Summary and Conclusions

Grand unified theories require an extremely daring extrapolation to distance scales of order $M_X^{-1} \sim 10^{-28}$cm, many orders of magnitude smaller than the distances that have been probed experimentally. Obviously, many things could cause this extrapolation to fail. For example, quarks and/or leptons may be composite objects or there could be other types of thresholds in the desert region between M_W and M_X. Perhaps there is no partial unification of the strong and electroweak interactions without quantum gravity, or perhaps local field theory breaks down at short distances. Nevertheless, grand unified theories have many attractive features and dramatic consequences. Even if it should turn out that they are wrong in detail there is a good chance that they are directing our attention in the right direction.

Predictions and Successes

Most grand unified theories predict the existence of incredibly weak baryon number violating interactions. These generally lead to proton and bound neutron decay, although other types of effects, such as n-$\bar{n}$ oscillations, are also possible. The baryon number violating interactions may also explain the baryon asymmetry of the universe. Most GUTS, with the exception of the minimal SU_5 model, predict nonzero neutrino masses, typically in the range 10^{-5} - 10^{+2} eV, which could lead to observable neutrino oscillations. Many larger GUTS involve horizontal FCNC interactions, a more complicated neutral current, technicolor, or other new interactions at some level, although such interactions do not require grand unification.

The basic idea of embedding the strong, weak, and electromagnetic interactions into a more fundamental underlying theory is highly attractive. The patterns of the observed interactions and of parity violation are then considerably less arbitrary: they are determined by the unification group, the representations, and the symmetry breaking pattern. Also, charge quantization occurs naturally in most models. Many models predict an approximately correct value for $\sin^2\theta_W$, and some predict m_b/m_τ as well.

Unsolved Problems

As attractive as grand unification may be, there are still a number of serious difficulties. One problem is that there is still a great deal of arbitrariness. There are few constraints on the choice of gauge group, on the fermion and Higgs representations, or on the many free parameters in most models (these are mainly in the Higgs potential and Yukawa couplings). This implies that we have little predictive power concerning the pattern of symmetry breaking in large groups. Similarly, grand unification has not explained the repetition of fermion families or the spectrum of fermion masses and mixing angles (Horizontal symmetries and mass generation via radiative corrections are promising directions, however).

A closely related problem is the proliferation of elementary fields. Even the minimal SU_5 model requires 24 gauge fields, 34 Hermitian Higgs fields and 45 two-component fermion fields.

A third difficulty that is probably far more serious is that both the standard model and grand unified theories have many small quantities that appear to be completely unnatural (i.e. they require an artificial fine tuning of parameters). These include:

(a) the ratios of fermion to W and Z masses (or, equivalently, of Yukawa to gauge couplings), such as $m_e/M_W < 10^{-5}$;

(b) The QCD θ parameter, which must be less than $10^{-9\pm1}$ (Section 2.4.4);

(c) The gauge mass^2 hierarchy $M_W{}^2/M_X{}^2 \lesssim 10^{-24}$ (Section 6.9);

(d) The ratio $\mu^2/m_p{}^2 \simeq 10^{-34}$ (for $\mu \simeq 100$ GeV), which requires a 34 decimal fine tuning of the Higgs bare mass^2 (Section 2.5.3);

(e) The cosmological constant induced by $SU_2 \times U_1$ SSB must be cancelled to at least 52 significant figures by a primordial cosmological term (i.e. a constant in the Higgs potential), as discussed in Section 2.4.4. The situation is far worse when one considers SU_5 breaking: the induced cosmological term scales roughly as $(M_X/M_W)^4$, so that a 100 figure adjustment is required! (For some recent speculations on this problem see [7.1].)

Finally, grand unified theories do not include gravity.

Other Directions

Many of the problems described above can be attributed to the existence of elementary scalar fields; they might be resolved if a realistic dynamical symmetry breaking scheme were found.

Two very promising directions have been omitted entirely from this article. One is the possibility that quarks and/or leptons and/or bosons may be composites of still more fundamental constituents. Such an approach could resolve the family problem and reduce the number of elementary fields, but at the cost of introducing another level of complexity. The other direction, the combination of grand unification with some form of supersymmetry [7.2], could lead to a full unification including gravity [7.3] and could conceivably help resolve the cosmological term problem [7.1].

Semi-simple groups leading to integer charge quarks were discussed in Section 3.4.5. Integer charge quark SO_{10} [3.56] and SU_5 [7.4] models have also been given.

Additions

An algorithm for embedding weak and strong subgroups into G has been given by Hacinliyan and Saclioğlu [7.5]. Dawson, Hagelin, and Hall [7.6] have estimated the radiative corrections to deep inelastic neutrino scattering and to the polarized eD asymmetry. Within the leading logarithm approximation, the central value of $\sin^2\theta_W$ is reduced from 0.229 to 0.224, in better agreement with the SU_5 prediction (Sections 4.3.1 and 6.2).

Acknowledgment

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Figure Captions

2.1 The vertices required by a U_1 gauge theory: (a) fermion-vector vertex; (b) complex scalar-vector vertices.

2.2 The vertices required by a non-abelian local symmetry: (a) fermion-vector vertex; (b) complex scalar-vector vertices; (c) Hermitian scalar-vector vertices. The momenta p_a and p_b both flow into the vertex. (d) Vector self interactions. The vertex factor in (d) is $-g\, c_{ijk} \left[g_{\mu\nu}\, (q-p)_\sigma + g_{\mu\sigma}\, (p-r)_\nu + g_{\nu\sigma}\, (r-q)_\mu\right]$. The vertex in (d') is $-ig^2 \left[c_{ijk}\, c_{klm}\, (g_{\mu\sigma}g_{\nu\rho} - g_{\mu\rho}g_{\nu\sigma}) + (j,\nu)\leftrightarrow(k,\sigma) + (j,\nu)\leftrightarrow(l,\rho)\right]$. The c_{ijk} are the group structure constants.

2.3 A scalar-vector vertex present in a spontaneously broken theory. The circle represents a scalar field "disappearing into the vacuum".

2.4 Ghost-ghost-vector and ghost-ghost-scalar vertices.

2.5 Lowest order Feynman diagrams for $e^-e^+ \to e^-e^+$ and $e^-d \to e^-d$ in QED. u_i and v_j represent Dirac spinors.

2.6 (a) Diagrams for β decay ($n \to pe^- \bar{\nu}_e$) and $\nu_e\, e^- \to \nu_e\, e^-$ in the Fermi theory. The circles represent the four fermion interaction. (b) Corresponding diagrams in the intermediate vector boson (IVB) theory. (c) A diagram for $e^+e^- \to W^+W^-$ in the IVB theory.

2.7 $V(\nu)$ for $\mu^2 > 0$ and $\mu^2 < 0$. λ is positive. The minima occur at $\nu = 0$ and $\nu = (-\mu^2/\lambda)^{1/2}$ in the two cases.

2.8 a) The anomalous triangle diagram for the $J_\mu^{\ i}\, J_\nu^{\ j}\, J_\rho^{\ k}$ vertex. b) The analogous diagram for the three gauge field vertex.

2.9 a) A contribution to neutrinoless double β decay. a is the $\bar{\nu}_L \nu_R^c$ Majorana mass.

b) A ν_L Majorana mass term induced by the ν_R term s $\bar{\nu}_R \nu_L^c$ and two Dirac mass insertions.

2.10 The one boson exchange model for the NN potential.

2.11 The deep inelastic reaction $ep \to e + X$. q is the momentum transfer and $Q^2 \equiv -q^2 > 0$.

2.12 (a) The quark-quark interaction, mediated by the exchange of a gluon. (b,c) Vacuum polarization diagrams which screen (b) or anti-screen (c) the interaction. q_μ is the momentum carried by the gluon.

2.13 The pion pole contribution to the vacuum polarization tensor. The pion is a bound state q-$\bar{q}$ pair.

2.14 Diagram generating a current algebra mass for quark q in an extended technicolor (ETC) scheme.

3.1 Variation of the running fine structure constants α_3, α_2, and α_1 of the SU_3, SU_2, and U_1 subgroups of G. Above the scale M_X^2 of spontaneous symmetry breaking they approach a common value. It is assumed that there are only two scales (M_W^2 and M_X^2) of symmetry breaking and that there is a plateau or desert with no new thresholds in between.

3.2 Typical vertices of the gauge bosons. The W bosons carry flavor but not color, the gluons carry color but not flavor, and the X and Y carry both. The X and Y bosons are referred to as lepto-quark bosons because of the vertices on the second line and as diquark bosons because of the vertices on the third line.

3.3 Diagrams for $p \to e^+\bar{u}u$ or $e^+\bar{d}d$. The $\bar{q}q$ pair can form into neutral mesons such as π^o, ρ^o, ω, η, $\pi^+\pi^-$, etc.
The first three diagrams also contribute to the decay of bound neutrons if the spectator u quark is replaced by a d.

3.4 Diagram for $p \to \bar{\nu}\bar{d}u$ or $n \to \bar{\nu}\bar{d}d$.

3.5 The behavior of the SU_3^c, SU_2, and U_1 coupling constants, $g_3 = g_s$, $g_2 = g_1$, and $g_1 = \sqrt{5/3}\, g'$. The apparent symmetry in each region is indicated.

3.6 Contribution to the B-L violating decays $n \to e^-\pi^+$, $e^-\rho^+$,... due to X', X_s mixing in SO_{10}.

3.7 The contribution of the lepto-quark X bosons of the $SU_4 \times SU_4$ extended color group to the process $e^+e^- \to dd^c$ in the SU_4^4 model. The X bosons have mass $M_X \simeq 10^{4-6}$ GeV.

3.8 Diagrams leading to B and L (but not F = 3B+L) violation in the ICQ model.

3.9 Diagrams leading to quark decay in the ICQ model. Diagrams (a) and (b) are expected to dominate.

3.10 A diagram for $p \to 3\nu + \pi^+$. Gluons or mesons can be exchanged between the quarks.

4.1 The relation of the gauge couplings of the effective $SU_3^c \times SU_2 \times U_1$ and the full SU_5 theory near the X and Y threshold in the $\overline{MS}$ scheme. Heavy scalars and fermions are ignored.

4.2 The relation between $\sin^2\theta_W$ and M_X and between $\sin^2\theta_W$ and $\Lambda_{\overline{MS}}$ for $n_H = 1$ and F = 3.

4.3 Typical higher order corrections to $\mathcal{L}^{\not{V}}_{eff}$. The exchanged bosons can be SU_3^c gluons or $SU_2 \times U_1$ bosons.

4.4 (a) Quark decay, (b) three body fusion, and (c) two body graphs for nucleon decay. Jarlskog and Yndurain [4.45] estimated that (a) and (b) are less important than (c). The lifetime from (a) is $\tau_p^{(a)} \sim 2 \times 10^{-26} M_X^4$, which is 10^2-10^3 longer than $\tau_p^{(c)}$. Process (b) can occur within the meson field of a nucleous, but is also estimated [4.45] to be small.

4.5 The prediction of τ_p as a function of $\Lambda_{\overline{MS}}$ in the minimal SU_5 model. The experimental range of $\Lambda_{\overline{MS}}$ and the lower limit on τ_p are also shown.

