end{pmatrix}, \; U_R = \begin{pmatrix} u_R^{(1)} \\ \cdot \\ \cdot \end{pmatrix}, \; D_R = \begin{pmatrix} d_R^{(1)} \\ \cdot \\ \cdot \end{pmatrix}$

- Yukawa couplings are now arranged in matrices and we define two, in general complex, mass matrices:

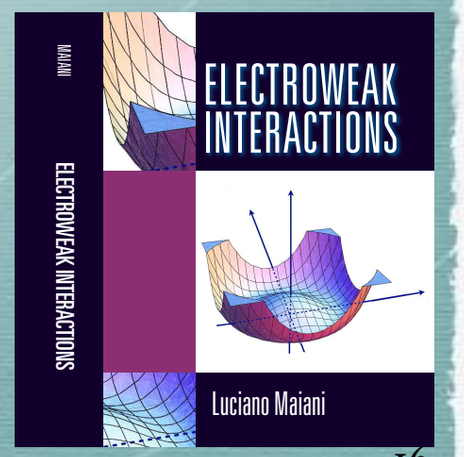
$$\mathscr{M}_u = g_u \eta; \;\; \mathscr{M}_d = g_d \eta$$

$$\mathscr{L}_{mass} = \bar{U}_L \mathscr{M}_u U_R \; + \; \bar{D}_L \mathscr{M}_d D_R \; + h.c$$

- the way to deal with the mass matrices is specified by the theorem: any complex matrix $\mathscr{M}$ can be written as:

$$\mathscr{M} = YDV; \;\; Y, V = \text{unitary matrices, D= real, diagonal}$$

- for a demostration see: L.Maiani, *Electroweak Interactions*, CRC Press (2016)



$$\mathscr{L}_{mass} = \bar{U}_L Z M_u Y U_R \; + \; \bar{D}_L V M_d W D_R \; + h.c$$

- M_u and M_d are the diagonal quark masses
- we can absorb the unitary matrices Y and W in a definition of the physical U_R and D_R fields, corresponding to diagonal masses
- similarly we can identfy $\bar{U}_L Z$ with the (physical) left-handed, weak $\bar{U}_L$ quark field and arrive to:

$$\mathscr{L}_{mass} = \bar{U}_L M_u U_R \; + \; \bar{D}_L V M_d D_R \; + h.c$$

- On the basis of the weak isospin $SU(2)_L$ symmetry, we identify $\bar{D}_L V$ with the state obtained by applying to U_L, the lowering operator T^- i.e. the phyical result of the weak transition: $U_L \rightarrow_W D_L V \rightarrow_W (D_L)_W$
- $(D_L)_W$ is, in general, not a mass eigenstate, but a linear combination of the eigenstates of M_d, i.e.

$$(D_L)_W = U_{CKM} D_L$$

- with U_{CKM} the Cabibbo-Kobayashi-Maskawa matrix.
- We therefore have: $D = D_L + D_R$; $U \rightarrow_W U_{CKM} D_L$, with:

$$(D_L)_W = U_{CKM} \begin{pmatrix} d_{ph} \\ s_{ph} \\ b_{ph} \end{pmatrix}_L$$

CP violation vs Number of Generation (K&M)

•A complex U_{CKM} may produce CP violation, if it introduces phases which cannot be eliminated by phase redefinition of the fermion fields. A simple counting goes like this:

•consider the generic form of a U(N) matrix $U = e^{iH}$, H Hermitian matrix:

•there are N^2 real parameters in H (corresponding to complex and real components in U):

$$N\ (\text{diag}) + 2\ \frac{N(N-1)}{2}\ (\text{off diag}) = N^2 = N_{Un}$$

• parameters in a real orthogonal matrix: $\frac{N(N-1)}{2} = N_{Ort}$

•one can make $N_{Red} = 2N - 1$ phase redefinitions of the fields: 2 fields in each generation (u, d), one overall phase has no effect;

• ***The total number of non-eliminable phases is then***:

$$N_{Un} - N_{Ort} - N_{Red} = N^2 - \frac{N(N-1)}{2} - \frac{4N-2}{2} = \frac{N^2 - 3N + 2}{2} = \frac{(N-1)(N-2)}{2}$$

» no phase for N=1 (Cabibbo), N=2 (GIM)

» one phase for N=3 (KM) !!!!

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 produce the observed CP violation in K decays and leads to a neutron electric dipole that vanishes at one loop (Pakvasa & Sugawara, Maiani, 1976);

Wolfenstein's parametrization

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

•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.

