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ELECTRO-WEAK NEUTRAL CURRENTS

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Résumé. - Ce rapport passe en revue l'information expérimentale sur les courants neutres. Les nouvelles données proviennent essentiellement d'expériences d'interférence faible-électromagnétique. Le domaine exploré en q^2 est très grand : depuis la physique atomique, où la violation de la parité peut maintenant être exploitée quantitativement, jusqu'à l'annihilation e^+e^- avec des q^2 de plus de 1000 GeV^2 . La théorie unifiée de Glashow, Salam et Weinberg est en excellent accord avec les données expérimentales, bien que certaines hypothèses assez fondamentales de la théorie ne puissent pas encore être bien vérifiées.

Abstract. - Experimental information on weak neutral currents is reviewed. New data are mostly from weak-electromagnetic interference, over a very large q^2 range : from P violation in atomic transitions to e^+e^- annihilation at q^2 of more than 1000 GeV^2 . Excellent agreement is observed with the minimal Glashow-Salam-Weinberg theory, even though some basic assumptions are not so well tested, as yet.

INTRODUCTION

Since the experimental discovery¹⁾ of weak neutral currents in 1973, most results and phenomenology on this subject²⁾ have come from neutrino experiments, essentially deep inelastic neutrino scattering ($\nu N \rightarrow \nu X$) and elastic neutrino-electron scattering ($\nu e \rightarrow \nu e$). A decisive step occurred in 1978 with the discovery of parity violation in neutral currents as manifested through their interference with the known electromagnetic current : this was observed at very low q^2 in atomic spectroscopy³⁾ and in inelastic electron-deuteron scattering at moderate q^2 ⁴⁾. All these data lead with minimal assumptions to a unique solution for the electron, u and d-quark couplings which were found to be consistent⁵⁾ with the standard Glashow-Salam-Weinberg theory⁶⁾.

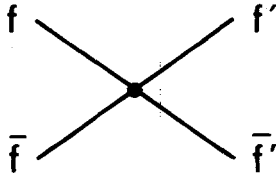
At this conference, for the first time, the emphasis of new data is clearly on weak-electromagnetic interference - the occurrence of weak neutral effects in processes described, some years ago, only in terms of quantum electrodynamics. These results provide measurements of new couplings, giving us insight into the weak interactions of the 2nd and 3rd generations of fermions. Extended q^2 range - from atomic physics to high energy e^+e^- annihilation - proves to be essential to rule out some non-standard theories.

This talk will cover the following subjects with their implications :

- I. Notations ; standard GSW model.
- II. Neutrino results : the 1st generation (e,u,d) couplings.
- III. e^+e^- annihilation into lepton pairs : e, μ , τ couplings and lepton universality.
- IV. Deep inelastic muon scattering : $\sin^2\theta_W$ from the 2nd generation.
- V. Parity violation in atomic physics : low q^2 test of the theory.
- VI. e^+e^- annihilation into hadrons : heavy quark couplings.
- VII. Tests of the standard theory.
- VIII. Discussion on alternatives to the standard theory.

I. NOTATIONS

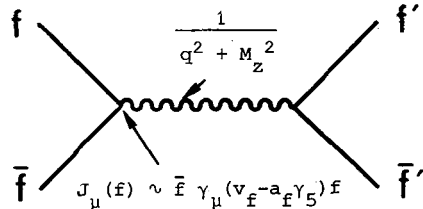
As a general framework to parametrize neutral currents, it is convenient to



introduce 4-point couplings (in the local limit) between fermion pairs. For the sake of not introducing yet another notation, I shall use the Hung-Sakurai notation⁷⁾ which applies to most measured processes so far and, although not transparent, provides a convenient parametrization. However, it assumes that :

- neutral currents have a Lorentz structure with only vector (V) and axial-vector (A) terms. There is no experimental evidence for other terms.
- flavour is conserved in neutral currents, as experiments have failed to observe the converse for strangeness, charm and beauty.
- hadronic neutral currents have only I = 0 and I = 1 strong-isospin components, as for the electromagnetic currents. Theoretically, this is of course guaranteed by the quark picture.

For most of the discussion, I shall assume factorization which implies the exchange of a single pole in the non-local limit :



For neutrinos, we have $v_\nu = a_\nu (=c_\nu)$. Of course factorization has to be tested experimentally, but, if it holds, data can then be parametrized with much fewer couplings to be compared to theoretical predictions.

Table I lists the most relevant couplings (for the 1st fermion generation) in the Hung-Sakurai "model-independent" form and their expressions, if factorization is assumed and in the standard model. Note that, originally, Hung and Sakurai assumed lepton universality : this can now be tested, as we shall see later.

In the standard GSW model, the electroweak interaction is described by the $SU(2) \times U(1)$ gauge group of weak isospin and hypercharge, the symmetry being broken down to $U_{EM}(1)$ by Higgs fields. Fermions appear in weak-isospin multiplets : on one hand, charged current phenomenology⁸⁾ imposes that left-handed fermions are in doublets - a property holding for all 3 generations now, as the CESR results on b spectroscopy suggest⁹⁾ ; on the other hand, the assignment of right-handed fermions is not fixed a priori and has to be determined experimentally.

In the local limit, the lagrangian density takes a current-current form :

$$\mathcal{L}_{q^2} \ll M_Z^2 = 4 \frac{G_F}{\sqrt{2}} \rho J_\mu^{NC} J^\mu NC \quad (1)$$

with the familiar expression for the neutral current

$$J_\mu^{NC} = J_\mu^3 - \sin^2\theta_w J_\mu^{EM} \quad (2)$$

The flexibility within the $SU(2) \times U(1)$ model appears in :

- the parameter ρ , which depends on the Higgs fields. For Higgs fields in doublets, $\rho = 1$ at the lowest order. Higher order corrections are expected to be small, but depend on the fermion mass spectrum¹⁰⁾,
- the Lorentz decomposition of J_μ^3 , given by the right-handed fermion weak-isospin assignments. More specifically, J_μ^{NC} is specified by

$$a_f = 2 [I_{3L}(f) - I_{3R}(f)], v_f = 2 [I_{3L}(f) + I_{3R}(f)] - 4 Q_f^2 \sin^2\theta_w \quad (3), (4)$$

where Q_f is the fermion charge.

TABLE I
First generation couplings

$V = \text{vector } (\gamma_\mu) \quad , \quad A = \text{axial vector } (\gamma_\mu \gamma_5) \quad , \quad x = \sin^2 \theta_w$

<u>Process</u>	<u>Model-independent</u>	<u>Factorization</u>	<u>Minimal</u> <u>SU(2) × U(1)</u>	
νN	$V_q (I = 1) = \alpha$	$\frac{c_v}{2} (v_u - v_d)$	$1 - 2x$	
	$A_q (I = 1) = \beta$	$\frac{c_v}{2} (a_u - a_d)$	1	
	$V_q (I = 0) = \gamma$	$\frac{c_v}{2} (v_u + v_d)$	$-\frac{2}{3} x$	
	$A_q (I = 0) = \delta$	$\frac{c_v}{2} (a_u + a_d)$	0	
eN	parity- violating	$A_\ell V_q (I=1) = \tilde{\alpha}$	$\frac{a_e}{2} (v_u - v_d)$	$-1+2x$
		$V_\ell A_q (I=1) = \tilde{\beta}$	$\frac{v_e}{2} (a_u - a_d)$	$-1+4x$
		$A_\ell V_q (I=0) = \tilde{\gamma}$	$\frac{a_e}{2} (v_u + v_d)$	$\frac{2}{3} x$
		$V_\ell A_q (I=0) = \tilde{\delta}$	$\frac{v_e}{2} (a_u + a_d)$	0
	parity- conserving	$A_\ell A_q (I=1)$	$\frac{a_e}{2} (a_u - a_d)$	-1
	\vdots	\vdots		
νe	$V_\ell = g_V$	$\frac{c_v v_e}{2}$	$-\frac{1}{2}+2x$	
	$A_\ell = g_A$	$\frac{c_v a_e}{2}$	$-\frac{1}{2}$	
$e^+ e^-$	$V_\ell V_\ell = h_{VV}$	$\frac{v_e^2}{4}$	$(-\frac{1}{2}+2x)^2$	
	$V_\ell A_\ell = h_{VA}$	$\frac{v_e a_e}{4}$	$\frac{1}{4} x$	
	$A_\ell A_\ell = h_{AA}$	$\frac{a_e^2}{4}$	$\frac{1}{4}$	
<u>Number of</u> <u>Parameters</u>	17	7	1	

This flexibility is removed in the minimal $SU(2) \times U(1)$ model where only one Higgs doublet is assumed (yielding one physical H^0 boson) and right-handed fermions are weak-isospin singlets. The only free parameter, as far as neutral-current couplings are concerned, is $\sin^2\theta_w$.

II. NEUTRINO REACTIONS

At previous conferences, most results on neutral currents came from neutrino reactions. For the first time, the interest has shifted to weak-electromagnetic interference. One of the reasons is that many data have already been accumulated with neutrino beams and improvement is slow : on one hand, neutrino-electron scattering is measured cleanly in bubble chambers, but statistics is sparse ; electronic experiments can accumulate more data, but background separation is a problem. On the other hand, results from neutrino scattering on nucleons are now essentially limited by systematic effects, which cannot be easily reduced. Some improvement could come from deuterium/hydrogen experiments in bubble chambers to get a better isospin separation of couplings.

1. - Neutrino-electron scattering

New results have been presented by the CHARM collaboration¹¹⁾ on scattering of ν_μ and $\bar{\nu}_\mu$ on electrons. CHARM has a fine-grain calorimeter which has good properties for detecting electron showers. Background from ν_e charged-current events and photon conversions from ν_μ neutral currents have been taken into account. The same selection criteria were applied for both ν_μ and $\bar{\nu}_\mu$ samples, therefore reducing the systematic error in the measured ratio of cross sections. From a data sample of 46 ± 12 ν_μ - induced events and 77 ± 19 $\bar{\nu}_\mu$ - induced events (above ~ 50 % background), they get

$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) / \sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e) = 1.37 \begin{matrix} + .65 \\ - .44 \end{matrix}$$

This leads to a determination of $\sin^2\theta_w$ (Fig. 1) from the electron g_V coupling independently of the value for ρ (which cancels out in the ratio) :

$$\sin^2\theta_w = \begin{matrix} .215 \pm .040 \pm .015 \\ \text{(stat) (syst)} \end{matrix}$$

This value agrees with previous measurements⁵⁾ with a reduced systematic uncertainty.

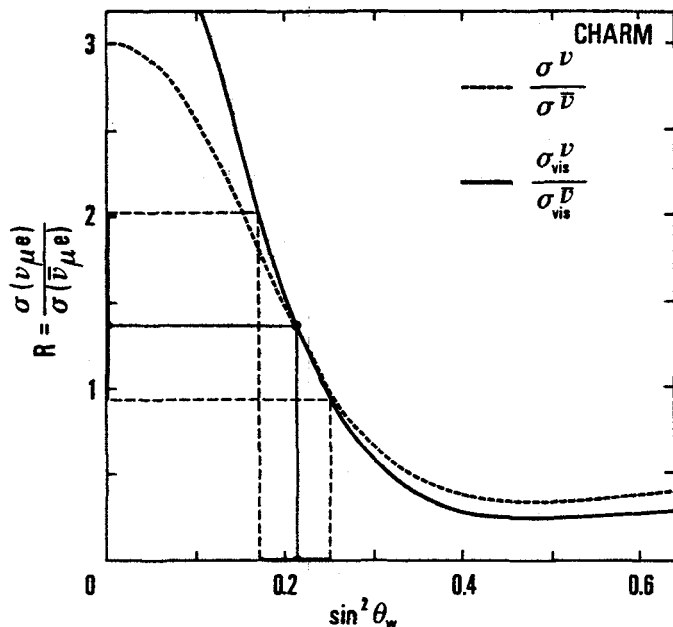


Fig. 1 - Determination of $\sin^2\theta_w$ from the ratio of ν_μ to $\bar{\nu}_\mu$ -e scattering cross sections by the CHARM collaboration¹¹⁾

2. - Inelastic neutrino-hadron scattering

No significant change has occurred in this field in the last two years. The overall experimental situation is well-known⁵⁾ and the measurements of the ratios of the inclusive neutral-to-charged-current cross sections R_ν and R_ν^- provide the most precise determination of $\sin^2\theta_w$. As pointed out before, the isospin decomposition of couplings through νn and νp^W data could still be improved. In this respect, some new data were discussed from the Chicago-Maryland-Stony Brook-Tohoku-Tufts collaboration¹²⁾ showing general agreement with previous determinations.

A discussion of neutrino data, together with results from the polarized electron-deuteron scattering experiment at SLAC⁴⁾, can be found in the review article of Kim et al.⁵⁾, where a good description of the data is achieved within the restrictive parametrization of the GSW model. I now proceed to discuss these important conclusions.

