INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - I

H4.SMR 346/2

SCHOOL ON NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

STANDARD MODEL AND BEYOND

by

G. Costa
Universita degli Studi di Padova
Italy

Standard Model and Beyond

1. Introduction
2. Unification of electroweak int.s
3. Tests of the SM
4. Inclusion of strong int.s
5. Grand unification
6. Supersymmetry
7. Conclusions

Trieste, April 88

1. INTRODUCTION

A constant trend in physics has been to explain all variety of phenomena in terms of FUNDAMENTAL INTERACTIONS of ELEMENTARY CONSTITUENTS.
The basic constituents have been changed from time to time, but this point of view still dominates the research in Particle Physics.

In the last 10~15 years new theoretical ideas and experimental discoveries have consolidated this picture.

Ordinary matter is composed by few "elementary" particles that are stable (N stable inside nuclei):

$$\boxed{P\ ,\ N\ ,\ e\ ,\ \gamma}$$

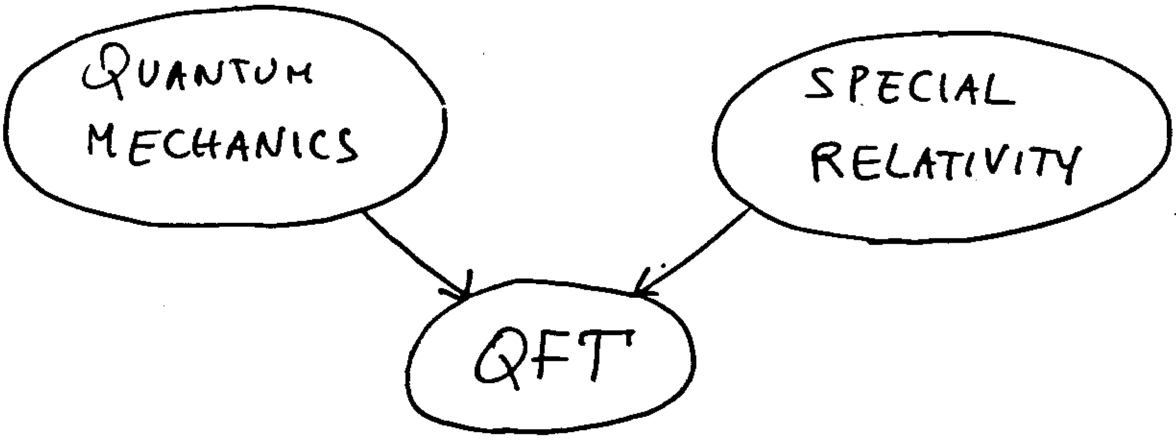
They manifest different <u>mutual</u> kinds of <u>interactions</u>.

The present understanding of the elementary constituents and their interactions is based on two great products of 20th century physics:

1) QUANTUM FIELD THEORY

2) ROLE OF SYMMETRY PRINCIPLES

Ingredients of QFT:



The interactions between 2 particles are not at-a-distance, but are transmitted by a <u>FIELD</u>: the interactions are mediated by the <u>QUANTA</u> of the field.

In the present picture :

MATTER consists of $\left\{ \begin{array}{ll} \text{LEPTONS} & (S=\frac{1}{2}) \\ (e, \nu, \ldots) & \\ & \\ \text{QUARKS} & (S=\frac{1}{2}) \\ (u, d, \ldots) & \end{array} \right.$

Nucleons (P, N) and their excited states =

DRONS $\left\{ \begin{array}{l} \underline{\text{BARYONS}} \text{ are made of 3 quarks ;} \\ \underline{\text{mesons}} \text{ (like } \pi^{\pm}, \pi^{0}\text{) are made of a quark-} \end{array} \right.$

antiquark pair

RADIATION consists of $\left\{ \begin{array}{ll} \text{PHOTONS} & (S=1) \\ W^{\pm}, Z^{0} & (S=1) \\ \text{GLUONS} & (S=1) \\ \text{GRAVITONS} & (S=2) \end{array} \right.$

Matter interacts through radiation :
all interactions can be grouped into
4 categories.

FUNDAMENTAL INTERACTIONS

Type of int.s	Example	Particles involved	strength ($\hbar = c = 1$)	range (cm)	particles exchanged
EM	atoms	charged	$\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$	∞	photons (γ)
Weak	β-decay	leptons & quarks	$\alpha_W = \frac{G_F m_p^2}{4\pi} \simeq 10^{-5}$	2.5×10^{-16}	$W^{\pm}$, Z^0
Strong	nuclei	quarks	$\alpha_S = \frac{g^2}{4\pi} \approx 1$	1.4×10^{-13}	gluons
Gravitational	solar system	all	$\alpha_G = \frac{G_N m_p^2}{4\pi} \approx 6 \times 10^{-39}$	∞	gravitons

NOTES

1) Range is related to mass of exchange particle by means of uncerteinty relation

$$\Delta r \approx c \Delta t \approx \frac{\hbar}{mc}$$

2) Quarks have replaced nucleons as sources of strong int.s, and gluons $\rightarrow$ mesons (in particular Yukawa "pions").

