Weak Neutral Currents in Nature: a Thirty Year Retrospective*

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Abstract

Neutral Currents play an important role in nature. We trace the early history of Neutral Charged Weak Current studies from the 1930's to the discovery of the W and Z in 1983. In the 1960's the null search for Neutral Currents that change Family combined with models of Weak Neutral and Charged Currents and led to the concept of Natural Family Conservation in Neutral Currents. In rapid order: Weak Neutral Currents (WNC) were discovered in 1973, were well understood by 1978 and were followed by the discovery of the W and Z in 1983. Neutral Currents (NC) are important in Supernova Explosions and the Early Universe. The search for NC that change Family extends our study of the subatomic world into the incredible range of 100 TeV and is on-going today. The super colliders, SSC at Dallas, USA, and LHC in Geneva, Switzerland, will allow us to extend this search considerably.

1 The Early Concepts of the IVB and Neutral Currents

As is well known, the weak interaction was accidentally discovered by H. Beckerel in 1896 when he placed Uranium and a photographic emulsion in the same drawer only to observe the emulsion had become exposed. This was the discovery of the charged current weak interaction. It took 77 years longer to discover the neutral current weak interactions in 1973. In the intervening years there were repeated suggestions that there could be a neutral current interaction. The earliest explicit suggestion seems to have been made by Gamov and Teller in 1937. In the 1950's and 1960's there were many models of the weak force that included a neural component. In Fig. 1 we illustrate many of the proposals for extensions of the Weak Interaction and the Intermediate Vector Boson (IVB) concepts.[1]

After the point interaction of Fermi in 1932, the first attempt to unify the charged and neutral current interaction seems to have been carried out by Oscar Klien in 1938. However, the real search for WNC started in the early 1960's in rare K decays[2]. As illustrated in Fig. 1, there were many theoretical models that suggested that neutral currents may exist. Thus, there was no real lack of motive to search for WNC but a strong general theoretical prejudice against the search. In Fig. 2 I attempt to give a history of the search and discovery of various forms of neutral currents[1].

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The year 1993 is a banner anniversary for our understanding of nature: it marks the 10th anniversary of the discovery of the carriers of the Weak force: the W and Z particles at CERN, the laboratory near Geneva, Switzerland; the 20th anniversary of the discovery of the Weak Neutral Currents, and the 30th anniversary of the first revealing but null searches for Weak Neutral Currents that change the Quark Family! All of these developments have left a profound mark on our study of the most fundamental aspects of nature: "the Elementary Particles and their Forces". These observations helped develop the foundation of the Standard Model of Elementary Particles. This article is a partial celebration of this anniversary and an attempt to peer into the future implications and gain a perspective on these accomplishments. As in the telling of the history of any human accomplishments, it will appear more logical than when it actually occurred. We will also describe how the intervening years have taught us the way in which Neutral Currents contribute to Astrophysics and the Explosion of Supernova, will help in future possible break-throughs in the study of Elementary Particles and possibly even the very nature of life on Earth: the double helix structure of DNA, present in all life forms!

It can now be said the there have been three major advances in Physics during the past 100 or so years. The Theory of Relativity can be dated as taking place during 1905-1919: the development of Quantum Mechanics between 1913-1930: the experimental and theoretical formulation of the Standard Model of Elementary Particles (Rise of the Standard Model), which began around 1960 and continued until approximately 1983. Of course, there have been many other important advances in Nuclear Physics, Condensed Matter Physics, Cosmology and so forth. However, the three advances mentioned above are distinguished by having led to a nearly complete picture of a major area of fundamental science that has stood the test of time and verification by many experiments. The period of the "Rise of the Standard Model" was full of major theoretical and experimental discoveries. Among the most important events during this period was the discovery of Neutral Currents (NC) in 1973.

All three of the break-through mentioned above have one thing in common: the basic theory has been greatly tested by experiment very early. For General Relativity the observed deflection of Starlight by the Sun in 1919 was a crucial experiment. For the Quantum Theory it was the study of various Atomic Physics systems as well as the observation of the particle-like nature of light (Compton Effect) and the wave like-nature of matter (2-Slit Electron Interference Pattern). For the Standard Model of Elementary Particles the key period of experimentation was between 1974 and 1978. It was during this period that the newly discovered Neutral Currents were quickly confirmed and studied in numerous experiments around the world. Given the breadth of the physical phenomena involved, this was a truly remarkable period.

To trace the history of the Weak interaction, it is necessary to place particular emphasis on the discovery of NC and the underlying theory of the Standard Model. The impact of the discovery of NC on our understanding of nature could turn out to be as important as that of the Weak Interaction or Radioactive Decay, which was discovered by H. Bequerel in 1896, and which we now know to be a Charged Current interaction in contrast to the Neutral Current. By 1933, thirty-seven years later, the source of the energy of the Sun was shown to come from the Weak Interactions by Hans Bethe of Cornell University, illustrating the great significance of that discovery.

2 The Search for WNC's in the 1960's

In Table 1 we report the important milestones for the search for WNC in the 1960's[1]. There were many zigs and zags in the search due to the great difficulty of reflecting various backgrounds.