4.6 The prediction of τ_p as a function of $\sin^2\theta_W$ in the minimal SU_5 model.

4.7 (a) A contribution to $n \to e^- K^+$ [4.72].

(b)-(c) Two contributions to $n \leftrightarrow \bar{n}$.

5.1 Tree and one loop diagrams contributing to $H \to q\ell$. The labels refer to the decay of H_p in the nonminimal SU_5 model, for which an asymmetry can be generated by the interference of the first two diagrams.

6.1 Two loop contribution to the Majorana mass for ν_R in an SO_{10} model without a 126 of Higgs. The SO_{10} and SU_5 representations are indicated. A $\phi_{16}\ \phi_{16}\ \phi_{10}$ coupling is required.

6.2 (a,b) Typical diagrams that generate a mass for the light fermion f at the one loop level. The heavy lines represent heavy fermions that acquire tree level masses. The tadpoles represent boson and fermion mass terms, treated perturbatively. (c,d) Divergent two loop diagrams that imply tree level masses for f.

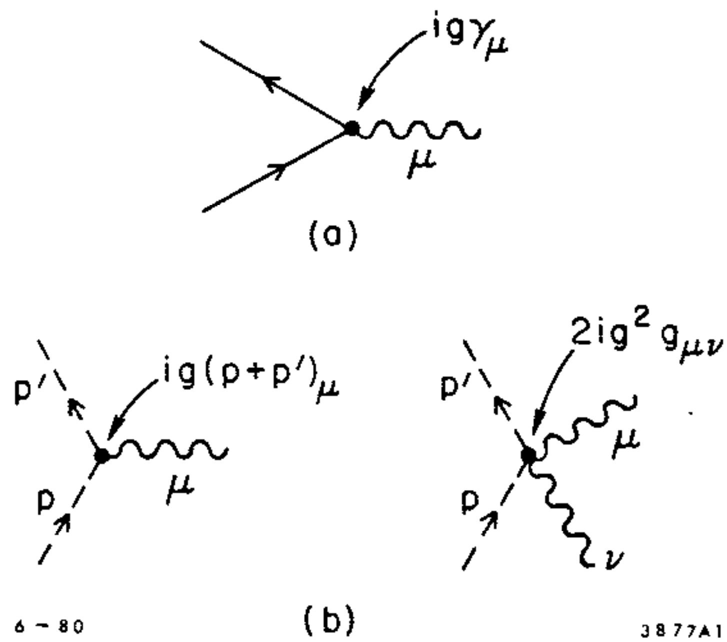
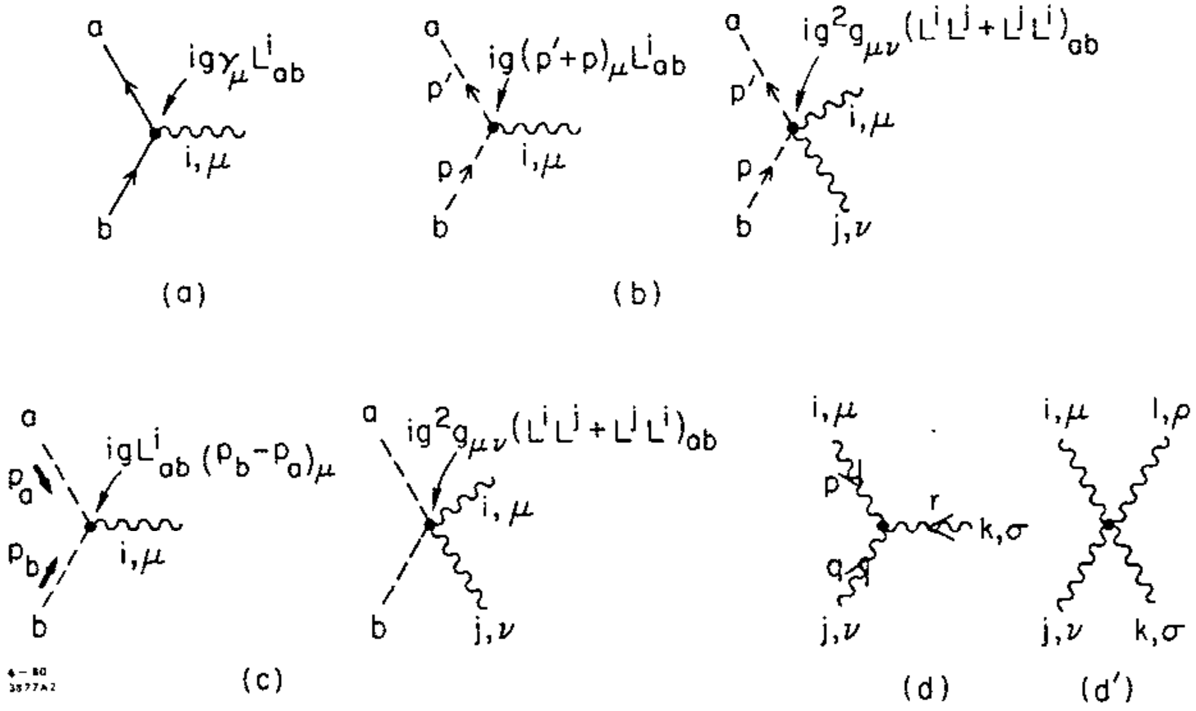


Fig. 2.1



a
b
igγ_μ L^i_ab
i, μ
(a)
p'
p
ig(p'+p)_μ L^i_ab
ig²g_μν (L^i L^j + L^j L^i)_ab
j, ν
(b)
p_a
p_b
igL^i_ab (p_b − p_a)_μ
(c)
i, μ
p
q
r
k, σ
j, ν
l, ρ
(d)
(d')

Fig. 2.2

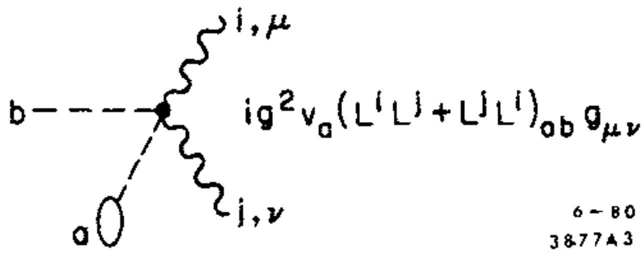


Fig. 2.3

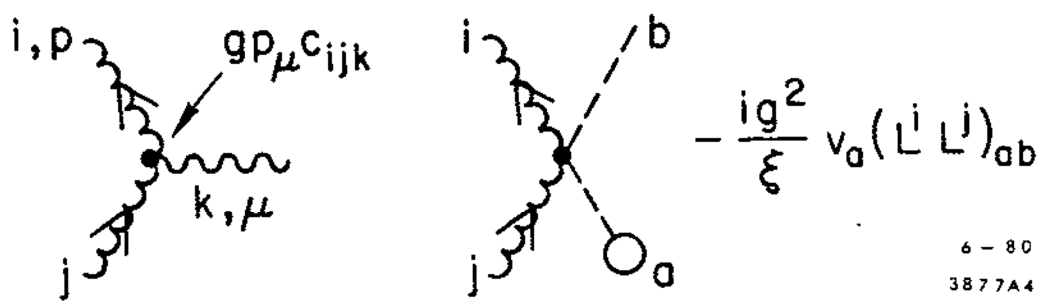
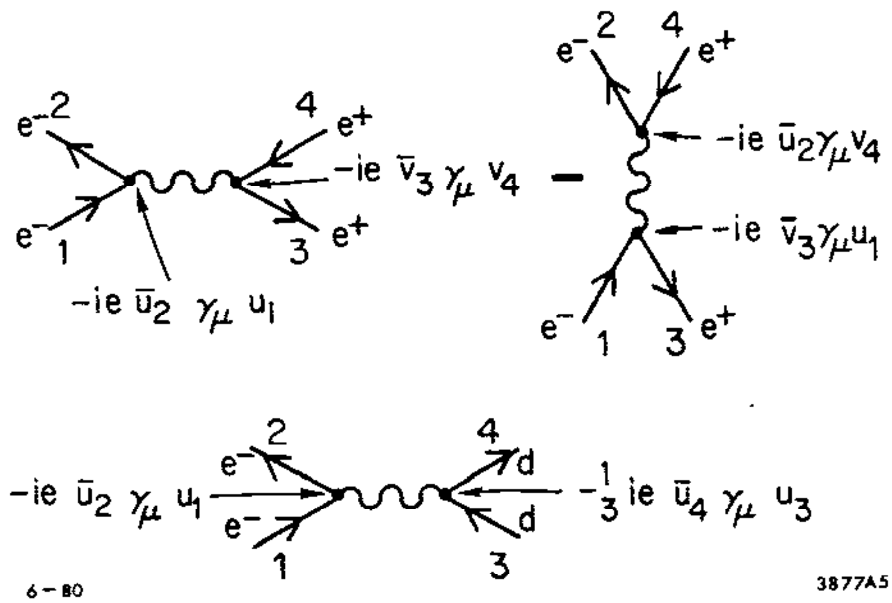
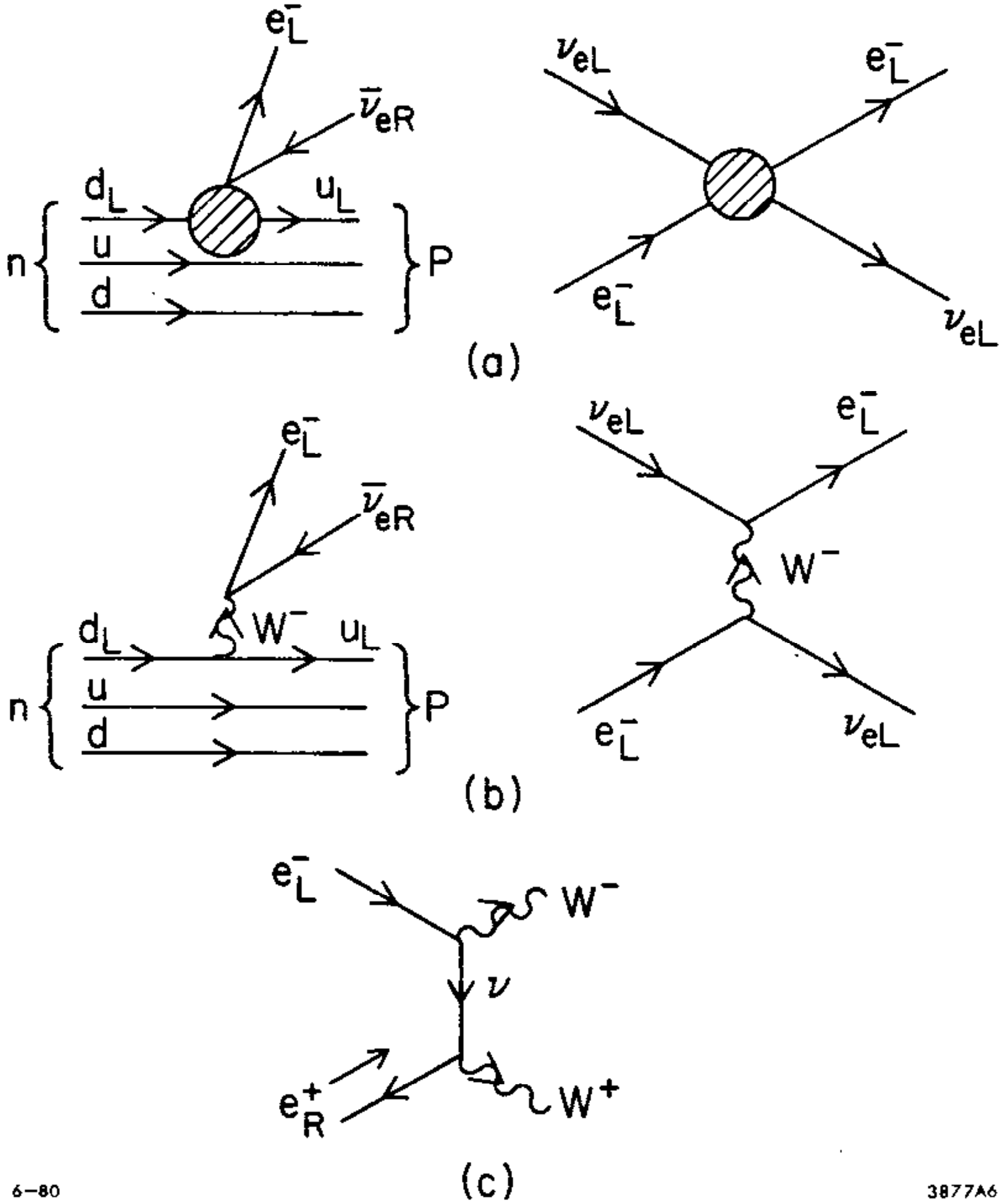


