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Production of Mirror Fermions near the Z^0 Peak*

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ABSTRACT

Several attractive theories predict the existence of mirror fermions. There is a good theoretical reason to expect that the lightest mirror fermions might have relatively long lifetimes. We explore the experimental consequences of such a possibility, focusing on mirror lepton production at the SLC near the Z^0 resonance. We find that by going slightly off resonance or by polarizing the electron beam one can clearly distinguish the mirror leptons from ordinary leptons.

Introduction

All experimental evidence indicates that weak interactions are chiral in nature. Weak W and Z bosons interact differently with left- and right-handed fermions. Many researches have taken this basic fact of physics at presently available energies as a fundamental guide in the search for an underlying theory of elementary particles. It is important to realize that this is not necessary. It is perfectly possible that the observed chiral structure is the result of spontaneous symmetry breaking in a theory with vector couplings. Such a theory must contain mirror fermions[1] - particles whose interactions are mirror images of those of quarks and leptons. For example, the right handed mirror electron interacts with the W while the left-handed one is an $SU(2)_L$ singlet. There are several attractive theories in which these mirror particles arise naturally. These include extended supersymmetry[2] as well as models in which the fermion generations are explained by spontaneous breakdown of the spinor representation of a large orthogonal group,[3] and all Kaluza-Klein theories in which gauge interactions arise solely from higher dimensional gravity.[4]

The masses of mirror fermions cannot be much higher than several hundred GeV. They arise from the same mechanism which is responsible for the spontaneous breaking of $SU(2) \times U(1)$ and their masses cannot be much higher than those of W and Z without interfering with the phenomenological successes of the standard model. Thus there is a very good chance that they can be produced in currently planned accelerators, possibly even SLC. It is clearly of great interest to search for mirror fermions.

There is one theoretically unattractive feature of theories with mirror fermions. One can write an $SU(2) \times U(1)$ invariant mass term mixing mirror fermions and ordinary fermions, which gives both types of particles mass. No principle prevents this mass from being very large.[5] One loses the understanding of why ordinary fermions are light (compared to the GUT or Planck scales) that was provided by the standard model.

Serious theories of mirror fermions resolve this problem by incorporating symmetries which forbid such a mass term. Senjanović, Wilczek and Zee[6] and Bagger and Dimopoulos[7] have pointed out that these symmetries also forbid all renormalizable interactions between ordinary and mirror fermions. The decays of mirror into ordinary particles are produced by a nonrenormalizable coupling of dimension 5 or greater. The resulting lifetimes for the lightest mirror quark and lepton are of order

$$\tau > \frac{M^2}{m^3}$$

where m is the particle mass and M the scale of the new physics, responsible for the nonrenormalizable interaction. In most models $M > 10^{12}$ GeV, which for $m \sim 100$ GeV leads to $\tau > 10^{-8}$ sec. Thus, for accelerator experiments, the mirror fermions are effectively stable particles.

The signal for the production of mirror fermions (particularly mirror leptons) in e^+e^- collisions is thus particularly clear and striking. It is of interest to see whether we will be able to distinguish them from new leptons with ordinary couplings. We have therefore calculated the cross sections for mirror lepton production near the Z^0 resonance. Our calculation includes the effects of initial state radiation and the experimental uncertainty in the beam energy, as well as the effect of polarizing the electron beam. We find that by going slightly off resonance or by polarizing the electron beam one can clearly distinguish the mirror leptons from ordinary leptons.

The process $e^+e^- \rightarrow f\bar{f}$

The process $e^+e^- \rightarrow f\bar{f}$ in which a charged fermion f is produced together with its anti-particle can proceed via γ or Z in the s-channel.

The general form of the coupling between Z and fermions is: $-ie\gamma^\mu\left(a - b\gamma^5\right)$.

For the electron:

$a_e = (-1 + 4\sin^2\theta_W)/(2\sin 2\theta_W); \quad b_e = -1/(2\sin 2\theta_W)$

for a *right-handed* or "mirror" fermion:

$a_f = (-1 + 4\sin^2\theta_W)/(2\sin 2\theta_W);\quad b_f = +1/(2\sin 2\theta_W)$

The vector coupling a and the axial-vector coupling b are given in terms of the left- and right-handed couplings g^L and g^R :

$a = \frac{1}{2}(g^L + g^R);\quad b = \frac{1}{2}(g^L - g^R).$

Using $m_Z = 94$ GeV, $\Gamma_Z = 2.9\ GeV$, $\sin^2\theta_W = 0.215$ we obtain

$$\begin{aligned} a_e &= -0.085, \qquad b_e = -0.609; \\ a_f &= -0.085, \qquad b_f = +0.609 \end{aligned} \tag{1}$$

or equivalently

$$\begin{aligned} g_e^L &= -0.694, \qquad g_e^R = +0.524; \\ g_f^L &= +0.524, \qquad g_f^R = -0.624 \end{aligned} \tag{2}$$

Thus *the right-handed and the left-handed couplings of a mirror lepton are interchanged with respect to those of an ordinary lepton.*

The vector coupling a is tiny for both left-handed *and* right-handed leptons and vanishes for $\sin^2\theta_W = 0.25$. This fact has important experimental consequences as we shall see in the following.