In 1963 a CERN neutrino group published a very low limit on WNC from their neutrino experiment of 0.03 (CERN Group, Physics Letters, 1964)[3]. See Fig. 3a (reproduced from the original article). This incorrect result diminished the prospects for detecting WNC and discouraged some groups (including a Wisconsin heavy liquid bubble chamber group) from searching for WNC in other proposed neutrino experiments. On the other hand, WNC could have been discovered in 1964, thus altering the history in this field considerably.

The null results of the WNC search reinforced much of the theoretical prejudice of the time, once again showing that sometimes experimentalists rely too heavily on the guidance of theory. On the other hand the search for WNC in the HPWF experiment benefited from S. Weinbergs advice, and it was for that reason that an "energy" trigger was installed in mid 1972 in that experiment.

However, even after the Weinberg-Salam Model was gaining acceptance the null results on WNC searches continued. In Fig. 3b I show the early limits on exclusive WNC channels up to 1972, when the limits were still well below the now measured values. This illustrates how difficult the discovery of WNC really was[1]!

3 The Significance of the Search for FCWNC in the 1960's

The concept of flavor was not well understood in the early and mid 1060's and it appeared that as good a technique as any to search for WNC was to study rare K decays. One of the earliest experiments set a limit of $\sim 10^{-6}$ on[4]

$$K^+ \rightarrow \pi^+ e^+ e^-$$

The limits on FCWNC were summarized in a report I wrote in 1967 (see Fig. 4a), which included $K \rightarrow \mu\mu$ and the search $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ from my early work[5].

In 1965-1970 a crucial search for

$$K^+ \rightarrow \pi^+ \nu\bar{\nu}$$

was started. This search was a pure FCWNC process, whereas all other searches had charged particles in the final state and may have been affected by electromagnetic interaction, as some people claimed. The history of the search for this decay mode is given in Fig. 4b; it continues today (see Fig. 4a as well)[1, 4].

By 1970 the correct CERN limit on WNC and the extremely strong limits on FCWNC caused most people to believe that neutral currents did not exist in nature. The GIM model was invented and showed that[6]

1. FCWNC could be suppressed in certain models
2. A hadron-lepton symmetry existed

Today the GIM mechanism has only been tested for light quarks. *Charm* and *B* quarks are a rich ground in which to continue the search for FCWNC and the search for FCWNC has started there.

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4 The 1973 Period: The HPWF Experiment

In 1973 the HPWF experiment at FNAL turned on[9]. Almost at the start 'μ-less' neutrino events were observed. Rumors of similar events at CERN set into motion an intense competition[10]. The HPWF group actually performed 2 complete experiments in 1973 and, after considerable confusion, the issue was fully resolved by December of that year. The early limit on WNC and the strong limits on FCWNC played a role in the HPWF groups confusion. However, along with the GGM evidence, the existence of WNC was fully established at this point, in 1973! The book and reports by Peter Galison gives an accurate Account of this period of history, in my opinion[11].

By 1973, when the Fermi National Accelerator Laboratory (FNAL) neutrino beam was just being commissioned and a large detector built by the experimental groups from Harvard, Penn and Wisconsin (HPW), the very large bubble chamber, Gargamelle, was taking copious data at CERN: the issue of the existence of NC was coming to a boil! It was in this year, starting with Gargamelle and the HPW experiments, that NC were observed (see Table 1). I was privileged to be the spokesperson for the HPW experiment and have the opportunity to live through the trials and tribulations of the discovery of neutral currents, having created some of them myself. The other senior members of the HPW team were A.K. Mann of Penn and C. Rubbia of Harvard.

The discovery of NC was not easy and the two experimental groups that were involved in the action in 1973 were anything but placid. In contrast, the early search for WNC was plagued with incorrect but placid results as recorded in Table 1. There were rumors and rumors of rumors, passing back and forth across the Atlantic between Batavia, Illinois (HPW) to Geneva, Switzerland (Gargamelle). Some of the messages were even being carried by members of one or the other team, since both groups had an international constitution.

The first to report a positive result was the Gargamelle Bubble Chamber group. But the HPW group's first data taking in 1973 showed a very large excess of the NC events and an early scientific paper was sent to a journal a few days after that of its European rival. Unfortunately, the paper sent by the HPW group was returned by the paper's referee for clarification, although it was later published.

During the discovery period of 1973, a complex set of events occurred. Fig. 2 shows an attempt to represent this sequence. For a more complete description one can recommend the book and various articles by Peter Galison, who has made a careful study of the historical events.

5 The Period Between 1973 – 1983

During the period between 1973 - 1977 an incredible synthesis occurred. The value of

$$\sin^2\theta_W = 0.25 \pm 0.04,$$

consistent with the present data from LEP of

$$\sin^2\theta_W = 0.230 \pm 0.002$$

was measured. All the data was described by two parameters, $\sin^2\theta_W$ and ρ, and many different types of data were involved. Fig. 5 gives an account of this period by the value of $\sin^2\theta_W$ that was being measured[1].

In 1977 parity violation in atoms was discovered at Novosibirsk and in 1978 at SLAC. The full $SU(2) \times U(1)$ model had been accepted by the high energy community by 1978. Thus, in a four year period WNC were understood whereas the corresponding understanding of charged currents took more than 30 years.

In 1976 an idea was put forward by C. Rubbia of CERN, P. McIntyre of Texas A & M and the author to convert either the CERN or FNAL Synchrotron to a proton-antiproton collider in order to discover the W and Z particles[12]. In 1983 the W and Z were discovered at CERN, the pinnacle of the Rise of the Standard Model!