Fig. 2.4



e⁻ 2
4 e+
e⁻ 1
3 e+
−ie ū2 γμ u1
−ie v̄3 γμ v4
−ie ū2γμv4
−ie v̄3γμu1
−ie ū2 γμ u1
−1/3 ie ū4 γμ u3
d
6−80
3877A5

Fig. 2.5



e_L^-
ν̄_eR
d_L
u_L
n
u
d
P
ν_eL
e_L^-
e_L^-
ν_eL
(a)
e_L^-
ν̄_eR
d_L
W^-
u_L
n
u
d
P
ν_eL
e_L^-
W^-
e_L^-
ν_eL
(b)
e_L^-
W^-
ν
e_R^+
W^+
(c)
6-80
3877A6

Fig. 2.6

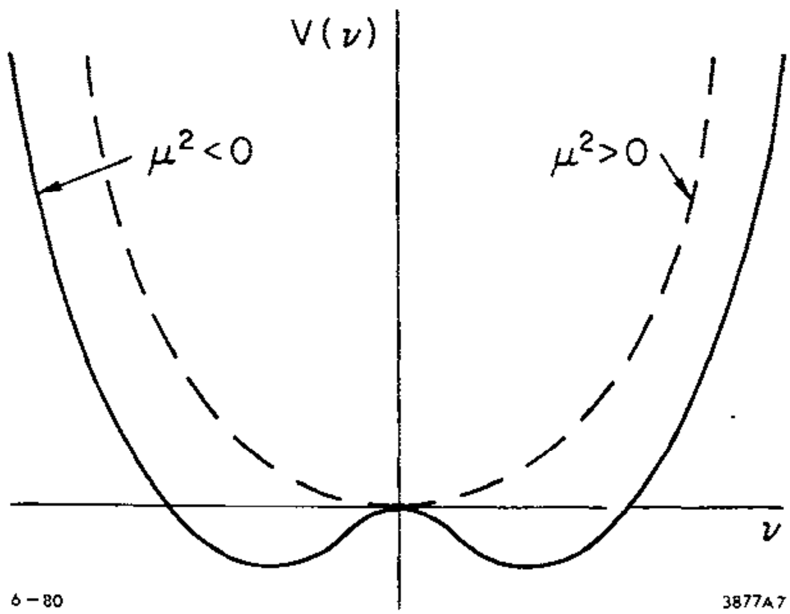


Fig. 2.7

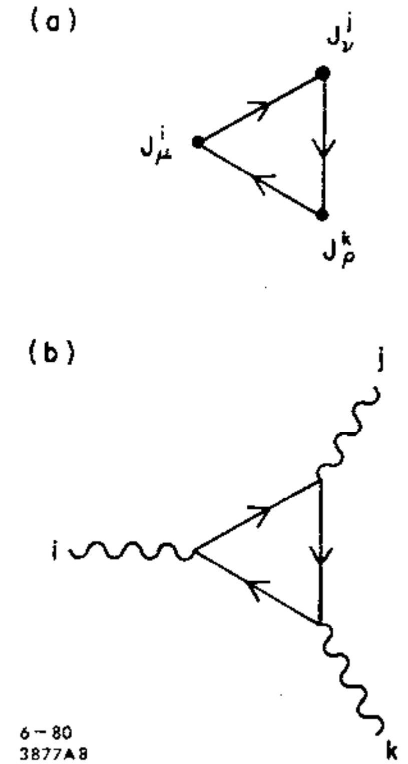


Fig. 2.8

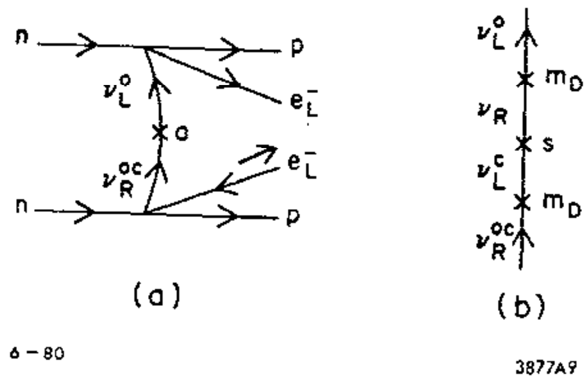

n
p
ν_L^o
e_L^-
a
ν_R^{oc}
e_L^-
n
p
(a)
ν_L^o
m_D
ν_R
s
ν_L^c
m_D
ν_R^{oc}
(b)
6 – 80
3877A9

Fig. 2.9

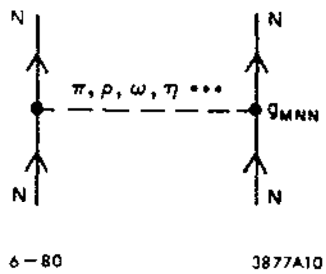


Fig. 2.10

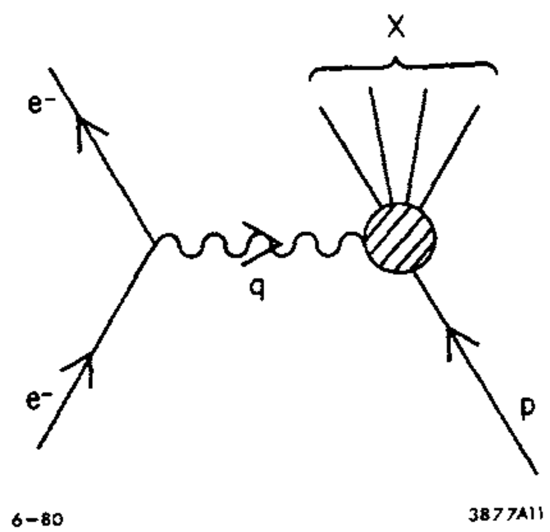
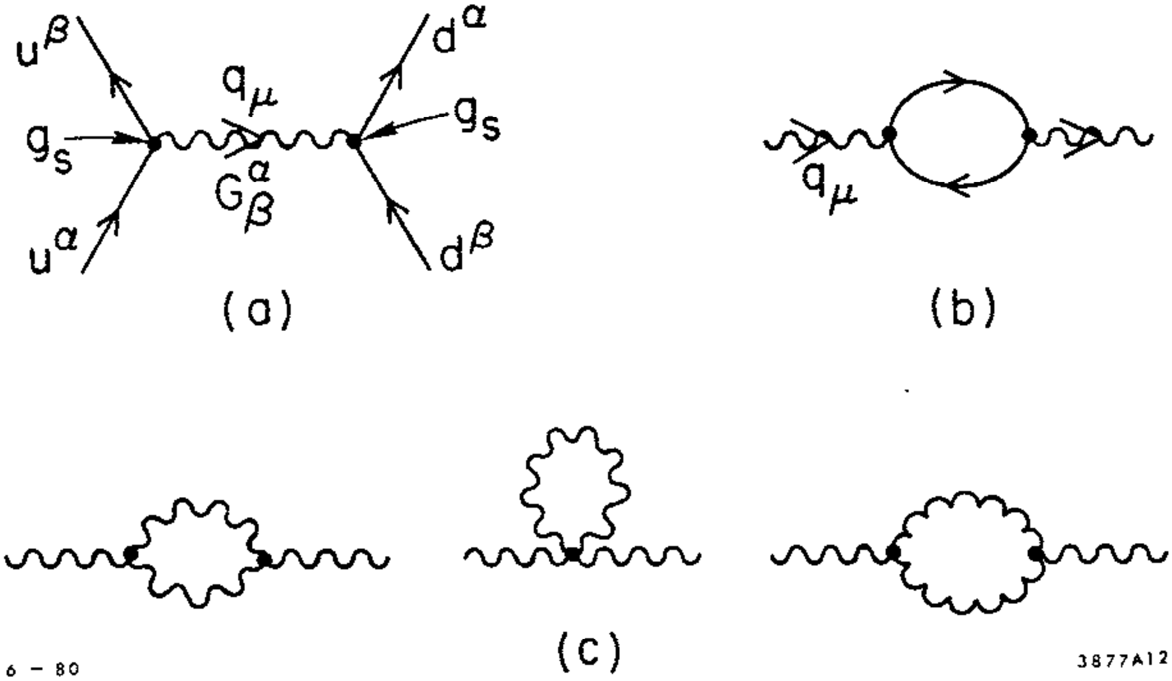


Fig. 2.11



u$^\beta$
d$^\alpha$
q$_\mu$
g$_s$
g$_s$
G$^\alpha_\beta$
u$^\alpha$
d$^\beta$
(a)
q$_\mu$
(b)
(c)
6 – 80
3877A12