The cross section for $e^+e^- \to f\bar{f}$ when final polarization is not observed is given by[8] :

$$\begin{aligned} \frac{d\sigma}{d\Omega} = \frac{2\alpha^2|p|^2}{s\sqrt{s}} \Bigg\{ & G_1\frac{s^2}{4}\left[1 + \left(1 - \frac{4M^2}{s}\right)\cos^2\theta\right] + G_2\frac{s^2}{2}\left(1 - \frac{4M^2}{s}\right)^{\frac{1}{2}}\cos\theta + G_3M^2s \\ & -P_L\left\langle G_4\frac{s^2}{4}\left[1 + \left(1 - \frac{4M^2}{s}\right)\cos^2\theta\right] + G_5\frac{s^2}{2}\left(1 - \frac{4M^2}{s}\right)^{\frac{1}{2}}\cos\theta + G_6M^2s\right\rangle\Bigg\} \end{aligned} \tag{3}$$

where

s is the square of CM energy;

θ is the scattering angle in CM;

p is the momentum of the fermion f;

Q_f is the f electric charge, ($Q_f = -1$ for mirror leptons);

M is the f mass;

$D_Z(s)$ is the Z inverse propagator, $D_Z(s) = s - m_z^2 + im_z\Gamma$;

P_L is the longitudinal polarization of the electron beam;

and the G-s are given by:

$$G_1 = \frac{Q_f^2}{s^2} - \frac{2Q_f}{s}\mathrm{Re}\left[\frac{a_e a_f}{D_Z(s)}\right] + \frac{\left(|a_e|^2 + |b_e|^2\right)\left(|a_f|^2 + |b_f|^2\right)}{|D_Z(s)|^2}$$

$$G_2 = -\frac{2Q_f}{s}\mathrm{Re}\left[\frac{b_e b_f}{D_Z(s)}\right] + \frac{4\mathrm{Re}\left(a_e b_e{}^*\right)\mathrm{Re}\left(a_f b_f{}^*\right)}{|D_Z(s)|^2}$$

$$G_3 = \frac{Q_f^2}{s^2} - \frac{2Q_f}{s}\mathrm{Re}\left[\frac{a_e a_f}{D_Z(s)}\right] + \frac{|a_e a_f|^2 - |b_e b_f|^2 + |b_e b_f|^2 - |a_e b_f|^2}{|D_Z(s)|^2}$$

$$G_4 = -\frac{2Q_f}{s}\mathrm{Re}\left[\frac{b_e a_f}{D_Z(s)}\right] + \frac{2\mathrm{Re}\left(a_e b_e{}^*\right)\left(|a_f|^2 + |b_f|^2\right)}{|D_Z(s)|^2}$$

$$G_5 = -\frac{2Q_f}{s}\mathrm{Re}\left[\frac{a_e b_f}{D_Z(s)}\right] + \frac{2\mathrm{Re}\left(a_f b_f{}^*\right)\left(|a_e|^2 + |b_e|^2\right)}{|D_Z(s)|^2}$$

$$G_6 = -\frac{2Q_f}{s}\mathrm{Re}\left[\frac{b_e a_f}{D_Z(s)}\right] + \frac{2\mathrm{Re}\left(a_e b_e{}^*\right)\left(|a_f|^2 - |b_f|^2\right)}{|D_Z(s)|^2}$$

From (3) we see that an experiment measuring $d\sigma/d\Omega$ can in principle distinguish between a right- and a left-handed lepton. We begin by discussing the qualitative features of such an experiment, to be followed by a more detailed calculation, incorporating initial-state radiative corrections and spread in the beam energy.

Let us first consider the case of an unpolarized electron beam, $P_L = 0$.*
In that case the only term in (3) which differentiates between the two kinds of leptons is G_2. The contribution of that term however vanishes upon θ integration, so the total cross section cannot be used to detect the handedness of f. Instead it is useful to consider the *forward-backward asymmetry*, $A(\theta_0)_{FB}$ defined as:

$$A(\theta_0)_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \tag{4}$$

where

$$\sigma_F = \int_{\theta=\theta_0}^{\pi/2} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

and

$$\sigma_B = \int_{\theta=\pi/2}^{\pi-\theta_0} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

with θ_0 denoting the minimum value of θ at which f can be detected. We have assumed $\theta_0 = 45^o$, a value which is representative of the relevant SLC detector, MARK II.

