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Forward-backward asymmetry in e^+e^- annihilation as a probe of new physics from E_6 theories

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The forward-backward asymmetry A_{FB} of lepton pairs produced in e^+e^- annihilation can be used to analyze possible new physics from E_6 models resulting from superstrings. In addition to the usual A_{FB} for muons we also consider the production of new particles such as E_6 exotic, mirror, or fourth-generation leptons. Our results clearly distinguish between these various possibilities and demonstrate the model dependency of A_{FB} in each case. The value of A_{FB} for *new* particles can then be used to test their origin as fourth-generation, E_6 exotic, or mirror fermions.

The recent revival of string theory[1] in the form of superstrings has led to renewed interest in the phenomenology of E_6 grand unified theories (GUT's).[2] This has resulted from the observation made by Green and Schwarz that such ten-dimensional string theories are anomaly-free[3] and can describe chiral fermions if one employs the gauge group $E_8 \times E_{8'}$ (Ref. 4). Upon compactification down to four dimensions with the assumption that the compactified manifold is simply connected and $N=1$ supersymmetry is maintained (in order to deal with the hierarchy problem) we arrive at E_6 as the effective GUT.

The phenomenology of E_6 is particularly rich due to the existence of exotic fermions (i.e., nonstandard fermions not falling into the usual generation pattern) as well as new gauge bosons. Since the number of generations (i.e., 27 representations of E_6) in addition to the number of generation-antigeneration pairs (i.e., $27+\overline{27}$'s) is, in principle, calculable in these theories one may also expect standard fourth-generation fermions as well as mirror fermions[5] also to exist. As we begin to probe new energy scales at KEK's TRISTAN, the Stanford Linear Collider, and CERN's LEP, and other accelerators one may expect to produce at least some of these new particles (or see their indirect effects) since their masses are *a priori* unknown and are uncalculable in a model-independent fashion. In principle, at least, these new particles may be light.

In this paper we are particularly interested in how the forward-backward asymmetry A_{FB}, now observed[6] at the SLAC and DESY e^+e^- storage rings PEP and PETRA for light fermions, can be used to probe the properties of extended gauge theories resulting from E_6 and the various fermions discussed above in particular.[7,8]

The differential cross section for the production of a pair of fermions $F\bar{F}$ in e^+e^- annihilation via s-channel gauge-boson exchange can be written as (for unpolarized beams)

$$\frac{d\sigma}{dz}(e^+e^- \to \bar{F}F) = \frac{N_c s}{32\pi}\beta \sum_{i,j=0}^{n} A_{ij}[B_{ij}(1+\beta^2 z^2) + 2C_{ij}\beta z + E_{ij}(1-\beta^2)] , \tag{1}$$

where $z=\cos\theta(e^-,F)$, N_c is the number of colors of the fermion F, s is the square of the center-of-mass energy, and $\beta=(1-4M_F{}^2/s)^{1/2}$ with M_F being the mass of the fermion F. The sum in (1) extends over the photon as well as neutral gauge bosons. The Feynman diagrams corresponding to the above differential cross section are shown in Fig. 1. The set of coefficients A, B, C, and E are defined via

$$\begin{aligned} A_{ij} &\equiv \frac{(s-M_i{}^2)(s-M_j{}^2)+(\Gamma_i M_i)(\Gamma_j M_j)}{[(s-M_i{}^2)^2+(\Gamma_i M_i)^2][(s-M_j{}^2)^2+(\Gamma_j M_j)^2]} , \\ B_{ij} &\equiv (v_i v_j + a_i a_j)_F (v_i v_j + a_i a_j)_e , \\ C_{ij} &\equiv (v_i a_j + a_i v_j)_F (v_i a_j + a_i v_j)_e , \\ E_{ij} &\equiv (v_i v_j - a_i a_j)_F (v_i v_j + a_i a_j)_e , \end{aligned} \tag{2}$$

where M_i (Γ_i) is the mass (width) of the ith gauge boson and the couplings are defined via the Lagrangian

$$L = \sum_{i=0}^{n} [\bar{F}\gamma_\mu(v_{iF} - a_{iF}\gamma_5)F + \bar{e}\gamma_\mu(v_{ie} - a_{ie}\gamma_5)e]Z_i^\mu . \tag{3}$$