Fig. 2.12

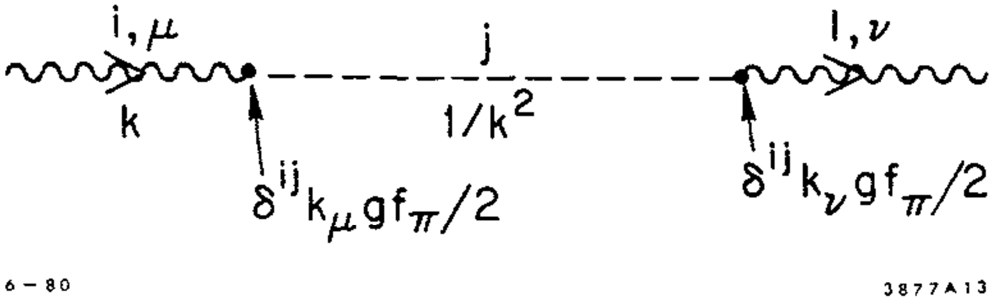


Fig. 2.13

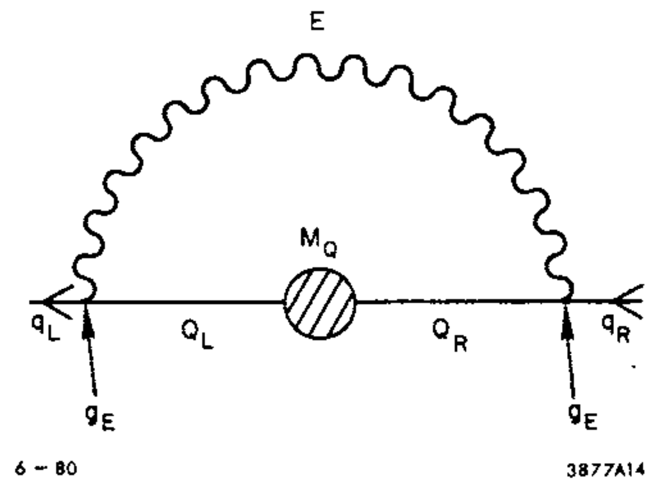
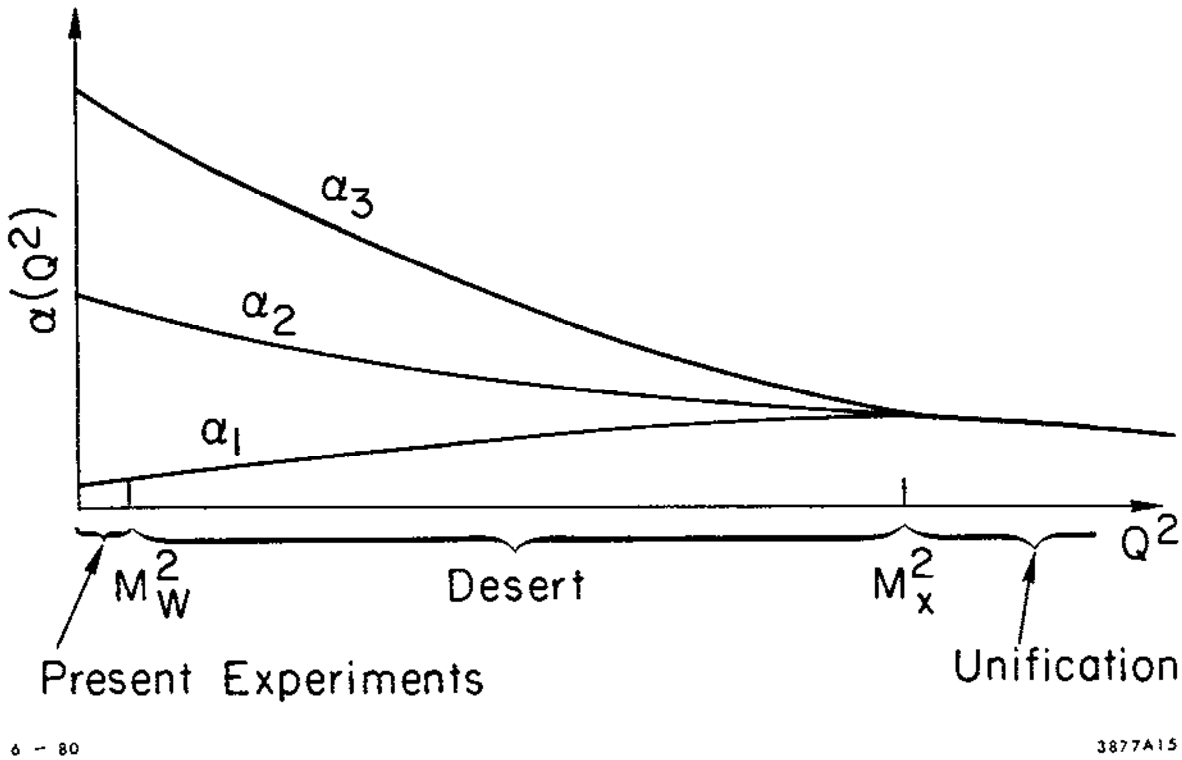
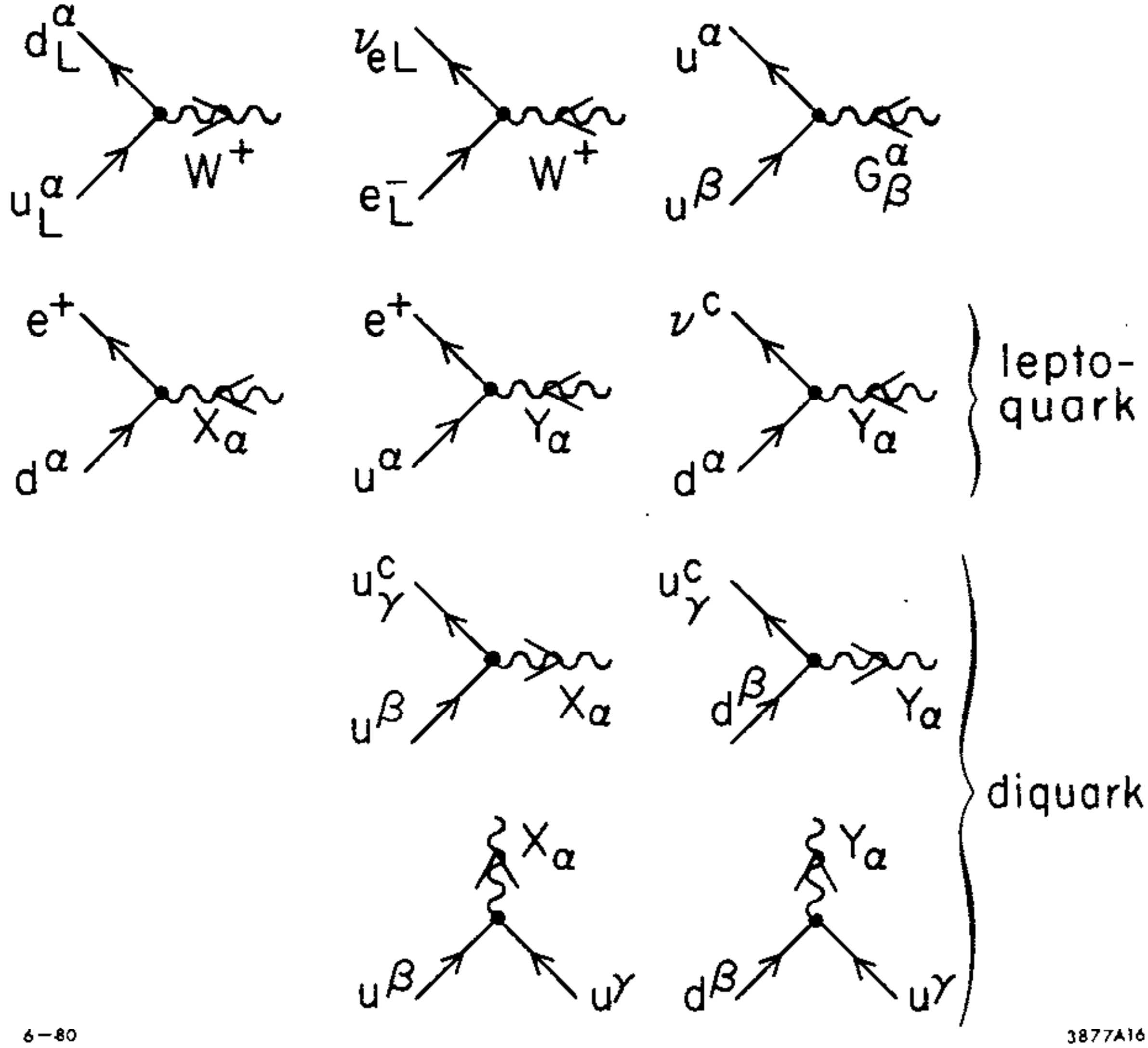


Fig. 2 .14



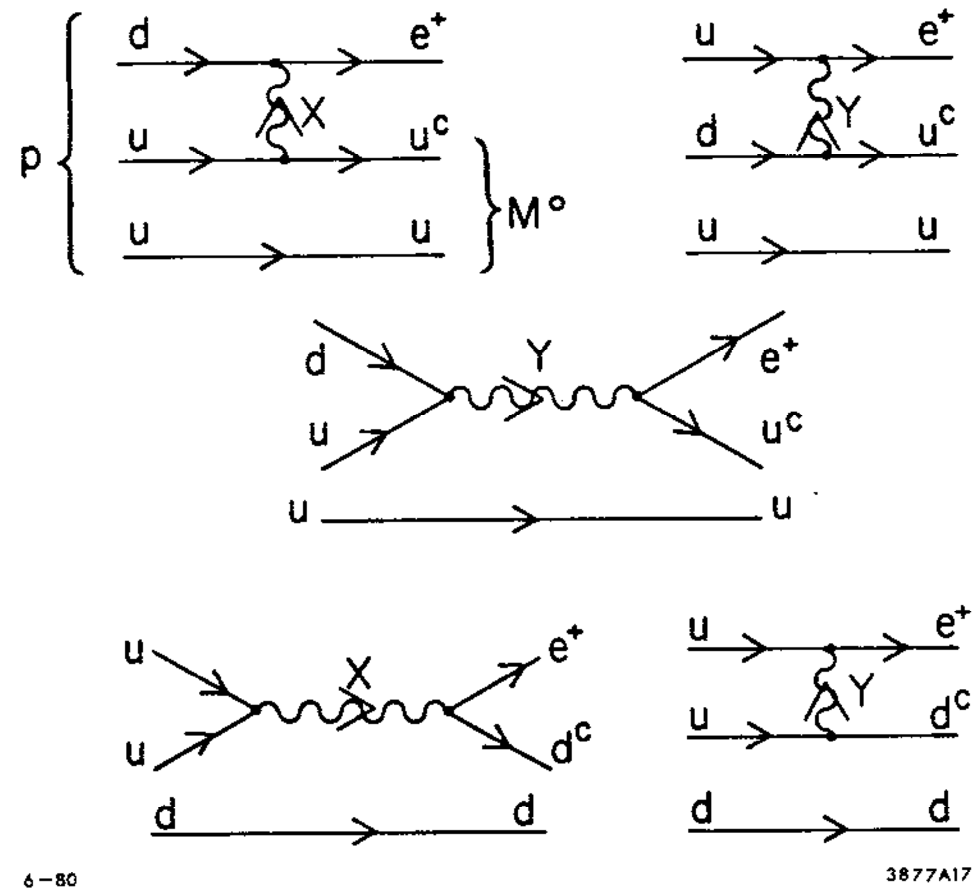
α(Q²)
α₃
α₂
α₁
Q²
M²W
Desert
M²x
Present Experiments
Unification
6 - 80
3877A15

Fig. 3.1



d_L^α
u_L^α
W^+
ν_{eL}
e_L^-
W^+
u^α
u^β
G_β^α
e^+
d^α
X_α
e^+
u^α
Y_α
ν^c
d^α
Y_α
lepto-
quark
u_γ^c
u^β
X_α
u_γ^c
d^β
Y_α
diquark
X_α
u^β
u^γ
Y_α
d^β
u^γ
6-80
3877A16