Within the framework of $SU(2) \times U(1)$, assuming that left-handed fermions are in doublets, $I_{3L}(f) = \pm 1/2$, a fit can be performed to the data for the remaining parameters, which turn out to be consistent with the minimal model :

$$\begin{aligned} I_{3R}(e) &= .04 \pm .05 \\ I_{3R}(u) &= -.01 \pm .04 \\ I_{3R}(d) &= -.10 \pm .06 \\ \rho &= 1.02 \pm .045 \\ \sin^2\theta_w &= .25 \pm .03 \end{aligned}$$

Clearly, the message is that e_L , u_R and d_R are weak-isospin singlets and a new fit can be tried, imposing $I_{3R}(e,u,d) = 0$. The result agrees remarkably with the minimal Higgs hypothesis ($\rho=1$, neglecting small higher order corrections) :

$$\begin{aligned} \rho &= 1.002 \pm .015 \\ \sin^2\theta_w &= .234 \pm .013 \end{aligned}$$

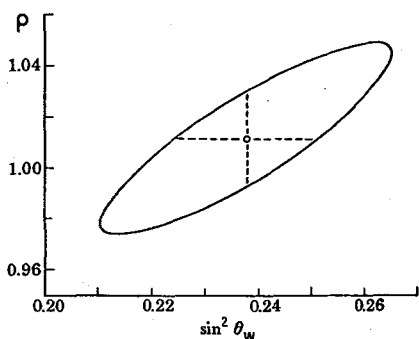
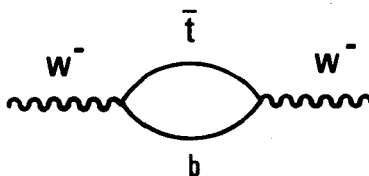


Fig. 2 - Correlation ellipse for the determination of ρ and $\sin^2\theta_w$ (from M. Roos et al. quoted in ref. 13)

It is worth noting¹³⁾, however, that the errors quoted for ρ and $\sin^2\theta_w$ are correlated, as observed in Fig. 2 from a similar fit. Therefore, one should reasonably consider that ρ can depart from unity by as much as $\sim .03$ even at the 68 % confidence level (CL). As a practical example, the upper limit for the t quark mass obtained from the 2nd order loop correction



to ρ comes out to be only

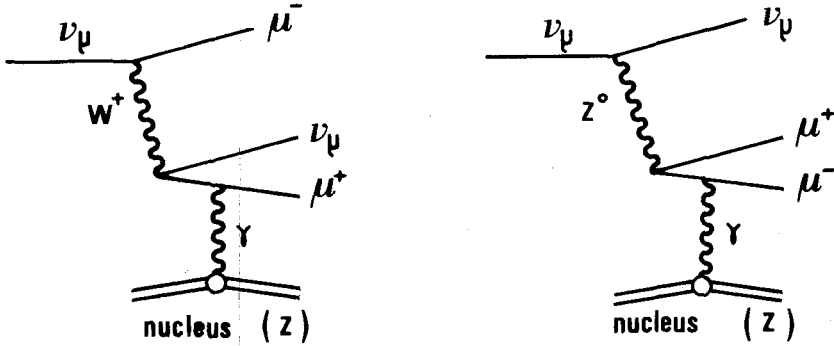
$$m_t < 2\pi \left(\frac{2\sqrt{2}\Delta\rho}{3G_F} \right)^{\frac{1}{2}} = 310 \text{ GeV} ! \tag{5}$$

3. - Search for trident production

A search for the Coulomb process

$$\nu_\mu Z \rightarrow \nu_\mu \mu^+ \mu^- Z$$

has been performed by the CHARM collaboration¹¹⁾. Such a process can, in principle, provide information on purely leptonic couplings :



Looking for this coherent di-muon production, 1.7 ± 1.7 events are obtained, giving an upper limit unfortunately still a factor of 2 larger than the theoretical prediction with $\sin^2\theta_w = 0.23$. A quite similar limit was obtained earlier by the CDHS collaboration¹⁴⁾.

At this level, however, the only conclusion to be drawn is that the neutral-current process

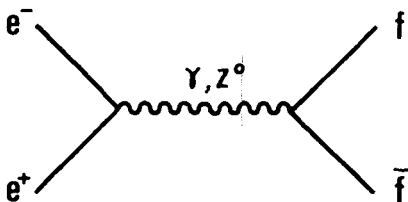
$$\nu_\mu \bar{\nu}_\mu \rightarrow \mu^+ \mu^-$$

has a rate which is not unexpectedly large and consistent with the standard theory.

III. ELECTRON-POSITRON ANNIHILATION INTO LEPTON PAIRS

1. - Observables

The processes, $e^+e^- \rightarrow \mu^+\mu^-$ or $\tau^+\tau^-$, proceed through s-channel γ and Z^0 exchange of the general type



where f stands for any fermion.

The total annihilation cross section for $e^+e^- \rightarrow f\bar{f}$ can be conveniently expressed in terms of the point-like QED cross section :

$$R_f = \frac{\sigma_f}{\sigma_{pt}} = Q_f^2 - 2 Q_f v_e v_f \chi + (a_e^2 + v_e^2)(a_f^2 + v_f^2) \chi^2 \quad (6)$$

with

$$\chi = g \frac{s M_Z^2}{s - M_Z^2} \quad \text{and} \quad g = \frac{G_F}{8\pi\alpha\sqrt{2}} = 4.5 \cdot 10^{-5} \text{ GeV}^{-2}$$

It has been implicitly assumed that $|s - M_Z^2| \gg \Gamma_Z M_Z$. The 3 terms in Eq. (6) are obviously identified to the $|\gamma|^2$, $\gamma.Z$ interference and $|Z|^2$ parts.

At PEP-PETRA energies, $\chi \sim 0.06$ and clearly $|\chi| \gg \chi^2$. However, we know that $v_e \sim 0$ (since $\sin^2\theta_W \sim 1/4$) and therefore, the interference term in R_f will be small. The conclusion is that R_f can hardly be expected to deviate from 1 for lepton (μ, τ) production.

A more favourable situation is encountered for the forward-backward asymmetry of the angular distribution. In the presence of $\gamma.Z$ interference, we have

$$\frac{d\sigma_f}{d\Omega} = \frac{\alpha^2}{4s} [R_f(1+\cos^2\theta) + b_f \cos\theta] \quad (7)$$

where θ is the angle between the incident e^- and the outgoing f , and

$$b_f = \frac{4\chi a_e a_f}{R_f} (-Q_f + 2 v_e v_f \chi) \quad (8)$$

The experimenters quote either the experimental asymmetry in a given acceptance ($\theta_m < \theta < \pi - \theta_m$)

$$\langle A_f \rangle_{\theta_m} = \frac{F - B}{F + B} \quad (9)$$

$$\text{with } F = \int_0^{\cos\theta_m} d\sigma_f \quad \text{and} \quad B = \int_{-\cos\theta_m}^0 d\sigma_f$$

or the extrapolated total asymmetry

$$\langle A_f \rangle = \frac{3}{8} b_f \quad (10)$$

In my discussion of the experimental results, I shall also use the "differential" asymmetry, $A(\cos\theta)$, defined for each $\pm \cos\theta$ bins of the angular distribution.

Since $|\chi| \gg \chi^2$, we expect

$$\langle A_f \rangle = -\frac{3}{2} \frac{a_e a_f}{Q_f} \chi \quad (11)$$

which is negative for μ and τ .

Bhabha scattering, $e^+e^- \rightarrow e^+e^-$, is more complicated, due to γ, Z^0 exchange in the t-channel also ; however, it yields information on the v_e, a_e couplings alone¹⁵).

In the Hung-Sakurai notation (with assumed lepton universality), R_f is mostly a measure of h_{VV} , while $\langle A_f \rangle$ is simply related to h_{AA} . In order to reach the parity violating h_{VA} term, one needs either cross section measurements with polarized e^\pm beams or a measurement of the final lepton polarization. The latter can be achieved through τ decays which can analyze the τ polarization: no results are yet available, essentially for lack of statistics. A preview of what might be obtained with more luminosity, is given by CELLO results on $\tau \rightarrow \rho \nu$ decays which can be clearly identified (Fig.3): the slope of the ρ laboratory momentum is proportional to the τ polarization and, clearly at this stage, no strong conclusion can be drawn.

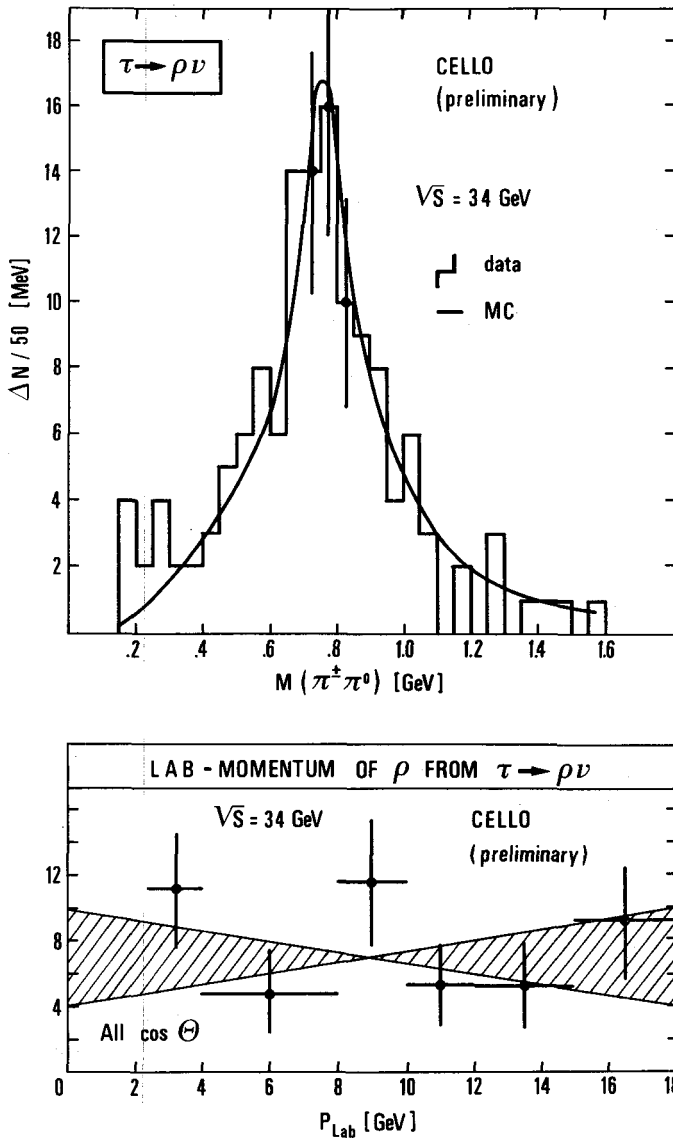


Fig. 3 - Measurement of the decay $\tau \rightarrow \rho \nu$ by the CELLO collaboration and ρ momentum spectrum: the hatched area corresponds to the allowed region, $|P_\tau| \leq 1$, where P_τ is the τ polarization.

In the past year a large amount of data has been accumulated : at PETRA, running at $\sqrt{s} = 35$ GeV, integrated luminosity has been increased fivefold, while PEP has seen an increase by a factor of 2 at 29 GeV.

2. - Bhabha scattering

The angular distribution has been measured with high statistics by the CELLO¹⁶⁾, Mark J¹⁷⁾ and TASSO¹⁸⁾ groups at PETRA, and the MAC¹⁹⁾ group at PEP. The point-to-point systematic error is small ($\sim 1\%$) as electrons are usually triggered upon by both tracking detectors and calorimeters, resulting in a very high efficiency. The overall normalization, typically $\sim 3\%$, is of crucial importance.

The results, shown in Fig. 4, do not exhibit significant deviations from QED. This process is in fact more sensitive to v_e than a_e and, consequently, the good agreement with QED means that v_e must be small, thus favouring the dominant axial solution found in ν -e analyses.

3. - Total cross sections for μ and τ pairs

Fig.5 shows the results obtained for the measurements of R_μ and R_τ as a function of s , by the four PETRA groups : CELLO, JADE²⁰⁾, Mark J and TASSO. Here again, no deviation from QED is observed : this corresponds to a very small interference term. Since this interference must be proportional to $v_e v_{\mu,\tau}$ and since $v_e = 0$ cannot be experimentally excluded, it is easy to see that total cross section data do not provide any constraint on v_μ and v_τ . This is a consequence of $\sin^2\theta_w \sim 1/4$ as determined experimentally for the 1st generation couplings.

If we accept factorization, no detectable weak effect is predicted in $R_{\mu,\tau}$ measurements which can in turn be used to probe the electromagnetic structure of μ and τ leptons. The agreement with the point-like cross section up to $s \sim 1200$ GeV² implies that the charge radii of the e , μ and τ leptons are smaller than $1.5 \cdot 10^{-3}$ f.

Finally, a word of caution : if the μ -pair cross section is relatively straightforward to measure, the problem is more difficult for τ pairs, where the measured rate depends on the branching fractions assumed for the detected decay modes. On one hand, CELLO and MAC use more than 90 % of the τ decays (70 % for JADE) and do not rely strongly on the knowledge of branching ratios ; Mark J only detects the final state with μ + hadrons, which is safe because the branching ratio for $\tau \rightarrow \mu\nu\nu$ is rather well known. On the other hand, TASSO has used only the 1-prong + 3-prong topology which is sensitive to the actual value of the topological branching fractions, B_1 and B_3 . The new measurements of CELLO²¹⁾, MAC¹⁹⁾ and Mark II²²⁾ are in agreement for a value of $B_3 = (15 \pm 2)\%$, instead of the old "world-average" value of 26 % (very imprecisely known). The TASSO τ cross section, which uses the old value, is therefore subject to caution.

