ARTICLES

The meaning of the phrase 'fundamental constituents of matter' keeps changing with time as one probes phenomena at shorter and shorter distances, hence at higher and higher energies. At the present time, this phrase applies to the quarks and leptons: the former rather elusive and only detectable indirectly, the latter more readily visible. In addition one has photons, W and Z mesons, gluons — the 'carriers' of various fundamental interactions. In this review, Prof. D. P. Roy discusses in a crisp and informative manner the prospects of and methods for detecting the sixth member of the family of quarks, the 'top' or 'truth'.

— N. Mukunda

TOP QUARK SEARCH*

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There are plenty of ups and downs;
And many a strange ones too.
Charm and beauty are there, though rare;
But we are yet to see the truth.

ABSTRACT

The article reviews our progress in the search for the truth (or top) quark—the last and heaviest member of the family of basic constituents of matter.

INTRODUCTION

As per our current wisdom the basic constituents of matter are a dozen of fermions: the six leptons—electron, muon, tau and their associated neutrinos; and the six quarks—up, down, strange, charm, beauty and truth (or more colloquially bottom and top) quarks. They can be arranged as three pairs or generations of leptons and quarks in increasing order of mass, as shown in table 1. The six quark types are usually called flavours.

Each pair represents two charge states differing by 1 unit of e. In addition, the quarks possess a new type of charge—the so called colour charge. All of these fundamental particles have been experimentally detected by now except for the last and the heaviest one, i.e. the top quark. Naturally top quark search is a high priority area of current and proposed particle physics experiments. The aim of this article is to give a simple overview of the top search programme—its present status and future prospects. To facilitate this discussion and fix the notations, it is useful to briefly review the basic interactions between these fundamental particles.

Apart from gravitation, which is too weak to be of interest to our discussion of subatomic particles, there are 3 basic interactions—strong, electromagnetic and weak. They are all gauge interactions mediated by vector particles. The strong interaction is mediated by the exchange of massless vector gluons, which couple to all coloured particles (quarks) with coupling proportional to the colour charge C (figure 1a). This is analogous to the electromagnetic interaction, mediated by exchange of

Table 1

Leptons			Charge	Quarks			Charge
ν_e	ν_μ	ν_τ	0	u	c	t	2/3
e	μ	τ	−1	d	s	b	−1/3

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*This article is dedicated to my teacher and one of the leading contributors to the quark model, Prof. A. N. Mitra, on the occasion of his sixtieth birthday.