Fig. 3.2



p
d
e+
X
u
u^c
u
u
M°
u
e+
Y
d
u^c
u
u
d
Y
e+
u
u^c
u
u
u
X
e+
u
d^c
d
d
u
e+
Y
u
d^c
d
d
6-80
3877A17

Fig. 3.3

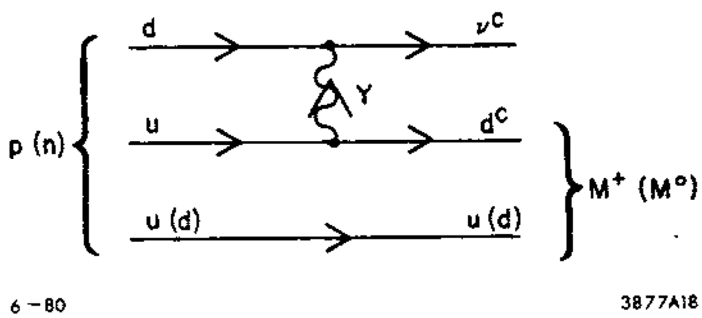
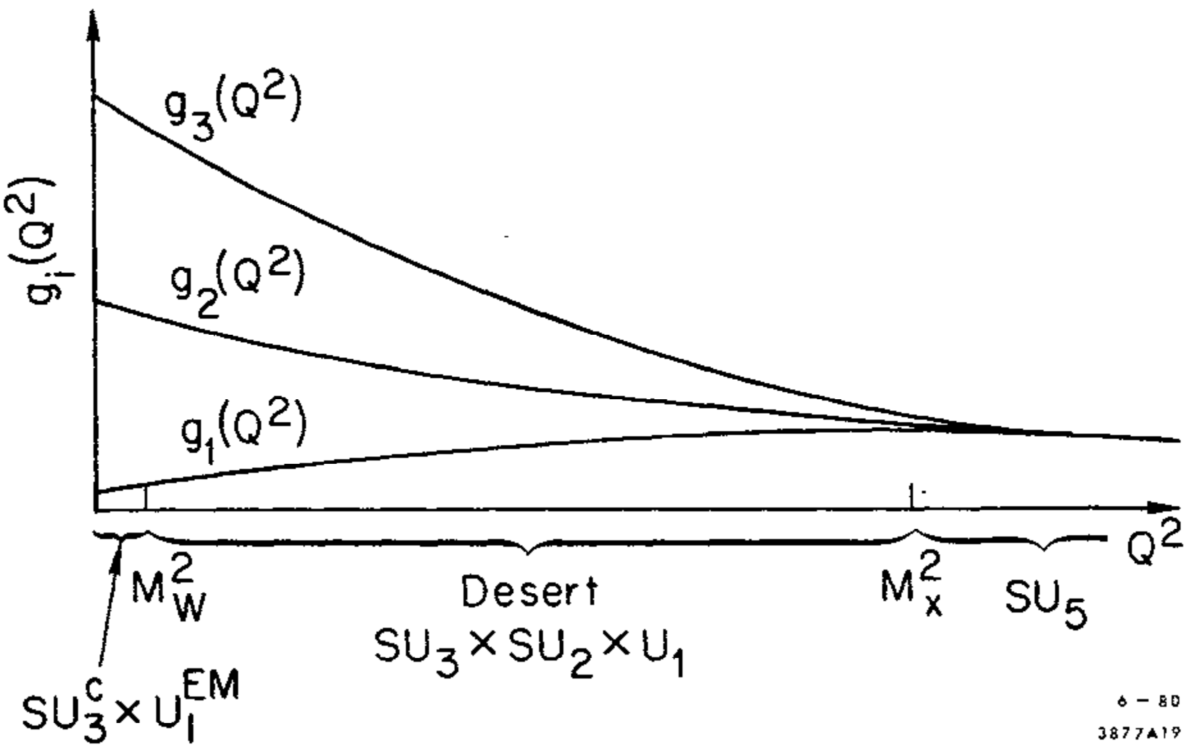


Fig. 3.4



$g_3(Q^2)$
$g_2(Q^2)$
$g_1(Q^2)$
$g_i(Q^2)$
Q^2
M_W^2
Desert
$SU_3 \times SU_2 \times U_1$
M_x^2
SU_5
$SU_3^c \times U_1^{EM}$
6 – 80
3877A19