4. - Forward-backward asymmetries

Angular distributions have been measured for both $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$. The experimental problems are of course different in the two cases, but the systematic effects, as far as the asymmetry is concerned, are quite small. For μ -pairs, ΔA_{syst} is certainly less than 1 % because backgrounds (Bhabha events, cosmic rays, 2-photon processes, τ -pairs) can be kept small and do not produce artificial asymmetries. For

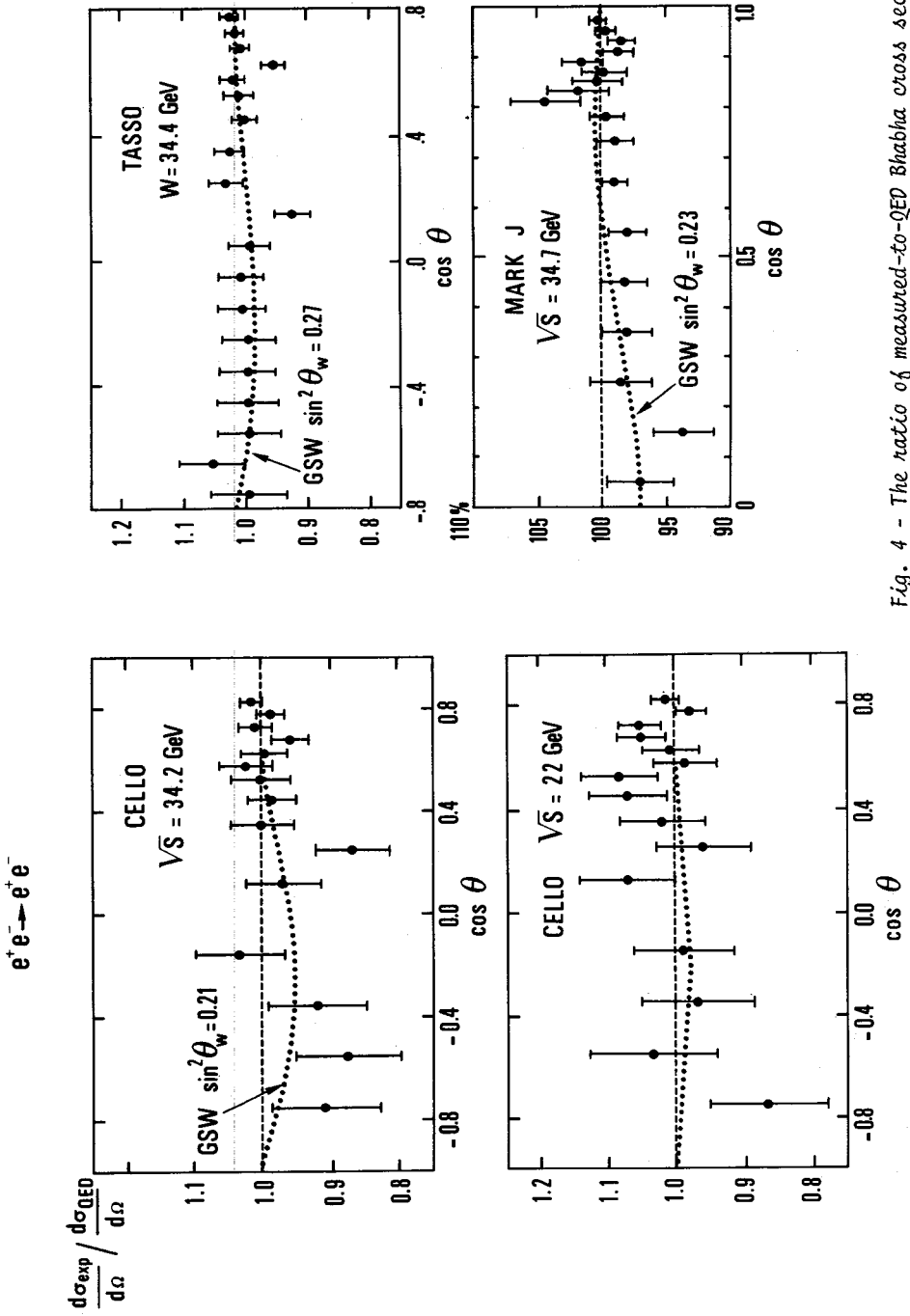


Fig. 4 - The ratio of measured-to-QED Bhabha cross sections

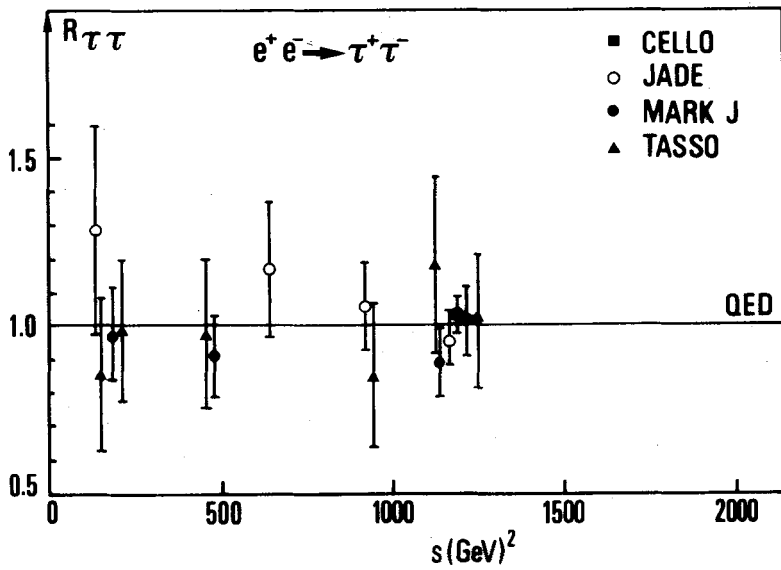
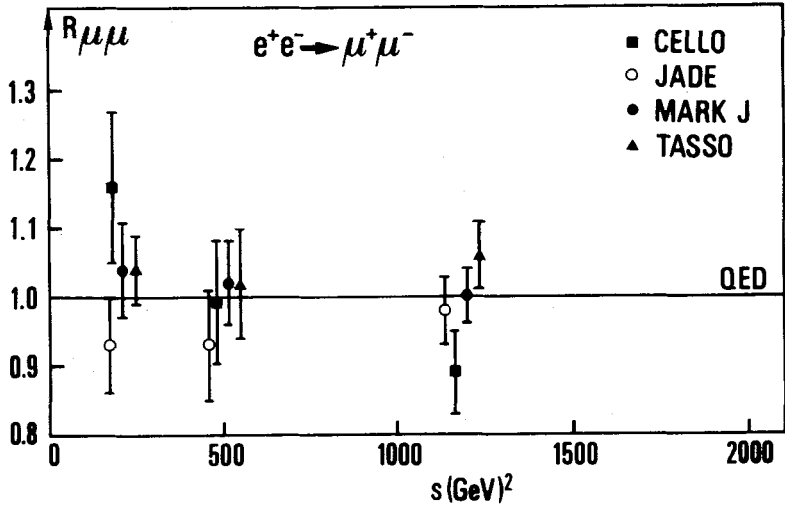


Fig. 5 - The ratios of measured $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ cross sections to the point like QED prediction

τ pairs, backgrounds are larger (Bhabha events with e^\pm radiation in the beam pipe, 2-photon processes, multihadron annihilation events) and their incidence on the final results depends on the detector ability to correctly identify the final states; the Bhabha contamination is particularly dangerous, since it produces an excess of events in the very forward region, thereby reducing an expectedly negative weak asymmetry. In general, $\Delta A_{\text{sys}}(\tau)$ is about 2%; however, CELLO rather quotes a value less than 1%.

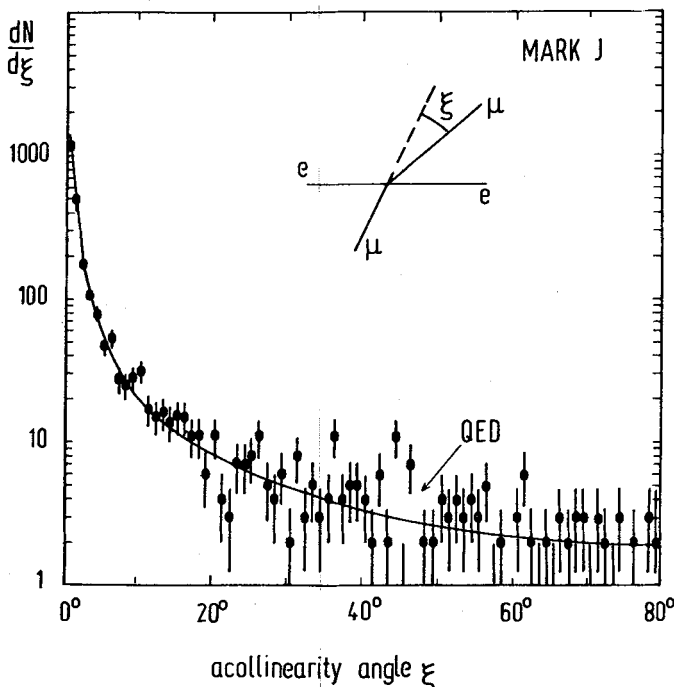


Fig. 6 - Acollinearity of the two muon tracks¹⁷⁾ in $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$ as compared to α^3 QED calculations

Higher order α^3 QED

corrections²³⁾ are applied to the experimental data. Within the acceptance of most detectors -

$|\cos\theta| < 0.80$ or slightly more - this correction corresponds to a positive asymmetry of $\sim 1.5\%$.

Checks of this procedure can be and have been performed by investigating distributions which are generated by radiative effects, for example the acollinearity distribution between the two muons, as shown in Fig. 6.

No correction has been applied in the data for higher order weak-electromagnetic effects, i.e. initial-state photon emission and loop corrections in the Z^0 amplitude. The angular distributions

for $e^+e^- \rightarrow \mu^+\mu^-$ presented by the JADE, MAC, Mark J and TASSO groups are given in Fig. 7 and 9. The CELLO results, corresponding to a smaller luminosity, have already been published²⁴⁾. The high-energy data from PETRA show a distinct deviation from the QED symmetric angular distribution and the magnitude of the deviation agrees well with the GSW model.

Table II summarizes the results available so far on the μ -pair asymmetry. Clearly significant progress has been achieved over the past year, each high-statistics experiment showing an effect of more than 4 standard deviations.

The angular distributions for $e^+e^- \rightarrow \tau^+\tau^-$ presented by the same groups are given in Fig. 8 and 9. The CELLO result is final²¹⁾, while the others are still preliminary. Taken individually, each experiment cannot establish a significant asymmetry; however, each one shows a 1 to 2-standard-deviation effect, always in the expected direction. This is shown quantitatively in Table III.

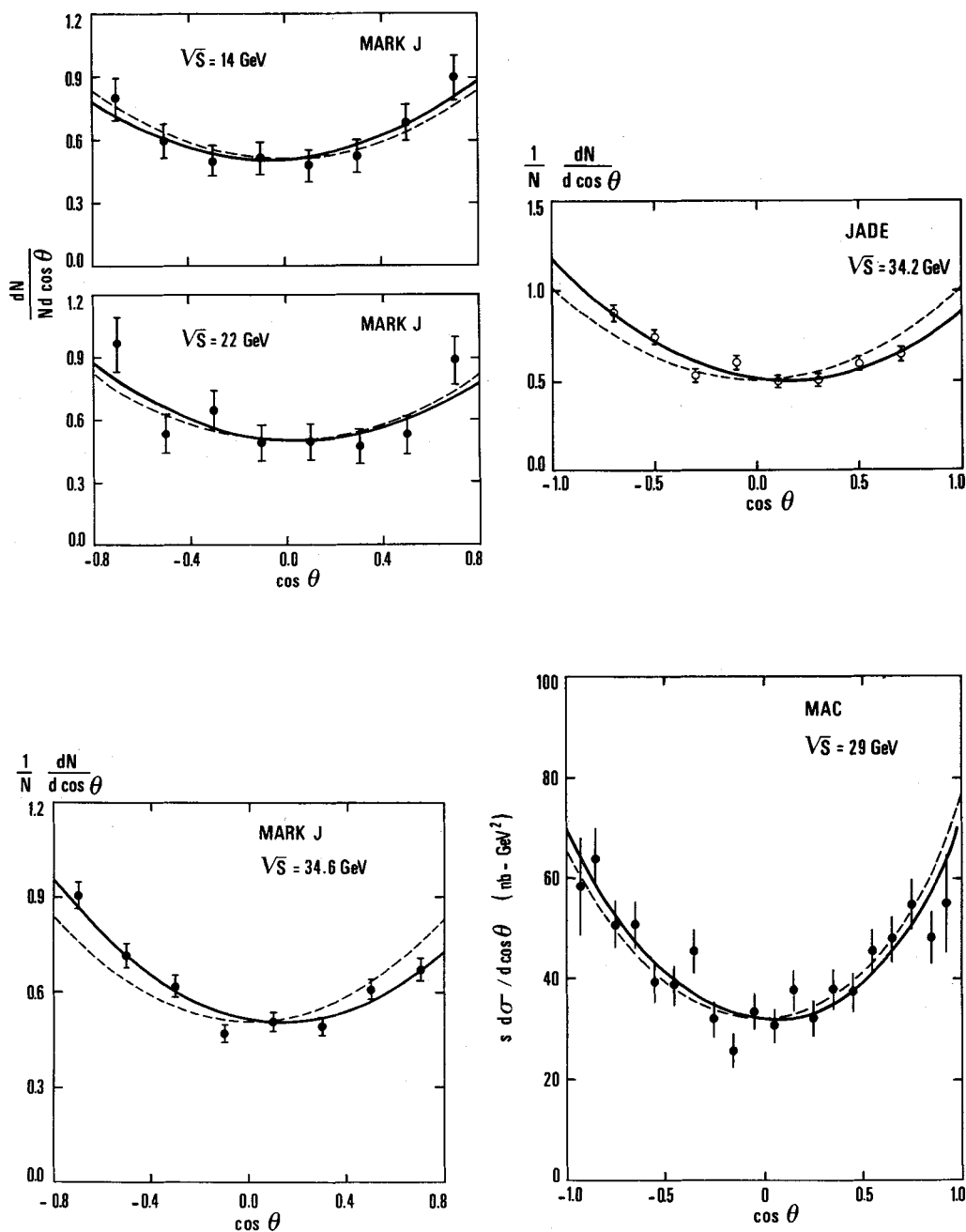


Fig. 7 - Data on $e^+e^- \rightarrow \mu^+\mu^-$ angular distributions. The solid curve corresponds to the GSW fit, while the broken curve is the expected QED distribution. All data, except MAC, are corrected for α^3 QED effects.