In the following:

1) Unification of electro-weak interactions

2) Inclusion of strong interactions
→ Standard Model

Beyond SM:

3) Unification of electroweak and strong interactions → GUT's

4) Inclusion of gravitational interactions
→ Supergravity → susy GUT's

2. EM and WEAK INTERACTIONS and their UNIFICATION

QED is the best example of quantum field theory. All predictions are in very good agreement with experiments.

It is a good example to illustrate the important role of symmetry.

In QED a system of (non-interacting) electrons is described by the Lagrangian

$$\mathcal{L}_0 = \frac{1}{2} i \bar{\psi}(x) \gamma^\mu \partial_\mu \psi(x)$$

which is invariant under global (or rigid) GAUGE TRASFORMATIONS, i.e. phase transf. of the electron field

$$\psi(x) \to e^{i\alpha} \psi(x)$$

$e^{i\alpha}$: element of the (Abelian) group $U(1)$

However, it is not invariant under local transf.s $(\alpha \to \alpha(x))$:

$$\delta \mathcal{L} = \alpha\, \partial_\mu J^\mu + (\partial_\mu \alpha)\, J^\mu \qquad (J^\mu = i\bar{\psi}\gamma^\mu \psi)$$

If one introduces a vector field $A_\mu(x)$ with transformation property

$$A_\mu \to A_\mu + \partial_\mu \alpha ,$$

the modified Lagrangian

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_A , \qquad \mathcal{L}_A = -\frac{1}{2}\bar{\psi}\gamma^\mu A_\mu \psi$$

gives

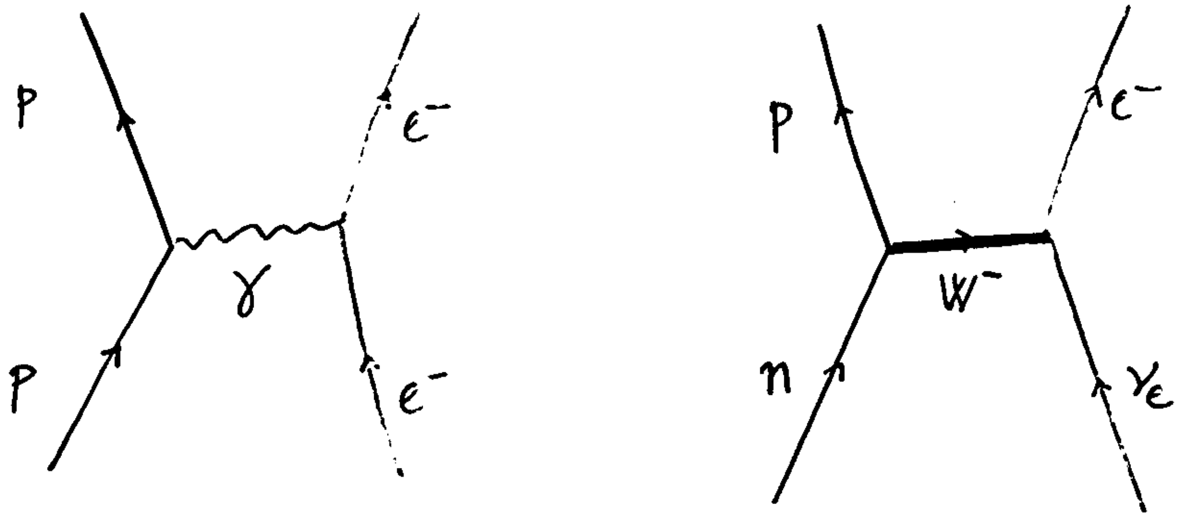
$$\delta \mathcal{L}_A = -(\partial_\mu \alpha) J^\mu$$

so that

$$\delta \mathcal{L} = 0 \qquad (\partial_\mu J^\mu = 0)$$

[Conclusion: local gauge invariance requires the introduction of the vector (massless) field A_μ.]

Next consider the <u>weak interactions</u>, and compare a weak process with an EM process:



$e^- p \to e^- p$ (EM)

$\nu_e\, n \to e^- p$ (Weak)

$\left[\begin{array}{l}\text{compare with:} \\ \quad n \to e^- p\, \bar{\nu}_e\end{array}\right]$

Replacing the <u>massless photon</u> by a MASSIVE BOSON ($m_W \approx 10 \sim 10^2$ GeV):

1) The <u>range</u> from ∞ reduces to $\sim \frac{1}{m_W} \sim 10^{-15} \sim 10^{-16}$ cm

2) The <u>strength</u> is reduced from α to $\alpha_W \approx \frac{\alpha}{m_W^2}$:

$\alpha_W \approx (10^{-2} \div 10^{-4}) \cdot \alpha$

Based on these analogies (in spite of the differences!) it was proposed (Weinberg, Salam '67) that EM and WEAK int.s were related by a gauge symmetry principle.