Fig. 3.5

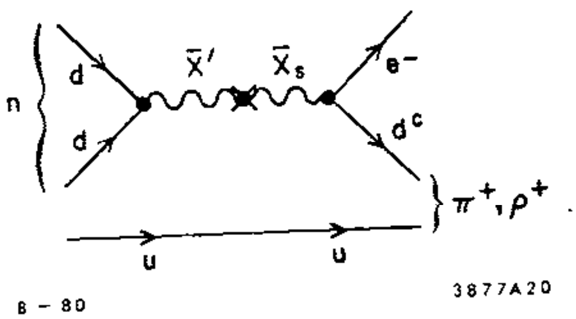


Fig. 3.6

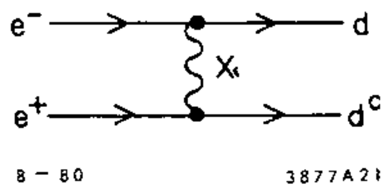


Fig. 3.7

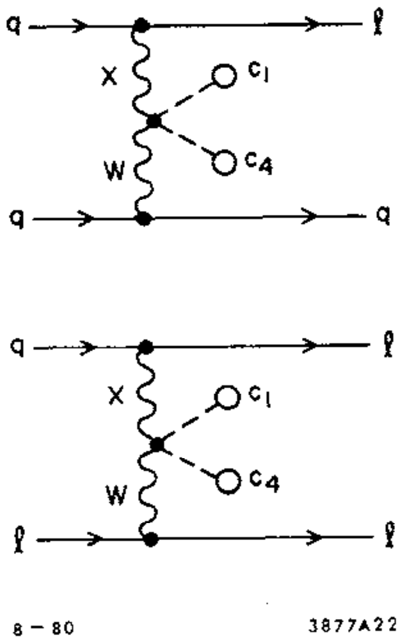


Fig. 3.8

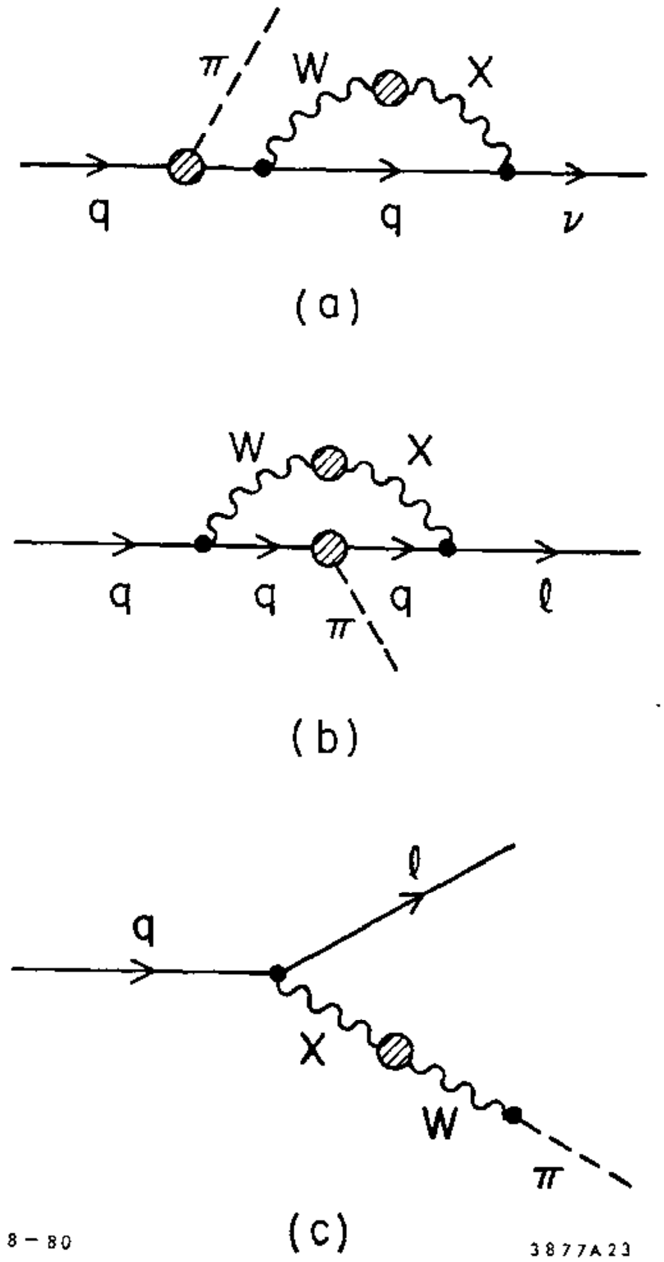


Fig. 3.9

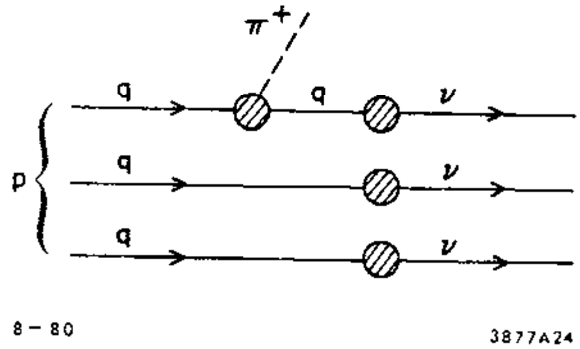


Fig 3.10

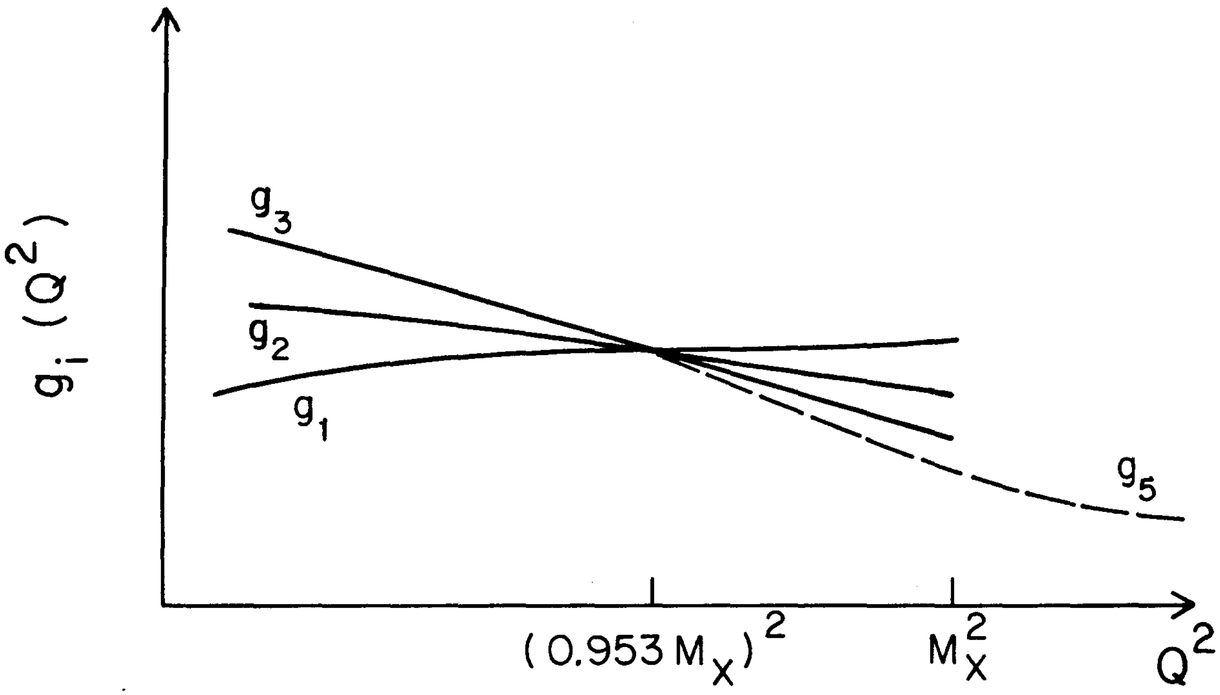
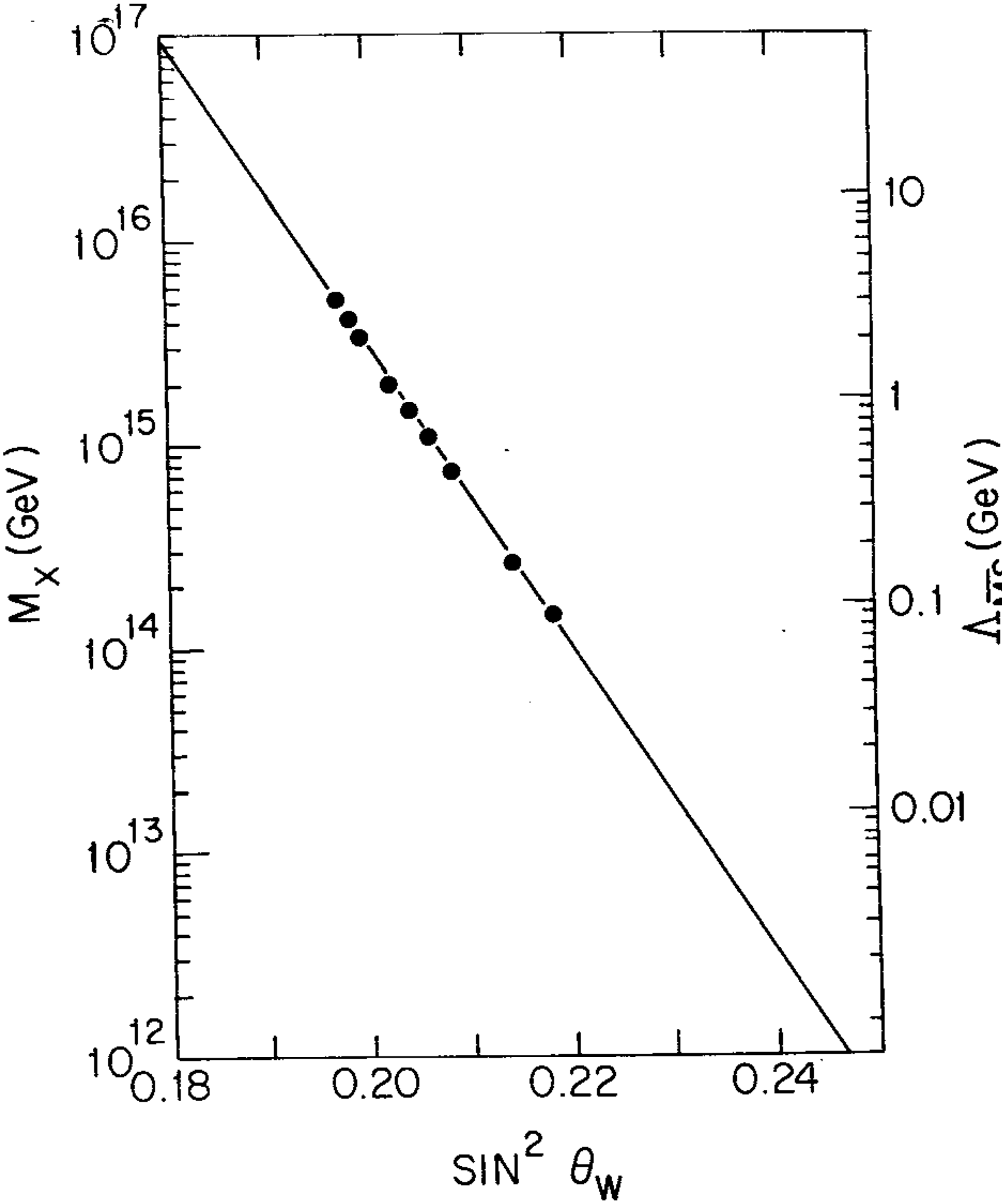


Fig. 4.1



10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
M_X (GeV)
10
1
0.1
0.01
$\Lambda_{\overline{MS}}$ (GeV)
0.18
0.20
0.22
0.24
$\sin^2 \theta_W$

