ELEMENTARY PARTICLE PHYSICS

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I shall cover the following topics, from the experimentalists' viewpoint

1. Status of the Standard Model (of electroweak and strong interactions)

2. Phenomena beyond the Standard Model (Higgs, GUTS, SUSY etc.)

3. New Accelerator projects

4. Outstanding problems, and the possible contributions from non-accelerator experiments.

1. THE STANDARD MODEL

1.1 Electroweak Interactions I - Neutral Currents

In the Weinberg-Salam model, the electroweak interactions are specified by a single parameter, $\sin^2\theta_W$ (in addition to G, α etc). All experiments to date are consistent with the W-S model and a unique value $\sin^2\theta_W \sim 0.22$. Table 1 gives a list (incomplete) of experimental results. The studies of the purely leptonic processes of $\nu_\mu e$ and $\overline{\nu}_\mu e$ elastic scattering at CERN and Fermilab are now reaching the precision to provide strong constraints on the world average value of $\sin^2\theta_W$. The other important leptonic reaction is

<u>Table 1</u> Values of $\sin^2\theta_w$

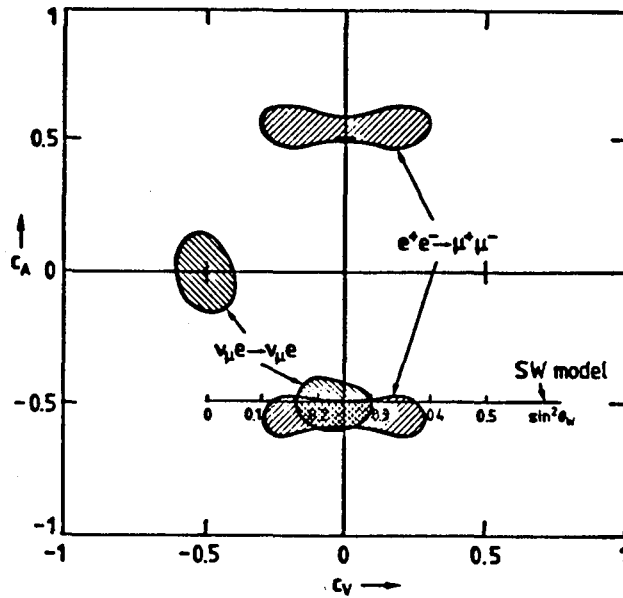| <u>Process</u>	<u>Experiment</u>	$\underline{\sin^2\theta_w}$
$\nu_\mu e \to \nu_\mu e$ $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	CERN FNAL	$0.22 \pm .03$
$\nu N \to \nu X$ $\bar{\nu} N \to \bar{\nu} X$	CERN FNAL	$0.22 \pm .01$
$e^-_{L,R} + d \to e^- + X$ $\mu^\pm_{L,R} + C \to \mu^\pm + X$	SLAC CERN	$0.22 \pm .02$ $0.23 \pm .02$
Parity violation in atomic transitions	Various	$0.21 \pm .05$
$1 - M^2_W/M^2_Z$	Sp$\bar{\text{p}}$S	$0.23 \pm .03$

Fig.1   Values of C_A and C_V, the axial and vector coupling
coefficients of the Z^0 to charged leptons. The
cross-sections for ν_μ and $\bar{\nu}_\mu$ scattering on electrons
and the asymmetry in $e^+e^- \to \mu^+\mu^-$ each constrain
solutions to two shaded areas. The common solution
has $C_A \simeq -0.5$, $C_V \simeq 0$ (i.e. $\sin^2\theta_w \simeq 0.25$).
(After Wu 1984)

$e^+e^- \rightarrow \mu^+\mu^-$, where Z^O as well as γ exchange gives a F/B asymmetry in the muon angular distribution. The asymmetry measures the axial vector coupling C_A of the charged leptons to the Z^O and confirms that $C_A = \frac{1}{2}$; the quantity $\sin^2\theta_w$ is not measured since the vector coupling of the charged leptons to the Z^O, $c_V = \frac{1}{2} - 2\sin^2\theta_w$ vanishes for $\sin^2\theta_w \approx 0.25$. The result of a recent survey is given in Fig.1.