(Clearly, the identification of the photon with Z_0^μ is im-

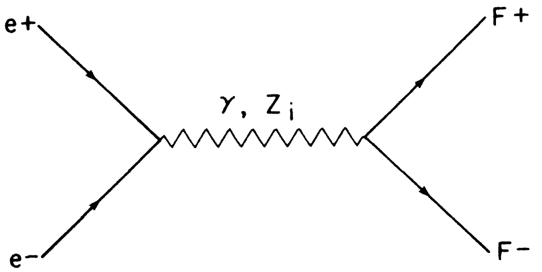

FIG. 1. Feynman diagrams for the production of heavy fermion pairs in e^+e^- annihilation.

TABLE I. Values of the quantum numbers and coupling constants for the various particles in the different models discussed in the text.

			A		C		D	
F	T_{3L}	T_{3R}	x_L	x_R	x_L	x_R	x_L	x_R
e,μ,L	$-\frac{1}{2}$	0	1	-1	-1	-2	$\frac{1}{2}$	0
E	$-\frac{1}{2}$	$-\frac{1}{2}$	-2	2	-1	4	$-\frac{1}{2}$	0
e^M,μ^M,L^M	0	$-\frac{1}{2}$	-1	1	-2	-1	0	$\frac{1}{2}$
E^M	$-\frac{1}{2}$	$-\frac{1}{2}$	2	-2	4	-1	0	$-\frac{1}{2}$
λ			0.44		0.30		2.45	

plied in the above expressions.)

Let us now concentrate on the low-energy sector of E_6 model which contains a single additional neutral gauge boson Z_2. In the limit that the mixing between Z_1 and Z_2 is small (which we found to be true in all the models we have so far analyzed[7]) we can write the couplings for an arbitrary fermion F as

$$\begin{aligned} v_{0F}&=eQ_F\,, \\ a_{0F}&=0\,, \\ v_{1F}&=\frac{g}{2c_W}(T_{3L}+T_{3R}-2x_WQ)_F\,, \\ a_{1F}&=\frac{g}{2c_W}(T_{3L}-T_{3R})_F\,, \\ v_{2F}&=\frac{g_x}{2}(x_L+x_R)_F\,, \\ a_{2F}&=\frac{g_x}{2}(x_L-x_R)_F\,, \end{aligned} \tag{4}$$

where g is the usual $SU(2)_L$ coupling constant, $x_W=\sin^2\theta_W=1-c_W{}^2\simeq 0.217$, Q_F is the electric charge of F, and T_{3LF} (T_{3RF}) is the weak isospin for F_L (F_R). g_x is the coupling constant associated with the Z_2 and x_{LF} (x_{RF}) are the couplings of F_L (F_R) which can be calculated using simple group theory as in our earlier work.[7] The value of g_x is also easily determined with some precision via a renormalization-group equation analysis of the running coupling constants. (In our earlier work, values of $\lambda\equiv 4g_xc_W/g$ were presented for seven possible E_6 models which have an additional Z at low energies.)

We now turn to a detailed discussion of our calculations; we take, of course, $M_0=\Gamma_0=0$ as well as $M_1=93$ GeV and $\Gamma_1=2.8$ GeV. We also take $\Gamma_2/M_2=\text{const}$ as we allow M_2 to vary and values of this ratio were calculated by us earlier. We will assume, for simplicity, that the fermion F is a negatively charged lepton ($N_c=1$) and avoid the problems associated with quark identification. To be specific, we concentrate on three particular models A, C, and D from our earlier work. The quantum numbers of the various lepton varieties are shown in Table I. Our notation is as follows: L represents a "standard" fourth-generation lepton whereas E represents an E_6 exotic lepton which is vectorlike with respect to $SU(2)_L\times U(1)_Y$. e^M, μ^M, and L^M represent the mirror fermions corresponding to the usual leptons and E^M is a mirror E_6 exotic lepton. Also displayed in the table are the values of λ used for each of the models used in our calculations. In all cases we take $\Gamma_2/M_2=0.01$ although values between 0.003 and 0.03 were examined corresponding to the ranges found in our earlier work. We find that our results are not very sensitive to the value chosen for