As a consequence of (2)and (3) the forward-backward asymmetry in mirror lepton production in the process $e^+e^- \to f\bar{f}$ has the opposite sign and the same absolute value as forward-backward asymmetry in production of ordinary left-handed leptons of the same mass:

$$A_{FB}(e^+ e^- \to f_R \bar{f}_R) \; = \; -A_{FB}(e^+ e^- \to f_L \bar{f}_L) \tag{5}$$

In G_2 there are two terms which contain information about the handedness of f; the first corresponds to $\gamma - Z^0$ interference and the second is a pure Z^0 exchange.

⋆ We shall assume throughout that the positron beam is unpolarized. While a polarized positron beam is possible in principle, polarized electron beams will be achieved in the near future.

These are shown in Fig. 1(a) for an ordinary lepton. The interference term changes sign at the Z^0 pole, so that at $s = m_z^2$ the only contribution to forward-backward asymmetry comes from pure Z^0 exchange. Despite enhancement by the Z^0 pole, that contribution is small, since it is proportional to the product of a_e and a_f, both of which vanish for $\sin^2\theta_W = 0.25$. As a result, the forward-backward asymmetry changes sign very close to the Z^0 pole. On the other hand, even though the asymmetry vanishes very close to the resonance, it changes rather rapidly with energy, so that one can distinguish a mirror lepton from an ordinary lepton by measuring the forward-backward asymmetry only a few GeV off the resonance.

If the electron beam is polarized, the situation changes drastically. Now, in addition to G_2, there is another term which differentiates between the two kinds of leptons - G_5. The forward-backward asymmetry receives contributions from both G_2 and G_5. G_5 is similar in structure to G_2: it contains a $\gamma - Z^0$ interference term and a pure Z^0 term. There is an important difference however. In G_5 the pure Z^0 term is only suppressed by one power of the small vector coupling a_e, while the interference term is small, being proportional to a_e and smaller near the Z^0 peak. The absolute and relative strength of the two terms in G_5 is therefore very different from G_2, as can be seen in Fig. 1(b). G_5 is much larger than G_2 and is dominated by pure Z^0 exchange, peaking at the resonance. As a result, given a polarized electron beam, one can clearly distinguish mirror leptons from ordinary leptons by measuring the forward backward asymmetry at the resonance. The effect is biggest when G_2 and G_5 work in the same direction, namely for $P_L = -1$. This can be intuitively understood from the fact that $P_L = -1$ corresponds to left-handed electron beam and that $|g_L^e|$ is somewhat bigger than $|g_R^e|$.

<u>Radiative corrections</u>

Let us now make a slight change in the notation and denote the cross section given in (3) by σ_0. The meaning of the "$_0$" subscript is that this is the "bare" cross-section, which does not include radiative corrections. The incoming electron or positron can lose part of its energy by emitting photons. This effect can be accounted for by folding the "bare" cross section with the probability distribution for the energy lost into radiation[9] :

$$\sigma(W) = t\int_0^{E_e} \frac{dk}{k}\left(\frac{k}{E_e}\right)^t \sigma_0(W-k) + \epsilon\sigma_0(W) - \frac{t}{E_e}\int_0^{E_e} dk\left(1-\frac{k}{2E_e}\right)\sigma_0(W-k) \quad (6)$$

where

W is the CM energy, $W = \sqrt{s}$;

$\sigma(W)$ is the radiatively corrected cross section;

E_e is the incoming electron (or positron) energy, $E_e = W/2$;

k is the energy of the emitted photon;

t is a very slowly varying function of s, $t = 2(\alpha/\pi)\left[\ln(W^2/m_e^2) - 1\right] \approx 0.11$ at $W \sim m_Z$;

$\epsilon = 2\alpha\pi\left(\pi^2/6 - 17/36\right) + 13/12t$.

The beam energy is in general subject to small fluctuations. In order to account for these fluctuations, we fold the radiatively-corrected cross section with the probability distribution $G(W - W')$ of the beam-energy:

$$\tilde{\sigma}(W) = \int_{-\infty}^{\infty} dW'\,\sigma(W')G(W - W') \quad (7)$$

where we have taken $G(w)$ to be a gaussian,

$$G(w) = \frac{1}{\sqrt{2\pi\sigma}}\exp\left(-w^2/2\sigma^2\right) \quad (8)$$

with a standard deviation σ of 0.5 GeV. Even though the actual energy distribution differs from a gaussian, our results are relatively insensitive to its exact form, since $\sigma_{E_{beam}} \ll \Gamma_Z$. Using (7) and (4) we obtain the experimentally measured forward backward asymmetry

$$A_{FB} = \frac{\tilde{\sigma}_F - \tilde{\sigma}_B}{\tilde{\sigma}_F + \tilde{\sigma}_B} \tag{9}$$

Figures 2(a) through 2(d) display $A_{FB}, \tilde{\sigma}_F$ and $\tilde{\sigma}_B$ as function of CM energy, $\sqrt{s}$, and the electron beam polarization P_L, for both ordinary and mirror heavy leptons and for several values of the lepton mass.