The experiment on deep inelastic neutrino-nucleon scattering measure the following cross-section ratios, which are predicted to have the values

$$R_\nu = \frac{\sigma^{\nu N}(NC)}{\sigma^{\nu N}(CC)} = \frac{1}{2} - x + \frac{20}{27} x^2 \qquad (1a)$$

$$R_\nu = \frac{\sigma^{\nu N}(NC)}{\sigma^{\nu N}(CC)} = \frac{1}{2} - x + \frac{20}{9} x^2 \qquad (1b)$$

where $x = \sin^2\theta_w$. Fig.2 shows a plot of R_ν versus $R_{\bar\nu}$ for recent experiments. The agreement of $R_{\bar\nu}$ with the Salam-Weinberg curve shows that the neutral/charged coupling factor $\rho = 1.00 \pm .02$ ($\rho = 1$ in the Salam-Weinberg model). The value of R_ν largely determines the value of $\sin^2\theta_w$ ($= 0.23$).

A third class of experiment deals with the deep-inelastic scattering of longitudinally polarised electrons or muons by nucleons. The SLAC experiment (Prescott et al 1979) measured the difference in cross-sections of LH and RH electrons on deuterons, resulting from the $\gamma - Z^O$ interference. The CERN experiment (Argento et al 1982) evaluated the scattering of both LH and RH μ^+ and μ^- on carbon.

Finally, atomic physics experiments measure the small parity-violation effect associated with Z^O exchange. For example, it results in a rotation of the plane of polarisation of plane-polarised light exciting energy levels in traversing bismuth vapour. The value of $\sin^2\theta_w$ in Table 1 is the average of several experiments (Fortson & Lewis 1984).
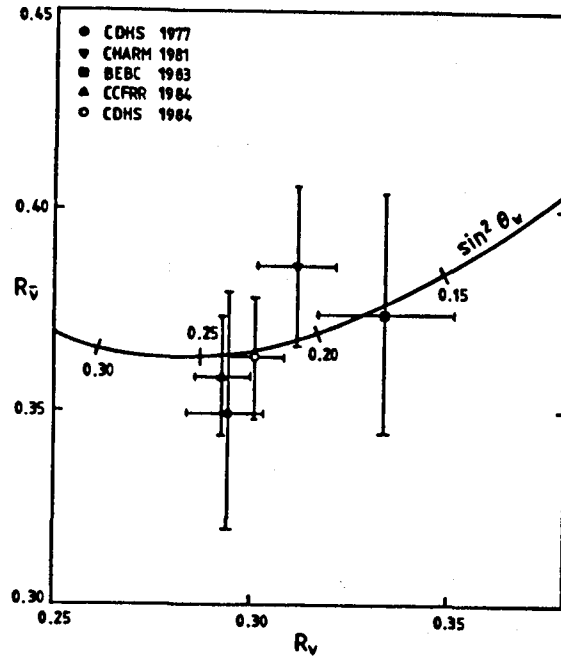
Fig.2 Values of ratio of neutral to charged current cross-
       sections of neutrinos and antineutrinos on nucleons.
       The data are consistent with the Weinberg-Salam model
       (full curve) with $\sin^2\theta_w \approx 0.23$.

1.2 Electroweak Interactions II - the W and Z bosons

CERN $p\bar{p}$ collider experiments have measured the W and Z masses,
with recent results given in Table 2. Through the relations

$$M_W = (\pi\alpha/\sqrt{2}\ G)^{\frac{1}{2}}\ \frac{1}{\sin\theta_w} = \frac{37.28}{\sin\theta_w}\ GeV$$

$$M_Z = M_W/\cos\theta_w \tag{2}$$

it is possible to calculate $\sin^2\theta_w$ from the masses: the values are
included in Table 1 for completeness.