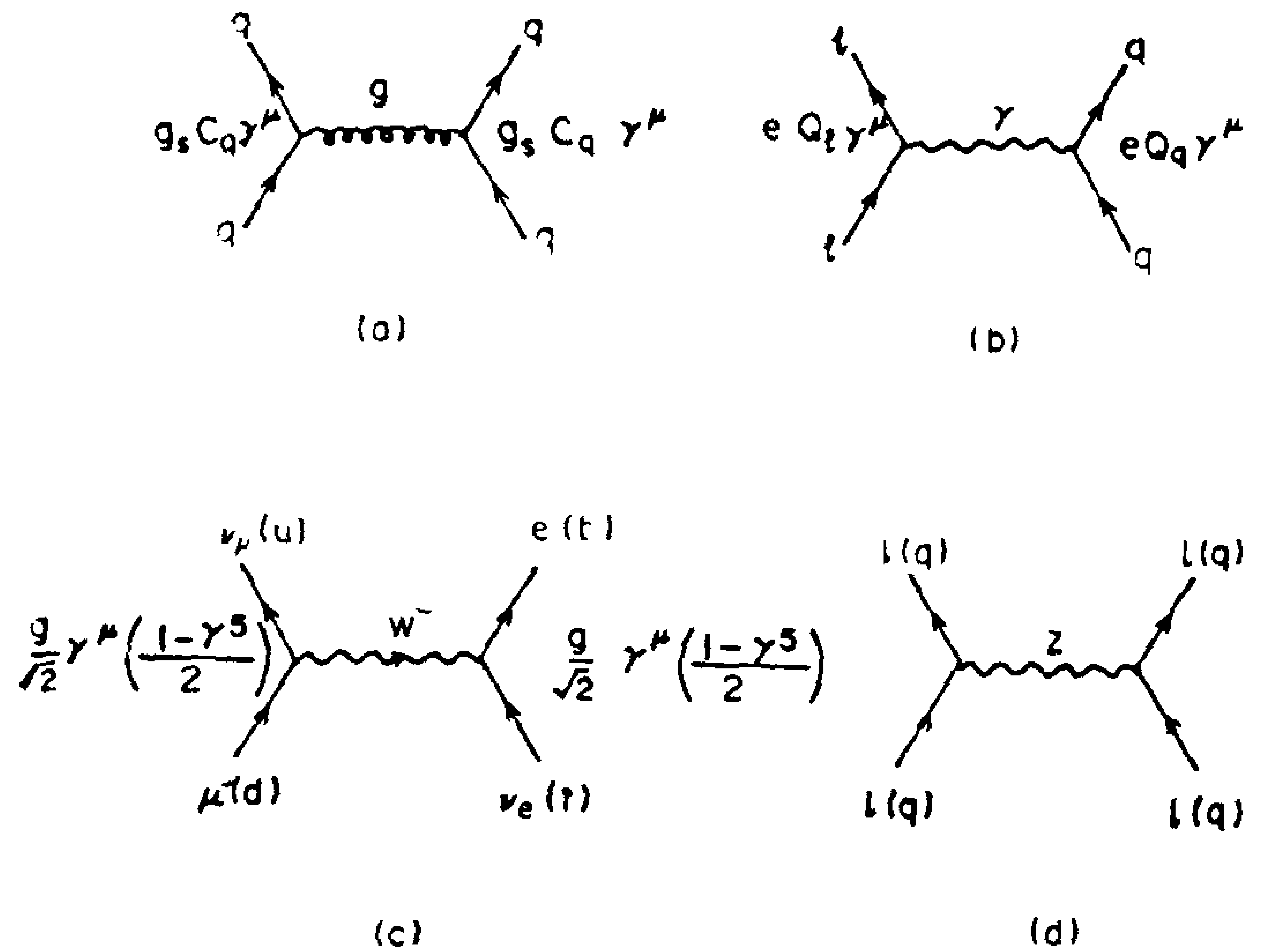

Figure 1. Basic interactions of quarks and leptons. **a,** Strong. **b,** Electromagnetic. **c,** Charged current weak. **d,** Neutral current weak.

massless vector photon, which couples to all charged particles (quarks and charged leptons) with coupling proportional to the electric charge Q (figure 1b). It is more customary to write the strong coupling as

$$\alpha_s = g_s^2/4\pi \tag{1}$$

in analogy with the fine structure constant

$$\alpha = e^2/4\pi. \tag{2}$$

The weak interactions are mediated by the massive charged and neutral vector bosons $W^{\pm}$ and Z^0. The charged $W^{\pm}$ boson couples to each of the above pairs of leptons and quarks with the same universal coupling g (figure 1c), where the combination of the Dirac γ matrices correspond to the famous V–A form of the charged current weak interaction giving rise to maximal parity violation. The neutral Z^0 boson couples to each quark and lepton (figure 1d), with couplings specified by the standard electro-weak model of Glashow, Weinberg and Salam. Here the weak and electromagnetic interactions are unified into a $SU(2)_L \times U(1)$ gauge interaction*, mediated by a charge triplet of gauge bosons $W^{\pm,0}$ with couplings proportional to the three $SU(2)$ generators $T^{\pm,3}$ (weak isospin) and a charge singlet B^0 with coupling proportional to the $U(1)$ generator (weak hypercharge). The two neutral bosons get mixed to give the physical Z boson and photon. It is customary to use the $SU(2)$ coupling g and the mixing angle θ_W as the 2 independent coupling parameters. Then the physical Z coupling is given by[1]

$$\frac{g}{\cos\theta_W}\left[T^3\gamma^\mu\frac{(1-\gamma^5)}{2} - \sin^2\theta_W\, Q\gamma^\mu\right], \tag{3}$$

and the physical photon coupling is related to these parameters by

$$e = g\sin\theta_W. \tag{4}$$

The quark and lepton pairs mentioned above are simply the weak isospin doublets with T^3 values $\frac{1}{2}$ and $-\frac{1}{2}$ for the upper and lower members.

INDIRECT EVIDENCE FOR TOP QUARK

There are two independent evidences for existence of a top quark as the weak isospin partner of the observed bottom quark.

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*The subscript L refers to the left handed (V–A) form of the weak interaction.

Forward–backward asymmetry in $e^+e^- \to \bar{b}b$

The axial·axial (AA) part of the Z exchange contribution to this process (figure 1d) interferes with the γ exchange (figure 1b) to give a forward–backward asymmetry in the produced b quark (see eqs. 3 & 4)[2],

$$\frac{\sigma(\theta<\pi/2)-\sigma(\theta>\pi/2)}{\sigma(\theta<\pi/2)+\sigma(\theta>\pi/2)} \simeq \frac{(-3/8)\,T_e^3\,T_b^3\,s/M_Z^2}{\sin^2\theta_W\cos^2\theta_W\cdot Q_b(s/M_Z^2-1)}. \tag{5}$$

With $T_e^3=T_b^3=-1/2$, $Q_b=-\frac{1}{3}$ and the experimental values of the Z mass and mixing angle (from neutrino scattering experiment)[3]

$$M_Z=92.4\pm1.8\ \text{GeV},\quad \sin^2\theta_W=0.233\pm0.006 \tag{6}$$

one predicts an asymmetry value of about -0.25 at a centre of mass energy $\sqrt{s}\simeq35$ GeV. The JADE collaboration has indeed observed a $25\pm6.5\%$ asymmetry with the right sign at this energy at the PETRA e^+e^- collider[4]. In the absence of a top quark, the bottom would be a weak isosinglet ($T_b^3=0$) resulting in zero asymmetry. Thus the JADE data constitute a respectable 4σ effect, suggesting the presence of a top quark[5].