6. CP Violation in K decays

- CP violating $K_L \to 2\pi$ decays proceed via two different mechanisms:
- mixing (ϵ) and CP-violation in non-leptonic Hamiltonian (ϵ').

$$\text{define: } K_1(\text{CP} = +1), K_2(\text{CP} = -1)$$

$$K_S = N(K_1 + \epsilon K_2),\ K_L = N(K_2 + \epsilon K_1),\ \text{(CPT conserv. assumed)}$$

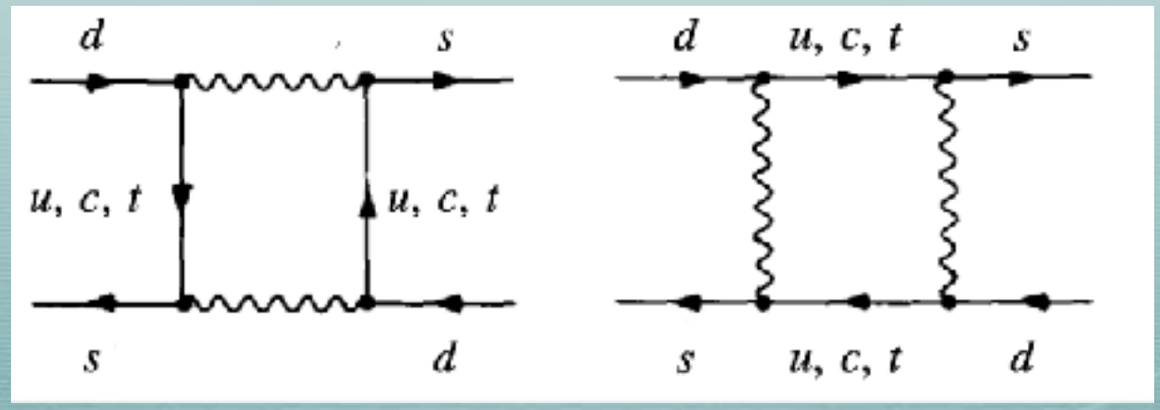
•(ϵ) is part of the $K^0 - \bar{K}^0$ mixing amplitude: 2nd order in the Weak Interaction, eventually with a contribution from a CP-violating Superweak Interaction

• (ϵ') competes with non leptonic interactions (at order G).

•In the Superweak theory, $\epsilon' = 0$,

•$\epsilon'/\epsilon \neq 0$ indicates a weak or milliweak nature of CP violation.

•In the Standard Theory ϵ arises from the familiar box diagrams, via the d-t, t-s couplings in the KM matrix, expected to be small: one expects a milliweak effect, even with a not-so-small CP violating phase.



Direct CP-Violation

•Starting from the definition of K_S, and K_L, one defines:

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)},\ \eta_{+-} = \epsilon + \frac{< K_2 | H_{NL} | \pi^+\pi^- >}{< K_1 | H_{NL} | \pi^+\pi^- >} = \epsilon + \epsilon'$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)},\ \eta_{00} = \epsilon + \frac{< K_2 | H_{NL} | \pi^0\pi^0 >}{< K_1 | H_{NL} | \pi^0\pi^0 >} = \epsilon - 2\epsilon'$$

•Non vanishing ϵ' requires a CP-violating component of H_{NL} (or T-violating, via CPT invariance), which is provided by the phase in the CKM matrix

- After several controversial results, a non vanishing value of ϵ'/ϵ has been established in 2001 by the KTeV (FermiLab) and NA48 (CERN) Collaborations, with the observation of the double ratio:

$$R = |\frac{\eta_{00}}{\eta_{+-}}|^2 = 1 - 6\mathscr{R}e(\epsilon'/\epsilon)$$

$\epsilon'/\epsilon \cdot 10^3 = 1.53 \pm 0.26$ (NA48); 2.07 ± 0.28 (KTeV) [PdG(2024) : 1.66 ± 0.23].

A. Lai et al. [NA48 Collaboration], CERN-EP-2001-067.
J. Graham [KTeV Collaboration], FNAL Seminar; R. Kessler, hep- ex/0110020.
see also M. Cirilli, arXiv:hep-ex/0111068 [hep-ex].