We see from Table 1 that widely different experiments are consistent with a unique value of $\sin^2\theta_W$. In fact the numbers shown need corrections if they are to be compared, since each experiment has cuts or kinematic selections, and the results should be "evolved" to the same value of q^2 (conventionally taken as $q^2 = M_W^2$). When these radiative corrections are taken into account the world average becomes

$$\sin^2\theta_W \ (M_W) = 0.215 \pm .015 \tag{3}$$

The great triumph of the electroweak theory was of course the successful prediction of the W and Z particles, observed in UA1 and UA2 experiments (Arnison et al 1983, Bagnaia et al 1983, Banner et al 1983) at the CERN $p\bar{p}$ collider, via the reactions $p\bar{p} \rightarrow W+\ldots$, or in terms of quarks

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu_e \tag{4}$$
$$\rightarrow \mu^+ + \nu_\mu$$

$$\begin{cases} u + \bar{u} \\ d + \bar{d} \end{cases} \rightarrow Z^0 \rightarrow e^+ e^-$$
$$\rightarrow \mu^+ \mu^-$$

The cross-section for W or Z production in $p\bar{p}$ collisions leading to decay $W^\pm \rightarrow e^\pm + \nu_e$ can be calculated from the quark momentum distributions in the nucleon (measured in νN scattering), and the W mass, partial width $\Gamma(e\nu) = GM_W^3/6\pi\sqrt{2}$ and total width $\Gamma \approx 12 \ \Gamma(e\nu)$. For 310 GeV p on 310 GeV $\bar{p}$, one expects $\sigma(W^\pm \rightarrow e^\pm) \approx 5pb$, that is about 10^{-8} of the total $p\bar{p}$ cross-section (60mb). The value of $\sigma(Z \rightarrow e\bar{e})$ is one order of magnitude smaller. The detection of such a rare signal is made possible because of the high p_T of the charged lepton(s) ——p_T up to $M_W/2 \sim 40$ GeV. Events are selected by requiring an isolated electron track of high p_T in the vertex detector pointing to the beam intersection region, and to a narrow electromagnetic shower without hadronic component.

Fig. 3(a) shows a plot of transverse momentum p_T^e of the single electron versus the <u>missing</u> transverse momentum in the whole event,

measured in the electron-beam plane. The fact that the two are roughly equal is clear evidence that an unseen particle (neutrino) was emitted to balance p_T^e, consistent with the decay $W \to e\nu$. Fig.3(b) shows the angular distributions of the decay electrons relative to the beam, evaluated in the W rest-frame. This has the $(1 + \cos\theta)^2$ distribution predicted from the V-A theory. As expected from helicity arguments (LH u quark and RH $\bar{d}$ quark in (4), leading to $J_Z = -1$ for W^+ if Z defines the proton beam direction), the e^+ from W^+ decay favours the same direction as the incident antiproton.
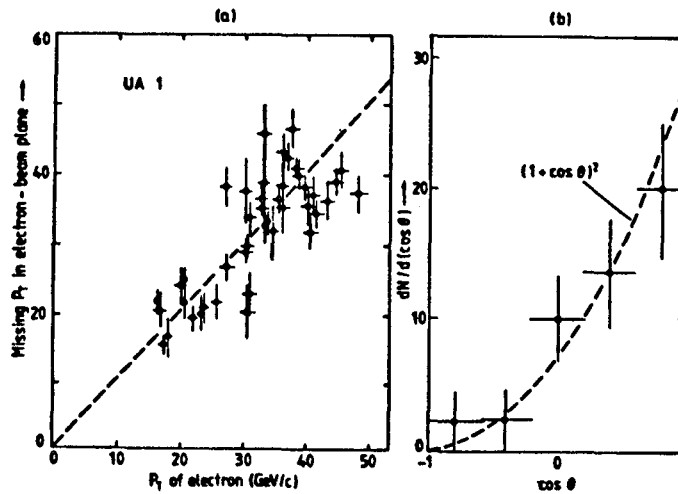

Fig.3   (a) Plot of missing p_T in electron-beam plane, against p_T of electron, in candidates for $W \to e + \nu$, from UA1 experiment.