Absence of the flavour changing neutral current decay $b \xrightarrow{Z} s, d$

The eigenstates of weak isospin given in table 1 are actually not pure quark flavour states but contain small admixtures of the other two flavours, i.e. they are

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{7}$$

where V is a unitary matrix with small but nonzero off-diagonal elements (the Kobayashi–Maskawa matrix)[1]. Thus the lighter quark of a generation can decay into a lower generation by charged current weak interaction, i.e. $b \xrightarrow{W} c$, u and $s \xrightarrow{W} u$ with couplings proportional to V_{cb}, V_{ub} and V_{us} respectively. In contrast, the flavour changing neutral current couplings cancel out by unitarity of V and the universality of Z coupling to the 3 generations, i.e.

$$Z(\bar{d}'d'+\bar{s}'s'+\bar{b}'b')=Z(\bar{d}d+\bar{s}s+\bar{b}b). \tag{8}$$

This cancellation mechanism was first used by Glashow *et al.*[6] in the context of a 2-generation quark mixing to show that the absence of the stangeness changing neutral current decay $s \xrightarrow{Z} d$ implied the existence of a c quark as the weak isospin partner of s. Similarly the absence of flavour changing neutral current decays $b \xrightarrow{Z} s, d$ suggests the existence of a t quark as the weak isospin partner of b[7]. Otherwise b' would be a $SU(2)$ singlet so that the $SU(2)$ part of its coupling to Z would vanish. The result is formally equivalent to transfering the universal $SU(2)$ coupling term $Z\bar{b}'b'$ to the right hand side of eq. (8). This would imply flavour changing neutral current decays $b \xrightarrow{Z} s$, d with couplings $Z\bar{b}s$, $Z\bar{b}d \propto V_{tb}V_{ts}$, $V_{tb}V_{td}$. And since the diagonal element $V_{tb}\simeq1$ and

$$|V_{ts}|^2+|V_{td}|^2=|V_{cb}|^2+|V_{ub}|^2 \tag{9}$$

by unitarity, the total rate for the neutral current decay $b \xrightarrow{Z} s, d$ should be comparable to that for the charged current decays $b \xrightarrow{W} c, u$. Multiplying this by the $Z\to\mu^+\mu^-$ branching ratio of 3%, one predicts a $\geqslant1\%$ branching ratio for the neutral current decay $b\to\mu^+\mu^-X$. The experimental upper limit for this decay branching ratio from the CLEO collaboration[8] is 0.12%. Thus the absence of neutral current b decay at a level comparable to its charged current decay provides a second evidence for the existence of t.

INDIRECT CONSTRAINTS ON TOP QUARK MASS

There are at least two indirect constraints on top quark mass as we see below.

Radiative correction to W & Z boson mass

It provides a clean upper bound on the top quark mass, assuming the standard model of electro-weak interaction[3, 9]. The observed rate of muon decay $\mu \xrightarrow{W} \nu_\mu e \bar{\nu}_e$ (figure 1c) determines the Fermi coupling

$$G_F=\frac{g^2\sqrt{2}}{8M_W^2}=\frac{\pi\alpha}{\sqrt{2}\cdot\sin^2\theta_W\cdot M_W^2} = 1.1663\times10^{-5}\ \text{GeV}^{-2}. \tag{10}$$

This gives an estimate of W mass by putting in the experimental value of $\sin^2\theta_W$ (eq. 6) and α. For a precise estimate of course one must take account of the radiative correction to the fine structure constant α. The dominant correction, coming from the photon