We notice that while the forward-backward asymmetry is largest far off resonance, the corresponding cross-sections are small. On the other hand, for an *unpolarized* electron beam the asymmetry vanishes very close to the resonance. Thus in that case it is best to measure the asymmetry a few GeV off resonance.

For a polarized electron beam the asymmetry is quite significant right at the resonance. The absolute magnitudes of the asymmetry for purely left- or purely right-polarized electron beams are very close to each other. On the other hand, the cross-section for a left-handed beam is significantly higher.

Our conclusion is that the best strategy for distinguishing mirror leptons from ordinary leptons is doing an experiment with a left-handed electron beam at the Z^0 resonance. For $M_f \gtrsim 40GeV$ the phase space at the resonance is rather small, but below 40 GeV the signal is quite clear and significant. In the absence of a polarized electron beam, a mirror lepton can be identified by going a few GeV off the resonance.

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FIGURE CAPTIONS

1. (a) G_2 as function of $\sqrt{s}$. The continuous curve corresponds to G_2. Contribution to G_2 from $\gamma - Z^0$ interference is shown in dot-dash line and contribution from pure Z^0 is shown in dotted line.

   (b) G_5 as function of $\sqrt{s}$. The continuous curve corresponds to G_5. Contribution to G_5 from $\gamma - Z^0$ interference is shown in dot-dash line and contribution from pure Z^0 is shown in dotted line.

2. Forward-backward asymmetry A_{FB}, for the process $e^+e^- \to f\bar{f}$.

   For each value of M_f the first plot shows A_{FB} as function of $\sqrt{s}$ for both ordinary (continuous lines) and mirror leptons (dot-dashed lines) and for $P_L = -1, 0, 1$.

   The second plot shows the corresponding $\tilde{\sigma}_F$ and $\tilde{\sigma}_B$ for ordinary leptons in units of $R = \sigma/\sigma_{QED}(e^+e^- \to \mu^+\mu^-)$.

   Continuous lines correspond to $\tilde{\sigma}_F$, dashed lines correspond to $\tilde{\sigma}_B$.

   (a) $M_f = 20$ GeV;

   (b) $M_f = 30$ GeV;

   (c) $M_f = 40$ GeV;

   (d) $M_f = 45$ GeV.

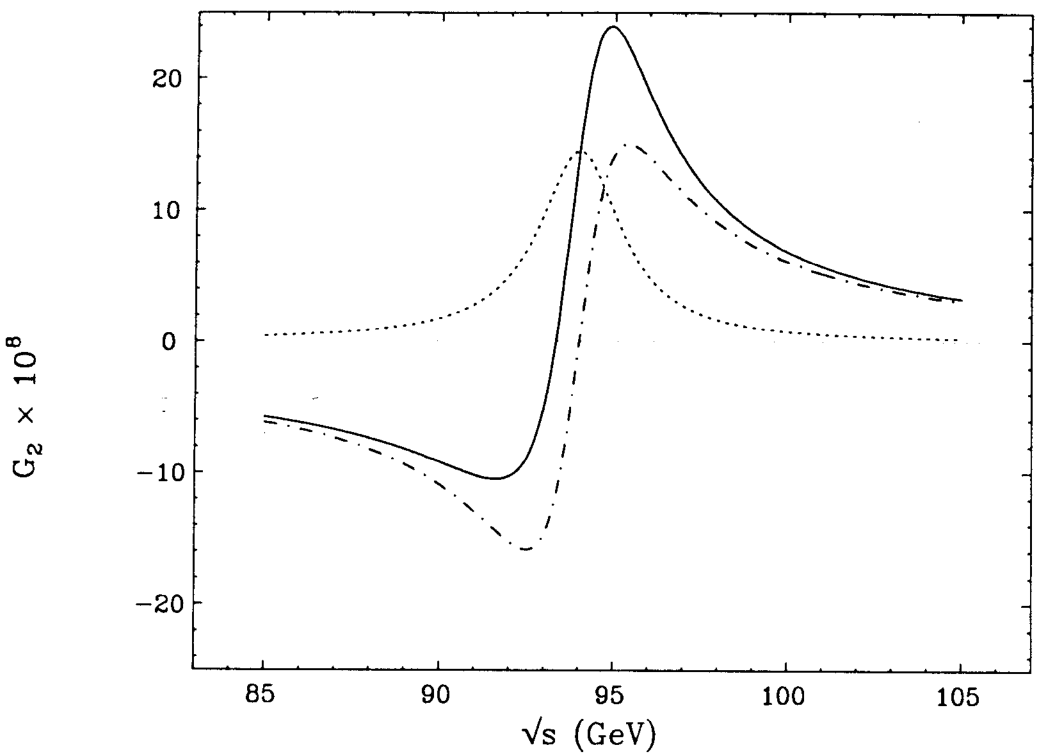


FIGURE 1(a)