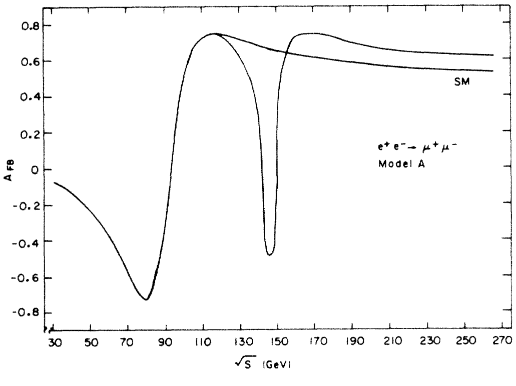

FIG. 2. A_{FB} as a function of $\sqrt{s}$ for the process $e^+e^-\rightarrow\mu^+\mu^-$ for the standard model (SM) and E_6 model A.

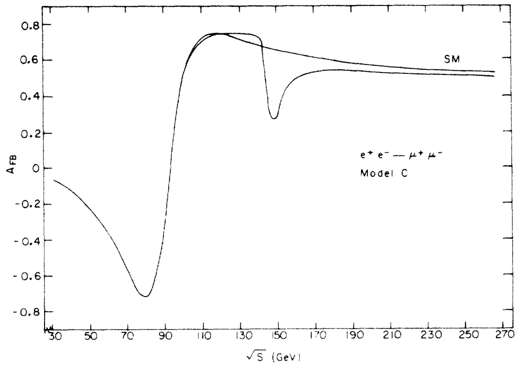

FIG. 3. Same as Fig. 2 but for E_6 model C.

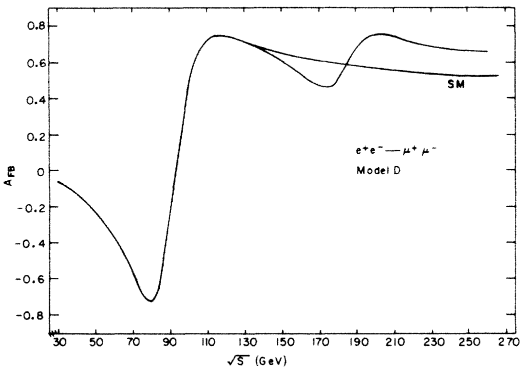

FIG. 4. Same as Fig. 2 but for E_6 model D.

Γ_2/M_2.

First let us consider the usual reaction $e^+e^-\rightarrow\mu^+\mu^-$. A_{FB} in this and all reactions is defined by

$$A_{FB}\equiv\frac{\int_0^1\left[\frac{d\sigma}{dz}\right]dz-\int_{-1}^0\left[\frac{d\sigma}{dz}\right]dz}{\int_{-1}^1\left[\frac{d\sigma}{dz}\right]dz} \tag{5}$$

and can be expressed in terms of A,B,C,E via Eqs. (2) and (3). Figures 2, 3, and 4 show A_{FB} as a function of $\sqrt{s}$ for models A, C, and D, respectively, in comparison to the prediction of the standard model (SM). In these figures we take $M_2=150$ GeV for purposes of demonstration and, as can easily be seen, this assumption does not significantly alter the SM predictions for $\sqrt{s}$ below $\simeq 110$ GeV or so in any of the cases A, C, or D. Also, the assumption maximizes the effect of the new Z^0 for the LEP II energy range. In our earlier analysis, however, we found that constraints from the ρ parameter and other neutral-current data imply a lower bound on M_2 somewhat greater than the 150-GeV value used here[7,8] in some of the models being considered.