ϵ'/ϵ: *Theory*

Wolfenstein's parametrization

$\lambda = \sin\theta_C = 0.2253 \pm 0.0007$

$A = 0.808^{+0.022}_{-0.015}$

$\rho = 0.132 \pm 0.018,\ \eta = 0.341 \pm 0.013$

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

$(\bar{t}\gamma_\mu d_L)^*$ $\quad$ $\bar{t}\gamma_\mu s_L$

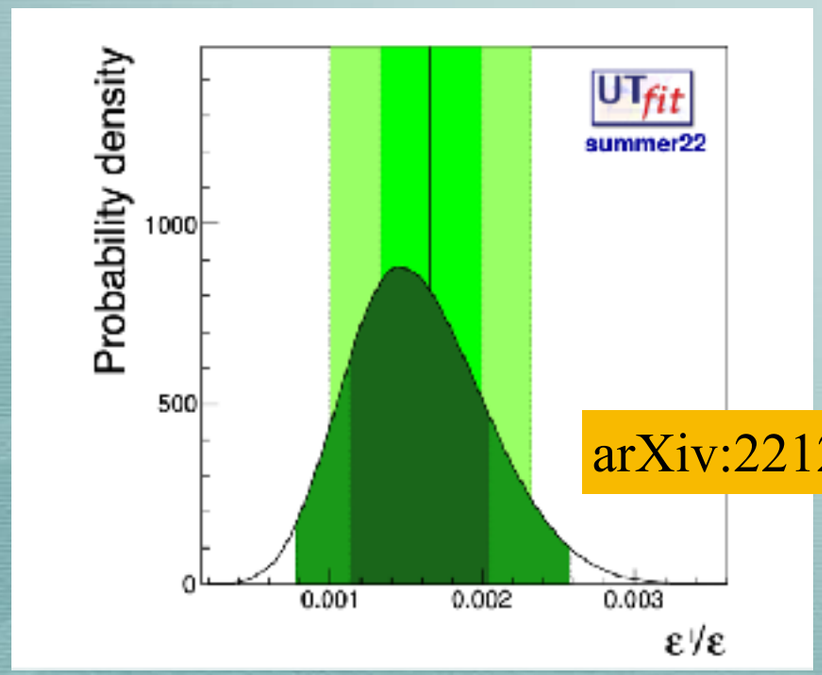
- CP violation is in the $t\bar{t}$ penguin

$$\frac{Im[\mathcal{O}_t]}{\lambda} = (-\eta A^2\lambda^4)\ (\bar{s}_L\gamma_\mu t^A d_L)(\bar{q}_R\gamma^\mu t^A q_R)$$

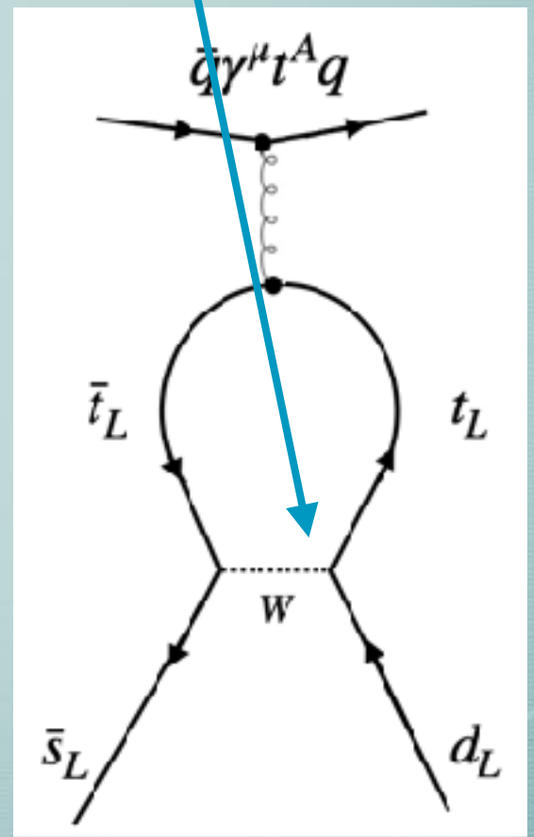
$$\eta A^2\lambda^4 \sim 0.5 \cdot 10^{-3}$$