        (b) Angular distribution of electrons relative to beam axis in $W \to e + \nu$ events,(Arnison et al 1983)

The identification of $Z^o \to e^+e^-$ decays proceeds by demanding two isolated high p_T electrons of large invariant mass. The muonic decays in UA1 ($W \to \mu\nu$ or $Z \to \mu^+\mu^-$) are identified by the penetration of the muons through many interactions lengths of steel of the magnet yoke, as well as the usual requirements of isolation, matching with a muon track in the inner detector and high p_T.

A recent compilation of results is given in Table 2. The predicted masses are from the relations (2), but with upward radiative corrections to the masses of order 4% (equivalent to renormalization of α in (2)). There is good agreement between observed and predicted

Table 2   Recent data on W, Z events

	UA1	UA2	
W → eν	172	122	Prediction
→ μν	44	-	(with radia-tive correc-
Z → ee	22	16	tions)
→ μμ	9	-	
M_W	80.9 ± 1.5 ± 2.4	81.2 ± 0.9 ± 1.2	83.0 ± 2.7 GeV
M_Z	95.6 ± 1.4 ± 2.9	92.4 ± 1.1 ± 1.4	93.8 ± 2.2 GeV

masses.

The width Γ of the Z^o boson, which depends on the number of neutrino generations, cannot be accurately measured at this time. However Γ_Z can be deduced by making some (fairly safe) assumptions. From the standard model one knows that

$$\Gamma_W(e\nu) = GM_W^3/6\pi\sqrt{2}$$
$$\Gamma_Z(\nu\bar{\nu}) = GM_W^3/12\pi\sqrt{2}$$

(5)

Then the observed cross-section ratio

$$R = \frac{\sigma(Z^0 \to e \bar{e})}{\sigma(W \to e\nu)} = \frac{\sigma(Z^0 \to all)}{\sigma(W \to all)} \frac{\Gamma_Z(e\bar{e})}{\Gamma_Z} \frac{\Gamma_W}{\Gamma_W(e\nu)} = 0.116 \pm .027 \qquad (6)$$

The first term on the RHS, the (total cross-section ratio $\sigma(Z^0 \to all)/\sigma(W \to all)$ can be calculated from the quark distribution function in the nucleon (measured in lepton-nucleon scattering) and from QCD (to evolve these distributions to the appropriate value of q^2). Also, the ratio $\Gamma_W/\Gamma_W(e\nu) \simeq 12$, assuming 3 generations of quarks and leptons of mass $< M_W$. $\Gamma_Z(e\bar{e})$ is also known from the standard model. The above equation yields

$$\Gamma_Z = 2.54 \pm 0.61 \text{ GeV} \qquad (7)$$

compared with $2.75 \pm .07$ GeV expected for 3 lepton (and quark) generations. However, if there are further massive charged leptons of mass $> M_Z/2$ and corresponding neutrinos of small mass, the result would be an increase in Z^0 width through the decay $Z^0 \to \nu_L \bar{\nu}_L$ ($\Delta\Gamma = 180$ MeV for each neutrino type). These considerations set a limit of $N_\nu < 7$ at 90% CL for the total number of lepton generations. This constraint will obviously be greatly improved at LEP or SLC.

1.3 Electroweak Interactions III - the Higgs particles

A very important component of the electroweak theory is the Higgs scalar boson and it has not yet been found. Recall that in the Weinberg-Salam model, the Higgs is postulated to account for spontaneous symmetry - breaking, through the generation of mass by self-interaction. The massless $W^\pm$ and Z^0 particles of the exact SU(2) and U(1) symmetry "eat" three of the four Higgs components (which appear as a doublet of complex fields), and so acquire mass. This leaves one massive neutral Higgs scalar as a physical particle.

The properties of the Higgs are ordained by the job it was invented to do. It cancels divergences in the process $e^+e^- \to W^+W^-$, requiring a coupling proportional to fermion mass; and in

$W^+W^- \to W^+W^-$, requiring a coupling proportional to boson mass, squared. These features determine the width of the Higgs and its decay branching ratios.