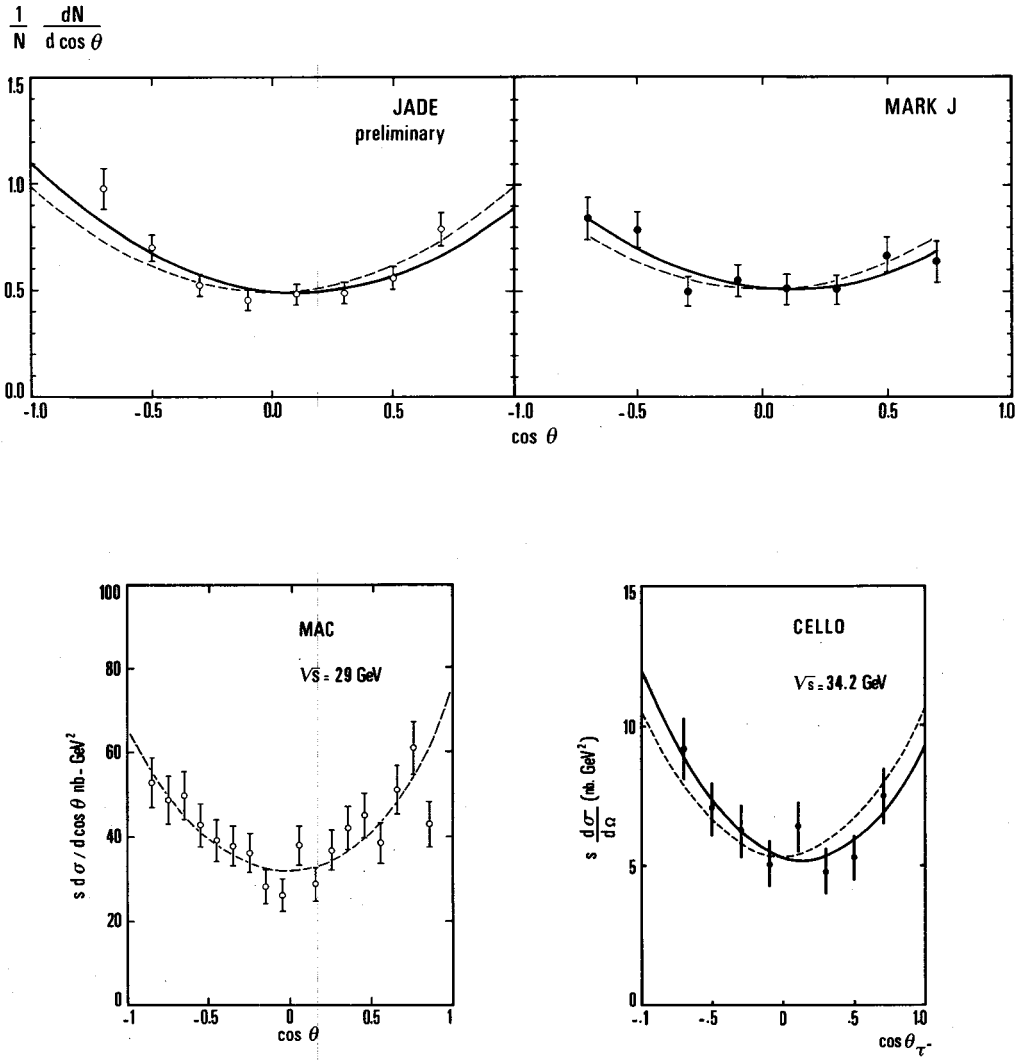


Fig. 8 - Data on $e^+e^- \rightarrow \tau^+\tau^-$ angular distributions. Curves have the same meaning as in Fig. 7.

Experiment	\sqrt{s} (GeV)	$\int \mathcal{L} dt$ (pb^{-1})	N_{events}	$\langle A_{\mu} \rangle$ (%)	$\langle A_{\mu} \rangle_{\text{GSW}}$ (%)
MAC ¹⁹⁾	29	25	1876	-4.4 ± 2.4	-6.3
Mark II ²⁵⁾	29	15.4	652	-9.6 ± 4.5	-6.3
CELLO ²⁴⁾	34.2	11.2	387	-6.4 ± 6.4	-9.2
JADE ²⁰⁾	34.4	47.7	2224	$-10.8 \pm 2.2 \pm 1$	-9.3
Mark J ¹⁷⁾	34.6	63.7	3209	-10.4 ± 2.1	-9.4
TASSO ¹⁸⁾	34.4	70.2	2391	-10.4 ± 2.3	-9.3

TABLE II
High-energy data on μ -pair asymmetries

Experiment	\sqrt{s} (GeV)	$\int \mathcal{L} dt$ (pb^{-1})	N_{events}	$\langle A_{\tau} \rangle$ (%)	$\langle A_{\tau} \rangle_{\text{GSW}}$ (%)
MAC ¹⁹⁾	29	25	1247	-1.3 ± 2.4	-6.3
Mark II ²⁵⁾	29	15.4	454	-3.9 ± 6	-6.3
CELLO ²¹⁾	34.2	11.3	434	-10.3 ± 5.2	-9.2
JADE ²⁰⁾	34.4	30	853	-7.9 ± 3.9	-9.3
TASSO ¹⁸⁾	34.4	65.8	517	-5.4 ± 4.5	-9.3
Mark J ¹⁷⁾	34.6	55.7	649	-7.4 ± 4.6	
				$ \cos\theta < .8$	

TABLE III
High-energy data on τ -pair asymmetries

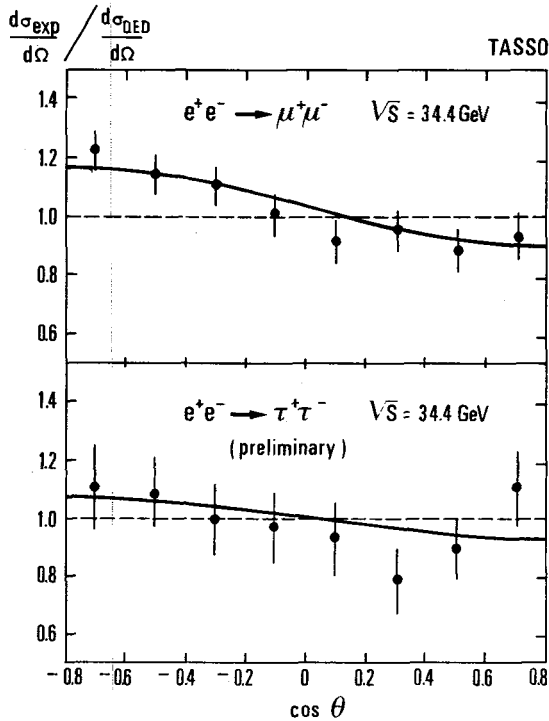


Fig. 9 - Ratios of $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$ measured cross sections¹⁸⁾ to the QED prediction

5. - Conclusion from $\langle A \rangle$ measurements

(a) Compilation of high-energy $\langle A \rangle$ measurements

It is obvious from the previous discussion that weak-electromagnetic interference has been observed unambiguously at PETRA, with the expected magnitude. Since data are still limited by statistics, it is fair to merge them if the resulting statistical error still exceeds the quoted systematic uncertainties. I have combined the angular distributions from the different experiments, by normalizing each one of them to the QED prediction at $\cos\theta = 0$. The results are shown in Fig.10 for $e^+e^- \rightarrow \mu^+\mu^-$ and Fig. 11 for $e^+e^- \rightarrow \tau^+\tau^-$: they both show strong departure from QED and quantitative agreement with the GSW theory. The combined statistics (8211 μ pairs and 2453 τ pairs) allows one to look at the asymmetry $A(\cos\theta)$ as a function of angle: the results, plotted in Fig.12, indicate clearly the linear $\cos\theta$ dependence expected for the quantity $(1+\cos^2\theta) A(\cos\theta)$, for both μ and τ pairs. A linear fit yields the following averaged asymmetries for PETRA experiments at $\sqrt{s} \sim 34.4$ GeV

$$\langle A_\mu \rangle = - .105 \pm .012$$

$$\langle A_\tau \rangle = - .080 \pm .023$$

As pointed out before, the general trend of $\langle A_\tau \rangle$ is made more quantitative and a non-zero asymmetry is therefore established at 3.5 standard deviations.

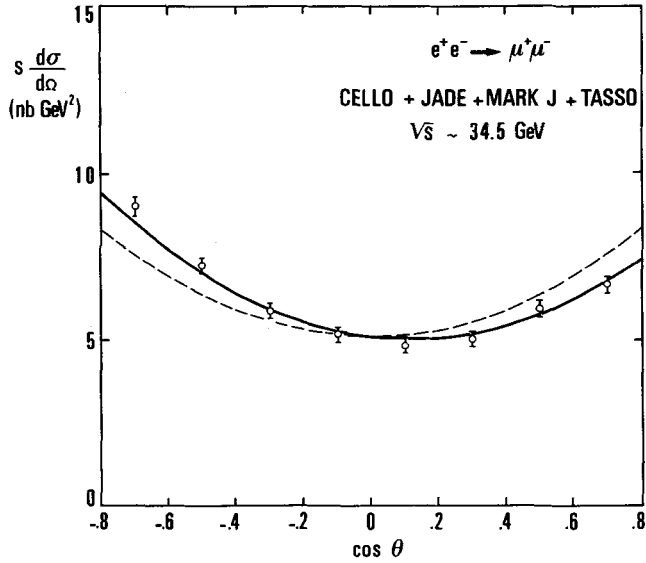


Fig. 10 - Compilation of PETRA high-energy data for the angular distribution of $e^+e^- \rightarrow \mu^+\mu^-$

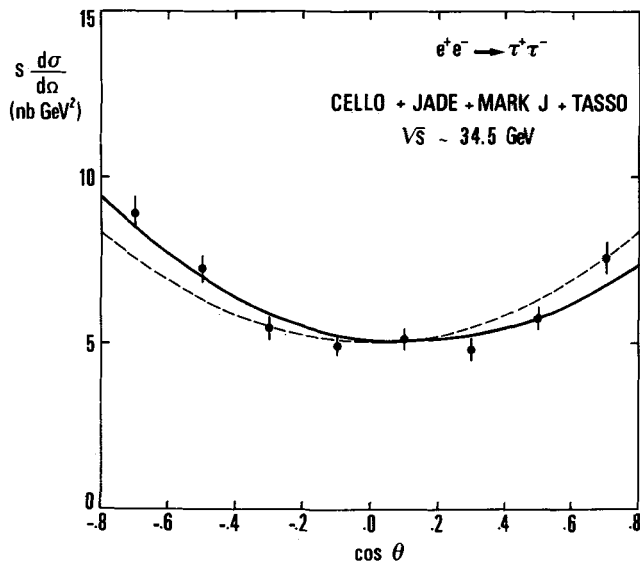


Fig. 11 - Compilation of PETRA high-energy data for the angular distribution of $e^+e^- \rightarrow \tau^+\tau^-$

(b) Determination of μ and τ axial-vector couplings

From Eq. (11), knowing a_e and assuming that $M_Z = 90$ GeV ($\sim 10\%$ effect compared to the local limit), one can calculate the a_μ and a_τ couplings, which turn out to be

$$a_\mu = -1.03 \pm .16$$

$$a_\tau = -.78 \pm .24$$

to be compared to the a_e coupling, independently determined by νe results (with V-A ambiguity removed by SLAC $e d$ results or better by Bhabha data from PETRA)

$$a_e = -1.09 \pm .11$$

In the framework of the $SU(2) \times U(1)$ gauge group with the help of relation (3), these values can be used to find out the μ_R and τ_R weak-isospin assignments. The results

$$I_{3R}(\mu) = .02 \pm .08$$

$$I_{3R}(\tau) = -.11 \pm .12$$

very clearly indicate that μ_R^- and τ_R^- are singlets of weak-isospin, like e_R^- as previously determined, and in agreement with the minimal GSW $SU(2) \times U(1)$ theory. This is the first test of right-handed multiplet structure in the 2nd and the 3rd fermion generations: it shows that, indeed, the 3 leptons behave in the same way (lepton universality).

(c) Leptonic couplings assuming universality

An overall description of weak-electromagnetic interference can be achieved for all three leptonic reactions $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$, in terms of universal a and v leptonic couplings. Also, M_Z can be varied as a function of $\sin^2\theta_w$ following the minimal $SU(2) \times U(1)$ relation²

$$M_Z = \frac{1}{2\sqrt{g}\sin\theta_w} = \frac{74.5 \text{ GeV}}{\sin 2\theta_w}$$

The results of such a fit by the four PETRA groups are given in Table IV.