While the parameters of WNC were being understood in the incredible period of just 3 – 4 years, several of us started to plan how to detect the W and Z bosons. The $\bar{p}p$ collider idea had been born in 1976 and the W and Z discovered in 1983. (Some of the members of the HPWF team were part of that discovery.)

During the period of 1975 - 1978 the value of $\sin^2\theta_W$stablized to the level of 0.22 - 0.25, implying a mass of the W and Z in the range of (78,85) and (82,92) GeV (see Fig. 5). At this point it was realized by Cline, Rubbia and McIntyre that a $\bar{p}p$ collider, with the center of mass energy of 600 GeV or greater, could be used to discover the W and Z, which they proposed. This concept was carried out at CERN where the W and Z were discovered in 1983. (This was the subject of another conference at UCLA in 1993.)

The completion of the Rise of the Standard Model occurred during the period of 1974 - 1978, when the WNC parameters $\sin^2\theta_w$ and ρ were measured in different reactions and found to be the same values within errors. The role of the null searches for FCNC on the Standard Model is illustrated in Table 2. The example of the measurement of $\sin^2\theta_w$ is shown in Figs. 5a and 5b. Future studies of Atomic Parity Violation may reach the same level of precision as LEP and thus be valuable to search for physics beyond the standard model.

6 The Future

The future study of elementary particles depends partially on two factors: (1) the detailed and precise measurements of NC parameters and (2) the continued search FCNC. LEP in Geneva, Switzerland, is being used to study the Z^0 by the millions and has improved our knowledge of the NC parameters. The key to future measurements are the Radiative Corrections to the Standard Model. So far, no direct evidence for Radiative loop corrections has been obtained from the several million Z^0 studied at LEP. Fig. 6a shows the kind of tools that will be used in the future to refine these measurements. By the year 2000, $\sin^2\theta_w$ may be known to better than four decimal points, an incredible accomplishment in 25 years of study!

The search for Neutral Currents that change Quark Flavor (FCNC) is also entering into a sensitive period. Fig. 6b shows one such experiment where the b (Beauty) quark to s (Strange) quark transition

$$b \rightarrow s + X^0 \quad \hookrightarrow \ell + \bar{\ell} \tag{1}$$

is being searched for. We can consider the X^0 particle to indicate a new level of substructure in physics. The most sensitive search to date was carried out at the CERN $\bar{p}p$ collider by the authors group [13]. The current limits in FCNC are shown graphically for several important processes in Fig. 6c and 6d. The other interesting FCNC process (s quark to d (Down) quark)

$$s \rightarrow d + X^0 \quad \hookrightarrow \nu + \bar{\nu} \tag{2}$$

can be searched for by the reaction

$$K^+ \rightarrow \pi^+ + \nu + \bar{\nu} \tag{3}$$

This search was started in 1965 by the author in order to search for a clean example of FCNC and continues today (see Fig. 6c). The level of sensitivity to the mass of the X^0 particle has now reached well beyond 10 TeV, the Superconducting Super Collider (SSC) energy. Future experiments can extend the range to 100 and even possibly 1000 TeV, far beyond that available to the SSC or LHC Super Colliders. Fig. 6a and b show the history of the limits on the search for FCNC both in the rates (b) and amplitudes (a)[13].

While the earliest searches for Flavor Changing Neutral Currents used the decay of K mesons and failed to observe neutral currents, we now know that these null results are a key component of the Standard Model. In the simplest version there is a sort of Flavor Conservation built into the Neutral Currents which in turn prescribes that only two types of quarks should exist in nature: charges $Q = -1/3$ and $Q = 2/3$. In other words, one of the great successes of the Standard Model is <u>the inability to observe Neutral Currents that change the Flavor of the quark</u> (Table 2)[1]. In contrast, the <u>observation of even a tiny FCNC signal</u> would imply structure beyond the Standard Model!

What can we hope to discover with such precise measurements of NC or searches for FCNC: A process that goes beyond the Standard Model to possibly illuminate the physics waiting there. We strongly believe that there should be some new substructure in the energy range from the W and Z to the Planck Scale, $\sim 10^{19}$ GeV. As illustrated in Fig. 7, the Rise of the Standard Model had many players. With the current excellent agreement between the LEP (5 million Z^0's) and the Standard Model, the search for FCNC is even more important!

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Table 1

SOME MILESTONES IN THE SEARCH FOR WNC
(1962 - 1973)
(D. Cline)[1]

