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THE ROLE OF THE SEARCH FOR FLAVOR CHANGING WEAK NEUTRAL CURRENTS IN THE RISE OF THE STANDARD MODEL*

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ABSTRACT

If history had been kinder or scientists luckier, flavor conserving weak neutral currents (WNC) would have been discovered at CERN or BNL in 1964 and then an intense search for flavor changing weak neutral currents (FCWNC) would logically have been initiated. In reality it happened in reverse order, detailed, sensitive and null searches for FCWNC started in the early 1960's and we will briefly review this important search. The limits set in these searches by 1970 were so impressive that the GIM model was partially invented to explain them and thus a *rise of the standard model* component emerged. These limits on FCWNC and an incorrect limit on WNC also set the stage for the search and discovery of WNC in 1973 and provided some of the confusion for the HPWF group's detection of WNC in 1973. While WNC are now well studied, the quest for FCWNC signals still continues and we believe the heavy quark system is likely to be the most sensitive to new physics. This paper also presents comments on the history of the discovery of *Charm*.

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1. INTRODUCTION

The search for Weak Neutral Currents (WNC) started in the early 1960's in rare K decays[1] . As illustrated in Fig. 1, there were many theoretical models that suggested that neutral currents may exist[1] . 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.

2. THE IMPACT OF THE FAILURE TO OBSERVE WNC AT CERN

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). See Fig. 3a (reproduced from the original article)[2] . 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.

3. THE IMPORTANCE OF THE EARLY SEARCH FOR FCWNC

The concept of flavor was not well understood in the early and mid 1960s 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[1,3]

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

The limits on FCWNC were summarized in a report I wrote in 1967 (Fig. 3b), which included $K \rightarrow \mu\mu$ and the search $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ from my early work.

In 1965 – 1970 a crucial search for[4,5]

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

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 interactions, as some people claimed. The history of the search for this decay mode is given in Fig. 4a; it continues today[6,7] (see Fig. 4b as well).

By 1970 the incorrect 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[8]

(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[6,7] .

4. THE 1973 PERIOD: THE HPWF EXPERIMENT

In 1973 the HPWF experiment at FNAL turned on. Almost at the start 'μ-less' neutrino events were observed[9,10] . Rumors of similar events at CERN set into motion an intense competition. 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] .

5. THE PERIOD BETWEEN 1973 – 1977

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.

In 1977 parity violation in atoms was discovered at Novosibirsk and in 1978 at SLAC. The full SU(2) × U(2) 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.

6. THE PRESENT AND FUTURE: 1980 – 1991

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[12] . 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[12] . This concept was carried out at CERN where the W and Z were discovered in 1983. (This will be the subject of another conference at UCLA in 1993.)

The search for FCWNC, especially in heavy quark systems, goes on today. This part of the story is not over! The history of the search for FCWNC is shown in Fig. 4b[6,7] .

7. POSTSCRIPT: THE HISTORY OF THE DISCOVERY OF CHARM

In addition to the discovery of WNC, the neutrino experiments provided the first real evidence for *charm*:

(i) $\mu^+\mu^-$ events in 1974 in HPWF[13]

(ii) Σ_c in the BNL Bubble Chamber (discussed by N. Samios at this meeting)

(iii) μe events in the FNAL Bubble Chamber

Thus FCWNC decays of *charm* would have been detected, such as

$$\nu_\mu + N \rightarrow \mu + C\,(\text{FCWNC})$$
$$\hookrightarrow \mu^+\mu^-$$

And it was from these experiments that the first limits on *charm* changing FCWNC came (D. Cline, meeting at BNL in 1976).

In terms of the amplitudes for FCWNC that can be expected from loop effects or various models that break GIM giving Tree Level FCWNC, I show the current limits on FCWNC and some expectations in Fig. 4b. Note that the heavy quark system search is far from complete. Thus, the story of Weak Neutral Currents may not be over yet!