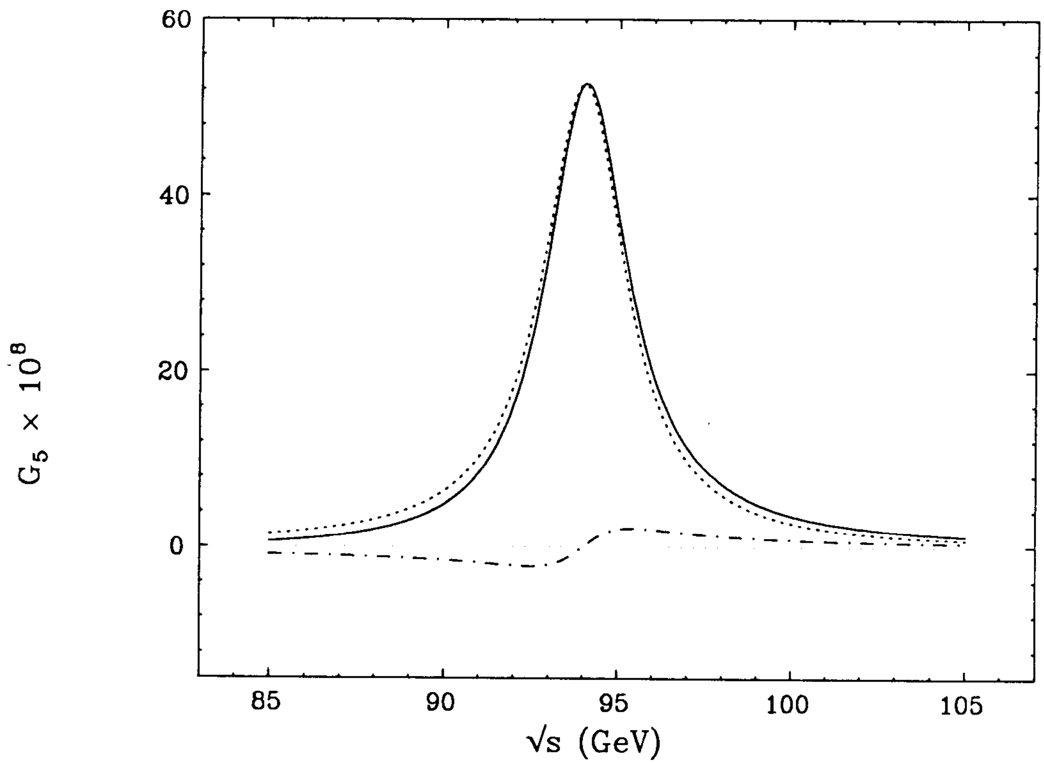
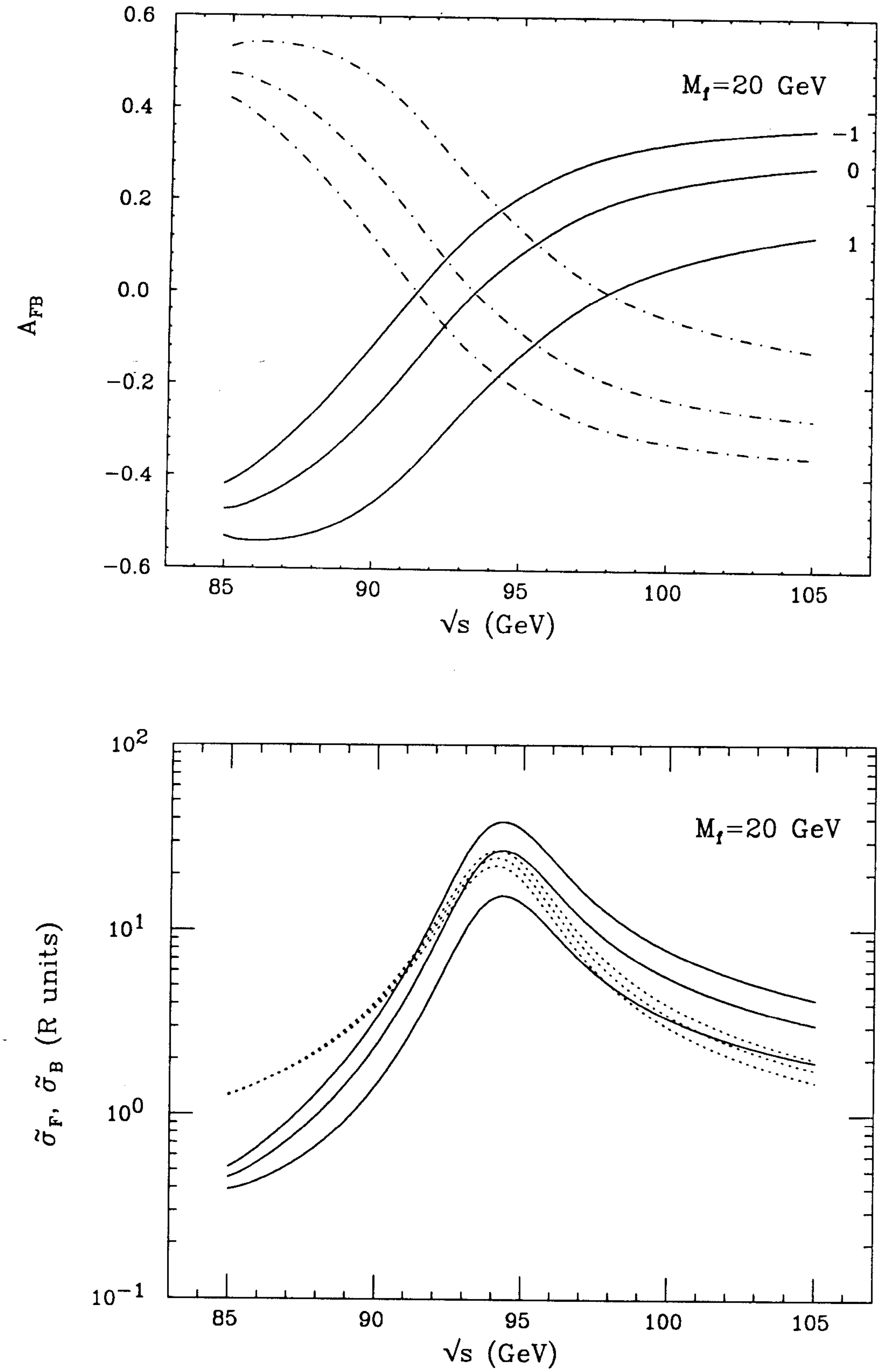