The group $U(1)$ of QED was extended to a (non-Abelian) group of transformations with 4 generators:

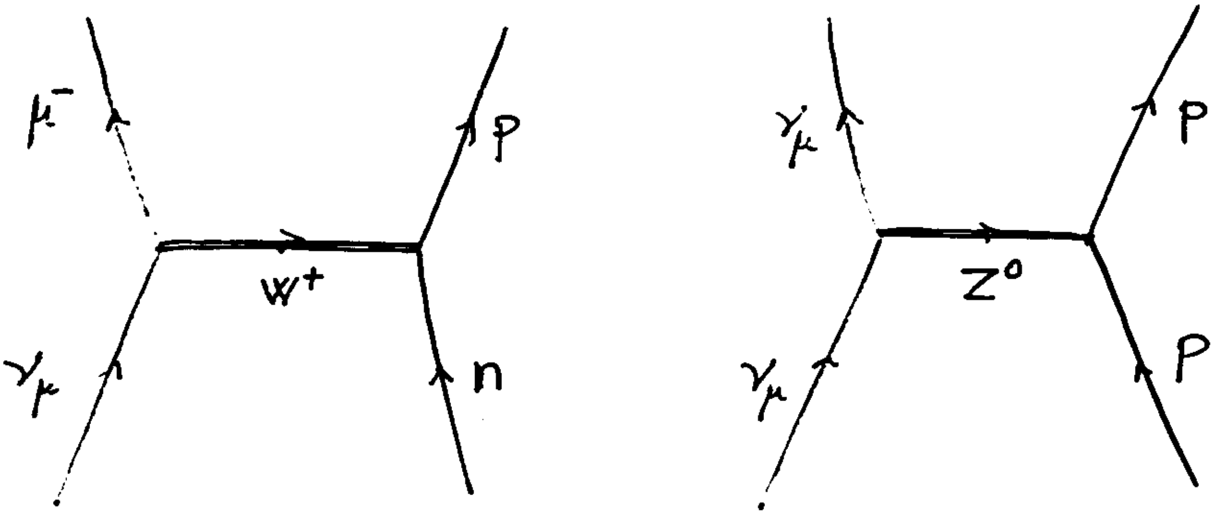
$$SU(2) \times U(1)$$

This structure was suggested by the properties of the currents:

besides the EM current (coupled to γ) there must be a charged weak current $J_W^{\pm}$ (coupled to $W^{\pm}$)

The symmetry $SU(2)$ implies that there is also a neutral weak current J_W^0, coupled to a neutral counterpart (Z^0) of $W^{\pm}$.

Notice the difference between a "charged current" process and a "neutral current" one



$(\nu_\mu\, n \rightarrow \mu^-\, p)$ $(\nu_\mu\, P \rightarrow \nu_\mu\, P)$

difficult to detect

easier to detect :

$$\left.\begin{aligned} \nu_\mu + p &\rightarrow \nu_\mu + p + \pi^0 \\ &\rightarrow \nu_\mu + n + \pi^+ \end{aligned}\right\}$$

Such events were discovered at CERN in 1973 (Gargamelle bubble chamber)

By now weak neutral currents are well established, with the specific properties predicted by the symmetry $SU(2) \times U(1)$.

However, the above picture is not consistent:

The photon is massless (2 degrees of freedom : 2 transverse states of polarization)

The $(W^{\pm}, Z^{0})$ bosons must be massive (3 degrees of freedom: transverse + longitudinal polarization)

But GAUGE INVARIANCE implies that the vector bosons are massless.

The puzzle is solved by making use of the concept of

SPONTANEOUS SYMMETRY BREAKING

a concept already introduced in solid state physics (e.g. spontaneous magnetization; superconductivity).

The Lagrangian (i.e. the equations of motion) of a system has a given symmetry, but the ground state can have a lower symmetry.

The electro-weak Lagrangian has the gauge symmetry $SU(2) \times U(1)$.

The ground state has, in general, the same symmetry, but below a certain energy scale (i.e. temperature) the ground states presents a lower symmetry:

$$SU(2) \times U(1) \rightarrow U(1)_{EM}$$

(only the symmetry of QED is preserved!)

The reduced symmetry does not prevent that 3 vector bosons acquire mass. (the photon remains massless).

The mechanism (Higgs 1964) requires the presence of scalar fields (Higgs fields) which are "eaten" by the massless vector fields which acquire the additional longitudinal components.

The mass is determined by a parameter, which is the analogue of the "order parameter" in a phase transition.