8. ACKNOWLEDGEMENTS

During my graduate training period I was introduced into the world of weak interactions and rare decay modes by Jack Fry, Ugo Camerini and Wilson Powell. Later I benefitted from working with Al Mann, Carlo Rubbia and many other fine scientists in HPWF and UA1 and other experiments. We are all indeed fortunate to have been a part of the incredible rise of the standard model during the period covered in by this conference. I wish to thank the Aspen Institute for Physics for the hospitality to complete this paper.

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FIGURE CAPTIONS

FIG. 1: Intermediate Vector Boson History.

FIG. 2: Experimental History of Weak Neutral Currents.

FIG. 3a: Limit on WNC from the CERN Group, Published in Phys.Letts. (1964).

FIG. 3b: The Limits on FCWNC from a 1967 Summary of D. Cline.

FIG. 4a: Search for $K \rightarrow \pi\nu\bar{\nu}$ – Direct FCWNC.

FIG. 4b: History of the Search for FCWNC from the Early 1960s to the Present.

FIG. 5: History of the value of $\sin^2\theta_W$ and M_W / M_Z.

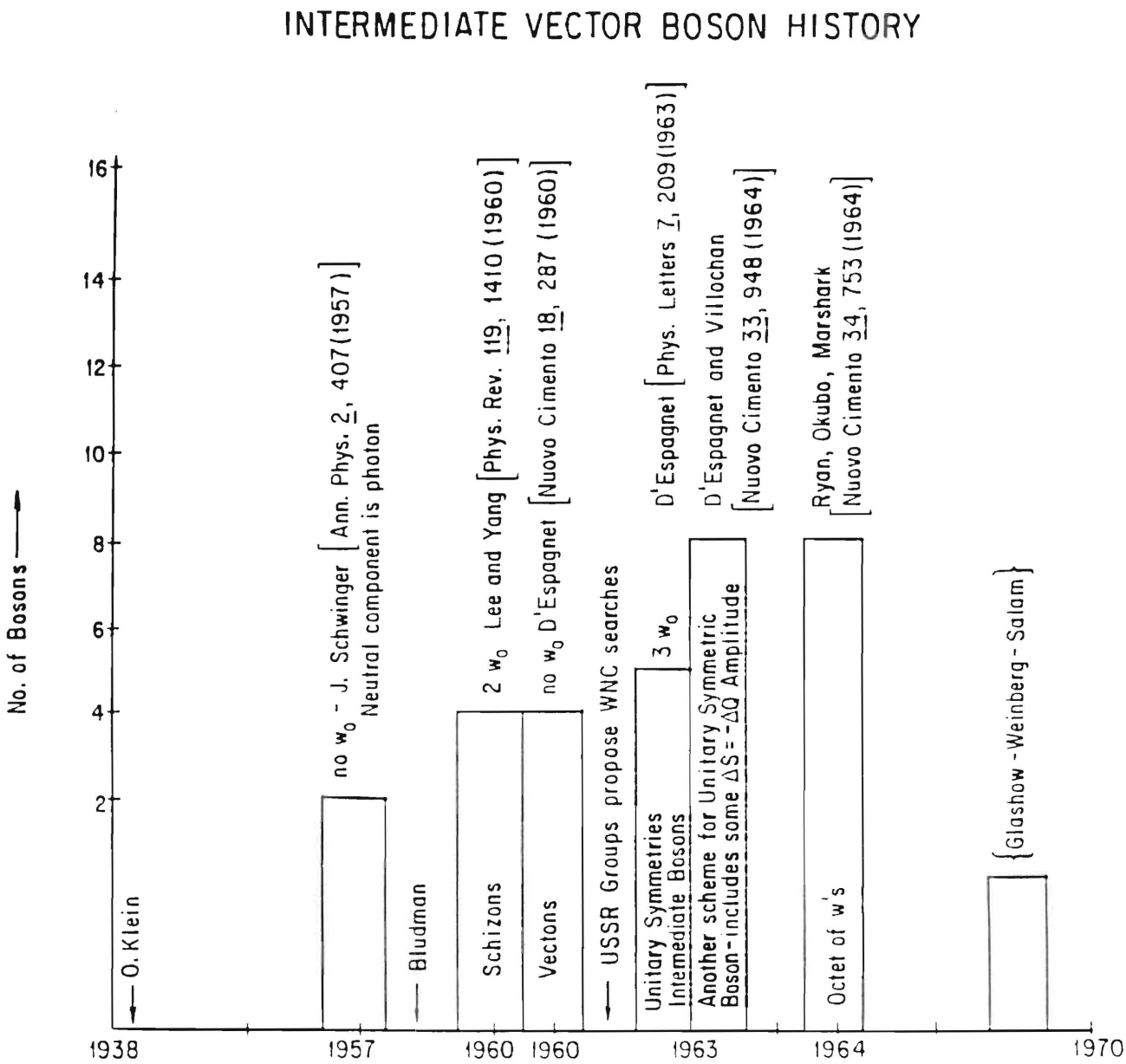

FIG. 1: Intermediate Vector Boson History.