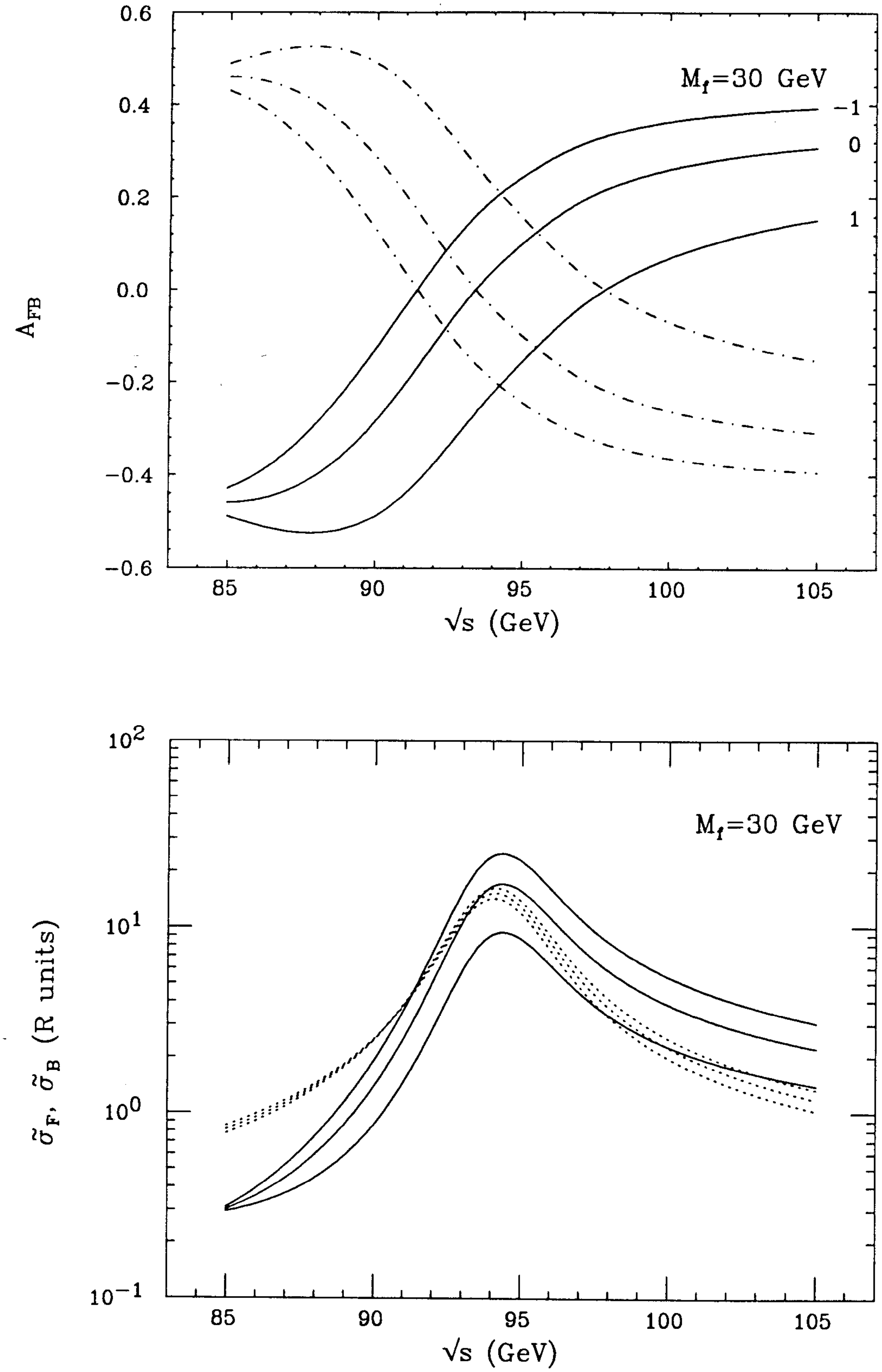