- Theoretical predictions:
  $\epsilon'/\epsilon = \mathcal{O}(10^{-3})$

- a Lattice QCD result for ϵ'/ϵ



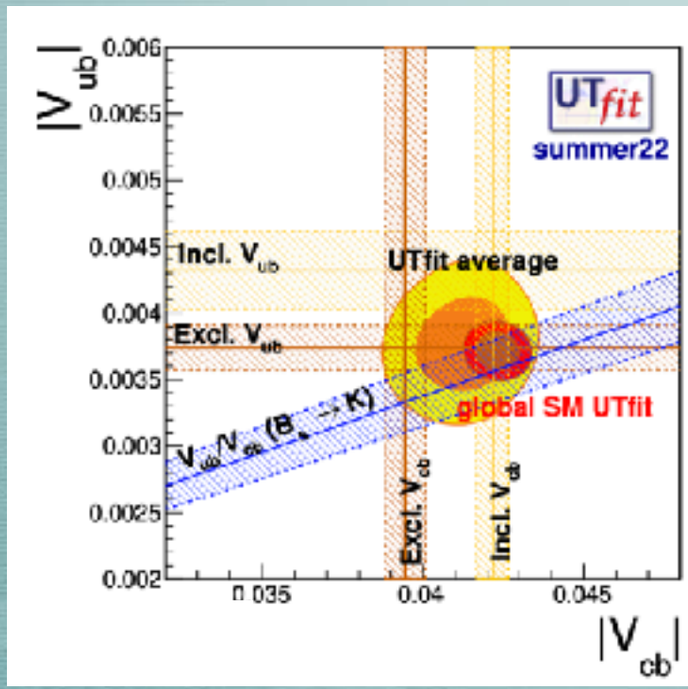
arXiv:2212.03894v1 [hep-ph]



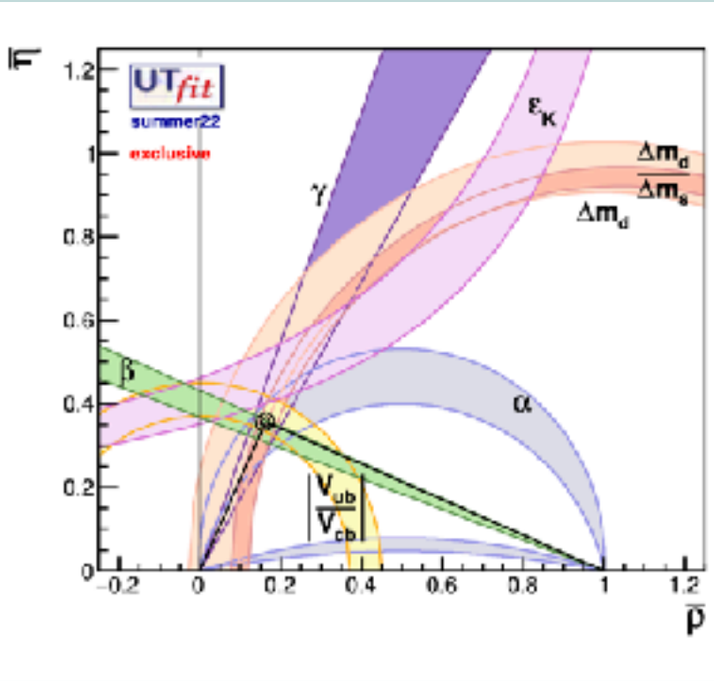
8. CP violation in B decays

CP **Violation in Heavy Flavor Decays: Predictions and Search Strategies.**
Ikaros I.Y. Bigi (SLAC) , A.I. Sanda (Rockefeller U.) . SLAC-PUB-3949, May 1986. 55pp.
Published in **Nucl.Phys.B281:41,1987**.

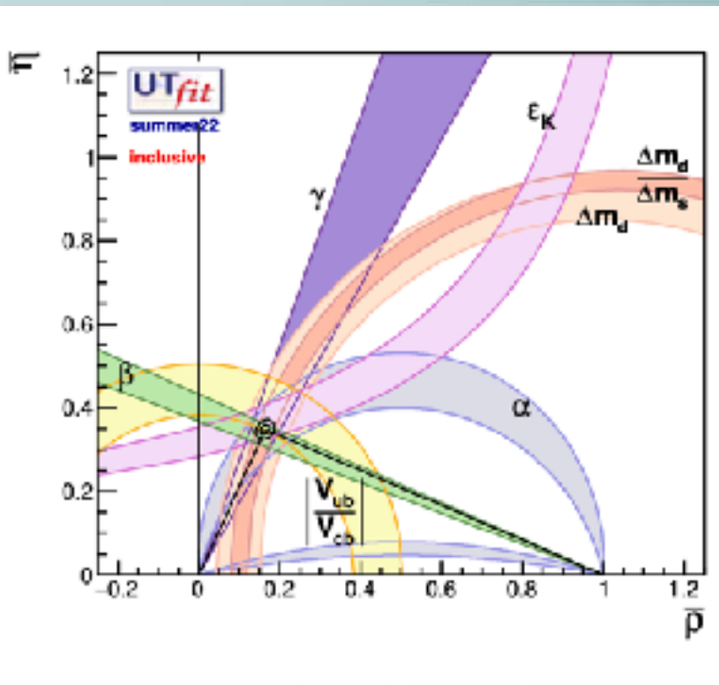
- 1986, I. Bigi and A. Sanda predict direct CP violation in B decay;
- 2001, Belle and BaBar discover CP violating mixing effects in B-decays.
- New impetus in theory calculations of V_{ub}, V_{cb}, f_B, …from particle phenomenology and Lattice QCD. Examples from the UT_{fit} Lattice Collaboration (arXiv:2212.03894v1 [hep-ph])



Ratio V_{ub}/V_{cb}



$\bar{\rho} - \bar{\eta}$ plane with ***exclusive*** inputs for V_{ub}, V_{cb}.