One method proposed to observe the Higgs (for $M_H < M_Z$) is via the decays

$$Z^0 \to H\gamma \qquad\qquad (8)$$

$$\to H\mu^+\mu^-$$

resulting in a photon or lepton pair of unique energy. The branching ratio (on account of the small lepton masses) is small, varying from 10^{-5} for $M_H = 20$ GeV to 10^{-7} for $M_H = 60$ GeV. This might be detectable if, as expected, the annual Z^0 production at LEP is 5.10^6 events. If $M_H < M_V$ where $V = t\bar{t}$ is the massive toponium state, then the decay

$$V \to H\gamma \qquad\qquad (9)$$

has a much larger (2-5%) branching ratio.

For $M_H > 0.2$ TeV, the decay $H \to W^+W^-$ will be dominant. On dimensional grounds, we expect the total width

$$\Gamma_H \propto GM_H^3 \qquad\qquad (10)$$

and an exact calculation shows $\Gamma_H \sim M_H$ for $M_H \sim 1.2$ TeV. This result implies that the Higgs (HWW) coupling is strong and the perturbation approach is wrong anyhow. One must then be entering a regime of fundamentally new physics: for example, the Higgs might be a composite rather than elementary particle, with new types of constituents and new types of coupling. If the Higgs is massive ($M_H > 2 M_W$), detection is bound to be difficult, firstly because the resonance will be broad and secondly because non-resonant background processes $e^+e^- \to W^+W^- + X$ or $p\bar{p} \to W^+W^- + X$ will be important and of comparable cross-section to the signal process, $e^+e^-(p\bar{p}) \to H + X$, $H \to W^+W^-$.

1.4   Strong Interactions Between Quarks - QCD

The basis for our belief in the gauge theory (quantum chromodynamics - QCD) of the colour interactions between quarks via

gluon exchange rested, until recently, on analysis of deep inelastic
lepton-nucleon scattering experiments and of the bound states of
heavy quarkonium (ψ,T spectroscopy) and in the observation of multi-
jet events in e^+e^- annihilation at high energy. During the last 2
years, strong and even more convincing support for QCD has been found
from CERN p$\bar{\text{p}}$ collider experiment measuring directly the scattering of
quarks and gluons at high momentum transfers.

The analysis is based on observation of events in which 2 jets
of hadrons are produced at large angle to the colliding beams.
Fig.4 shows an example of such an event in the UA1 detector
(Arnison et al 1984) The 2 jets emerge at 180° in the azimuth, as
expected if they result from fragmentation of quark/gluon constituents
of the incident beams after a two-body scattering. The polar angles
are not equal and opposite, since in general the colliding consti-
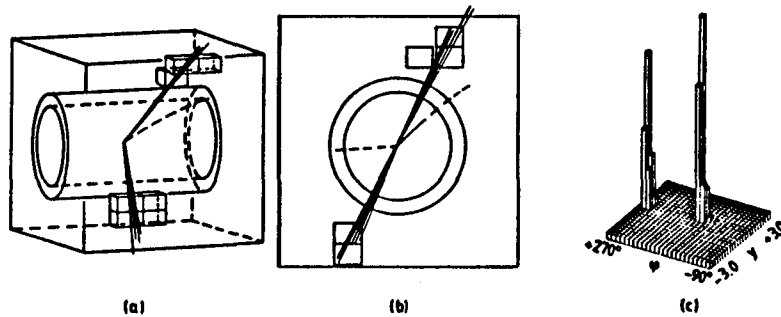tuents can carry different fractions of the momenta of the p and $\bar{\text{p}}$.

(a)   (b)   (c)

Fig.4   Example of 2-jet event in CERN SPS p$\bar{\text{p}}$ collider
        (a) reconstruction of event (b) projection in
        azimuthal plane normal to beam (c) energy
        deposition in calorimeter as a function of azimuth
        ϕ and rapidity y.