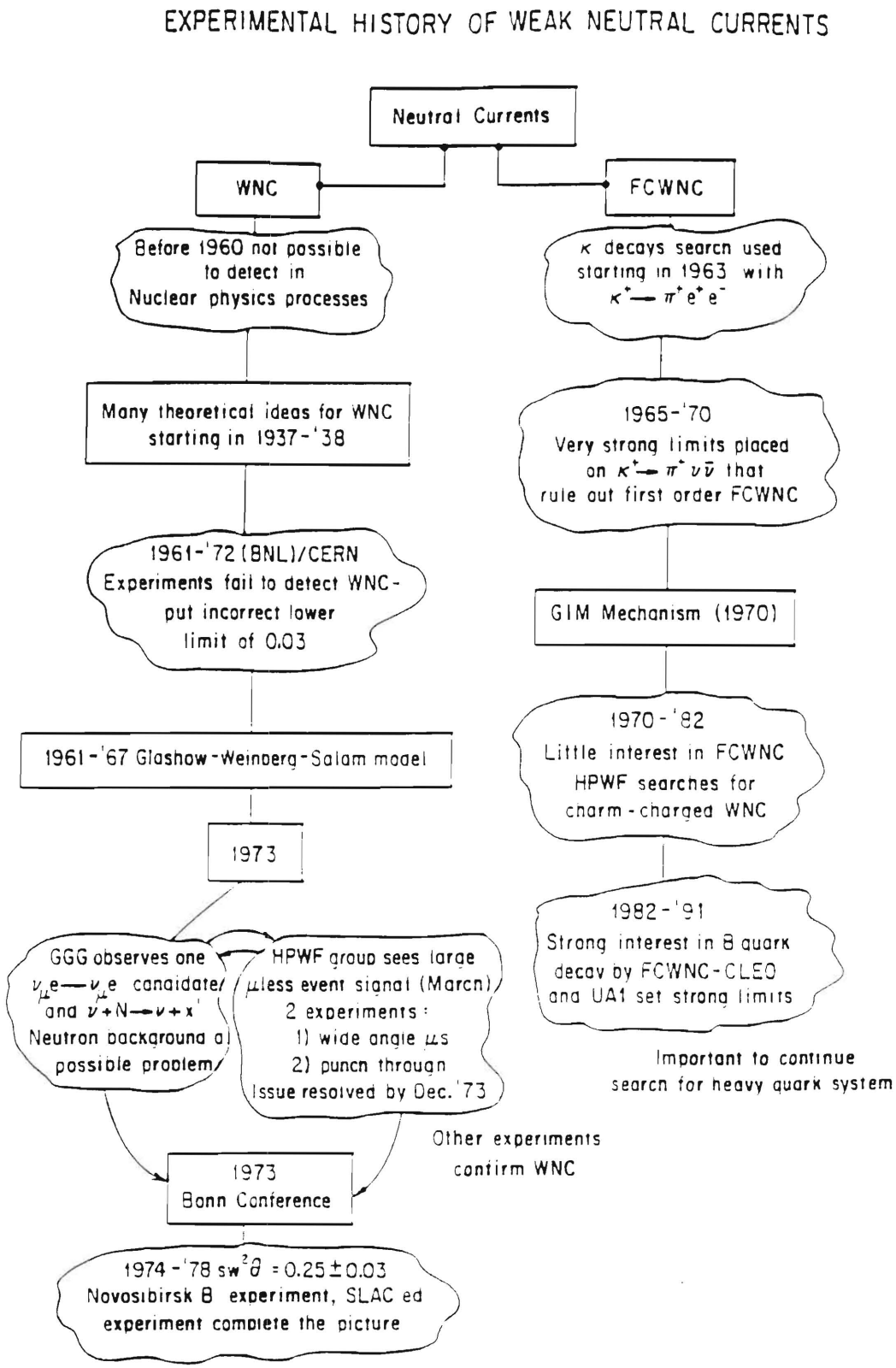

FIG. 2: Experimental History of Weak Neutral Currents.

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%;

($\Delta S = 0$, neutral 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 $\nu_\mu + n \to W_\mu' \to \mu^- + p$. If its properties are as predicted [10, 11] its mass is > 5.5 GeV.

FIG. 3a: Limit on WNC from the CERN Group, Published in Phys.Letts. (1964).

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] $35 < T_\pi < 80$ 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 [7]
$K_1^0 \to \mu^+\mu^-$	$< 7.3 \times 10^{-5}$	$g^A(\mu^+\mu^-)/g^A(\mu^+\nu_\mu)$	1.6×10^{-3}	Bott - Bodenhausen et al [7]
$K_2^0 \to \pi^0\mu^+\mu^-$	No estimate	$g^V(\mu^+\mu^-)/g^V(\mu^+\nu)$	no estimate	
$K_2^0 \to \pi^0 e^+ e^-$	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 [8]
$K^+ \to \pi^+\mu^+ e^-$	$< 3 \times 10^{-5}$		violates lepton conservation	Cline [8]
$K_2^0 \to \mu^\pm e^\mp$	$< 9 \times 10^{-6}$		violates lepton conservation	Bott - Bodenhausen et al [7]

*All estimates are 90% confidence limits

FIG. 3b: The Limits on FCWNC from a 1967 Summary of D. Cline.