We have the following scheme:

$$\boxed{SU(2)_L \times U(1)_Y}$$

generators	I_i	Y
couplings	$g_2 \equiv g$	$g_1 \equiv g'$
<u>gauge fields</u> $(i=1,2,3)$	A^i_μ	B_μ

<u>scalar fields</u>

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \phi^* = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix}$$

$\Big\}$ spontaneous symmetry breaking

$$U(1)_{EM} \equiv \boxed{U(1)_Q}$$

$$\langle \phi^0 \rangle = \frac{1}{\sqrt{2}} v_0$$

generator	$Q = I_3 + \frac{1}{2} Y$
coupling	$e = g_2 \sin\theta_W = g_1 \cos\theta_W$
gauge field	A_μ (photon)

scalar field H

(3 components of ϕ, ϕ^* are eaten by A^i_μ, B_μ to give massive $W^\pm$ & Z^0)

$$\boxed{\frac{1}{e^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}}$$

<u>Note</u>: the parameter <u>θ_W</u> (<u>Weinberg angle</u>) is defined by

$$\tan\theta_W = g_1/g_2 = g'/g$$

The <u>massive vector bosons</u> are given explicitly by

$$W^\pm_\mu = \sqrt{\tfrac{1}{2}}\,(A^1_\mu \pm i A^2_\mu)$$

$$Z^0_\mu = \sin\theta_W \cdot B_\mu - \cos\theta_W A^3_\mu$$

and

$$\boxed{M_W = \frac{1}{2} g v_0} \quad ; \quad \boxed{M_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v_0 = \frac{M_W}{\cos\theta_W}}$$

The <u>matter fields</u> (quarks and leptons) have the following <u>(I,Y) assignment</u> (for each generation) :

1st	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	$I = \frac{1}{2}$, $Y = \frac{1}{3}$
	u_R^i , d_R^i	$I = 0$, $Y = 4/3, -2/3$
	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	$I = \frac{1}{2}$, $Y = -1$
	e_R	$I = 0$, $Y = -1$

Similarly for :

2nd $(c, s \; ; \nu_\mu , \mu)$

3rd $(t, b \; ; \nu_\tau , \tau)$ <u>Note</u> : top not yet discovered!

Besides the <u>charged</u> <u>(V-A)</u> <u>currents</u>

$$J_\mu^{\pm} = J^1_{V-A} \pm i\, J^2_{V-A}$$

the theory predicts a <u>neutral current</u> with the structure

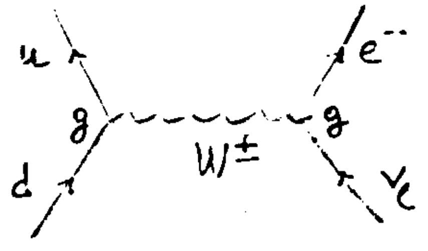
$$\boxed{J_\mu^0 = J^3_{V-A} - \sin^2\theta_W \, J_V^{em}}$$

They are coupled, respectively, to $W^\pm$ and Z^0.

Low-energy four-fermion REACTIONS are described by the effective Lagrangians (of FERMI type):

a) <u>charged currents</u> (V−A)

$$\mathcal{L}_{ch} = \frac{G_F}{\sqrt{2}} J^{(+)}_{\mu}(x)\, J^{(-)\mu}(x)$$



$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}$$

b) <u>neutral currents</u>

$$\mathcal{L}_n = \rho \frac{G_F}{\sqrt{2}} J^{(0)}_{\mu}(x)\, J^{(0)\mu}(x)$$

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$$ In minimal SM : $\rho = 1$.

It took many years to build the SM (Glashow, Weinberg, Salam 1961-68).
Essential ingredient for obtaining a <u>renormalizable</u> theory is the Higgs mechanism (1964), as shown in the work by 't Hoofts (1971).

The crowning of the theory came from the experimental <u>discovery</u> of <u>$W^{\pm}$ and Z^0</u> (UA1 and UA2, CERN 1983).

Other features of the model :

- Fermion masses are generated by Yukawa couplings $g_f(\bar{f}_R f_L \phi)$, $g_f'(\bar{f}_R f_R \phi^\dagger)$, and since g_f , g_f' are arbitrary, charged lepton and quark masses are arbitrary parameters.

- Quark mass eigenstates are not the states appearing in charged currents, but these are "rotated" by a mixing matrix U (Kobayashi & Maskawa 1973)

$$J_\mu = (\bar{u}, \bar{c}, \bar{t})\gamma_\mu U \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$U = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ -s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

$s_1 = \sin\theta_1 = 0.231 \pm 0.003$ (Cabibbo angle)

δ : introduces CP-violation

- Neutral currents are flavour conserving (to order $G_F^2 m_i^2$)
  This is due to the suppression caused by the GIM mechanism (Glashow, Iliopoulos, Maiani: 1970)

- Neutrino are massless in minimal model.
  No right-handed counterpart ν_R
  B and L global symmetries (non-perturbative violation gives too small effects).

3. TESTS of the SM (Electroweak Sector)

Crucial tests are those related to the neutral currents (NC).