From the energies and angles, the events are first transformed into
the CMS of the colliding constituents, and the scattering angle in
this frame and q^2 are evaluated. When due account is taken of
experimental cuts (on transverse energy, $E_T > 15$ GeV), the angular
distribution is found to have the Rutherford form

$$\frac{d\sigma}{d\Omega} \sim \sin^{-4} \frac{\bar{\theta}}{2} \qquad (11)$$

for small $\bar{\theta}$ - see Fig.5. Since it is impossible to know which jet
originates from which beam particle, the smaller of the two possible
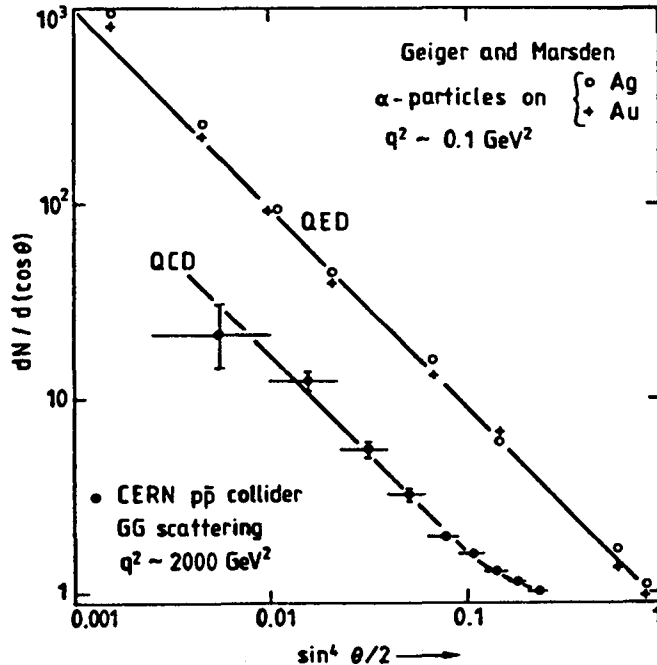scattering angles ($\bar{\theta}$ or $\pi - \bar{\theta}$) is taken. This fact, and the

Fig.5 Differential cross-section for 2-jet events in terms of
CMS scattering angle θ. Rutherford scattering predicts
a $\sin^{-4}(\theta/2)$ dependence. The Geiger-Marsden results
(1911) on α-particle scattering by gold and silver
nuclei is shown for reference.

existence of spin terms leads to deviations from the Rutherford
formula (for non-relativistic spinless scattering) near $\bar{\theta} = \pi/2$.
The form of the angular distribution (11) is exactly that expected
(for small $\bar{\theta}$) if the quark-quark, quark-gluon or gluon-gluon inter-
action is mediated by single massless vector boson (i.e. gluon)
exchange.

The beam particles $(p, \bar{p})$ contain Q, $\bar{Q}$ and G constituents. There
are colour coupling factors which are 9 for GG scattering, 16/9 for
$Q\bar{Q}$ or $Q\bar{Q}$ scattering and 4 for GQ or $G\bar{Q}$ scattering. Thus, GG
scattering dominates. Although there are small differences in the
angular distribution near $\bar{\theta} = \pi/2$ for the different processes, to a
good approximation they can be described by the GG distribution over
the angular range covered. In this case, the scattering cross-section
is described by an effective structure function

$$F(x) = G(x) + \frac{4}{9} (Q(x) + \bar{Q}(x)) \qquad (12)$$

where $G(x)$, $Q(x)$, $\bar{Q}(x)$ are the momentum distributions of gluons,
quarks and antiquarks in the proton (antiproton) and x is the
fractional beam momentum carried by a constituent.