Experiment	Data used	a^2	v^2	$\sin^2\theta_w$
CELLO ¹⁶	$ee, \mu\mu, \tau\tau$	$1.22 \pm .47$	$-.12 \pm .33$	$.21^{+.14}$ $-.09$
JADE ²⁰	$\mu\mu$	$1.17 \pm .24$	$.20 \pm .32$	
Mark J ¹⁷	$ee, \mu\mu, \tau\tau$	$1.12 \pm .24$	$-.08 \pm .20$	$.26 \pm .09$
TASSO ²⁶	$ee, \mu\mu$	$1.04 \pm .28$	$-.16 \pm .24$	$.27^{+.06}$ $-.07$
average		$1.13 \pm .14$	$-.06 \pm .13$	

TABLE IV

Overall fit of $e^+e^- \rightarrow$ lepton pairs

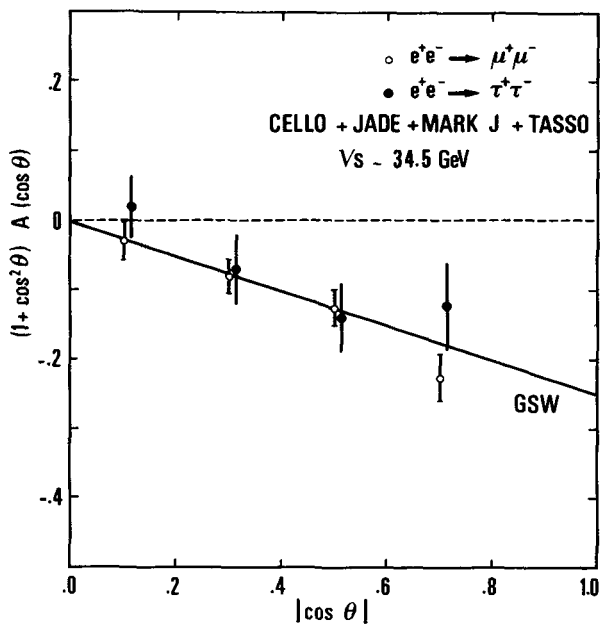


Fig. 12 - Compilation of PETRA asymmetries for $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$

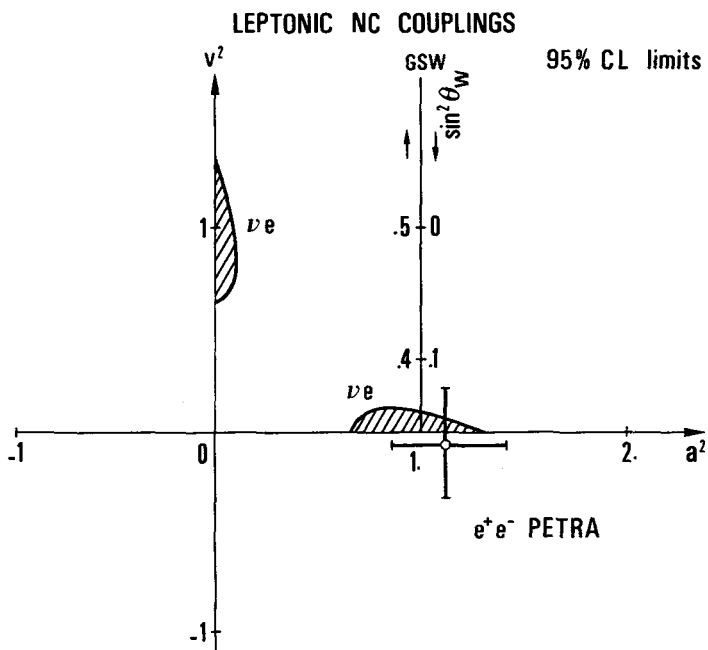


Fig. 13 - Determination of leptonic couplings, v^2 and a^2 , from PETRA data and comparison with the ν_e solutions found in ν_e analyses (hatched areas)

The average v^2 value translates into a value of $\sin^2\theta_w = 0.25 \pm .07$ for these purely leptonic processes. The precision on the measurement^w of the leptonic couplings in e^+e^- annihilation now competes with that of νe scattering, as evidenced by Fig.13, and the V-A ambiguity of the latter results is dramatically resolved.

(d) Looking for a deviation from the local limit : M_Z mass ?

The asymmetry measurements at PETRA are the highest q^2 data ($\sim 1200 \text{ GeV}^2$) when neutral weak currents have been studied. It is therefore intriguing to search for effects induced by a finite Z^0 mass. In fact,

$$\langle A \rangle = \frac{M_Z^2}{M_Z^2 - s} \langle A \rangle_{M_Z \rightarrow \infty} \tag{12}$$

with $\langle A \rangle_{M_Z \rightarrow \infty}$ is a linear function of s , at least for s not too large.

The s dependence of $\langle A \rangle$ and $\langle A \rangle_{M_Z \rightarrow \infty}$ is examined in Fig.14, where combined values have been used at fixed energies.

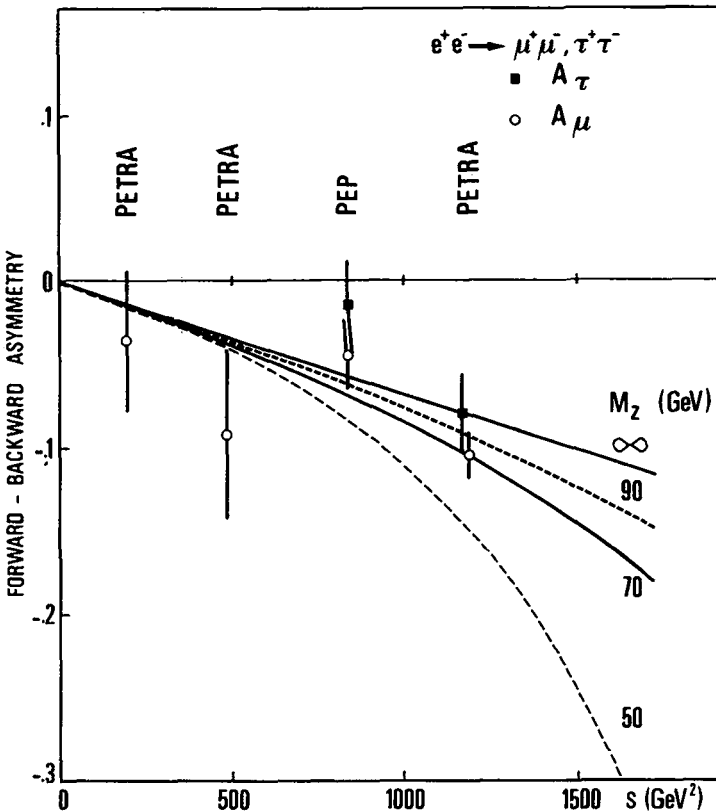


Fig. 14 - Energy dependence of μ and τ asymmetries. The different curves correspond to different assumed Z masses.

The PETRA data are on the verge of delivering a finite Z^0 mass. In fact, assuming $a^2 = 1$, one gets

$$M_Z = (76 \begin{smallmatrix} +21 \\ -11 \end{smallmatrix}) \text{ GeV}$$

corresponding to the more conservative limit

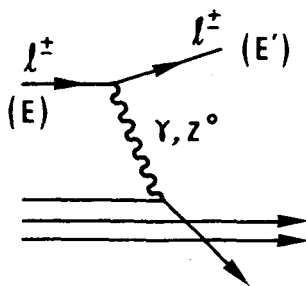
$$M_Z > 59 \text{ GeV at } 95 \% \text{ CL}$$

Clearly the expected energy jump of PETRA to $\sqrt{s} = 45 \text{ GeV}$ over the next year will provide a tantalizing challenge to indirectly "see" the Z^0 boson.

IV. WEAK-EM INTERFERENCE IN MUON SCATTERING

1. - Possible observables

The deep inelastic scattering of longitudinally polarized leptons can reveal interference between the γ and Z^0 currents which scatter off the sub-nucleonic quarks. The interference cross section depends on the lepton charge and initial polarization. One can define two types of asymmetries²⁷⁾ between different polarization states (P_1 and P_2) :



$$A_{\ell}^{\pm}(P_1, P_2) = \frac{d\sigma_{\ell}^{\pm}(P_1) - d\sigma_{\ell}^{\pm}(P_2)}{d\sigma_{\ell}^{\pm}(P_1) + d\sigma_{\ell}^{\pm}(P_2)} \quad (13)$$

$$= -g Q^2 \left(\frac{P_1 - P_2}{2} \right) \left[\bar{a}_{\ell} V_q + v_{\ell} A_q \right]$$

$$B_{\ell}(P_1, P_2) = \frac{d\sigma_{\ell}^{+}(P_1) - d\sigma_{\ell}^{-}(P_2)}{d\sigma_{\ell}^{+}(P_1) + d\sigma_{\ell}^{-}(P_2)} \quad (14)$$

$$= -g Q^2 \left[a_{\ell} A_q + \left(\frac{P_1 - P_2}{2} \right) v_{\ell} A_q - \left(\frac{P_1 + P_2}{2} \right) a_{\ell} V_q \right]$$

where g has been defined in the previous section and $Q^2 = -q^2 > 0$. For an $I = 0$ target and assuming validity of the quark-parton model, we have

$$\begin{aligned} V_q &= \frac{6}{5} (2 v_u - v_d) \\ A_q &= \frac{6}{5} (a_d - 2a_u) g(y) \end{aligned} \quad (15)$$

$$\text{with } g(y) = \frac{1 - (1-y)^2}{1 + (1-y)^2} \quad \text{and } y = \frac{E - E'}{E}$$

The 1978 SLAC measurement⁴⁾ was done with longitudinally polarized electrons (polarization $\pm P$), yielding

$$A_e(P, -P) = -PgQ^2 \left[-a_e v_q + v_e A_q \right] \quad (16)$$

Such an asymmetry is an explicit P-violating effect ; the study of the y dependence allowed the separation of the two products of couplings.

2. - Results from μ^\pm scattering at CERN

New results²⁸⁾ have been presented at the conference by the Bologna-CERN-Dubna-Munich-Saclay collaboration (BCDMS) working at CERN with the 200 GeV muon beam incident on a 40m-long carbon target. Muons from π decays are polarized : in the experimental conditions, $P = .81$ at 200 GeV, i.e. almost right-handed μ^- 's. The easiest way to reach the weak-EM interference is to measure the B asymmetry, since switching the beam polarity also flips the polarization P. The experiment therefore measures the inelastic rate of μ scattering under beam and spectrometer polarity reversals, thereby yielding

$$B_\mu(-P, P) = -gQ^2(a_\mu - Pv_\mu) A_q \quad (17)$$

The first term in Eq.(17) is dominant and parity-conserving (A-A term as in e^+e^- asymmetries), while the second one - although much smaller - is parity-violating.

The BCDMS group has done a careful study of systematic effects occurring in the sequential polarity-reversing runs. The QED radiative corrections to the asymmetry are large and have been applied to the data.

At this stage in the analysis, only the slope of B_μ versus $Q^2g(y)$ has been used (i.e. no constraint on normalization has been applied yet), giving

$$\frac{B_\mu}{g(y)Q^2} = -(1.40 \pm .35 \pm .2) 10^{-4} \text{ GeV}^{-2} \begin{matrix} \text{stat} \\ \text{syst} \end{matrix}$$

whereas the GSW prediction (+ quark-parton model) is -1.51. Therefore good agreement is found with orthodoxy. The data points are displayed in Fig.15, for 120 and 200 GeV beam energies ; the magnitude of the radiative correction (+ $0.7 10^{-4}$ for the slope) is also indicated.

3. - Vector coupling of the muon

The μ^\pm CERN experiment measures a linear combination of a_μ and v_μ , while we have seen that the asymmetry in $e^+e^- \rightarrow \mu^+\mu^-$ at PETRA yields a_μ alone. The combination of the two approaches allows one to separate v_μ . This is attempted in Fig.16 with the result :

$$v_\mu = -.17 \pm .36$$

This value can be turned into a measurement of $\sin^2\theta_w$ from μ NC couplings alone :

$$(\sin^2\theta_w)_\mu = .21 \pm .09$$

This is the first test of μ -e universality for the vector part (the only one depending on $\sin^2\theta_w$).

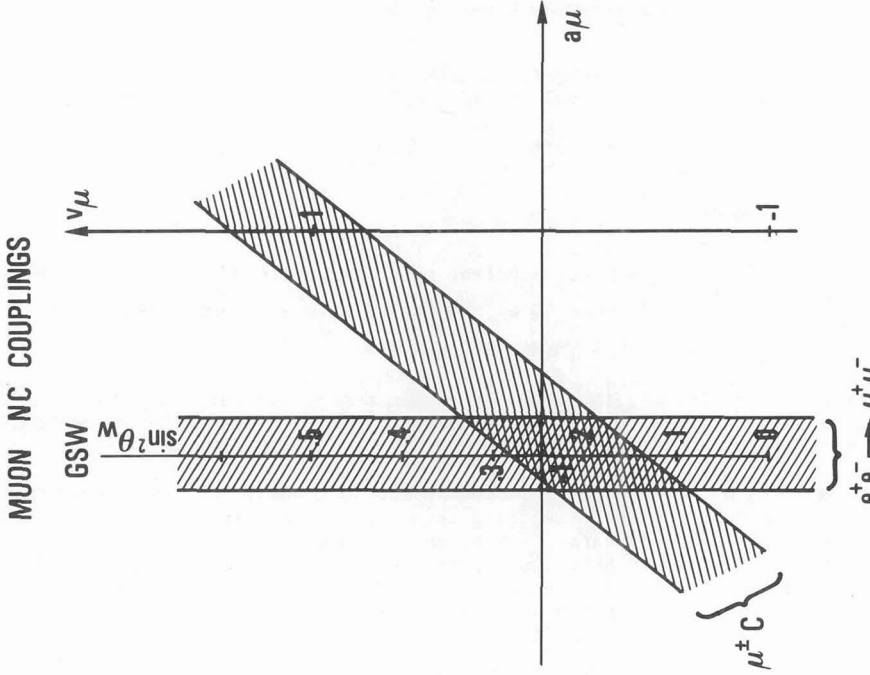


Fig. 16 - Determination of the vector and axial muon couplings from μ inelastic scattering and PETRA asymmetries