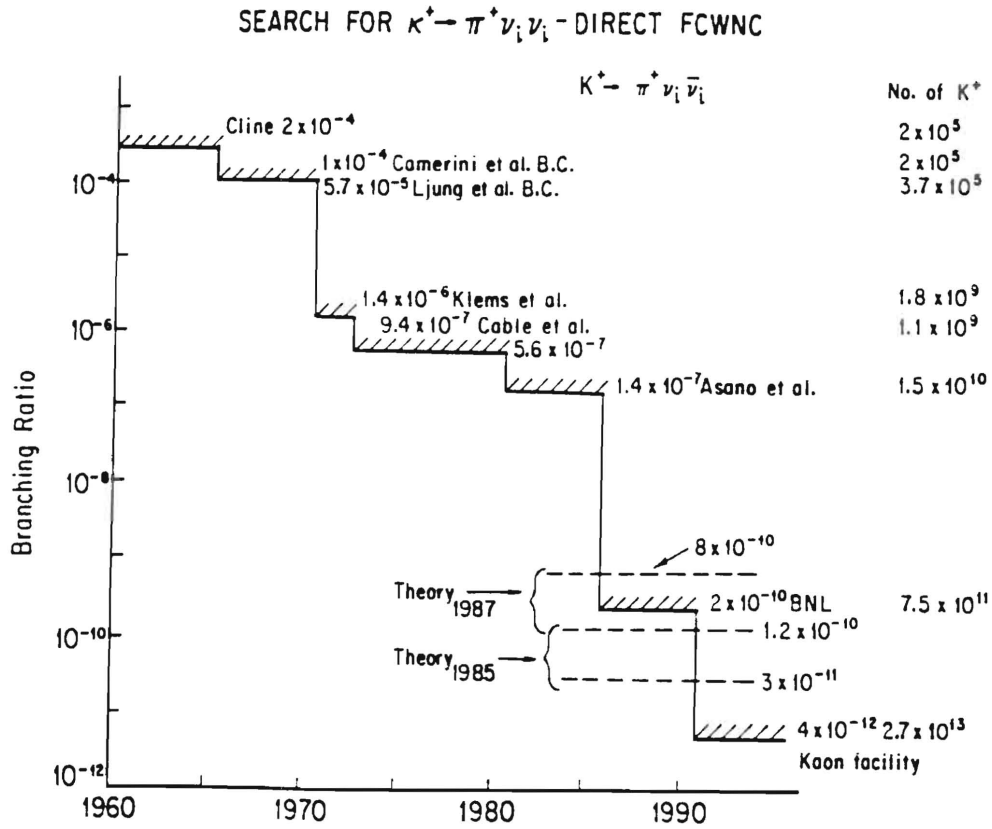

FIG. 4a: Search for $K \to \pi\nu\bar{\nu}$ – Direct FCWNC.

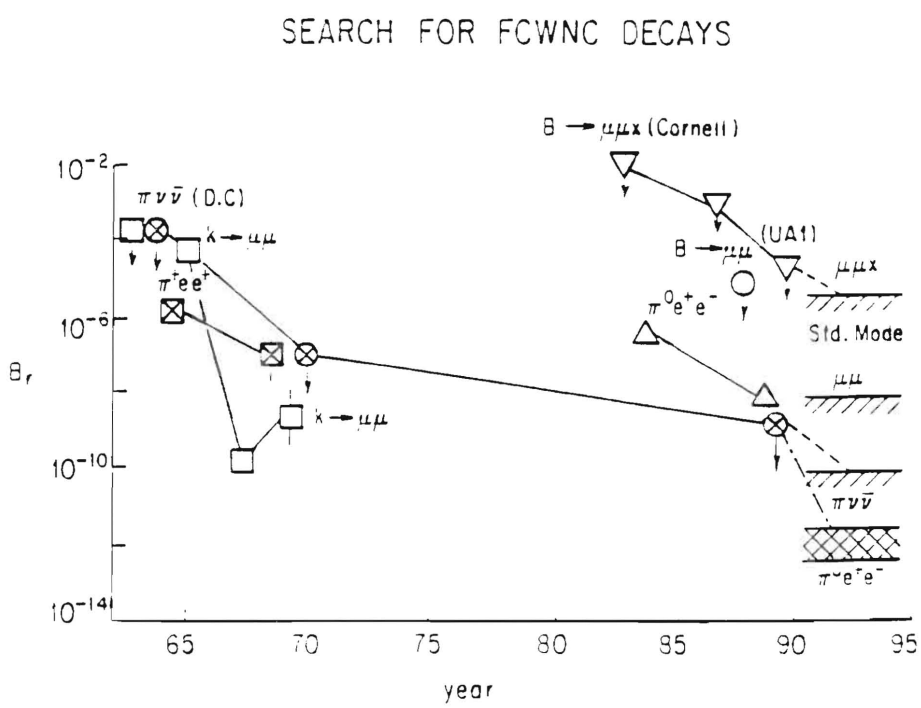

FIG. 4b: History of the Search for FCWNC from the Early 1960s to the Present.