Fig.6 shows the UA1 and UA2 results on $F(x)$, in comparison with
the same quantity deduced at $q^2 \sim 50$ GeV^2 from deep-inelastic neutrino-
nucleon scattering at CERN and Fermilab. The latter results were
evolved according to QCD to the region $q^2 \sim 2000$ GeV of the collider
data. There is remarkably close agreement between the two quite
different types of experiment. Note that the gluon contribution is
vital to account for the collider data, especially at small x. So
this is a direct proof of GG scattering by G exchange, that is of the
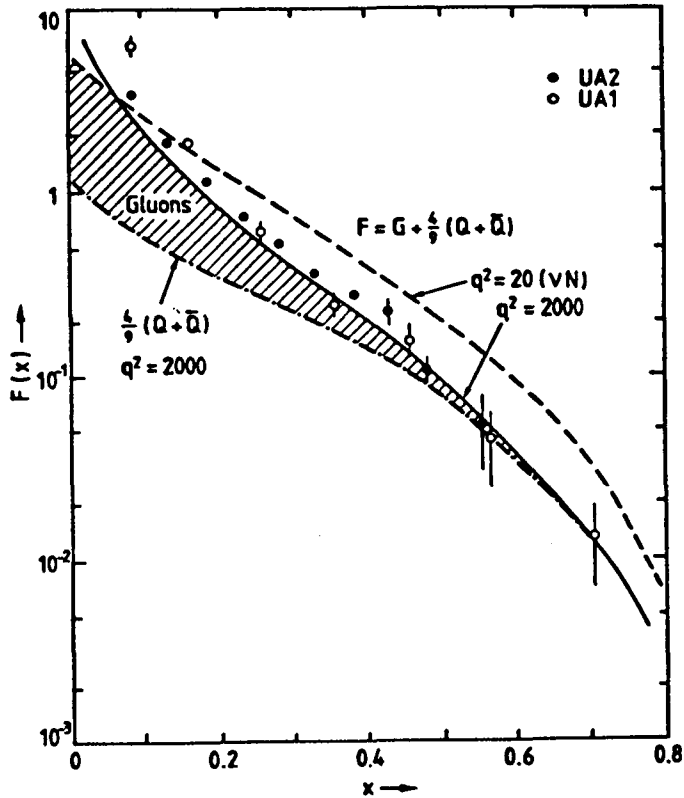existence of the triple gluon vertex.

Fig. 6   Effective structure function F(x) = G(x)

F(x) = G(x) + $\frac{4}{9}$ (Q(x) + $\bar{Q}$(x)) measured in

p$\bar{p}$ collider experiment. The full line is the

prediction from neutrino-nucleon scattering

data, evolved to q^2 = 2000 GeV^2. Note that

the gluon contribution (shaded) dominates at

small x.   UA1 data from Arnison et al (1984);

UA2 data from Bagnaia et al (1984)

2. BEYOND THE STANDARD MODEL

We have already said that the perturbative approach of the standard model breaks down for Higgs masses $M_H \sim 1$ TeV. This is not the only potential problem associated with the Higgs. One is dealing with different mass scales for the various gauge interactions: the scale parameter $\Lambda \sim 0.2$ GeV for QCD, the scale $M_{W,Z} \sim 100$ GeV for electroweak interactions, and $M_X \sim 10^{15}$ GeV for the masses of the bosons X, Y mediating quark-lepton transitions in grand unified theories (GUTS). The GUT symmetry breaking (the difference in photon, W/Z and X/Y boson masses) is described in terms of massive GUT Higgs of mass $\sim M_X$. The theoretical values of M_W and M_Z will receive radiative contributions from the massive Higgs and lead to uncontrollable quadratic divergences unless one can arrange some clever cancellations (to the level of $M_W/M_X \sim 10^{-13}$!). So theorists have invented mechanisms to cure this so-called "hierarchy problem". One such is supersymmetry (SUSY) in which all fundamental fermions (bosons) have boson (fermion) partners. The radiative corrections to $M_{W,Z,H}$ from boson and fermion loops have opposite signs and one can get the desired cancellation. $\delta M_H \sim \alpha |M_B^2 - M_F^2|$ and thus $|M_B^2 - M_F^2| < 1$ TeV^2. Table 3 gives a list of SUSY particles. Most models involve R symmetry: particles are produced in pairs with R = ±1. Thus one gets associated production of squarks by quarks

$$q\bar{q} \rightarrow \tilde{q}\, \bar{\tilde{q}}$$

As a consequence of R conservation, the lightest SUSY particle (Photino?) must be stable. Decay of a squark

$$\tilde{Q} \rightarrow Q + \tilde{\gamma}$$

would be manifest in the large missing p_T of the photino, so the signature would be dramatic.