We see that for the models under discussion (A, C, and D) the value of A_{FB} takes a dip in the 140–180-GeV region resulting from the Z_2^0 resonance at 150 GeV which would be clearly visible in any $\bar{f}f$ channel. The three model predictions are clearly distinct from each other and from the SM even away from the resonance region although the overall deviation is not very large. The basic reason for this in cases A and C is the small value of the coupling (g_x) of the second Z^0 to fermions resulting from our renormalization-group analysis.

Next, we turn to the possibility of being able to distinguish between new exotic leptons, mirror leptons, and the (somewhat less exotic) standard fourth-generation charged lepton. We considered two possible values for the masses of the new lepton, $M=30$ or 60 GeV, so that the threshold for pair production was not too close to the lowest Z^0 resonance. In Fig. 5 we compare the values of A_{FB} for a 30 GeV, fourth-generation lepton L in the SM with a 30-GeV exotic lepton E for E_6 models A, C, and D. It was assumed in this calculation that t-channel diagrams for E^+E^- pair production are sufficiently suppressed by mixing angle factors so that they can be safely ignored. We see from the figure that the values of A_{FB} are clearly distinct in the four cases and that in the case of exotic-lepton production the values of A_{FB} remain small for a significant range of energies above threshold in comparison to the case of a fourth-generation lepton. The explanation of this is clear—near threshold it is the photon as well as the lowest mass Z^0 which are dominating the cross section. The exotics have vectorlike couplings to the lightest Z^0 and so in the $M_2\rightarrow\infty$ limit will have $A_{FB}=0$ apart from radiative corrections. Once the Z_2 contribution becomes significant (for $\sqrt{s}\gtrsim 110$ GeV or so) we begin to observe a nonzero A_{FB} since the exotic-lepton couplings to Z_2 are not vectorlike. The fourth-generation lepton, however, does have a large A_{FB} immediately above threshold since its couplings to both Z^0's is not vectorlike. To obtain the results for mirror lepton (L^M or E^M) production simply let $A_{FB}\rightarrow -A_{FB}$ in Fig. 5 since L^M and L (E^M and E) have the same couplings except for the change of sign $a_{iF}\rightarrow -a_{iF}$ ($i=1,\ldots$). Clearly the mirror leptons are themselves distinguishable from the other cases once energies in the $\simeq$120-GeV range or so are obtained.

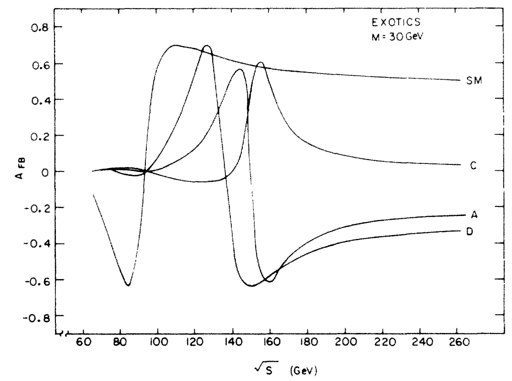

FIG. 5. A_{FB} for the production of a new 30-GeV lepton. SM is the curve for the production of a fourth-generation lepton, whereas curves A, C, and D correspond to A_{FB} for exotic-lepton production in the corresponding E_6 models.

What happens for heavier leptons is somewhat similar; Fig. 6 shows A_{FB} for SM L's and exotics in models A, C,

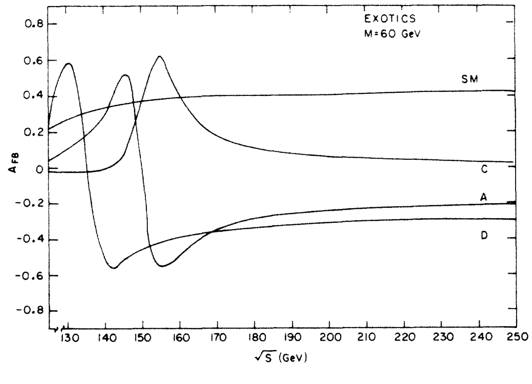

FIG. 6. Same as Fig. 5 but for new leptons of mass 60 GeV.