	MILESTONES	COMMENTS
1962	BNL Neutrino Experiment Detects 2nd Neutrino: Unusual Events noted in PhD students Thesis (Little Cràppers)	Strange events are likely incorrect associated with neutrons from the shield
1964	CERN Bubble Chamber Group*(a)* Reports a limit of 3% for WNC	Reason for this incorrect limit later given in 1970 paper
1967	E.C. Young Thesis at Oxford notes *Neutral Current-like Events* exist in Data	
1967	Large Heavy Liquid Bubble Chamber studied by the MURA-Wisc.-UCB Group to Search for WNC ($\nu_p \rightarrow \nu_p$) at ANL Later Proposed for BNL then Rejected! Proposed for BNL then Rejected!	Gargamelle Bubble Chamber already approved Incorrect CERN limits on WNC Discourage other Experimenters
1969	HPW Experiment Proposed - Only Mention of Neutral Currents is for Leptonic Processes	'64 Limit on WNC Makes Search for This Process Difficult so Leptonic Processes Considered
1970	CERN Group Revises '64 Limit *(b)* on WNC to $\sim$ 12%	
1972	Schwartz-Mann-SLAC *Black Hole* Experiment finds Some Neutral Current-like Events	Too Few Events to make Conclusive Arguments
1972	Perkins Reports Limits on WNC at FNAL Meeting	Limit still Below Currently Observed Values
1973	Gargamelle HPW	Struggle with Large WNC Signal (see Ref. 12)

(a) M. M. Block, et al. Phys. Rev. Lett. 12 (1964)
(b) D. Cundy, et al., Phys. Lett. 31B 479 (1970)

Table 2

IMPACT OF FCNC SEARCH ON THE RISE OF THE STANDARD MODEL

PROCESS	PERIOD	IMPLICATION
$s \not\to d$ $(K^+ \to \pi^+ \nu\bar{\nu})$	$\sim$ 1963 $\sim$ 1970	FCNC Absent at first level of Weak Interaction [GIM Mechanism]
$s \not\to$ Loop $\not\to d$ $K^0 - \bar{K}^0$, $K_S - K_L$ mixing	$\sim$ 1960 – 74	New quark in Loop, $m_q \sim 2\,\mathrm{GeV}$ *(Charm)*
$s \not\to d$ $c \not\to u$ etc.	$\sim$ 1970's	Natural Flavor Conservation for NC implies only $Q = -1/3$, $Q = 2/3$ quarks exist in doublets in nature
$b \not\to d$ $b \not\to s$, $B^0 - \bar{B}^0$ mixing	$\sim$ 1980	Necessary existence of (massive) t quark
STRONG LIMITS ON		
$s \not\to d$ $b \not\to d$ $\nu_e \not\to \nu_\mu$ $K \to \mu_e$	$\sim$ 1990's	Limits on supersymmetric interactions and other exotics