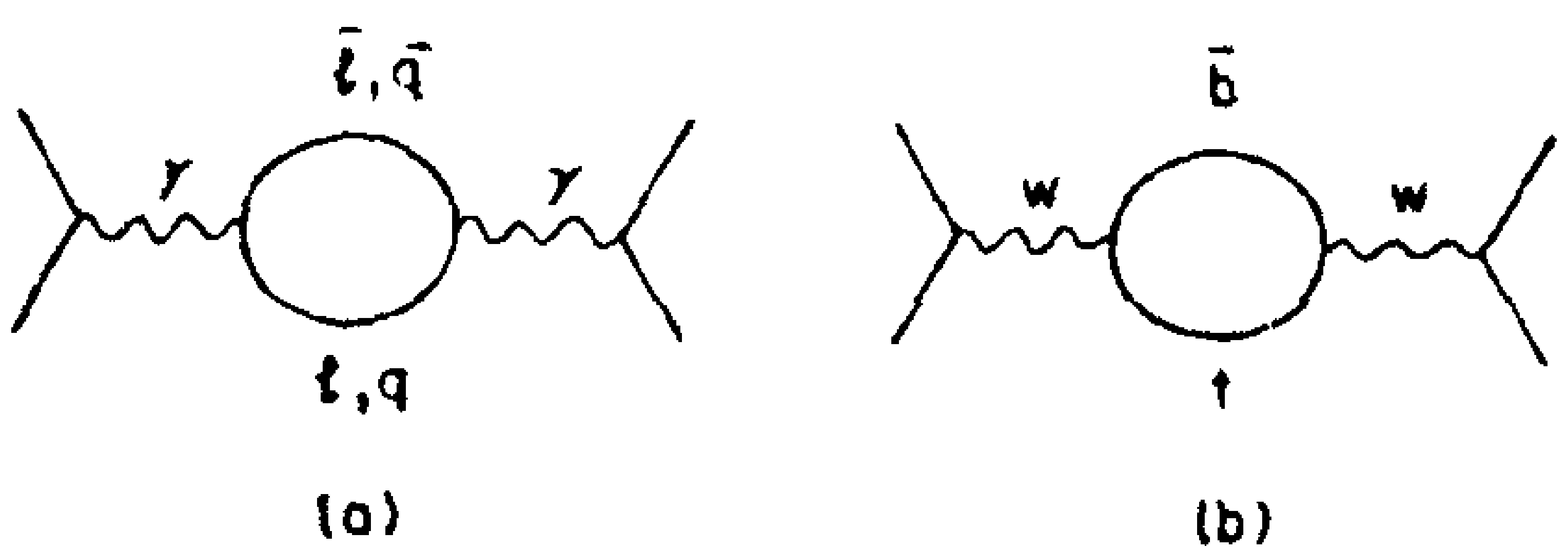

Figure 2. **a,** Lepton and quark pair contributions to photon self-energy. **b,** $t\bar{b}$ contribution to W self-energy.

self-energy diagram (figure 2a), makes α run with the mass scale, i.e.

$$\alpha(M_W^2) = \alpha(m_e^2)\left[1 + \frac{\alpha(m_e^2)}{3\pi}\left\{\sum_l Q_l^2 \ln\frac{M_W^2}{m_l^2} + 3\sum_q Q_q^2 \ln\frac{M_W^2}{m_q^2}\right\}\right] \tag{11}$$

to leading order in α. The summation runs over the charged leptons e, μ, τ and the light quarks u, d, s, c, b; and the factor 3 corresponds to the 3 colour states of a quark. The radiative correction factor can be easily calculated to be about 7%, i.e.

$$\begin{aligned}\alpha(M_W^2) &= \alpha(m_e^2)\,[1 + \Delta r] \\ &\simeq (1/137)(1 + 0.07) \simeq 1/128.\end{aligned} \tag{12}$$

Since the electro-weak couplings are related at the mass scale of M_W^2, one has to use this value of α in eq. (10) to predict M_W. It gives

$$M_W^{\text{Th}} = 80 \pm 1.5\ \text{GeV} \tag{13}$$

in agreement with the experimental value of

$$M_W^{\text{Exp}} = 81 \pm 1.3\ \text{GeV}. \tag{14}$$

One should note that, without this radiative correction the predicted value is

$$M_W^0 \simeq 77.2 \pm 1.5, \tag{15}$$

i.e. on the margin of disagreement with data. One has a similar results for Z mass as well.

What about the radiative correction to the remaining factors of eq. (10)? It turns out to be negligible provided top quark is not heavier than W boson. For $m_t > M_W$, however, there is a significant contribution coming from the W self-energy diagram of figure 2b and the corresponding one for Z. The reason is that the longitudinal W, Z boson couplings are proportional to the fermion mass like the Higgs coupling, since the W, Z mass and longitudinal components arise by absorbing Higgs particles. Consequently the radiative correction has a quadratic M_t dependence $\left(\simeq -\dfrac{\cos^2\theta_W}{\sin^2\theta_W}\cdot\dfrac{3\sqrt{2}G_F}{16\pi^2}\cdot m_t^2 \text{ for large } m_t\right)$*. For $m_t \simeq 200$ GeV it cancels out the 7% radiative correction in eq. (12). Thus

$$m_t > 200\ \text{GeV} \Rightarrow \Delta r < 0 \Rightarrow M_W^{\text{Th}} < 77\ \text{GeV} \tag{16}$$

in conflict with the experimental value of eq. (14). This gives an indirect upper bound on top quark mass of about 200 GeV.

$B_d - \bar{B}_d$ Mixing

There is a lower bound on top quark mass coming from the observed $B_d - \bar{B}_d$ mixing, i.e. transition between the B_d meson (bound state of the quark-antiquark pair $b\bar{d}$) and its antiparticle $\bar{B}_d$. This is a second order weak process, occurring via u, c and t quark exchanges (figure 3). If t quark was