So far, no SUSY particles have been observed. Limits to the mass are more than 20 GeV for $\tilde{Q}$, $\tilde{l}$ and $\tilde{W}$ and more than 4 GeV for G. At new colliders with sufficient CMS energy (several TeV) to be sure of producing SUSY particles (if they exist), these new phenomena should

Table 3. Supersymmetric particles

Particle		Spin	Sparticle		Spin
Quark	Q	$\frac{1}{2}$	Squark	$\tilde{Q}$	0
Lepton	ℓ	$\frac{1}{2}$	Slepton	$\tilde{\ell}$	0
Photon	γ	1	Photino	$\tilde{\gamma}$	$\frac{1}{2}$
Gluon	G	1	Gluino	$\tilde{G}$	$\frac{1}{2}$
	$W^{\pm}$	1		$\tilde{W}^{\pm}$	$\frac{1}{2}$

be very easy to find.

3. NEW ACCELERATOR PROJECTS

A list of present and future colliders is given in Table 4. The e^+e^- colliders SLC at Stanford and LEP at CERN are designed to study the electroweak interactions, in particular to serve as Z^0 factories. VLEPP (Novosibirsk) is just a super linear collider (LC) proposal. The pp and $p\bar{p}$ colliders UNK (Serpukhov), LHC (CERN) and SSC (USA) are intended to attack the multi-TeV energy region mentioned above, and none of them is likely to be ready before the late 1990's.

HERA is so far the only ep collider, and provides a logical extension to $q^2 \sim 20,000$ GeV of lepton-nucleon scattering experiments at fixed target machines (SPS and Fermilab). The actual direction taken by colliders in the future will depend on the success or otherwise of the linear e^+e^- collider project at Stanford, physics results from the existing SPS and TeV I hadron colliders, and on developments of radically new methods of particle acceleration with high accelerating fields.

Table 4. Colliders

a)

e^+e^-	Year	#I.R.	E(GeV)	L $cm^{-2}sec^{-1}$
SLC (LC)	1987	1	50 + 50	$10^{29} - 6.10^{30}$
LEP I	1989	4	50 + 50	10^{31}
LEP II	1992?	4	95 + 95	10^{31}
TRISTAN	1987	4	30 + 30	-
VLEPP (LC)	-	1	150 + 150	- (project)

b)

$pp,p\bar{p}$	Year	#I.R.	E(TeV)	
$Sp\bar{p}S$	1982-1987	2	0.3 + 0.3	$10^{29} - 10^{30}$
TeVI($p\bar{p}$)	1987	2	0.8 + 0.8	$10^{29} - 10^{30}$
UNK (pp)	-	-	3 + 0.4 or 3 + 3	started
LHC (LEP tunnel)	-	-	5 + 5	under study
SSC (pp)	-	-	20 + 20	10^{32}; R and D

c)

ep	Year	#I.R.	E(TeV)	
HERA	1990	2 (+2)	$0.82p + 0.03e^{\pm}_{L,R}$	$10^{31} - 10^{32}$

4. ROLE OF NON-ACCELERATOR EXPERIMENTS

Of the urgent problems in high energy physics that confront us now, many - such as the existence of Higgs scalars, supersymmetric particles or other new phenomena in the TeV energy range - are exclusively the province of the giant colliding beam machines.

There are many other problems which these accelerators will not address - for example, proton decay, GUT monopoles, neutrino masses and mixing. Then there is potentially new physics of which hints have come from cosmic ray studies, for example underground muons possibly related to point stellar sources (Cygnus X3, Hercules XI etc).

It is clear that non-accelerator experiments have a big role to play for very many years to come.

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