Four parameters are involved, but only one is independent:

$$(g_1, g_2, v_0, \rho) \longrightarrow \text{weak angle } \theta_W$$

$$g_1 \cos\theta_W = g_2 \sin\theta_W = e \quad \rightarrow \tan\theta_W = g_1/g_2$$

$$v_0 \longrightarrow \quad G_F = \frac{1}{\sqrt{2}\, v_0^2}$$

In the minimal model (only isospin doublets in the Higgs sector)

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 .$$

However, it is useful to keep ρ as a free parameter, to test possible extensions of SM.

In the following, we consider the 2 independent parameters

$$x \equiv \sin^2\theta_W \quad \text{and} \quad \rho$$

All the low-energy NC reactions can be expressed in terms of the coefficients entering the effective Lagrangians

$$\mathcal{L}_{eff}^{(\nu q,\nu l)} = -\frac{G_F}{\sqrt{2}}\left[\bar\nu\gamma_\mu(1-\gamma_5)\nu\right]\cdot$$

$$\Big[\, u_L\,\bar u\gamma^\mu(1-\gamma_5)u + u_R\,\bar u\gamma^\mu(1+\gamma_5)u$$
$$+ d_L\,\bar d\gamma^\mu(1-\gamma_5)d + d_R\,\bar d\gamma^\mu(1+\gamma_5)d$$
$$+ g_L\,\bar e\gamma^\mu(1-\gamma_5)e + g_R\,\bar e\gamma^\mu(1+\gamma_5)e\,\Big]$$

$$\mathcal{L}_{eff}^{(eq)} = \frac{G_F}{\sqrt{2}}\Big[(\bar e\gamma_\mu\gamma_5 e)(C_{1u}\,\bar u\gamma^\mu u + C_{1d}\,\bar d\gamma^\mu d)$$
$$+(\bar e\gamma_\mu e)(C_{2u}\,\bar u\gamma^\mu\gamma_5 u + C_{2d}\,\bar d\gamma^\mu\gamma_5 d)$$
$$+(\bar e\gamma_\mu\gamma_5 e)(h^u_{AA}\,\bar u\gamma^\mu\gamma_5 u + h^d_{AA}\,\bar d\gamma^\mu\gamma_5 d)\Big]$$

The theoretical expressions of the coefficient in the SM are given by:

$$u_L = \left(\frac{1}{2} - \frac{2}{3}x\right)\rho$$

$$d_L = \left(-\frac{1}{2} + \frac{1}{3}x\right)\rho$$

$$u_R = -\frac{2}{3}x\cdot\rho$$

$$d_R = \frac{1}{3}x\cdot\rho$$

$$e_L = \left(-\frac{1}{2} + x\right)\cdot\rho$$

$$e_R = x\cdot\rho$$

$$C_{1u} = \left(-\frac{1}{2} + \frac{4}{3}x\right)\cdot\rho$$

$$C_{1d} = \left(\frac{1}{2} - \frac{2}{3}x\right)\cdot\rho$$

$$C_{2u} - \frac{1}{2}C_{2d} = \left(-\frac{3}{4} + x\right)\cdot\rho$$

$$h^u_{AA} = \frac{1}{2}\rho$$

$$h^d_{AA} = -\frac{1}{2}\rho$$

Predictions of the SM for the NC coefficients

Moreover, the SM predicts the masses of $W^\pm$ and Z^0 :

$$M_W = \left(\frac{A_c}{x}\right)^{1/2}$$

$$M_{Z^0} = \left(\frac{A_c}{\rho\, x(1-x)}\right)^{1/2}$$

where

$$A_c = \left(\frac{\pi\alpha}{\sqrt{2}\, G_F}\,\frac{1}{1-\Delta r}\right)^{1/2}$$

$$A_c = 37.281 \text{ GeV}$$

$\Delta r = 0.0713 \pm 0.0013$ (from radiative corrections evaluated with $m_t = 40$ GeV, $M_H = 100$ GeV)

Two recent analyses of all available experimental data on NC have been performed independently, and give very similar fits

(U. Amaldi et al.)

(G.C. Fogli et al.)

The results of the latter are summarized in Tables and Fig. 1.

Data are obtained from different sets of experiments:

1) ν – deep inelastic scattering on isoscalar targets, ν–P, etc. (u_L, u_R, d_L, d_R)

2) $\nu_\mu - e$ (g_L, g_R)

3) parity violation in atoms (C_{1u}, C_{1d})

4) asymmetries in e–d, μ–C (C_{1u}, C_{1d}, $C_{2u} - \frac{1}{2} C_{2d}$)

5) forward-backward asymmetries in $e^+e^- \to q\bar{q}$ ($q = c, b$)