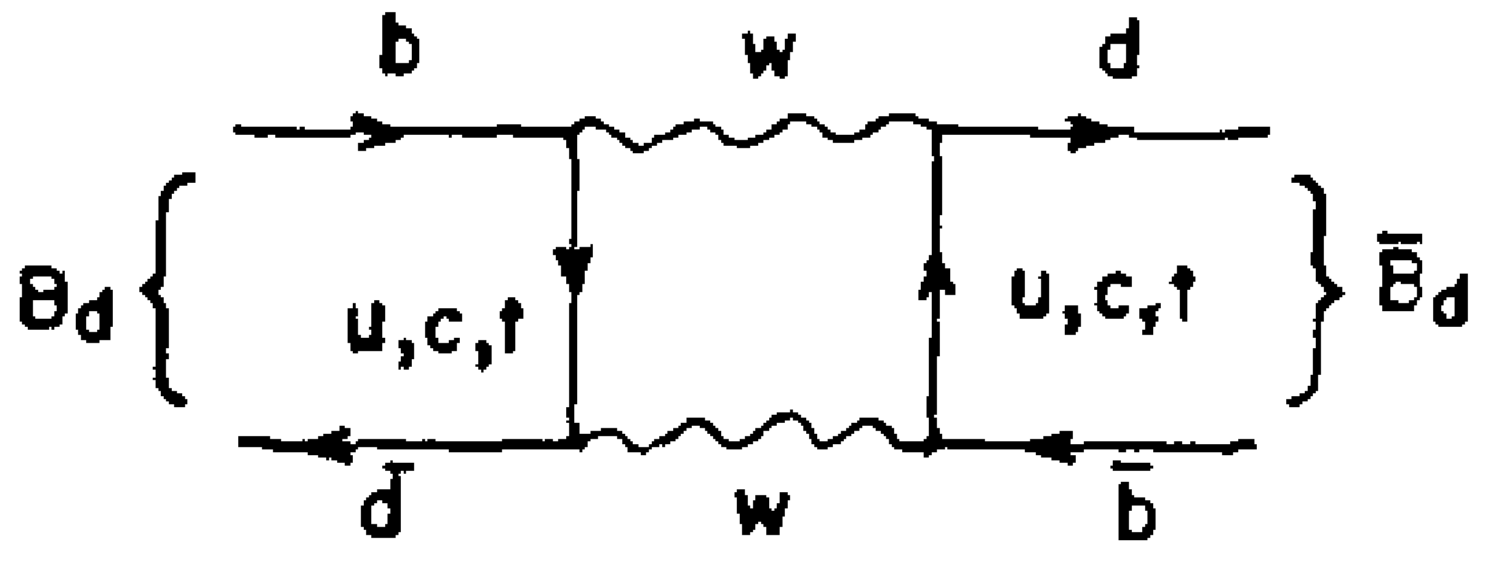

Figure 3. The second order weak process responsible for $B_d - \bar{B}_d$ mixing. There is a second diagram corresponding to the interchange of the internal quark and W boson lines.

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*Due to the W, Z mass shifts from the self-energy diagrams the standard model mass formula $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ (used to estimate the $\sin^2\theta_W$ of eq. 6) acquires a radiative correction term $\propto m_t^2$. Adding this in the denominator of eq. (10) the result follows.

light like u and c, the GIM cancellation mechanism (unitarity of the V matrix) would effectively suppress this diagram. For a heavy t quark, however, there is no effective cancellation. Even more importantly, the longitudinal W contribution grows quadratically with m_t, since its coupling is proportional to the quark mass. This leads to a mixing parameter (off-diagonal element in the $B_d-\bar{B}_d$ mass matrix)[10]

$$M_{12}\simeq G_F^2 f^2 B\, m_{Bd}\,[(V_{td}^* V_{tb})^2 m_t^2+\ldots]/12\pi^2 \quad (17)$$

where higher order terms in m_t^2/M_W^2 are not shown explicitly. The factor f^2B arises from the strong interaction dynamics of quark-antiquark ($b\bar{d}$) binding inside the B_d meson[11]. There is no unambiguous estimate for this quantity; but various model estimates suggest the range[10]

$$f^2B\simeq(0.10-0.16\ \mathrm{GeV})^2. \quad (18)$$

The diagonal matrix element $V_{tb}\simeq 1$, and one gets an upper bound on V_{td} from unitarity and the knowledge of the other off-diagonal elements, i.e.

$$V_{td}\leqslant 0.02. \quad (19)$$

Thus the observation of a sizable $B_d-\bar{B}_d$ mixing would give a significant lower bound on top quark mass. The ARGUS group[12] has observed such a mixing with rate

$$r=\frac{(Re\,M_{12})^2}{\Gamma^2/2+(Re\,M_{12})^2}=0.2\pm 0.1,$$

$$\Gamma^{-1}=\tau_{Bd}\simeq 10^{-12}\ \mathrm{sec}; \quad (20)$$

where r corresponds to the probability of finding $B_d B_d$ and $\bar{B}_d\bar{B}_d$ final states in e^+e^- collision relative to $B_d\bar{B}_d$. This result has more recently been confirmed by the CLEO group. Taking the lower limit of r (eq. 20) and the upper limit of f^2B (eq. 18) gives a conservative lower bound

$$m_t\geqslant 40-50\ \mathrm{GeV}. \quad (21)$$

One should bear in mind of course that the second input is not unambiguous.

Ratio of W and Z widths

The ratio of W and Z boson widths provides an indirect probe of top quark mass up to about 60 GeV. It is simple to see this for the interesting t mass range of 40–60 GeV, in which case the $Z\to t\bar{t}$ channel is kinematically forbidden but the $W\to b\bar{t}$ channel is open, i.e.

$$W^-\to e\bar{\nu}+\mu\bar{\nu}+\tau\bar{\nu}+3d\bar{u}+3s\bar{c}+3b\bar{t}. \quad (22)$$

The opening of the $b\bar{t}$ channel would naively correspond to a 30% enhancement of Γ_W (or decrease of the ratio Γ_Z/Γ_W); but the kinematic supression factor for $m_t=40$–60 GeV reduces it to a 15% effect. In fact the ratio does not decrease any further with m_t, since the opening of $Z\to t\bar{t}$ width compensates the further increase of $W\to b\bar{t}$ width. Thus a measurement of this ratio would tell whether there is a t quark below 60 GeV, provided the experimental accuracy is better than 15%. The ratio has been indirectly measured from the relative number of $W\to ev$ and $Z\to e^+e^-$ events at the CERN antiproton–proton collider (figure 4), i.e.