INTERMEDIATE VECTOR BOSON HISTORY

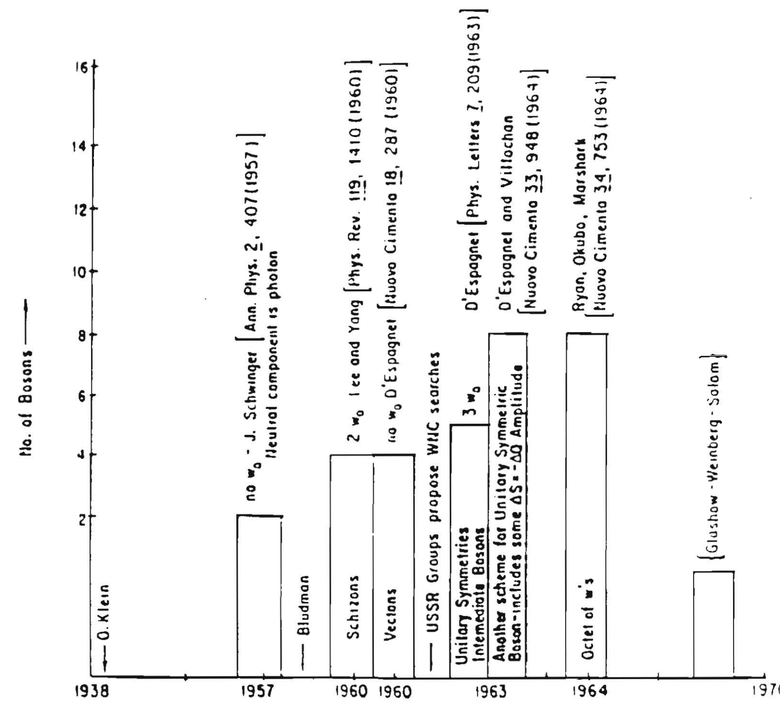

Fig. 1: Intermediate vector boson history

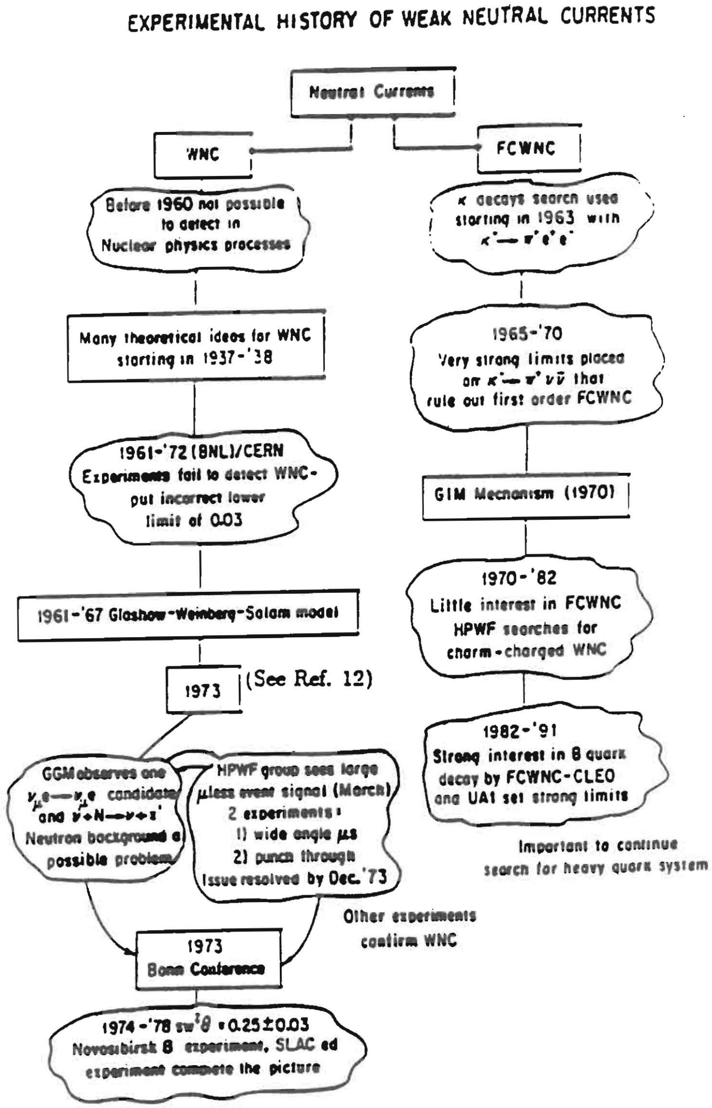

Fig. 2: Experimental history of Weak Neutral Currents

Other conclusions. A number of other fundamental questions were discussed in our previous report [1], their present status is:

Violation of muon number conservation

$(\nu_e \neq \nu_\mu) < 1\%$;

Violation of leptonic conservation $< 6\%$

($\Delta S = 0$, nuctral current coupling / $\Delta S = 0$, charged current coupling) $< 3\%$;

Neutrino flip intensity / no neutrino flip intensity

$$= \frac{K \to \mu + \nu_e}{K \to \mu + \nu_\mu} < 10\%$$

A boson has been postulated which produces a resonance of the type $\nu_\mu + n \to W_{\mu'} \to \mu^- + \mathrm{p}$. If its properties are as predicted [10, 11] its mass is $> 5.5\,\mathrm{GeV}$.

Fig. 3a: Limit on Weak Neutral Currents from the CERN Group (published in Phys. Letts., 1964)

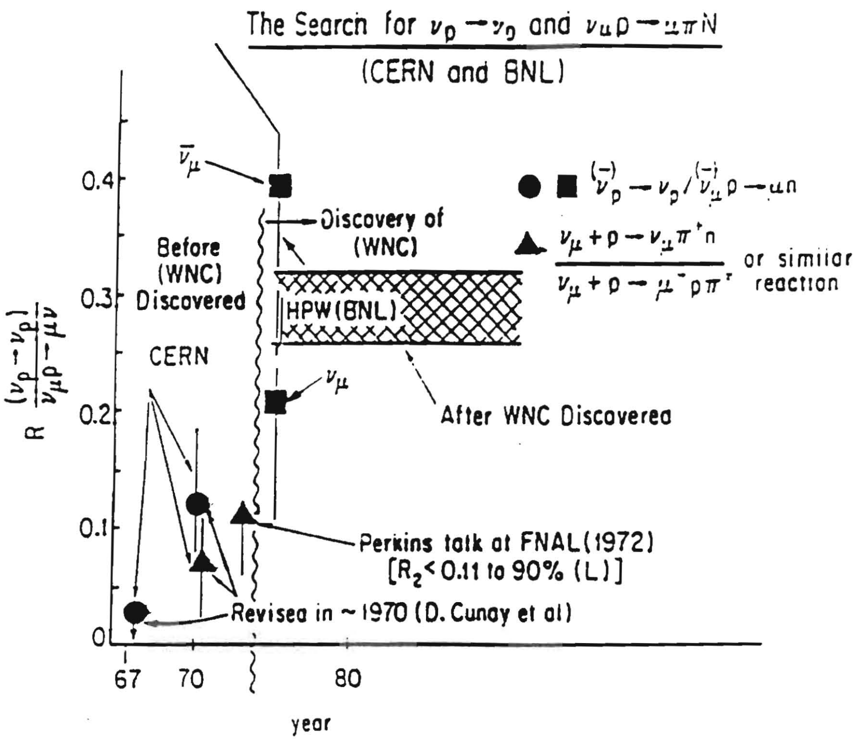

Fig. 3b: CERN results (1967 - 1972) were well below the current and observed value of the Weak Neutral Current level after 1973 - 1974