Fig. 4.2

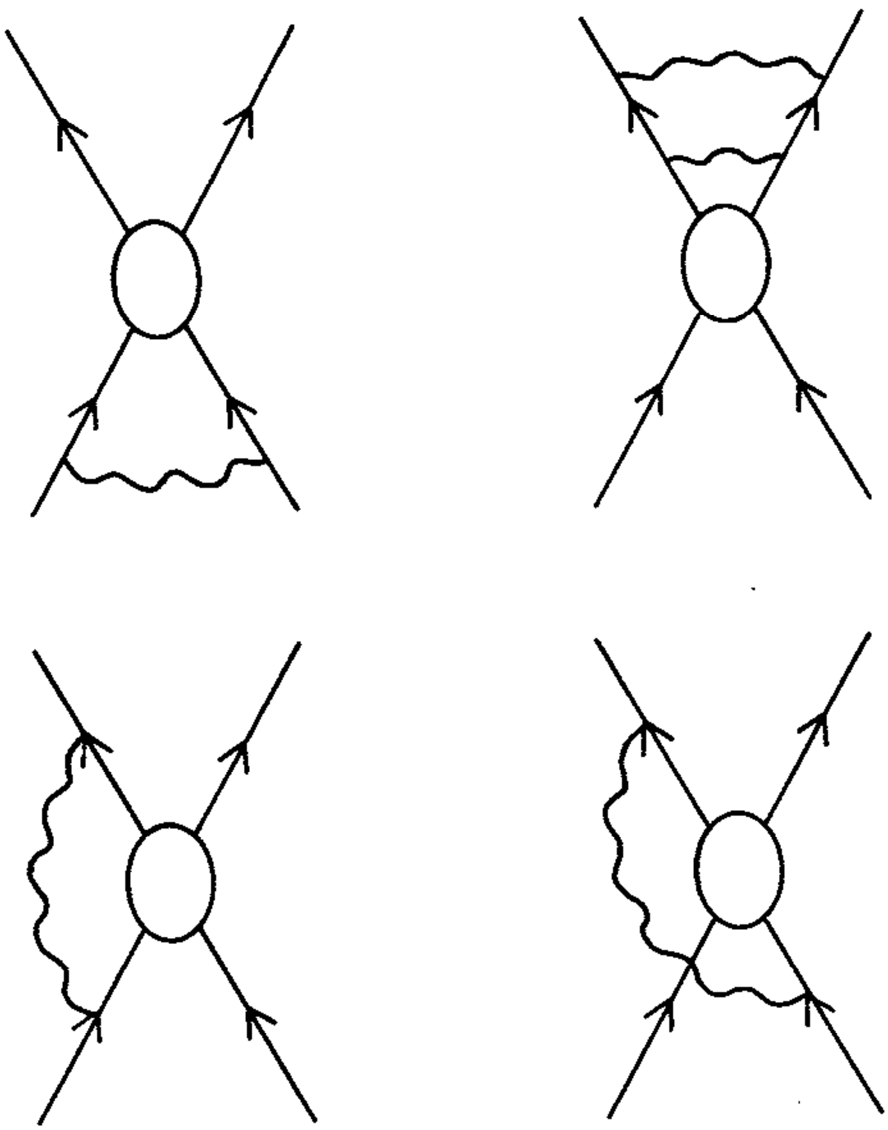


Fig. 4.3

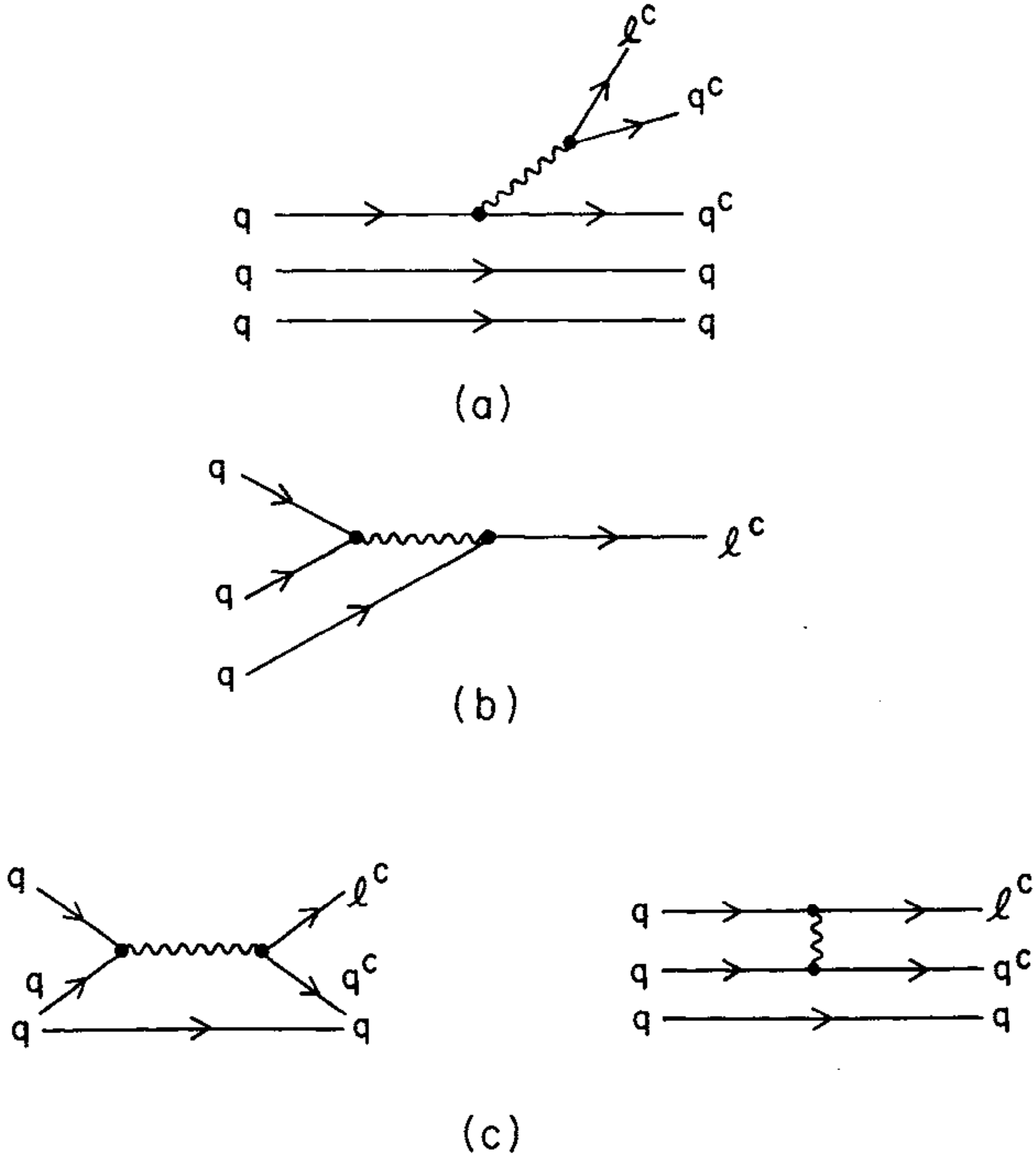
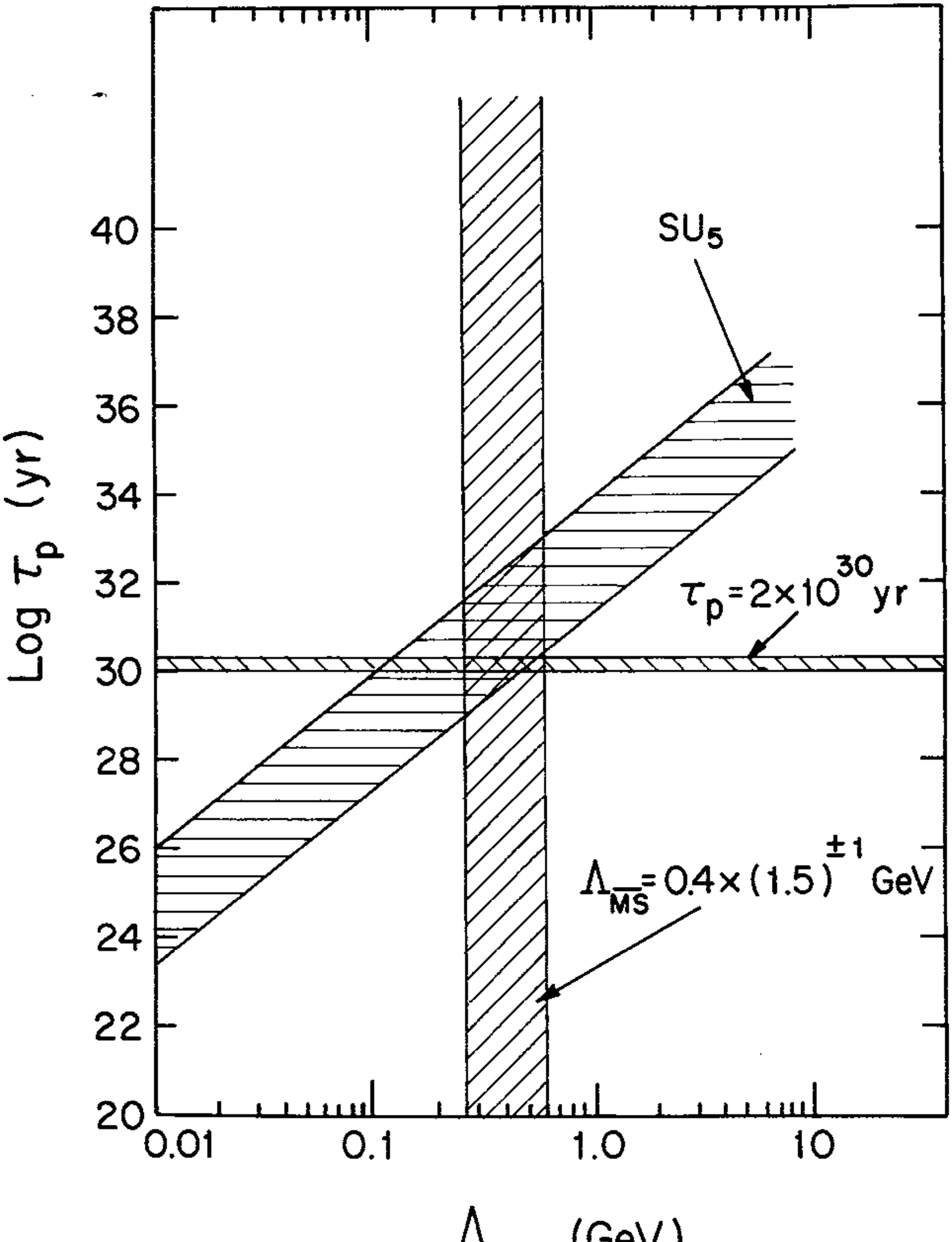
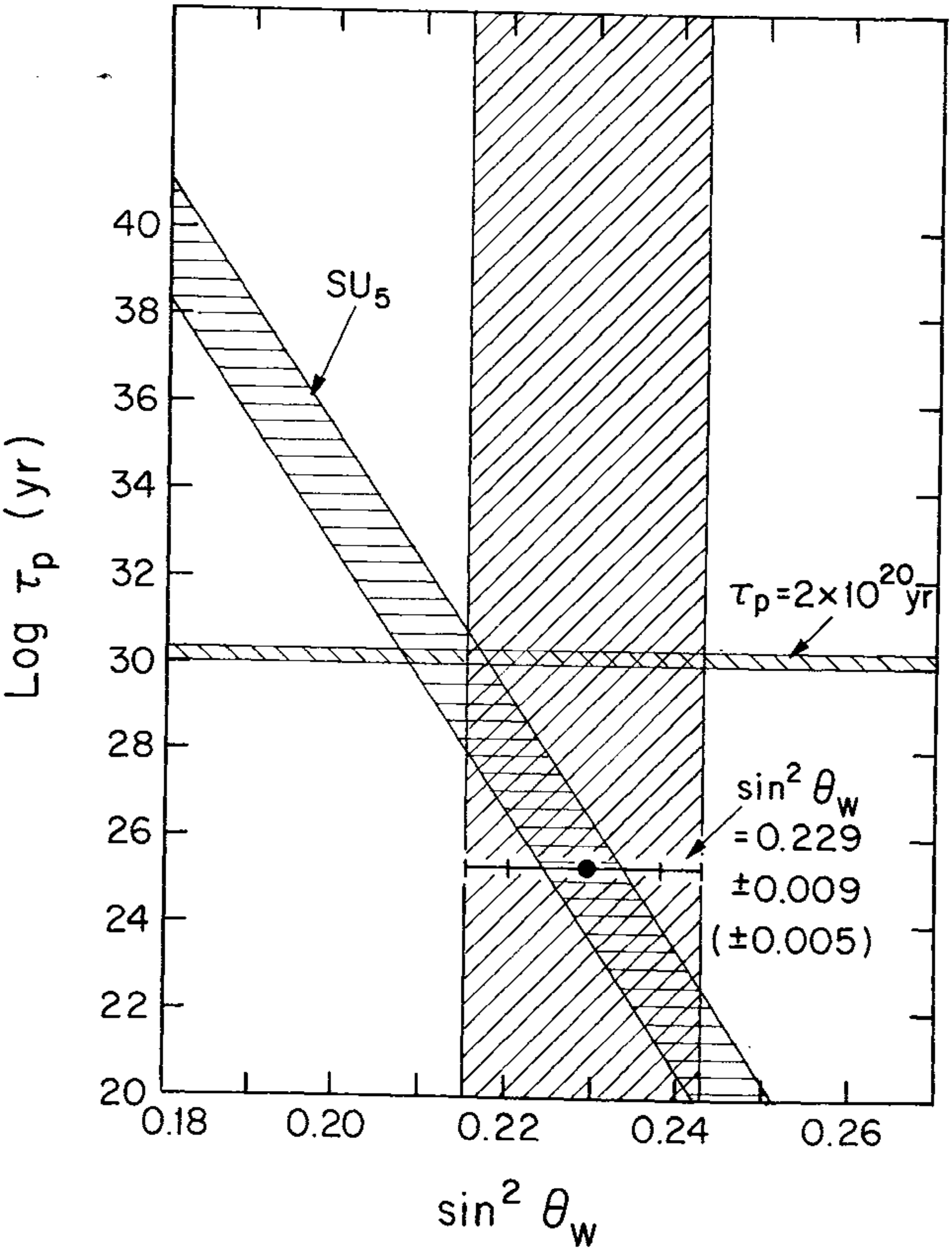


Fig. 4 . 4



Log τ_p (yr)
40
38
36
34
32
30
28
26
24
22
20
0.01
0.1
1.0
10
$\Lambda_{\overline{MS}}$ (GeV)
SU_5
$\tau_p = 2\times10^{30}$ yr
$\Lambda_{\overline{MS}} = 0.4\times(1.5)^{\pm1}$ GeV

Fig. 4. 5



Log τ_p (yr)
40
38
36
34
32
30
28
26
24
22
20
SU5
$\tau_p = 2\times 10^{20}$ yr
$\sin^2\theta_W$
= 0.229
± 0.009
(± 0.005)
0.18
0.20
0.22
0.24
0.26
$\sin^2\theta_W$