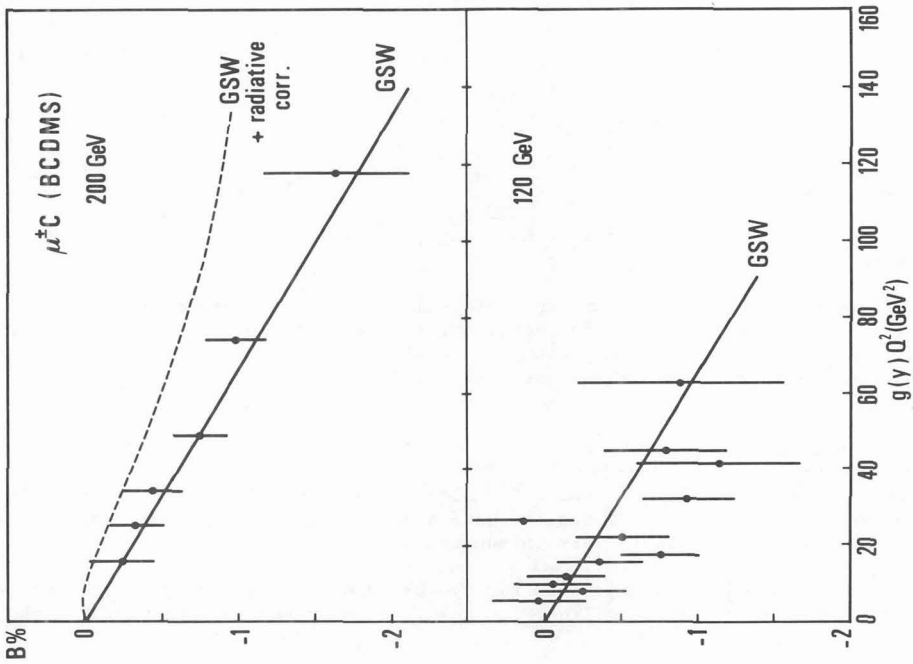


Fig. 15 - The μ^\pm beam asymmetries measured in deep inelastic μ -carbon scattering at CERN⁽²⁸⁾

V. PARITY VIOLATION IN ATOMS

1. - Introduction

If the weak neutral current interferes with the EM current, then atomic levels are not pure P-eigenstates: each level should receive a small admixture of the opposite parity state. Parity violation could manifest itself by different absorption rates between two atomic levels for left or right-handed photons, i.e. a circular dichroism

$$A = \frac{\sigma(\xi=+1) - \sigma(\xi=-1)}{\sigma(\xi=+1) + \sigma(\xi=-1)}$$

Very naively, as for other weak-EM asymmetries, A is of the order $G_F / \frac{e^2}{Q^2} \sim 10^{-4} Q^2 (\text{GeV}^2)$, giving the correct magnitude of the SLAC ed and the PETRA e^+e^- asymmetries. Since, in atoms $Q^2 \sim R_{\text{atom}}^{-2} \sim m_e^2 \alpha^2$, we expect very small effects indeed.

Fortunately, these P-violating asymmetries can be considerably enhanced²⁹⁾: while heavy atoms are favoured by $\sim Z^3$, it is also possible to work with a strongly forbidden EM transition.

What do we learn by studying P-violation in atomic transitions? In principle, the same thing we get from inelastic lepton scattering. In practice, the situations are quite different: first of all, the Q^2 ranges are remote to one another; secondly, it turns out that, in the static limit, the A_V term is dominant in atoms (because the nucleons add coherently via their weak charge Q_W^e), whereas the V_{eQ} term is very small (because nucleon spins cancel). More precisely,

$$Q_W = \tilde{\alpha} (N-Z) - 3 \tilde{\gamma} (N+Z) \quad \text{with } A = Z+N \quad (18)$$

is a combination essentially orthogonal to one of the two quantities measured in the SLAC ed experiment

$$A \sim a_1 + a_2 g(y)$$

$$\text{with } a_1 = \tilde{\alpha} + \frac{\tilde{\gamma}}{3} \quad \text{and } a_2 = \tilde{\beta} + \frac{2\tilde{\gamma}}{3}$$

Indeed, for example:

$$Q_W(\text{Cs}) = 23 \tilde{\alpha} - 17.3 \tilde{\gamma}$$

The combination of measurements of a_1 (SLAC) and Q_W (P-violation in atoms) therefore allows one to separate $\tilde{\alpha}$ and $\tilde{\gamma}$.

In designing atomic experiments on P-violation, two important considerations have to be taken into account: on one hand, experimental feasibility and control of systematic effects, and on the other hand, reliability of atomic physics calculations. One or the other has traditionally plagued this field in the past years.

2. - Previous experimental situation

The experimental results on atomic P-violation have been somewhat confusing in the past. Some early (too early?) results gave a null effect in contradiction to the GSW prediction, while some others were in support of the theory.

Most results have been obtained so far by observing a P-violating optical rotation in atomic Bi near a resonance line. The result is expressed as the ratio of the

imaginary part of the P-violating E_1 amplitude to the allowed M_1 transition amplitude :

$$R = \frac{\text{Im } E_1^{\text{PV}}}{M_1}$$

Experiments have been performed on two different transitions, $\lambda = 648$ and 876 nm. Table V presents a summary of the results and the theoretical expectations of atomic physics calculations (recall that Bi has 3 valence electrons) where the weak current is described by the GSW model. It is not unfair to say that the experimental and theoretical situations are not very well understood. However, it is clear from the most recent measurements and in particular, the Novosibirsk results, that P-violation occurs in atomic transitions - a very important fact. It is hard, nevertheless, to turn these measurements into accurate determinations of NC couplings.

A different type of experiment has been performed by the Berkeley group⁴⁰⁾ : here, a P-violating electronic polarization of Tl is observed from interference with a Stark-induced E_1 transition. Parity violation is observed at a level of 3 standard deviations (Table V). Calculations could, in principle, be more reliable than for Bi, as Tl has only one valence electron, however unfortunately close to the next 2-electron shell.

3. - New results on P-violation in cesium

In an experiment⁴³⁾ performed at the Ecole Normale Supérieure in Paris, a clear P-violation has been observed in the 6S-7S transition of Cs atoms placed in an external electric field, \vec{E}_0 . The experimental set-up and its principle are shown in Fig.17.

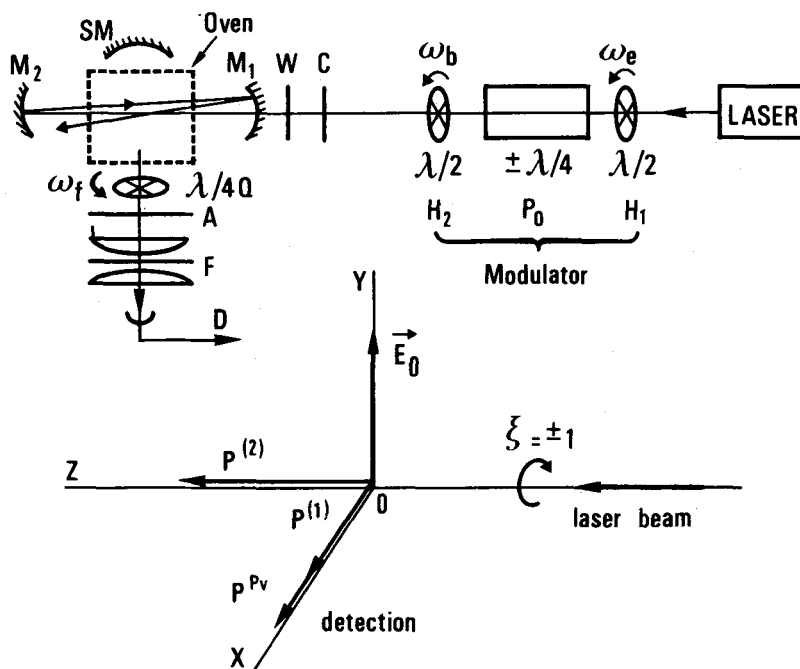


Fig. 17 - Schematic lay-out of the ENS Cs experiment⁴³⁾

TABLE V
 Results on atomic P-violation

Atomic transition	Experiment	Theory*
Bi $\lambda = 648$ nm $10^8 R$	Oxford ³⁰ 2.7 ± 4.7	Novikov ³³ -17
	Oxford ³¹ -10.7 ± 1.5	Khriplovich ³⁴ -18.8
	Novosibirsk ³ -20.2 ± 2.7	Sandars ³⁵ -13
	Moscow ³² -2.3 ± 1.3	Martensson ³⁶ -11.1
Bi $\lambda = 876$ nm $10^8 R$	Seattle ³⁷ $-2.4 \pm 1.4^{**}$	Novikov ³³ -13
	Seattle ³⁸ -10.4 ± 1.7	Carter ³⁹ -8
		Sandars ³⁵ -11
		Martensson ³⁶ -8.3
Tl $\lambda = 293$ nm $10^3 A$	Berkeley ⁴⁰ $2.8 \pm \begin{matrix} 1.0 \\ 0.9 \end{matrix}$	Neuffer ⁴¹ $2.1 \pm .7$
		Das ⁴² $1.65 \pm .24$
Cs $\lambda = 539$ nm $\frac{\text{Im } E_1^{\text{pv}}}{\beta}$ (mV/cm)	Paris ⁴³ $-1.34 \pm .22 \pm .11$ (syst)	Bouchiat ⁴⁴ $-1.73 \pm .07$ $\pm .20^{***}$

* $\sin^2 \theta_w$ values are in the range .22 to .25 (not very sensitive)

** quoted error did not include systematic uncertainties

*** quoted errors are from $\sin^2 \theta_w$ uncertainty and overall systematic uncertainty of atomic physics calculations.

Basically, what is observed is an electronic polarization produced by interference of the P-violating amplitude with a Stark-induced amplitude : this polarization is found to behave like a vector under a reversal of the incident photon helicity - a signature for P-violation. The experiment relies in part on very good tagging of photon helicities (flips and modulation of different helicity states). Three polarizations have to be separately detected (Fig.17) : the normal 7S polarization has a large $P^{(2)}$ component which is used for calibration, while the $P^{(1)}$ component competes with the sought-for P^{PV} polarization. $P^{(1)}$ is odd under beam direction reversal and is therefore considerably reduced by using a multi-pass cell.

The electric dipole operator for the 6S-7S E_1 transition has the general form

$$\vec{d} = -\alpha \vec{E}_0 - i\beta\vec{\sigma} \times \vec{E}_0 - i\vec{\sigma} \text{Im} E_1^{PV} \quad (19)$$

where α and β are the scalar and vector polarizabilities. The 3 contributions $P^{(1)}$, $P^{(2)}$ and P^{PV} arise from the interference of the α term with the (forbidden) M_1 , β and $\text{Im} E_1^{PV}$ terms. The P-violating polarization therefore measures $\text{Im} E_1^{PV}/\alpha E_0$ and since the apparatus is calibrated on the P-conserving polarization proportional to β/α , the final result is expressed in terms of the $\text{Im} E_1^{PV}/\beta$ ratio.

The experiment has a good control of systematic effects with on-line monitoring of defects and redundancy in the asymmetry measurements. The new result needs only very small corrections, to finally obtain

$$\frac{\text{Im} E_1^{PV}}{\beta} = (-1.34 \pm .22 \pm .11) \text{ mV/cm}$$

which is a 6σ effect for a violation of parity.

The atomic physics calculations are expected to be on a firmer basis here, since Cs has a single outer electron around a tight core. Calculations have been performed⁴⁴⁾ with many checks on the Cs spectroscopy : when taken together with the experimental result, they yield

$$Q_w(\text{Cs}) = -55 \pm 9 \pm 3(\text{syst})$$

which can be expressed as a measurement of $\sin^2\theta_w$

$$\sin^2\theta_w = .15 \pm .04 \pm .04(\text{syst})$$

in fair agreement with accepted values. It should be remarked that : (1) Q_w is not a sensitive function of $\sin^2\theta_w$ as demonstrated below in Fig.21 and (2) electroweak radiative corrections^{45,46)} will affect Eq.(18). The latter correction can be expressed as an effective $\sin^2\theta_w$ value, which is found⁴⁷⁾ to be equal to .207 for Cs, when $\sin^2\theta_w = 0.23$ (from ν results) is taken as an input : clearly, such a correction brings the Cs measurement in good agreement with the theory.

The lesson is that the standard theory again describes well experimental results in widely different q^2 regimes.

VI. ELECTRON-POSITRON ANNIHILATION INTO HADRONS

1. - Total hadronic cross section

In the quark-parton model, the ratio of the total hadronic cross section to the point-like QED cross section is given by

$$R_h = 3 \sum_q Q_q^2 + 6 \chi v_e \sum_q Q_q v_q + 3(a_e^2 + v_e^2) \chi^2 \sum_q (a_q^2 + v_q^2) \quad (20)$$

QCD corrections and threshold factors have been calculated⁴⁸⁾, but in the higher PETRA energy range, a very good approximation is to multiply Eq. (20) by a factor $(1 + \frac{\alpha_s}{\pi})$.

A measurement of R_h is, in principle, sensitive to the quark weak couplings since all quark (u,d,s,c,b) vector couplings enter in the interference term with basically the same strength (up to a factor of 2 due to the different charges). It, therefore, offers the possibility to explore the NC behaviour of the heaviest quarks, for which no information is available as yet. In practice, this hope turns out not to be rewarded, since the electron vector coupling, v_e , which has to appear also in the interference, is not known precisely enough and remains compatible with zero : as a result, no bound can be obtained for the sum $\sum_q Q_q v_q$.

Some information can be inferred from the squared weak term, but it does not yet constrain the couplings in a significant way. An analysis by JADE⁴⁹⁾ gives

$$(a_e^2 + v_e^2) \sum_q (a_q^2 + v_q^2) < 60$$

which can be translated into a limit for unknown couplings

$$\sum_{c,s,b} (a_q^2 + v_q^2) < 58$$

The corresponding value for the GSW theory is about 4 !

The s dependence of R_h is therefore controlled by v_e , itself determined by the departure of $\sin^2\theta_w$ from $\frac{1}{4}$: then, precise R_h measurements can be used to determine $\sin^2\theta_w$ (knowing α_s , or the converse, depending on one's interest).