$$\frac{\#W\to e\bar{\nu}}{\#Z\to e^+e^-}=\frac{\sigma_W}{\sigma_Z}\cdot\frac{\Gamma(W\to e\bar{\nu})}{\Gamma(Z\to e^+e^-)}\cdot\frac{\Gamma_Z}{\Gamma_W}. \quad (23)$$

The resulting Γ_Z/Γ_W ratio, taken at its face value, appears to favour $m_t<60$ GeV[13]; but the errors are much too large to draw any meaningful conclusion. There is a 15% statistical error coming from the limited number of $Z\to e^+e^-$ events (~ 50) and a systematic error of similar magnitude from the estimated ratio of W and Z cross-sections[14]. The latter arises from the uncertainty of u and d quark flux distributions inside the proton, used in the cross-section estimates (figure 4). Hence it does not give any meaningful constraint on top quark mass so far.

DIRECT SEARCH FOR TOP QUARK

The progress and prospect of direct top quark search in different colliders are discussed below.

Electron–positron collider

The e^+e^- colliders provide the cleanest probe for t quark; but unfortunately the energies are too low. The simplest way to look for $e^+e^-\to\bar{t}t$ (figure 1b) is

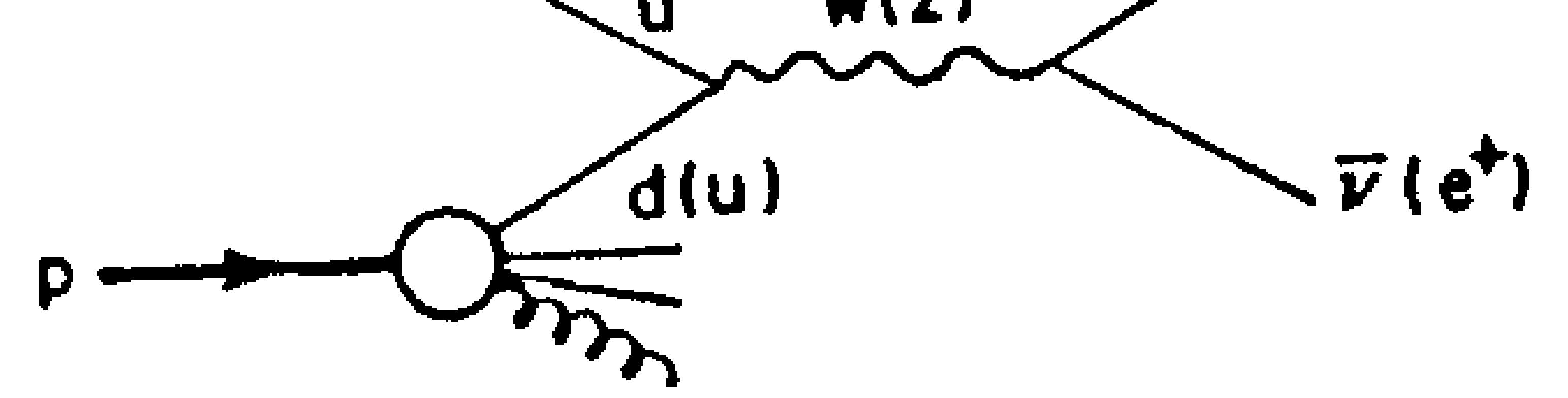

Figure 4. Production of $W\to e^-\bar{\nu}(Z\to e^-e^+)$ events in antiproton-proton collision.

through the ratio

$$R=\frac{\sigma(e^+e^-\rightarrow \text{hadrons})}{\sigma(e^+e^-\rightarrow \mu^+\mu^-)}$$

$$=\frac{\sigma(e^+e^-\rightarrow \Sigma\,\bar{q}q)}{\sigma(e^+e^-\rightarrow \mu^+\mu^-)}\simeq 3\sum Q_q^2 \qquad (24)$$

which should show a jump of $\Delta R=3Q_t^2=4/3$ units across the $\bar{t}t$ threshold. The second way is to look at the event shape. The lighter quark pairs fly off back to back carrying the total centre of mass energy and thus give highly collinear events. In contrast, near the $t\bar{t}$ threshold, this heavy quark pair will be produced practically at rest. And each will decay into 3 quarks (figure 1c).

$$t\rightarrow b\,u\,\bar{d},\, b\,c\,\bar{s}. \qquad (25)$$

Thus the total centre of mass energy would be shared amongst 6 light quarks, giving rise to more spherical (isotropic) events.

The PETRA and more recently TRISTAN colliders have searched for $\bar{t}t$ production using both these methods and found none. Thus they give lower mass bounds equal to their respective beam energies. TRISTAN gives the larger bound[15]

$$m_t \geqslant 26\ \text{GeV}, \qquad (26)$$

which is evidently not large enough. The LEP collider, starting later in this year, can probe top quark mass up to its beam energy of about 50 GeV. As we have already seen in eq. (21), however, it is likely to be a barren region. The LEP-II beam, scheduled for the mid-ninties, can probe top quark mass up to nearly 100 GeV. This mass range is already being probed by the current antiproton–proton colliders, as we shall see below. If they find a top quark in this mass range, then LEP-II will be very useful for a detailed investigation of its properties.