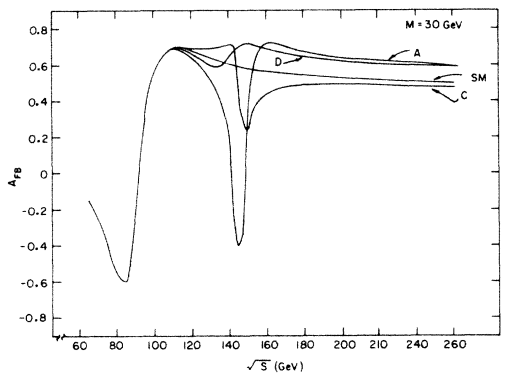

FIG. 7. A comparison of A_{FB} for fourth-generation leptons of mass 30 GeV in the standard model (SM) and E_6 models A, C, and D.

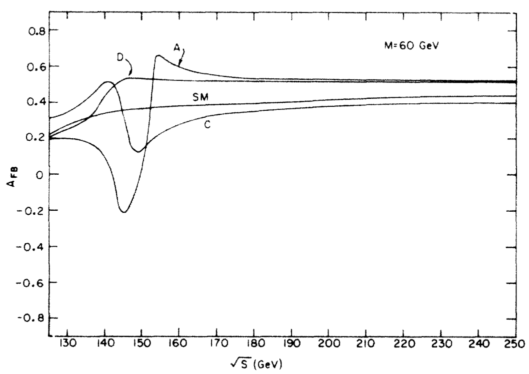

FIG. 8. Same as Fig. 7 but for a fourth-generation-lepton mass of 60 GeV.

and D. Again, near threshold, L's have a large A_{FB} whereas the A_{FB} for exotics is quite small for the same reasons as discussed above. The only exception to this is case D where the coupling constant is so large that A_{FB} is large just above threshold. The four cases are still quite distinct since the exotics undergo rapid oscillatory behavior in the M_2 resonance region whereas the curve for the fourth-generation case remains quite smooth. To obtain the parallel set of curves for mirror leptons we simply let $A_{FB} \rightarrow -A_{FB}$.

The last possibility we will entertain is the production of 30- or 60-GeV fourth-generation leptons assuming E_6 model couplings to an extra Z^0 for these particles as well and compare with the SM predictions for A_{FB}. Figure 7 shows A_{FB} for $M(L)=30$ GeV in the SM as well as the E_6 models A, C, and D. Notice that below $\sqrt{s} \simeq 110$ GeV or so the four models are impossible to distinguish. However, for higher energies the four models are very easily distinguishable especially due to the complex behavior of A_{FB} near the second Z^0 resonance. For $M(L)=60$ GeV, as shown in Fig. 8, we see a similar situation. The SM curve is quite smooth while the E_6 model curves undergo oscillatory behavior near the Z_2 mass. Far above threshold and the Z_2 resonance region all four curves become quite smooth and somewhat more difficult to untangle. The results for the corresponding mirror leptons can be similarly obtained by the usual change in sign of A_{FB}, i.e., $A_{FB} \rightarrow -A_{FB}$.

In conclusion we have calculated the values of the forward-backward asymmetry A_{FB} as a function of center-of-mass energy for μ pair production as well as the pair production of new charged leptons of various types in the SM and in three E_6-motivated extended models. The types of new leptons considered were fourth-generation leptons L in the SM and in E_6 models, exotic leptons coming from E_6 models, and mirror leptons, i.e., mirrors of the usual SM leptons as well as the E_6 exotic leptons. Pair mass values below and above that of the SM Z^0 were analyzed. In all the cases examined we found that A_{FB} for μ pair production in e^+e^- as well as for the production of new fermions, such as new heavy leptons, can be a powerful tool in understanding the fundamental theory of the electroweak interactions.

Note added. After this work was completed our attention was drawn to the work of several authors[9,10] who have considered the influence of new E_6 interactions on A_{FB} for μ pair production. These authors have not considered the possibility of using A_{FB} to probe the properties of new fermions.

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