Best Experimental Limits on

Neutral Current K Decays

Process	Branching Ratio	Coupling Constant Ratio	Upper Limit on the C.C. Ratio	Reference
$K^+ \to \pi^+ e^+ e^-$	$< 8.8 \times 10^{-7}$*	$g^V(e^+e^-)/g^V(e^+\nu_e)$	7×10^{-4}	Cline, et al.[5,6]
$K^+ \to \pi^+ \mu^+ \mu^-$	$< 3 \times 10^{-6}$	$g^V(\mu^+\mu^-)/g^V(\mu^+\nu_\mu)$	1.4×10^{-2}	Camerini, et al.[6]
$K^+ \to \pi^+ \nu\bar{\nu}$	$< 1.1 \times 10^{-4}$	$g^V(\nu\bar{\nu})/g^V(e^+\nu_e)$	6×10^{-2}	Cline[8] $55 < T_\pi < 80$ MeV
$K_2^0 \to \mu^+ \mu^-$	$< 1.6 \times 10^{-6}$	$g^A(\mu^+\mu^-)/g^A(\mu^+\nu_\mu)$	7.4×10^{-4}	Bott-Bodenhausen, et al.
$K_1^0 \to \mu^+ \mu^-$	$< 7.3 \times 10^{-5}$	$g^A(\mu^+\mu^-)/g^A(\mu^+\nu_\mu)$	1.6×10^{-3}	Bott-Bodenhausen, et al.
$K_2^0 \to \pi^0 \mu^+ \mu^-$	No estimate	$g^V(\mu^+\mu^-)/g^V(\mu^+\nu)$	no estimate	
$K_2^0 \to \pi^+ e^+ e^-$	No estimate	$g^V(e^+e^-)/g^V(e^+\nu_e)$	no estimate	
$K^+ \to \pi^+ \pi^0 e^+ e^-$	$< 8 \times 10^{-6}$		no estimate	Cline[3]
$K^+ \to \pi^+ \mu^+ e^-$	$< 3 \times 10^{-5}$		violates lepton conservation	Cline[8]
$K_2^0 \to \mu^\pm e^\mp$	$< 9 \times 10^{-6}$		violates lepton conservation	Bott-Bodenhausen, et al.

*All estimates are 90% confidence limits

Fig. 4a: The limits on Flavor Changing Weak Neutral Currrents from a 1967 summary of D. Cline

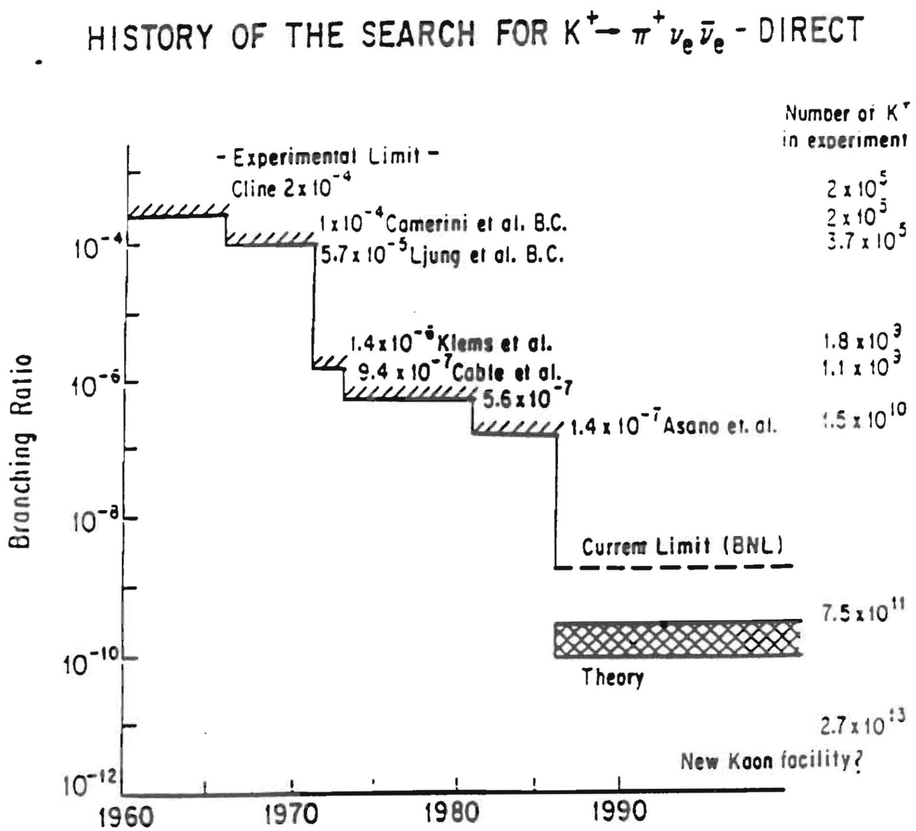

Fig. 4b: Search for $K \to \pi\nu\bar{\nu}$ – direct Flavor Changing Weak Neutral Currents