Fig. 4.6

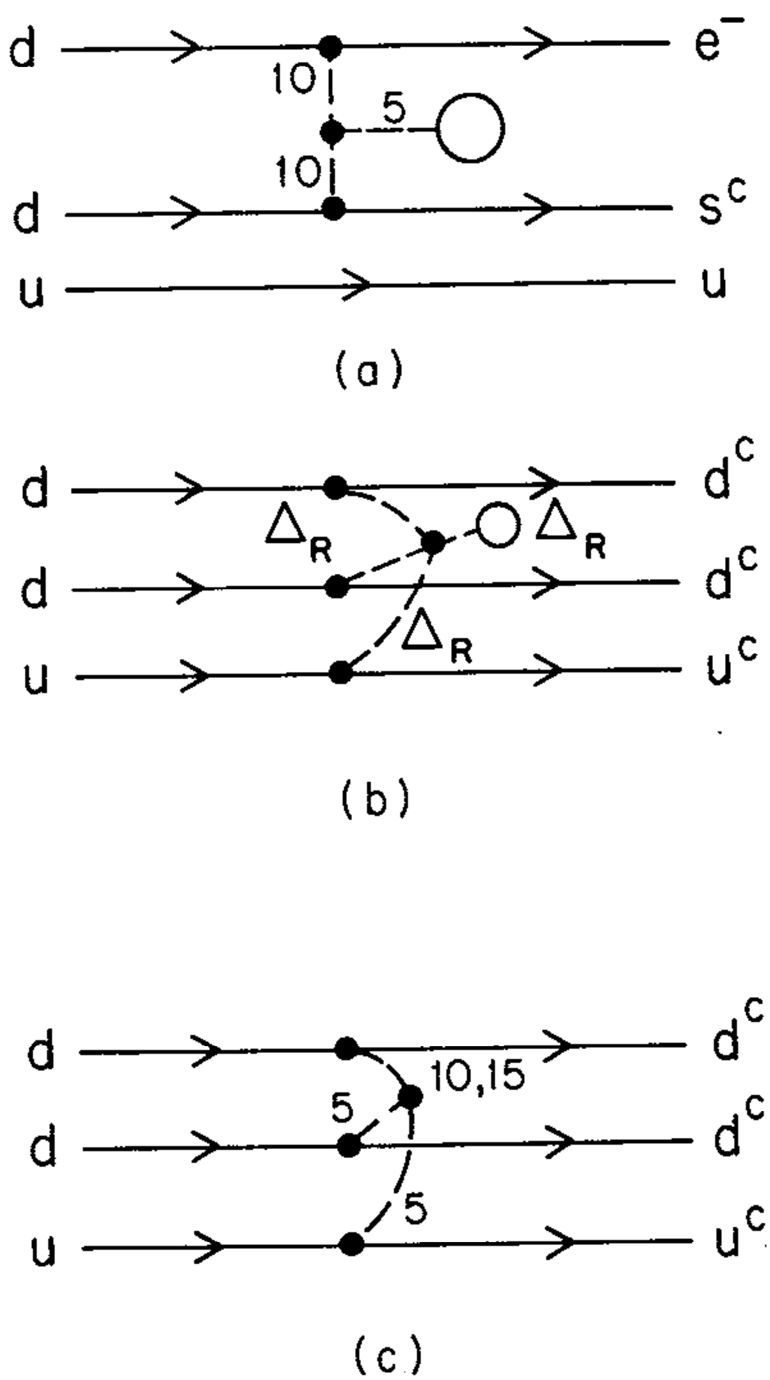


Fig. 4.7

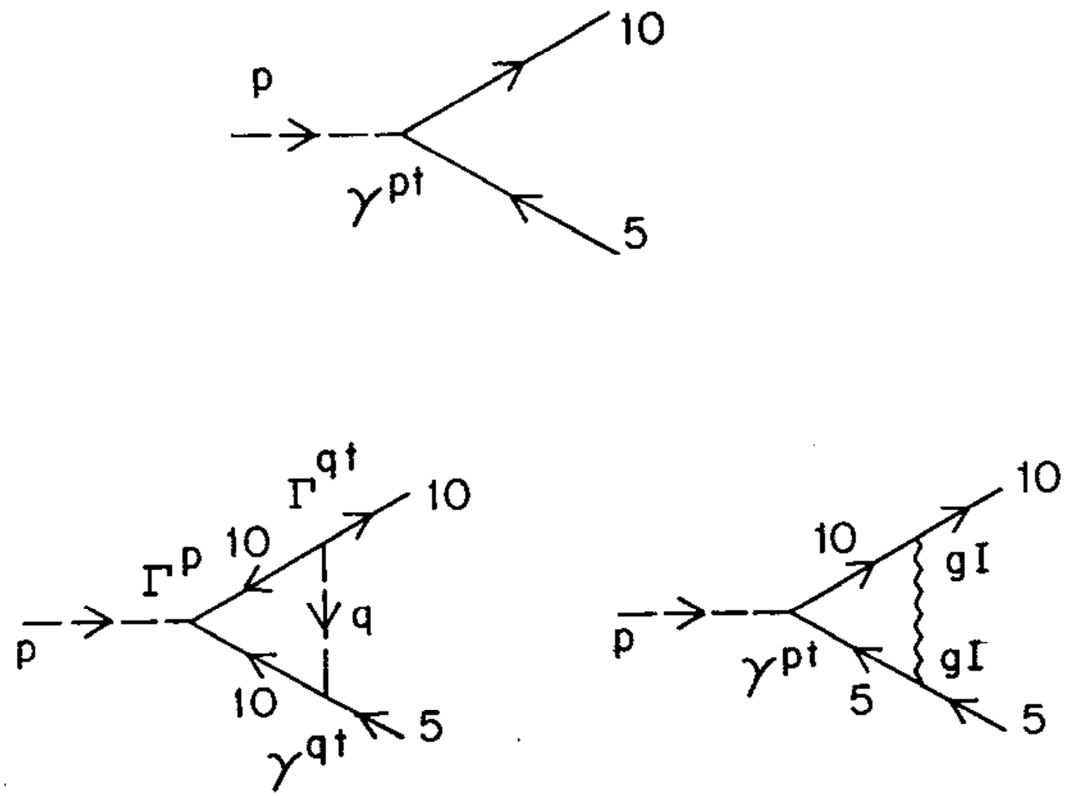
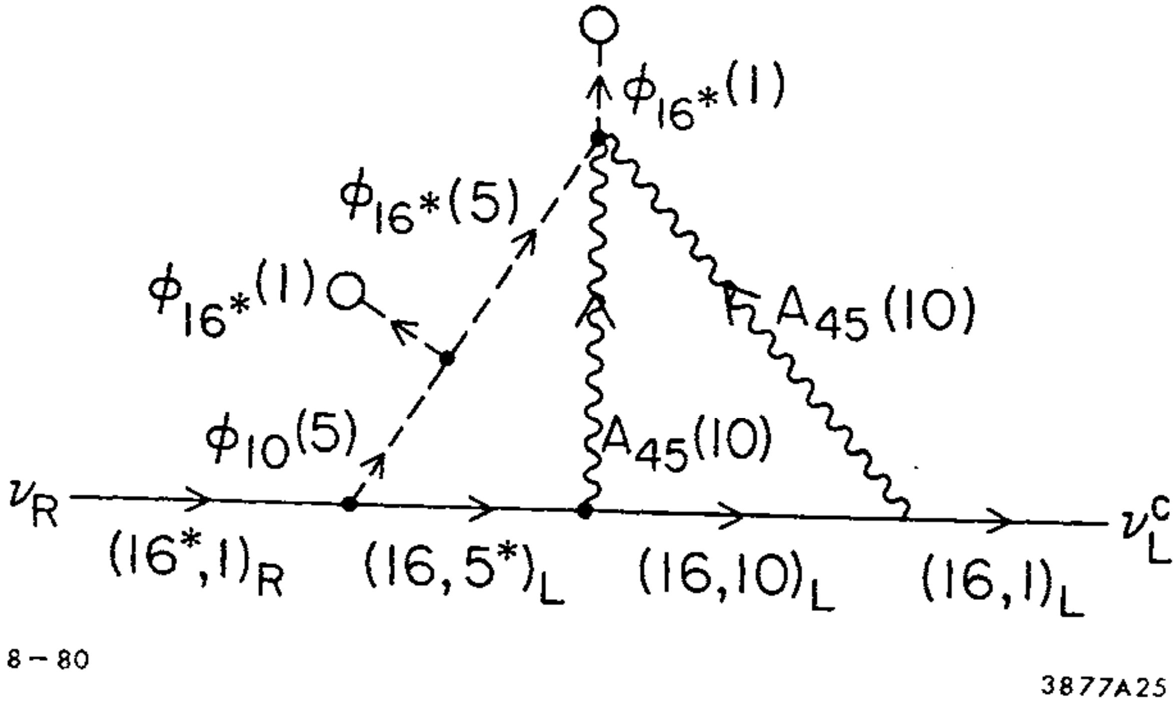


Fig. 5.1



$\phi_{16^*}(1)$
$\phi_{16^*}(5)$
$\phi_{16^*}(1)$
$A_{45}(10)$
$\phi_{10}(5)$
$A_{45}(10)$
ν_R
ν_L^c
$(16^*,1)_R$
$(16,5^*)_L$
$(16,10)_L$
$(16,1)_L$
8 − 80
3877A25

Fig. 6.1

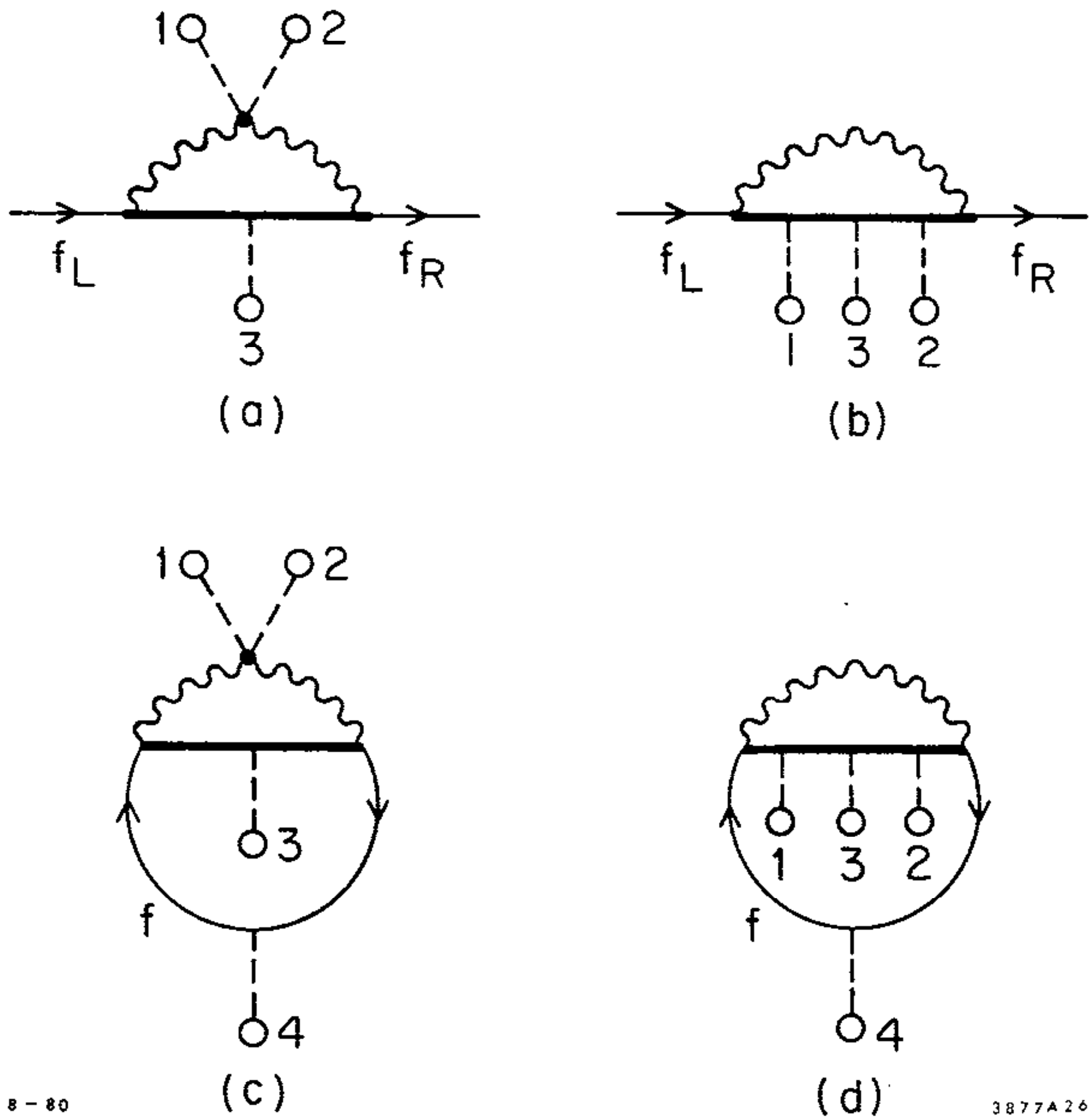


Fig. 6.2

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