Antiproton–proton collider

The $\bar{p}p$ collider can probe a larger mass range of top quark because of its higher energy. But the signal is dirty; and one has to use special tricks to clean it up. The dominant mechanisms for top quark production are the Bethe–Heitler process of gluon–gluon fusion (figure 5)

$$gg\rightarrow \bar{t}t \qquad (27)$$

and via W (figure 4)

$$\bar{q}q\rightarrow W\rightarrow \bar{t}b. \qquad (28)$$

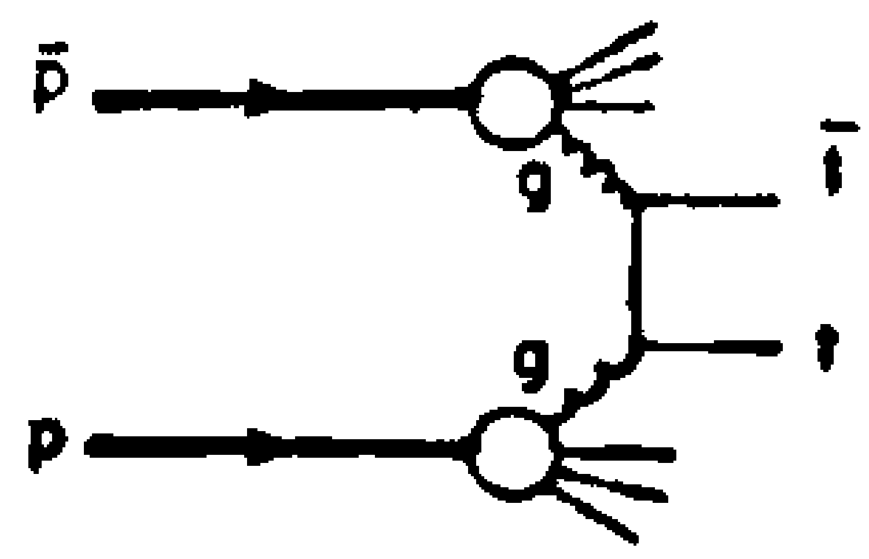

Figure 5. Top quark production in $\bar{p}p$ collision via the Bethe–Heitler process of gluon–gluon fusion.

The best way to look for top is to look for the charged lepton (e or μ) coming from its leptonic decay (figure 1c)

$$t\rightarrow b\nu e^+\,(\mu^+),\ \bar{t}\rightarrow \bar{b}\bar{\nu}e^-\,(\mu^-), \qquad (29)$$

which eliminates the background from gluon and ordinary quark (u, d, s) scattering. Of course, the charged lepton could come from the remaining (unstable) quarks b and c, e.g.

$$b\rightarrow c\bar{\nu}e^-\,(\mu^-),\ \bar{c}\rightarrow \bar{s}\bar{\nu}e^-\,(\mu^-). \qquad (30)$$

These background can be effectively suppressed by requiring the charged lepton to be isolated from the other particles. Because of the large energy release in the massive top quark decay, the decay products come out wide apart. In contrast the energy release in the light b or c quark decay is small, so that the decay products come together in a narrow cone, i.e. the charged lepton appears as part of the decay quark jet. The isolated electron (or muon) provides a simple but very powerful signature for top quark, first suggested in ref. 16.

Top quark search has been carried out at the CERN $\bar{p}p$ collider ($S\bar{P}PS$), at a centre of mass energy of 630 GeV, using the isolated electron (muon) signature. And the absence of such events gives a lower mass limit[17]

$$m_t \geqslant 40\ \text{GeV}. \qquad (31)$$

This is the best mass limit from direct top quark search so far, and similar to the indirect limit from

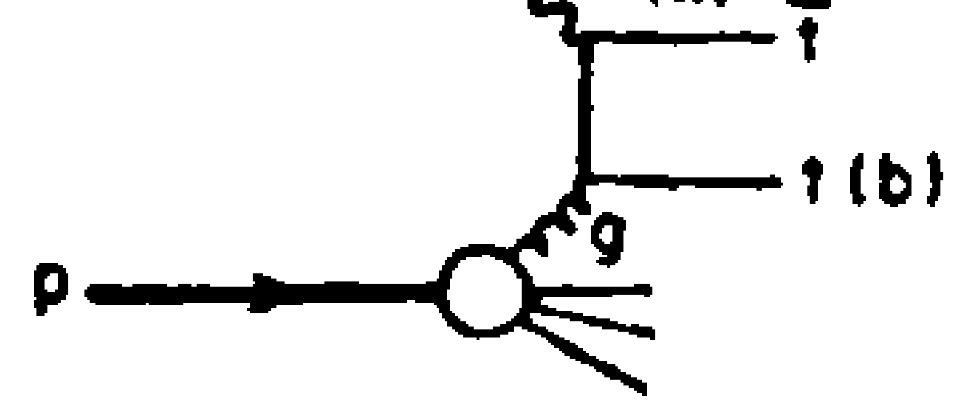

Figure 6. Top quark production in ep collision via the Bethe–Heitler processes of photon–gluon and W boson–gluon fusion.