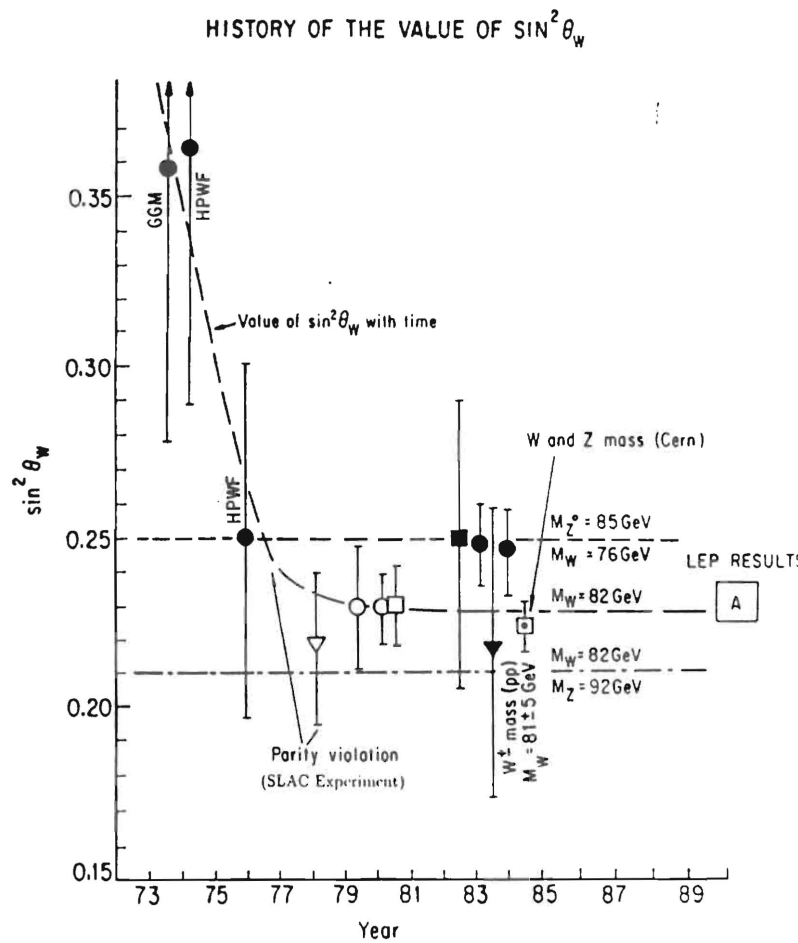

Fig. 5a: The history of the value of $\sin^2\theta_W$

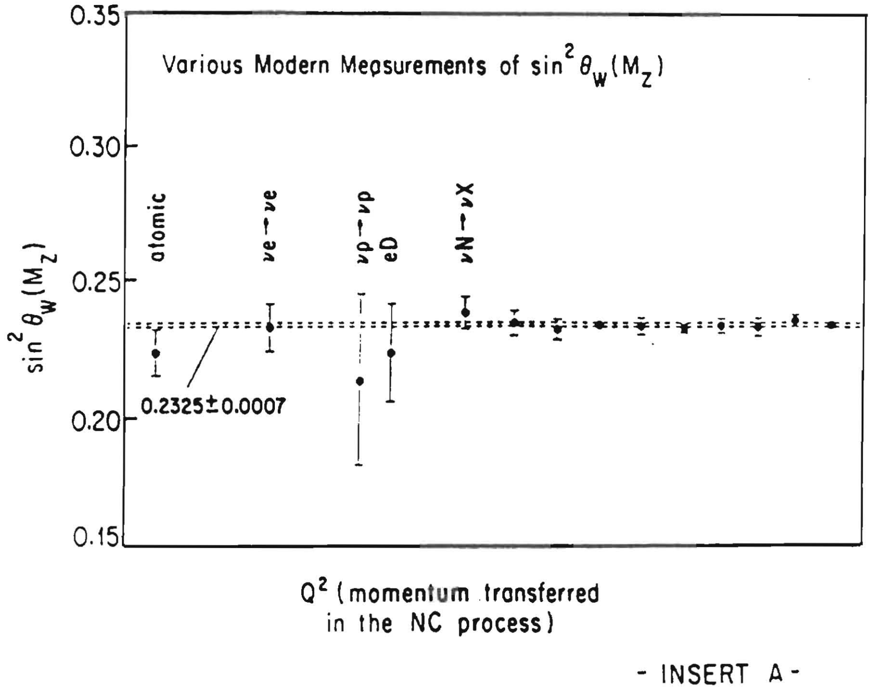

Fig. 5b: Insert A of Fig. 5a

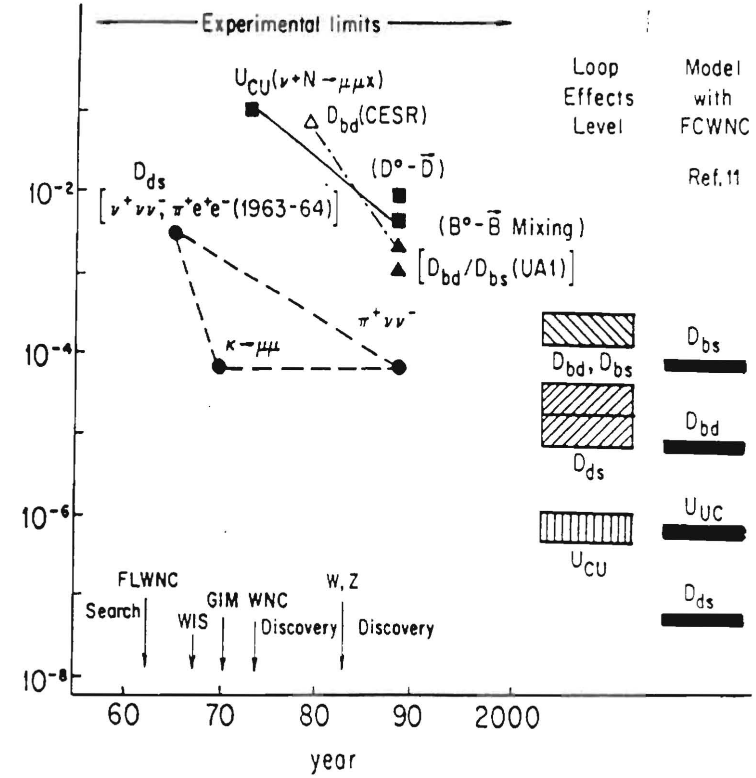

Fig. 6a: History of the search for Flavor Changing Weak Neutral Currrents from the early 1960's to the present