Table 10

Case (a): One-parameter fits within the Standard Model

	(ν-q)	(ν-e)	(e-q)	(e-q) + (e-L)
$\sin^2\theta_w$	$0.2283^{+0.0048}_{-0.0048}$	$0.2271^{+0.0143}_{-0.0143}$	$0.2272^{+0.0112}_{-0.0112}$	$0.2277^{+0.0111}_{-0.0111}$
m_{Z^0}	$92.15^{+0.68}_{-0.67}$	$92.33^{+2.18}_{-1.94}$	$92.31^{+1.67}_{-1.53}$	$92.24^{+1.65}_{-1.51}$
χ^2	0.47/3	$0.6 \times 10^{-3}/1$	1.48/4	1.99/6
	Low-energy	(m_W, m_Z)	(e-L) + (m_W, m_Z)	Everything
$\sin^2\theta_w$	$0.2281^{+0.0042}_{-0.0042}$	$0.2279^{+0.0089}_{-0.0084}$	$0.2282^{+0.0089}_{-0.0084}$	$0.2281^{+0.0038}_{-0.0038}$
m_{Z^0}	$92.18^{+0.59}_{-0.58}$	$92.21^{+1.24}_{-1.22}$	$92.17^{+1.24}_{-1.22}$	$92.18^{+0.53}_{-0.52}$
χ^2	2.54/12	0.13/1	0.64/3	2.65/14

Note that the qualities of the fits in this and the subsequent Tables, as measured by the χ^2/DOF values, are always very good. This may indicate that the errors have been treated very conservatively.

Table 11

Case (b): Two-parameter fits within the Standard Model

	$(\nu\text{-q})$	$(\nu\text{-e})$	(e-q)	(e-q) + (e-L)
$\sin^2\theta_w$	$0.2310^{+0.0113}_{-0.0116}$	$0.2272^{+0.0146}_{-0.0150}$	$0.2278^{+0.0116}_{-0.0116}$	$0.2280^{+0.0114}_{-0.0113}$
ϱ	$1.0031^{+0.0121}_{-0.0121}$	$1.0014^{+0.0557}_{-0.0557}$	$0.9695^{+0.0463}_{-0.0452}$	$0.9917^{+0.0346}_{-0.0347}$
m_{Z^0}	$91.64^{+2.22}_{-2.00}$	$92.25^{+3.98}_{-3.47}$	$93.66^{+2.81}_{-2.55}$	$92.59^{+2.24}_{-2.07}$
χ^2	0.47/2	0	1.05/3	1.93/5
	Low-energy	$(m_W + m_Z)$	$(\text{e-L}) + (m_W + m_Z)$	Everything
$\sin^2\theta_w$	$0.2284^{+0.0068}_{-0.0069}$	$0.2294^{+0.0101}_{-0.0095}$	$0.2299^{+0.0098}_{-0.0092}$	$0.2287^{+0.0056}_{-0.0056}$
ϱ	$1.0004^{+0.0080}_{-0.0080}$	$1.0090^{+0.0258}_{-0.0244}$	$1.0110^{+0.0228}_{-0.0220}$	$1.0010^{+0.0071}_{-0.0071}$
m_{Z^0}	$92.12^{+1.32}_{-1.24}$	$91.59^{+2.14}_{-2.14}$	$91.43^{+1.97}_{-1.94}$	$92.06^{+1.07}_{-1.03}$
χ^2	2.53/11	0	0.39/2	2.65/13