Data have been presented by JADE, Mark J and TASSO with increased statistics and reduced systematic errors. The results, shown in Fig. 18, are in reasonable agreement with one another and do not indicate a strong interference with would be driven by $\sin^2\theta_w$ values much different from $\frac{1}{4}$.

2. - Quark asymmetries

If axial couplings are given by Eq.(3) with $I_{3R}(f) = 0$, then one expects sizeable asymmetries for quarks :

$$A_{d,s,b} = 2 A_{u,c} = 3 A_{\mu} \quad (21)$$

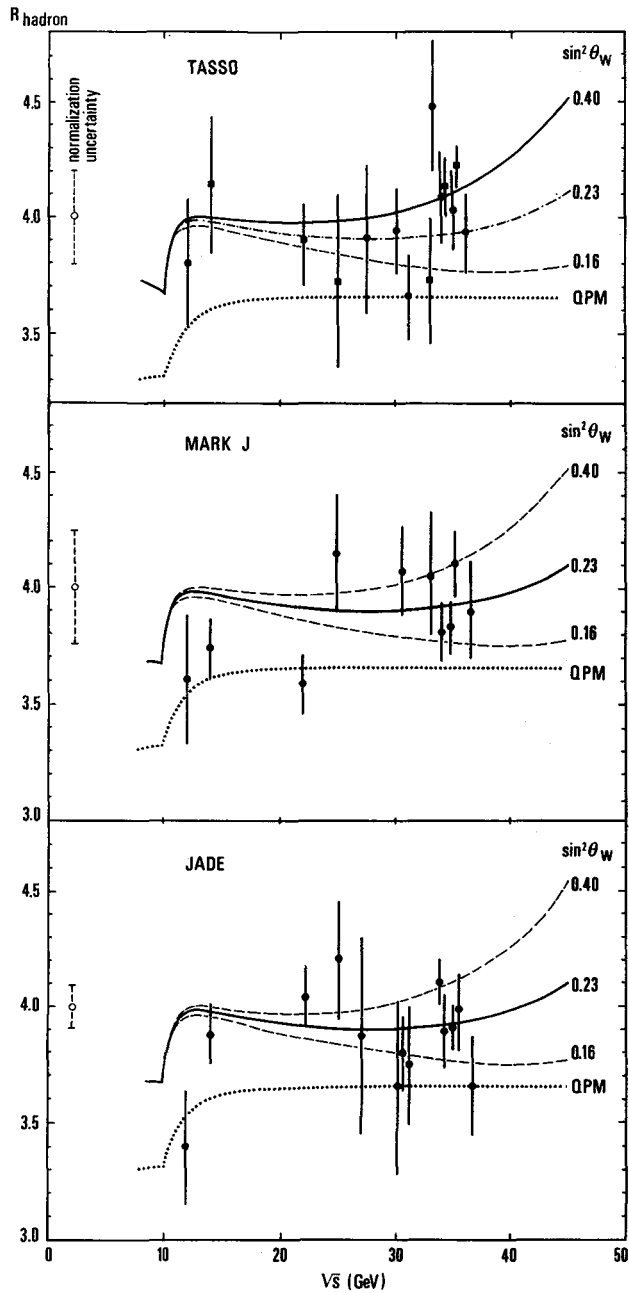


Fig. 18 - Total hadronic cross sections from PETRA experiments with predictions of the quark parton model (QPM) and the QCD-electroweak theory with $\alpha_s = 0.17$ and different values of $\sin^2 \theta_W$

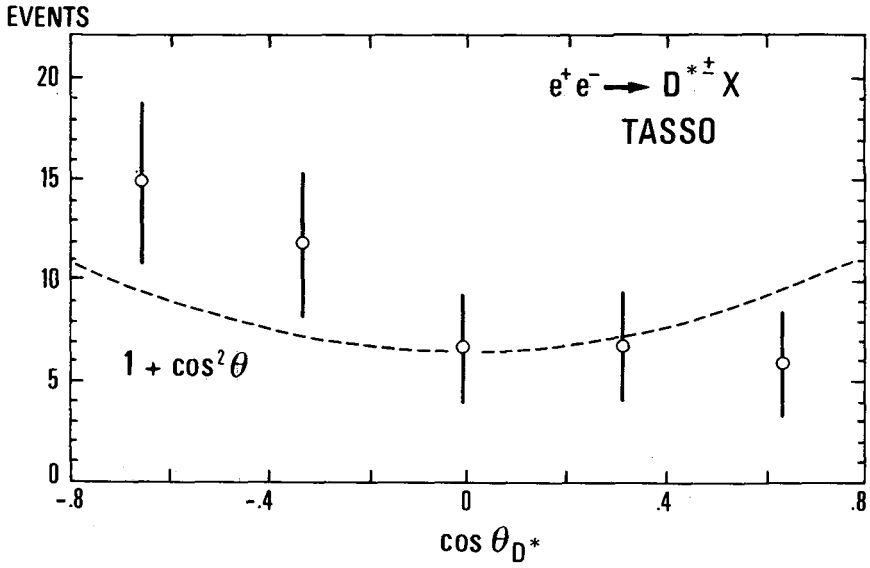


Fig. 19 - Preliminary results on the angular distribution of $e^+e^- \rightarrow D^{*\pm}X$ as a measure of c quark asymmetry¹⁸⁾

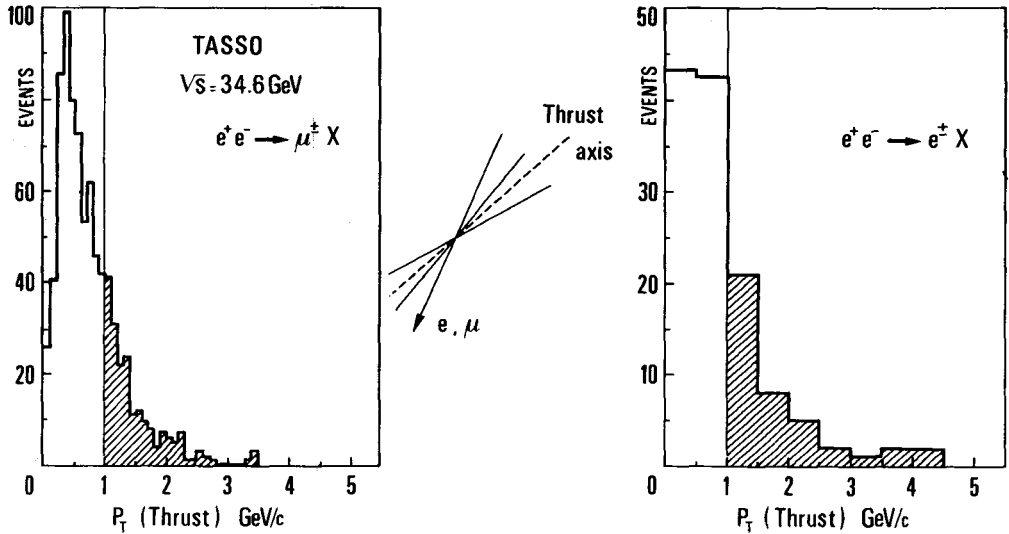


Fig. 20 - Transverse momentum of leptons with respect to the jet axis in multi-hadronic events¹⁸⁾. The hatched area ($P_T > 1 \text{ GeV}$) contains an enriched sample of $e^+e^- \rightarrow b\bar{b}$ events

Exp	Nb of hadronic events	Particle detected	Nb of events	quark	$\frac{\text{Signal}}{\text{Signal+backgr.}}$	Measured asymmetry	expected asymmetry
		D*	47	c	.41	$-.35 \pm .14$	$-.14$
TASSO ¹⁶⁾	20224	μ	201	b	.35	$-.17 \pm .10$	$-.084$
		e	41	b	.44	$-.11 \pm .17$	
				c	.52	$-.07 \pm .05$	$-.04$
Mark J ¹⁷⁾	15500	μ	561	b	.37	$-.20 \pm .10$	$-.05$

TABLE VI

Early results on quark asymmetries in e^+e^- annihilation $\sqrt{s} \sim 34$ GeV

We remain with the problem of actually being able to experimentally determine the flavour and the charge of a quark jet. Litterature abounds on the subject, in contrast to still little experimental information. The trend seems now more interesting, with the availability of higher statistics, and two approaches have been tried so far : c quark tagging by D^* identification and tagging of b and c quarks through semi-leptonic decays of heavy mesons.

The identification of $D^{*18,22)}$ is greatly simplified by the small Q value (5.7 MeV) in the $D^{*+} \rightarrow D^0 \pi^+$ decay, resulting in a mass difference between $(K^- \pi^+ \pi^+)$ and $(K^- \pi^+)$ of 145 MeV which can be measured to a few MeV accuracy : no particle identification appears necessary for a clean D^* signal. It is also fortunate that D^* production appears to be a major part of c-quark fragmentation²²⁾. All these favourable conditions set the stage for a first look at the angular distribution of the $e^+ e^- \rightarrow c \bar{c}$ process, performed by TASSO (Fig.19). The resulting asymmetry for leading D^* 's ($\langle z \rangle \sim .8$) is

$$\langle A_c \rangle = - .35 \pm .14$$

in fair agreement with a prediction of $-.14$.

The situation is less straightforward in semi-leptonic channels, because of backgrounds (μ or e misidentification) and feedthrough between b and c-quark decays, including $b \rightarrow c$ cascades : these effects are large, and imply large corrections and an unavoidable dilution of the asymmetry. Typical lepton spectra are shown in Fig.20 and results are given in Table VI. Some separation between b and c quark can be achieved by p_T cuts. These preliminary results are encouraging, but it will take some time before a quantitative determination of b and c axial couplings from semi-leptonic decays can be reliably performed.

VII. SUMMARY OF TESTS OF THE GSW MODEL

1. - Factorization

Factorization is a basic ingredient of the standard model, but it is not well checked experimentally. Going back to the Hung-Sakurai parametrization (which does not assume factorization ; see Table I), in fact only 3 relations can be subjected to experimental test : the first one involves the ratio of $I = 0$ to $I = 1$ vector quark couplings as measured with neutrinos or with electrons (the last case implies both SLAC ed and atomic physics results) ; the second relation assumes μ -e universality and involves the ratio of vector to axial leptonic couplings as measured with $e^+ e^-$ annihilation or νe scattering ; the third relation also pertains to the vector to axial electron couplings as measured in νe scattering and a combination of νN and eN scattering data.

$$\begin{aligned} \text{Test n}^\circ 1 \quad \frac{Y}{\alpha} &= \frac{\tilde{Y}}{\tilde{\alpha}} & (22) \\ & - .46 \pm .15 & - .16 \pm .09 \text{ (Cs experiment)} \\ & & - .37 \pm .19 \text{ (T\% experiment)} \end{aligned}$$

$$\begin{aligned} \text{Test n}^\circ 2 \quad \frac{h_{V\nu}}{h_{AA}} &= \frac{g_V}{g_A} & (23) \\ & & \\ & < .20 & < .13 & \text{ (95 \% CL limits)} \end{aligned}$$

Test n° 3

$$\frac{g_V}{g_A} = \frac{(\alpha + \frac{\gamma}{3}) (\beta + \frac{\delta}{3})}{(\alpha + \frac{\gamma}{3}) (\beta + \frac{\delta}{3})} \quad (24)$$

$$-.12 \pm .15 \quad \quad \quad -.27 \pm .46$$

A preliminary conclusion is that factorization is not so well tested : a visual impression of the quality of these tests can be gathered from Fig.21 and Fig.13. As far as relation (22) is concerned, one should keep in mind that electro-weak radiative corrections have to be applied, resulting in effective $\sin^2\theta_w$ values which can vary by $\sim .025$, giving a better agreement to the data : this is of course a violation of factorization, but occurring in higher orders of a theory which has a single pole at the lowest order. At this stage, there is no indication against the single Z^0 hypothesis, realized in the simplest gauge group : $SU(2) \times U(1)$.

2. - Symmetry breaking

The only (indirect) evidence for the symmetry breaking scheme used in $SU(2) \times U(1)$ is the fact that ρ is found to be consistent with 1 : this is in agreement with the postulated existence of doublets of Higgs fields.

There are no good direct evidence against (and even less for !) the existence of a single H^0 . For example a Higgs boson with a mass $M_H < 10$ GeV could be seen in T radiative decays with, however, a negligible rate. Due to its larger mass, toponium would be much more suitable.

If more than one Higgs doublet come into play, then, one would observe charged Higgs bosons, which are much easier to look for since they could be pair-produced in e^+e^- annihilation :

$$e^+e^- \rightarrow H^+H^-$$

A great deal of experimental effort has been spent over the past year to look for such states, in the mass range between 2 and 15 GeV. Limits depend on possible decay modes : if decays of a single H^0 would clearly be dominated by pairs of heavy fermions, the situation is not so in the general case of several Higgs bosons. Searches have been conducted under the assumption that dominant decay modes in the 2-15 GeV mass range would be $H^- \rightarrow \tau^- \bar{\nu}_\tau$ and $H^- \rightarrow$ hadrons (mostly $\bar{c}s$ and $\bar{c}b$) : these assumptions are in fact rather loose, and the absence of any signal is strong evidence against the existence of any charged Higgs boson in this mass range. The experimental contributions are from CELLO⁵⁰⁾, JADE⁵¹⁾, Mark J⁵²⁾, TASSO¹⁸⁾ (new preliminary data looking for hadronic modes only) and Mark II²²⁾ ; they are summarized in Fig.22.

3. - Fermion multiplets of weak isospin

We have strong evidence that left-handed fermions are in doublets : for the b quark, we have the results on B decays from CESR and we await the discovery of the t quark ; for the τ , the new lifetime measurements⁵³⁾ give a stronger basis for the existence of a τ neutrino, different from ν_e or ν_μ .