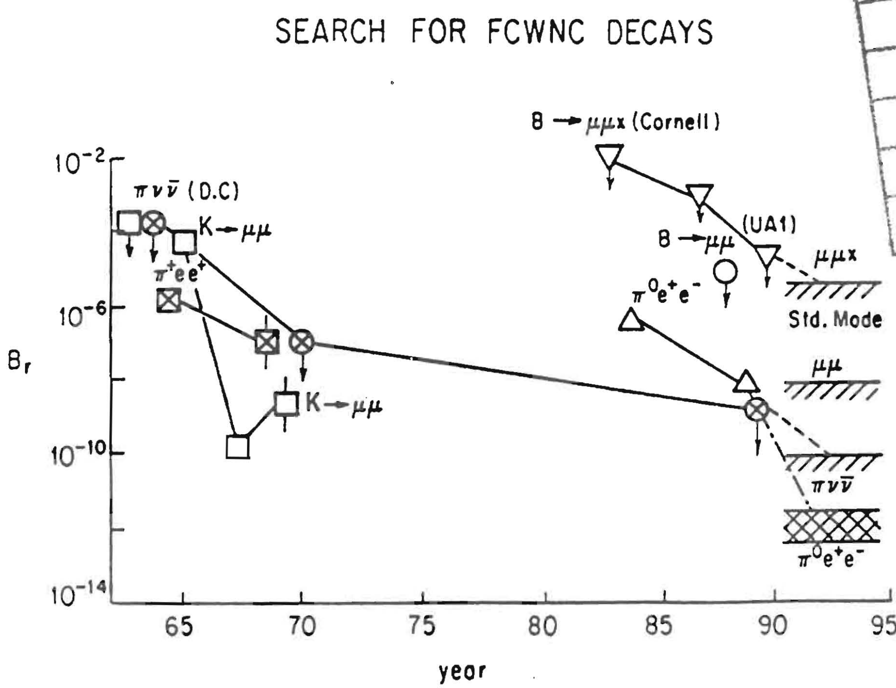

Fig. 6b: Search for Flavor Changing Weak Neutral Current Decays

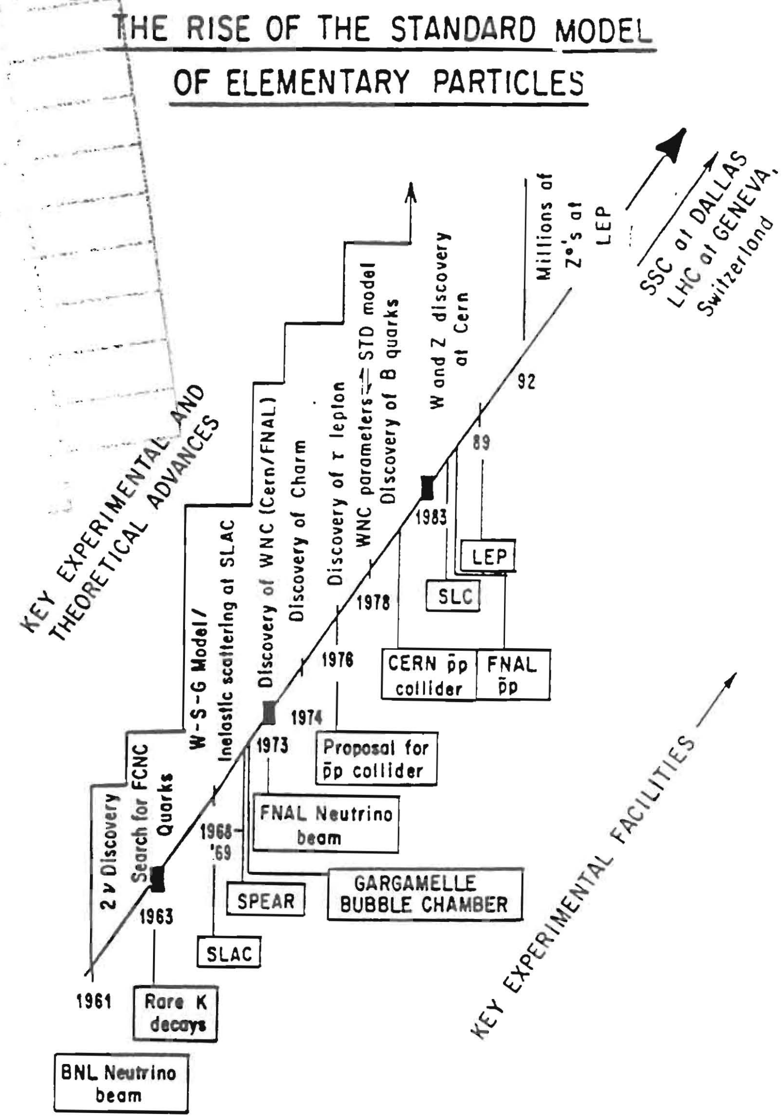

Fig. 7: The rise of the Standard Model