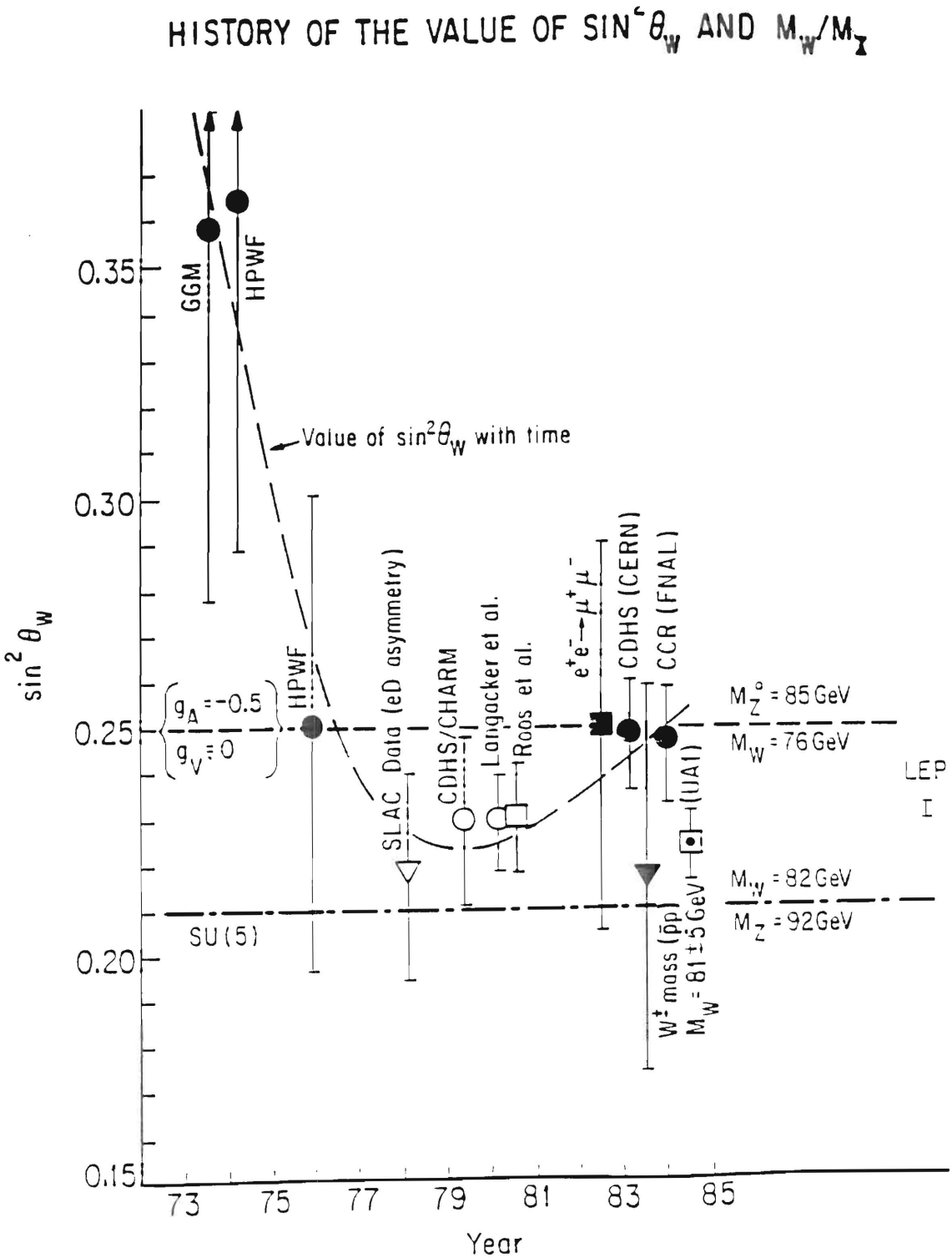

FIG. 5: History of the value of $\sin^2\theta_W$ and M_W / M_Z.