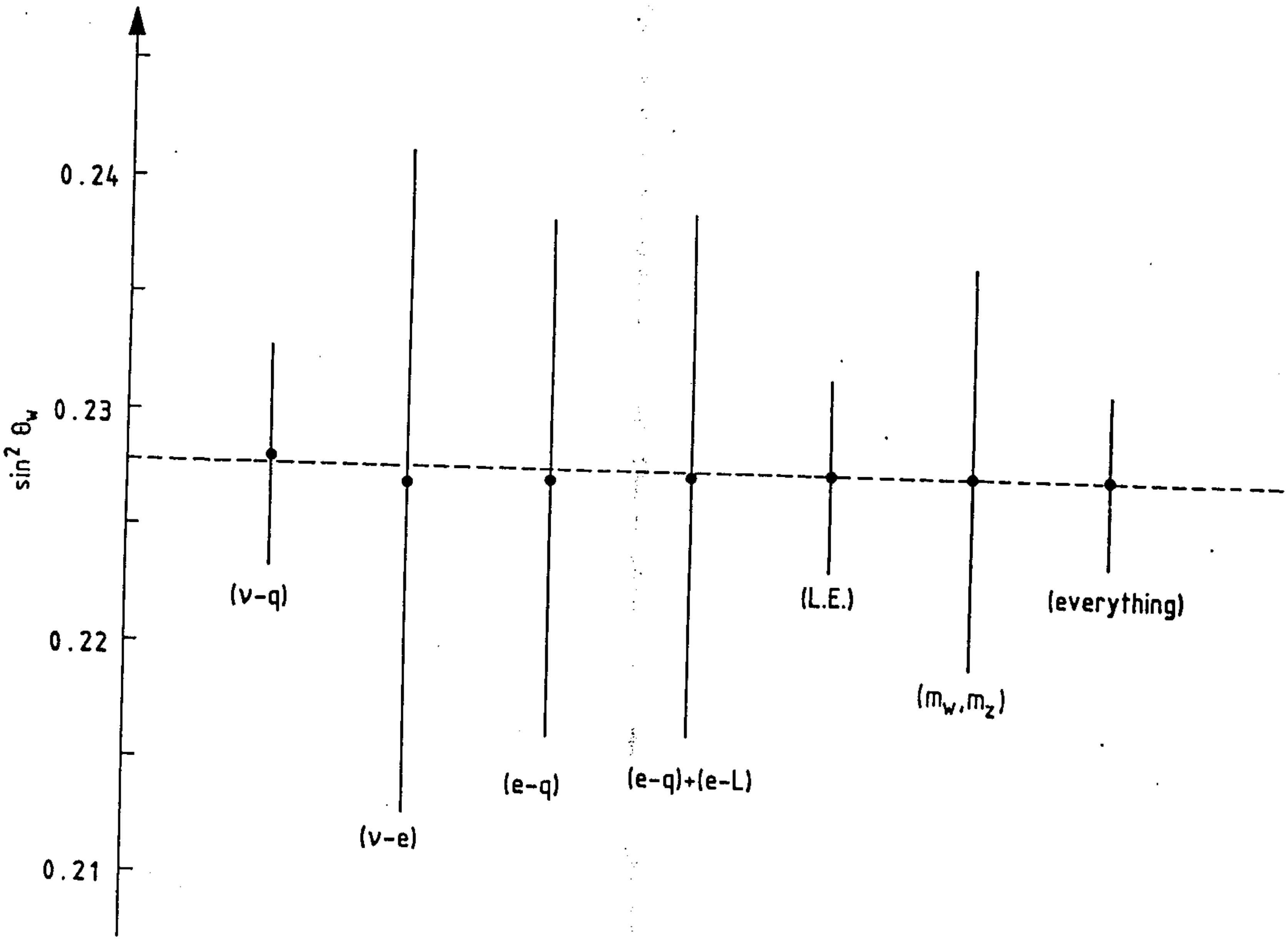


Fig. 1

In conclusion, <u>all</u> <u>experimental</u> <u>information</u> is in agreement with the prediction of the S.M:

- charged and neutral currents are tested to the level of higher order corrections
- rare decays (flavour changing NC effects) provide other tests of loop effects
- CP violation effects in K^0-$\bar{K}^0$ consistent with CKM scheme
- B^0-$\bar{B}^0$ mixing compatible.

Two important points still missing:

1) <u>Higgs boson</u>

very important for a definite test of the mechanism of spontaneous symmetry breaking.

Its mass is not predicted by the SM; consistency gives the bound

$$7\ \text{GeV} \lesssim M_H \lesssim 1\ \text{TeV}$$

If not found, new physics should be revealed around 1 TeV.

Note (at page 23)

Production of Higgs bosons

i) by heavy fermions (quarkonium)

$$(Q\bar{Q}) \longrightarrow H + \gamma$$

coupling $\quad f_H \approx g \frac{m_f}{M_W} \propto G_F m_f$

ii) by gauge bosons

$$Z^0 \to H + \gamma$$
$$\to H + e^+ + e^-$$

iii) high energy colliders

$$e^+ e^- \to Z^0 + H$$

$$\bar{p}\, p \to Z^0 + H + X$$

Compare fits of Low-energy data with fits of M_W, M_{Z^0} measurements at UA1, UA2

a) <u>One-parameter fits</u>

LE	(M_W, M_Z) *
$\sin^2\vartheta_W = 0.228 \pm 0.004$	0.228 ± 0.009
[$M_{Z^0} = 92.2 \pm 0.6$ GeV	92.2 ± 1.2 GeV]

b) <u>two-parameter fits</u>

LE	(M_W, M_Z)
$\sin^2\vartheta_W = 0.228 \pm 0.007$	0.229 ± 0.010
$\rho = 1.000 \pm 0.008$	1.009 ± 0.026
[$M_{Z^0} = 92.1 \pm 1.3$ GeV	91.6 ± 2.1 GeV]

<u>Note on radiative corrections</u> :

Radiative corrections have been taken into account in the fits (they improve the fits in the different sectors) :

$$\sin^2\theta_W = (\sin^2\theta_W)^0 + \underbrace{\Delta s^2}_{-0.009} \qquad : \qquad \left|\frac{\Delta s^2}{s^2}\right| \sim 4\%$$

Note on $W^\pm$ and Z^0

Both $W^\pm$ and Z^0 were discovered at CERN in 1983, at the $\bar{p}p$ collider:

$$\bar{p} + p \to W^\pm + \dots$$
$$\hookrightarrow e^\pm + \nu_e$$

$$\bar{p} + p \to Z^0 + \dots$$
$$\hookrightarrow e^+e^-, \mu^+\mu^-$$

The present values of M_W and M_{Z^0} are (average of UA1 and UA2 values):

$$M_W = 80.76 \pm 1.72 \text{ GeV}$$

$$M_{Z^0} = 91.59 \pm 2.14 \text{ GeV}$$

2) TOP quark

It is the missing particle in the 3rd generation.