FIGURE 1(b)



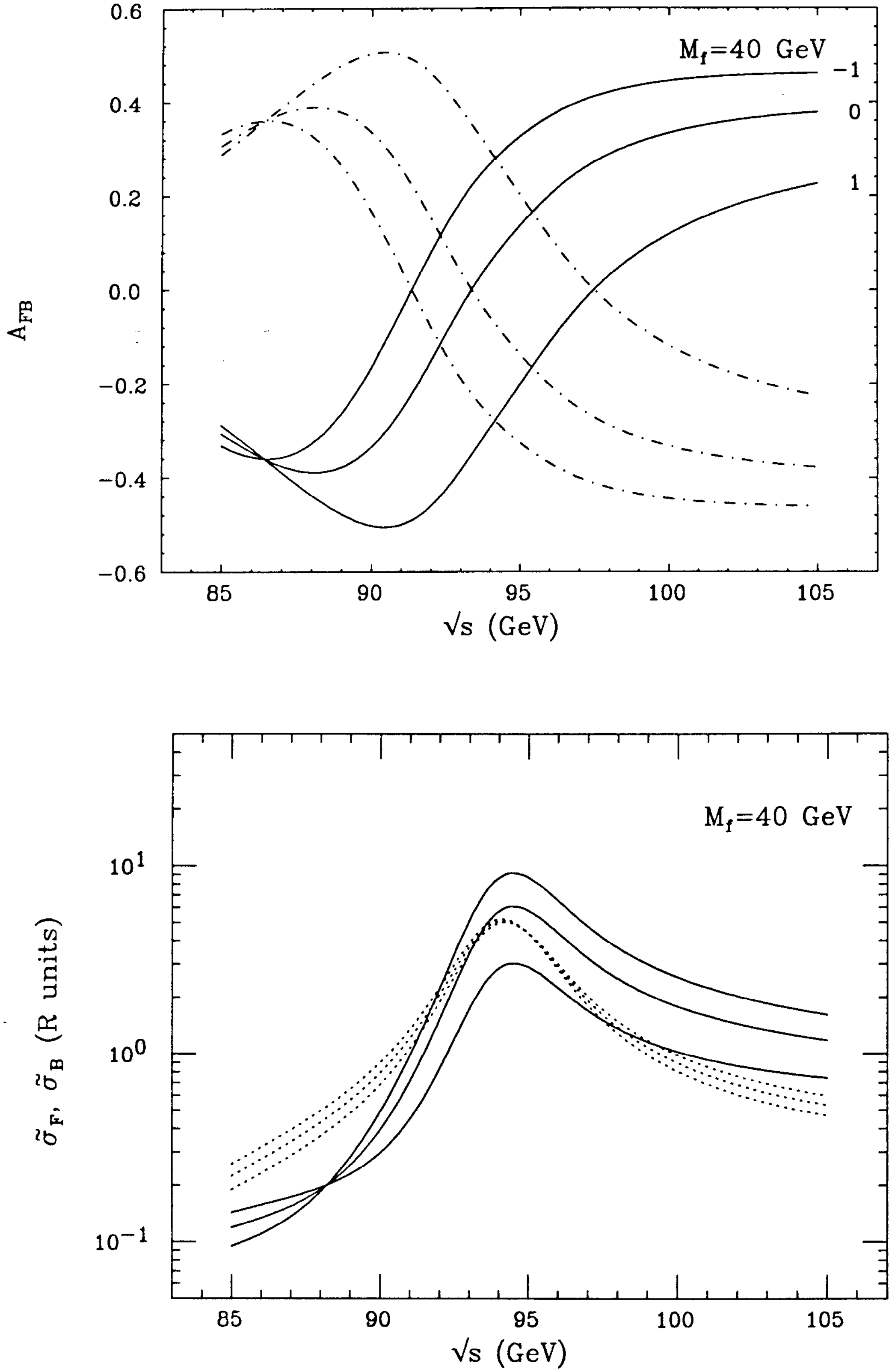
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
A_{FB}
M_f=20 GeV
−1
0
1
85
90
95
100
105
√s (GeV)
10^2
10^1
10^0
10^{-1}
$\tilde{\sigma}_F$, $\tilde{\sigma}_B$ (R units)
M_f=20 GeV
85
90
95
100
105
√s (GeV)

FIGURE 2(a)