As far as the right-handed fermions are concerned, we have a clear experimental situation : e_R, u_R, d_R, μ_R and τ_R are weak-isospin singlets. Some hope exists that a

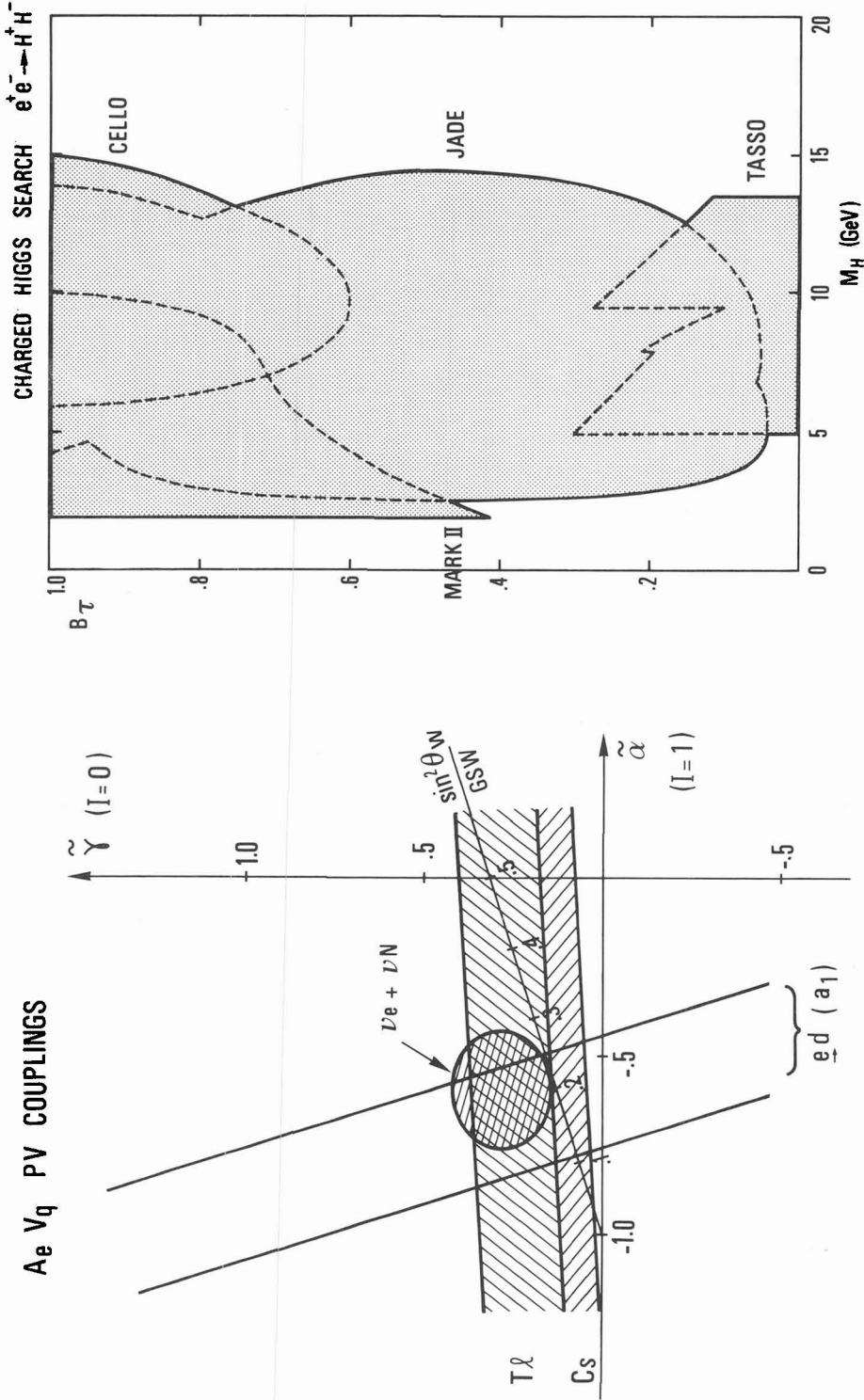


Fig. 22 - Charged-Higgs search in $e^+e^- \rightarrow H^\pm H^\mp$. The contours correspond to a 95 % CL limit on the H^\pm mass. References are given in the text

Fig. 21 - $A_e V_q$ couplings obtained from SLAC ed results⁴⁾ and P-violation in $C_s^{4,3}$ and $Tl^{4,0}$. The ellipse represents the 90 % CL limits for the same quantities as measured in ν reactions. The GSW prediction is a line with the indicated $\sin^2\theta_w$ dependence

determination of I_{3R} for c and b quarks can be achieved, as we have seen in the previous section.

4. - Consistency between couplings

As far as NC couplings are concerned, the standard model has only one parameter. At least as long as we can ignore higher orders, a consistent value of $\sin^2\theta_w$ should be found for different, independently measured, couplings. This can now be done experimentally for the electron, the u and d quarks and the muon :

$$\begin{aligned}\sin^2\theta_w(e) &= .25 \pm .04 \\ \sin^2\theta_w(u,d) &= .24 \pm .05 \\ \sin^2\theta_w(\mu) &= .21 \pm .09\end{aligned}$$

At this stage, the agreement with the $SU(2) \times U(1)$ model is excellent.

VII. SHORT DISCUSSION ON ALTERNATIVES TO THE $SU(2) \times U(1)$ MODEL

1. - Larger gauge groups

Since the simplest gauge group describes the whole of the electroweak data, there is no strong motivation to consider a more complicated structure. However, present data put severe constraints on larger groups.

Groups of the type $SU(2) \times U(1) \times G$ have been considered⁵⁴ : as a consequence, two Z^0 bosons appear and some low q^2 properties are altered ; for example the current-current form (1) is no longer exactly true and the low-energy lagrangian becomes

$$\mathcal{L}_{q^2} \ll M_{Z_1}^2, M_{Z_2}^2 = \frac{4G}{\sqrt{2}} \left[(J_\mu^3 - \sin^2\theta_w J_\mu^{EM})^2 + C (J_\mu^{EM})^2 \right] \quad (25)$$

Such an additional term cannot be seen in ν reactions and in P-violation experiments. It would, however, show up in e^+e^- reactions through a VV transition, so that

$$a^2 = (1 - 4 \sin^2\theta_w)^2 + 16 C$$

The PETRA experiments have given new limits on such a parameter C : 95 % CL limits are .031 (CELLO), .021 (Mark J) and .020 (TASSO). These restrictive values limit the mass range available for the 2 Z bosons in definite models : Fig.23 gives the relevant limits for $C < .02$, in the 2 cases where G is given by another $U(1)$ or $SU(2)$ groups. At least in one case, $G = U(1)$, the larger group is becoming essentially degenerate with $SU(2) \times U(1)$.

Left-right symmetric models, such as $SU(2)_L \times SU(2)_R \times U(1)$ are aesthetically appealing⁵⁵. It is clear that right-handed currents must be associated to a Z boson, still heavier than the GSW Z^0 , in order to satisfy low q^2 phenomenology. The interesting region to test these models is really beyond the 100 GeV mass range.

Some other ways to break the symmetry are available in larger groups : let us consider for a while a group⁵⁶⁾, inspired by supersymmetry, $SU(2) \times U(1) \times U'(1)$. It is different from the one we have considered above, in the sense that two Higgs_± doublets are used to break the symmetry : this procedure leads to the "usual" W^\pm , Z^0 γ family from $SU(2) \times U(1)$ and a new gauge boson, U , from $U'(1)$. The lagrangian picks up a new piece :

$$\mathcal{L}_{q^2} \ll M_Z^2 = \frac{4G}{\sqrt{2}} \left[J_Z^2 + r^2 \frac{M_U^2}{q^2 + M_U^2} J_U^2 \right] \quad (26)$$

with $r = 1$ in the simple model. Such a theory has non-trivial consequences for the q^2 dependence of NC phenomena : in general, effects are expected for $q^2 < M_U^2$. The fact that $\langle A_\mu \rangle$ and $\langle A_\tau \rangle$ agree with the GSW prediction rather than twice this value, means that M_U has to be $\lesssim 20$ GeV. Then it is sufficient to run down the experiment's list as q^2 decreases - νN , νe , and finally P violation in atoms - to reach the conclusion that the hypothetical U boson must be very light, \lesssim a few MeV. In the simplest model, this last case is ruled out by the absence of $\psi \rightarrow \gamma U$ decays. I do not wish to elaborate more on this model, but I think it is instructive, because it warns us that important modifications of the standard model could still occur and that experiments have to be performed over the widest possible energy range. It is clear in that respect, that atomic physics experiments do not just provide redundant information : they play an important role and should be improved further.

2. - Non-unified theories

It appears possible to describe the NC experimental situation without the concept of weak-EM unification within a gauge group. One could start with a global $SU(2)$ symmetry (W^+ , W^- , W^0 triplet) and mix γ and W^0 currents⁵⁷⁾ : low energy phenomenology would be preserved, as such a prescription leads to an effective current-current form. Since the model uses one more parameter than $SU(2) \times U(1)$, no definite prediction can be made on the W mass : therefore a crucial distinctive test lies in the observation of the weak bosons and their mass values. Some theoretical support for this view is given by composite models, where such a picture can emerge⁵⁸⁾ : in this latter case one could even foresee a whole spectrum of W , Z bosons. Some confusion could even persist after the experimental observation of W and Z bosons near the GSW masses⁵⁹⁾ : in that case, a detailed study of Z^0 decays at LEP could be required to sort out the matter⁶⁰⁾.

IX. CONCLUSIONS

At the end of this talk, let me try to summarize the salient facts of electro-weak phenomenology :

- many neutral-current transitions have been observed and studied : a qualitative summary is given in Fig. 24
- all experimental data on NC are in agreement with the minimal $SU(2) \times U(1)$ model
- however, little has been really tested as far as some basic assumptions of the model are concerned, namely : factorization and symmetry breaking
- the standard model is most successful in predicting neutral couplings : weak-isospin assignments of fermions are confirmed and there is consistency with a

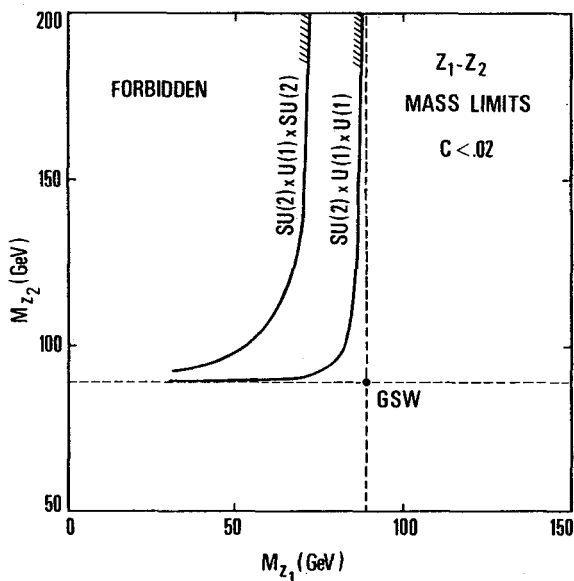


Fig. 23 - Mass limits for the 2 Z^0 bosons of $SU(2) \times U(1) \times SU(2)$ and $SU(2) \times U(1) \times U(1)$ models, obtained from $C < 0.02$ (typical 95 % CL from PETRA experiments). The upper space above the curves are excluded by data

MEASURED NC TRANSITIONS

	ν_e	ν_μ	ν_τ	e	μ	τ	u	d	s	c	b	
				X			.	.				ν_e
				X	.		X	X	.			ν_μ
												ν_τ
				X	X	X	X	X		.	.	e
							X	X				μ
												τ
f												u
f'												d
\bar{f}												s
\bar{f}'												c
												b

NC COUPLINGS (FACTORIZATION)

	e	u	d	μ	c	s	τ	t	b
v	X	X	X	X					
a	X	X	X	X	.		X		.

Fig. 24 - A summary of the measured $f\bar{f} \rightarrow f'\bar{f}'$ transitions induced by neutral currents and the factorized axial and vector couplings for each fermion. The crosses (X) indicate good measurements, whereas a dot (.) mostly means a qualitative attempt

unique $\sin^2\theta_w$ value, best measured in neutrino neutral currents :

$$\sin^2\theta_w = .23 \pm .01$$

- the experimentally available q^2 range, over which the standard model has been tested, has been extended considerably by more reliable atomic physics experiments on parity violation. This is shown schematically in Fig.25.

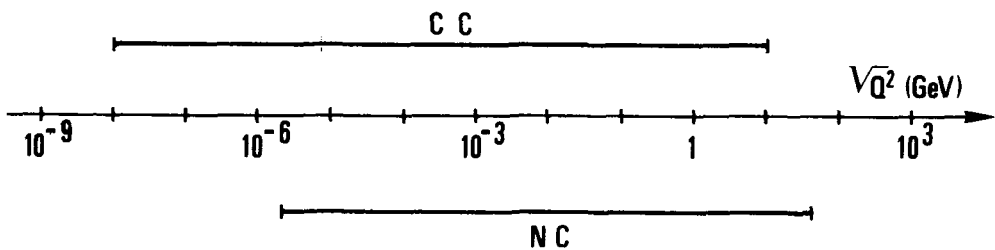


Fig. 25 - A schematic view of q^2 coverage in the experimental study of charged and neutral currents

In the near future, more data will come in to strengthen our understanding :

- more precise ν_e data
- heavy quark couplings from PEP and PETRA
- higher energies at PETRA (s going from 1200 to 2000 GeV^2) and a chance to observe the effect of a finite Z mass
- CERN $p\bar{p}$ collider results of the W and Z-boson searches. It is conceivable that these undertakings will provide the conclusive evidence for the GSW theory, in confirming the W and Z mass prediction. Despite the tremendous successes achieved so far, only then will we be sure of the reality of weak-EM unification.

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