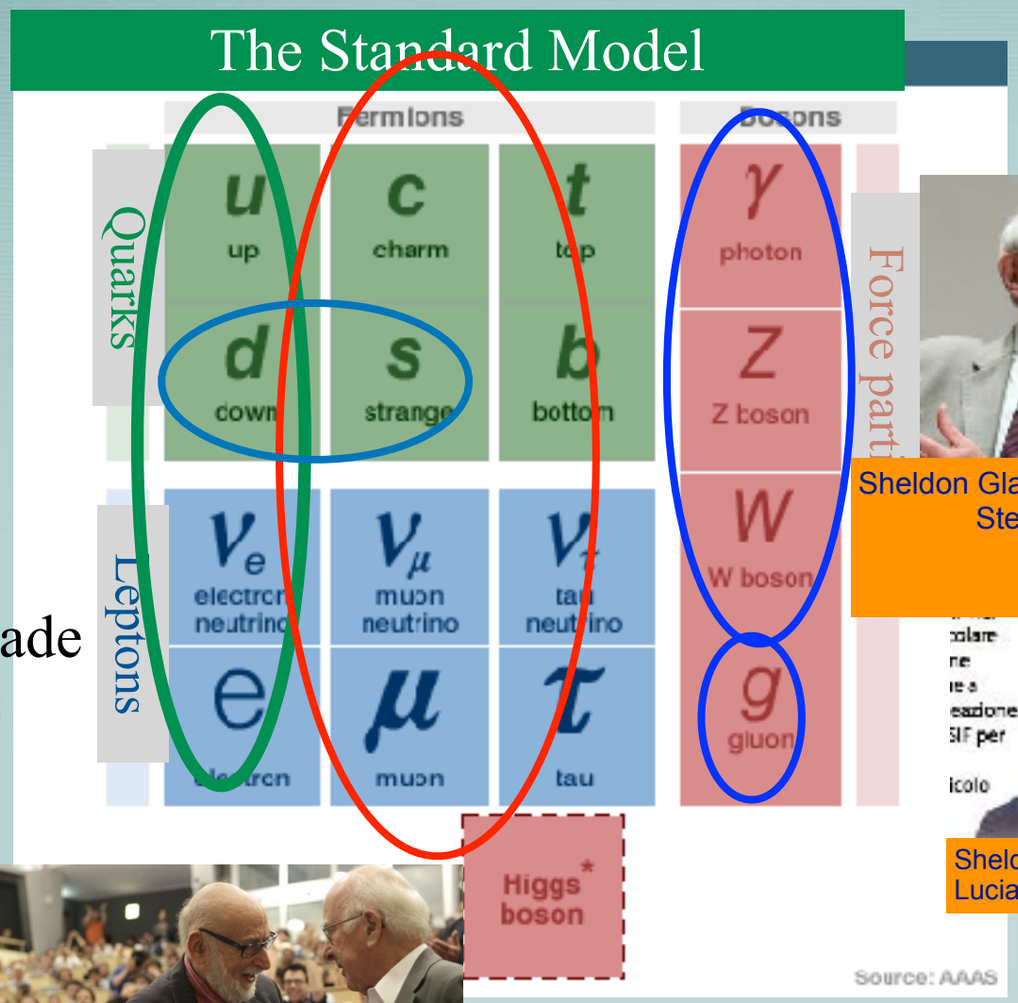
$\bar{\rho} - \bar{\eta}$ plane with ***inclusive*** inputs for V_{ub}, V_{cb}.

Constituents of matter and fundamental forces (circa 2005)



Murray Gell-Mann

Ordinary matter is made of the lightest quarks and leptons.





Nicola Cabibbo



Sheldon Glashow
Steven Weinberg
Abdus Salam
@ ICTP Trieste



Carlo Rubbia



Sheldon Glashow, John Iliopoulos, Luciano Maiani



Makoto Kobayashi , Toshihide Maskawa



Robert Englert e Peter Higgs



Heavier quarks are unstable: what is their role in the early Universe?

Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free
Gross&Wilczeck, Politzer (1973)