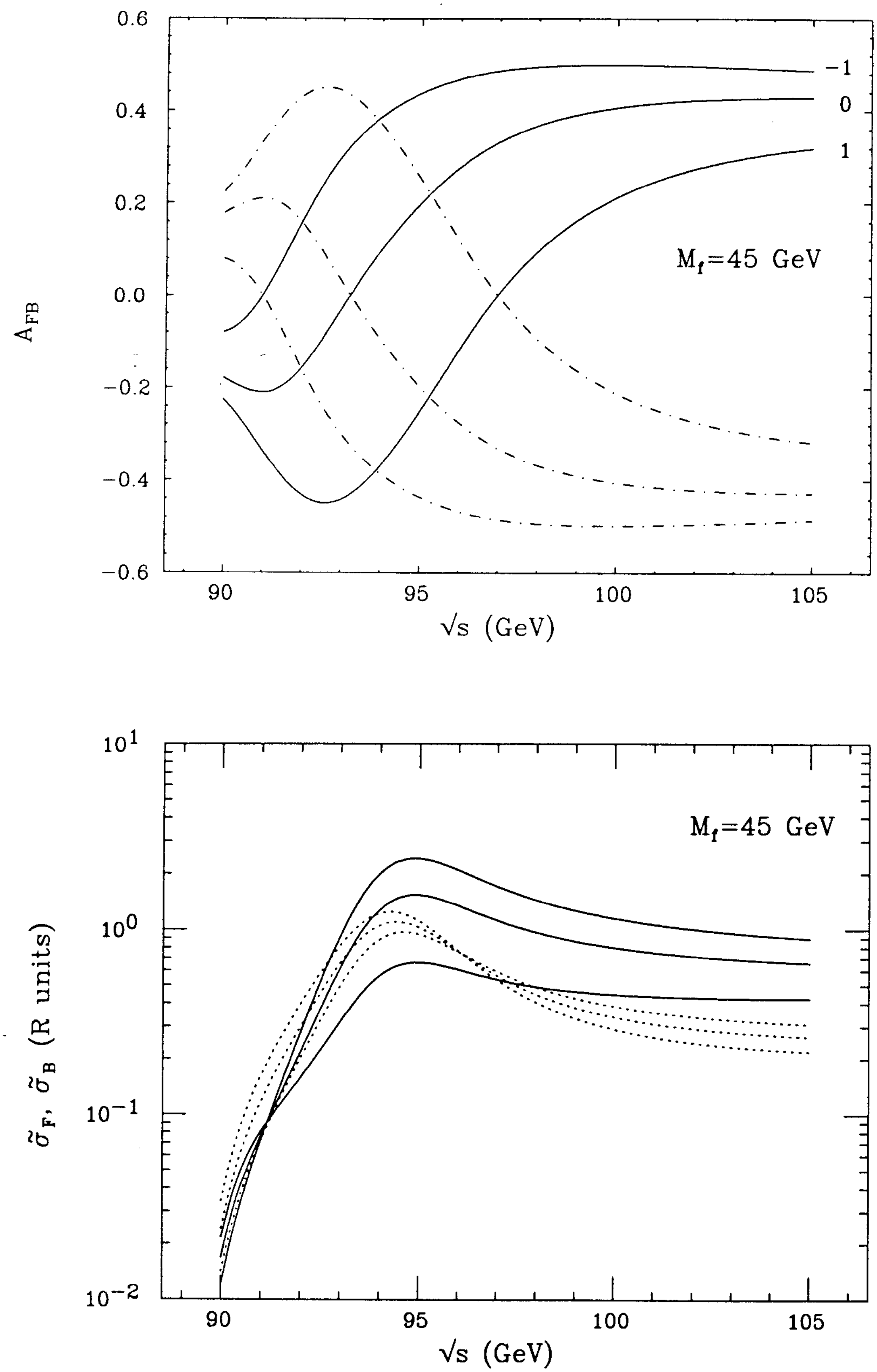
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
A_{FB}
M_f=30 GeV
−1
0
1
85
90
95
100
105
√s (GeV)
10^2
10^1
10^0
10^{-1}
$\tilde{\sigma}_F$, $\tilde{\sigma}_B$ (R units)
M_f=30 GeV
85
90
95
100
105
√s (GeV)

FIGURE 2(b)



0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
A_{FB}
M_f=40 GeV
−1
0
1
85
90
95
100
105
√s (GeV)
10^1
10^0
10^{-1}
$\tilde{\sigma}_F$, $\tilde{\sigma}_B$ (R units)
M_f=40 GeV
85
90
95
100
105
√s (GeV)

FIGURE 2(c)



0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
A_{FB}
−1
0
1
M_f=45 GeV
90
95
100
105
√s (GeV)
10^1
10^0
10^{-1}
10^{-2}
$\tilde{\sigma}_F$, $\tilde{\sigma}_B$ (R units)
M_f=45 GeV
90
95
100
105
√s (GeV)

FIGURE 2(d)