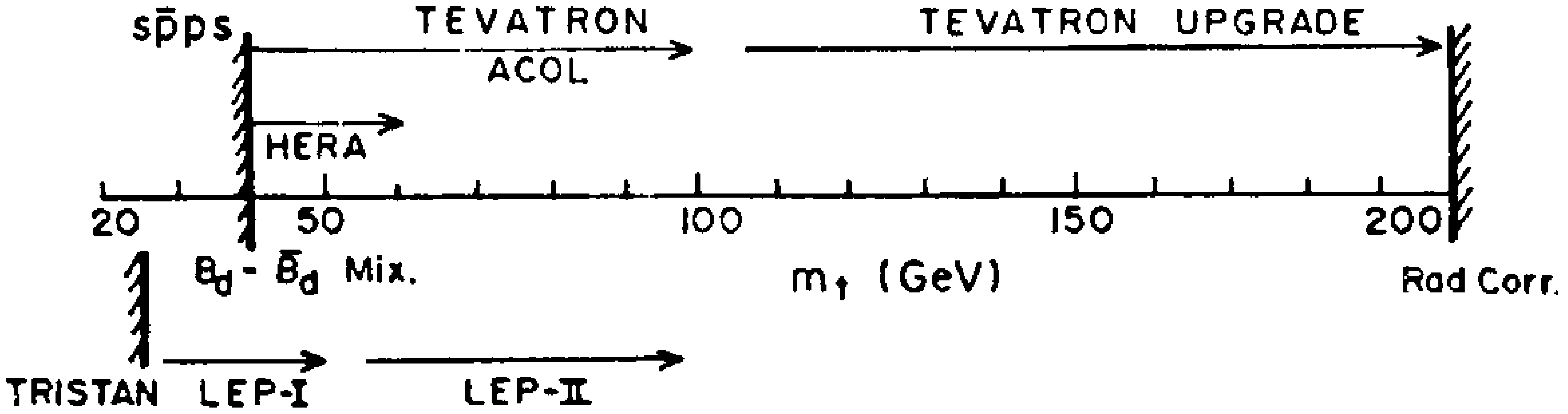

Figure 7. Top quark mass limits from the present collider experiments and discovery limits of the future ones. The indirect mass limits from $B_d-\bar{B}_d$ mixing and radiative correction to W, Z boson masses are also shown on the mass axis.

$B_d-\bar{B}_d$ mixing (eq. 21). Two top search experiments are now in progress—(i) at the Tevatron $\bar{p}p$ collider having a higher centre of mass energy of 2 TeV; and (ii) at the upgraded CERN collider (ACOL), which has an order of magnitude higher luminosity now. They are expected to probe top quark mass up to nearly 100 GeV[18]. Thus one expects to see the top quark within this year if its mass is within 100 GeV. If not then the search has to be extended to the upper mass limit of 200 GeV (eq. 16). This would be possible at the upgraded Tevatron collider[19], scheduled for the mid-ninties. Finally the superconducting super collider (SSC), expected to come at the turn of the century, can probe quark mass up to 500 GeV.

Electron–proton collider

The HERA ep collider is scheduled to start operation in 1990. Unfortunately the ep collider does not provide as clean a top quark signal as the e^+e^- collider, nor does it have the mass reach of the $\bar{p}p$ machine. The dominant top quark production mechanisms are the Bethe–Heitler processes of photon–gluon and W boson–gluon fusion (figure 6)[20],

$$\gamma g\to\bar{t}t,\ W^-g\to\bar{t}b. \tag{32}$$

The best way to look for top is again through its leptonic decay channel (eq. 29) using isolation. Since the leptonic branching ratio is about 10%, one needs at least 50–100 top quark events for its identification. This corresponds to a top quark discovery limit of about 60 GeV at the HERA collider, for the expected centre of mass energy of 300 GeV and luminosity of 200 events/picobarn.

SUMMARY

The main results are summarized in figure 7.

(i) There are indirect evidence for t quark from the observed forward–backward asymmetry in $e^+e^-\to\bar{b}b$ as well as the absence of flavour changing neutral current decay of b quark.

(ii) There are indirect constraints on t quark mass from (1) the radiative correction to W, Z boson masses, and (2) the $B_d-\bar{B}_d$ mixing. They imply 40 GeV $< m_t <$ 200 GeV.

(iii) The e^+e^- colliders are the cleanest machines for direct t quark search; but unfortunately their energies are rather low. The results from PETRA and TRISTAN imply $m_t >$ 26 GeV. The LEP (I) and LEP (II) can extend the probe to 50 and 100 GeV respectively.

(iv) The $\bar{p}p$ colliders are more promising because of their higher energy reach. Although the t signal is dirty, it can be cleaned up considerably using the isolated electron (or muon) signature. The result from the CERN $\bar{p}p$ collider suggests $m_t >$ 40 GeV. The ongoing searches at the Tevatron and the upgraded CERN colliders are expected to probe t mass up to nearly 100 GeV. The search can be extended to 200 GeV at the upgraded Tevatron collider, scheduled for the mid-ninties.

(v) Thus one expects to see the t quark within a year if its mass is within 100 GeV. If not one has to wait for at least five years.

ACKNOWLEDGEMENT

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