Lower bound from UA1

$$m_t > 44 \text{ GeV} \quad (95\% \text{ C.L.})$$

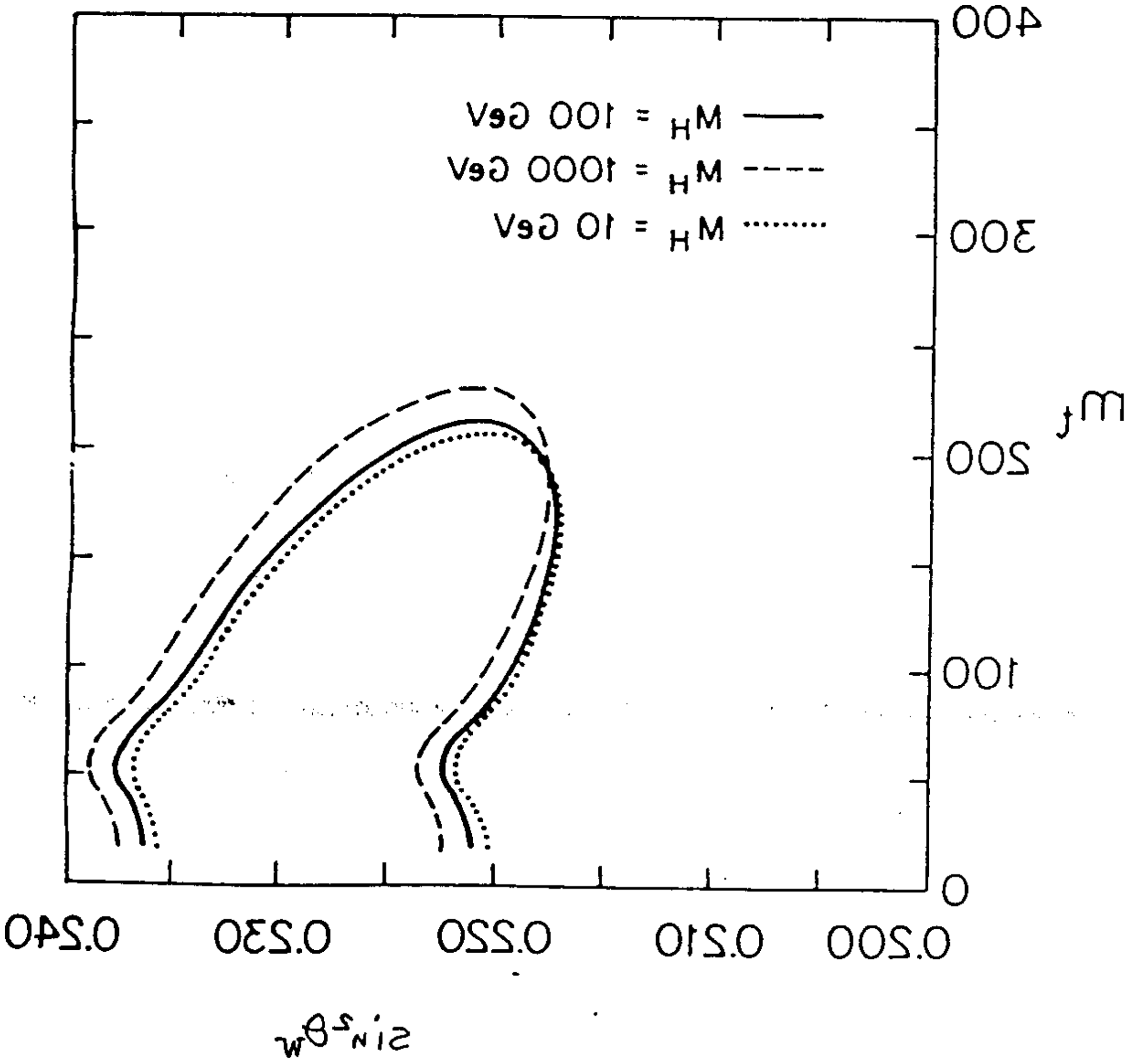
An upper bound can be obtained from a simultaneous fit of low-energy NC data and M_W, M_{Z^0} masses :

$$m_t < 180 \text{ GeV} \quad (90\% \text{ C.L.})$$

Note - Radiative corrections are sensitive to isospin breaking associated with a large m_t.

The values of $\sin^2\theta_W$ obtained from the different sectors agree very well for low values of m_t ($m_t = 40$ assumed in the fits), but show deviations for large m_t.

A simultaneous fit of $\sin^2\theta_W$ and m_t gives the above bound. (see also fig.)



M_H = 100 GeV
M_H = 1000 GeV
M_H = 10 GeV
M_t
0
100
200
300
400
0.200
0.210
0.220
0.230
0.240
$\sin^2\theta_W$