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Production of E_6 heavy leptons at supercollider energies

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We evaluate the cross sections in pp collisions at 10–40 TeV for the production of very heavy charged and neutral exotic leptons that occur in the **27** representation of E_6. Drell-Yan and gluon-fusion subprocesses are considered. The exotic-lepton decays can lead to distinctive final states with two or four W bosons and like-sign W pairs.

According to superstring theory,[1] the exceptional group E_6 may describe particle interactions below the Planck scale.[2] The pattern of E_6 breaking may give an extra U(1) symmetry[3] beyond the standard model at low energy:

$$E_6 \rightarrow SU(3)\times SU(2)_L \times U(1)\times U(1)' . \tag{1}$$

In such a case, there would exist an extra neutral gauge boson,[4–7] the Z'. Also, since fermions would belong to the fundamental **27** representation of E_6, there may exist exotic states[5–10] in addition to the known fermions. The left-handed fermions of the first-generation **27**, labeled by SO(10) and SU(5) decompositions, are

$$\begin{aligned}
&(16,5^*) \quad d^c + \binom{\nu_e}{e} ,\\
&(16,10) \quad u^c + \binom{u}{d} + e^c ,\\
&(16,1) \quad N^c ,\\
&(10,5^*) \quad h^c + \binom{\nu_E}{E} ,\\
&(10,5) \quad h + \binom{E^c}{N_E^c} ,\\
&(1,1) \quad n .
\end{aligned} \tag{2}$$

There is a new quark h of charge $-\frac{1}{3}$, a charged heavy lepton E, and neutral leptons N, ν_E, N_E, n. These new fermions and the Z' boson may have significant implications for experiments at supercolliders at very high energy and high luminosity. Of particular interest to us is the possible production of heavy E_6 leptons via the γ, Z, and Z' bosons in the Drell-Yan and gluon-fusion subprocesses shown in Fig. 1.

Our considerations parallel the recent work of Willenbrock and Dicus[11] for the production of a fourth-generation charged heavy lepton via the standard-model γ and Z bosons. (We denote fourth-generation leptons by ν_L, L and fourth-generation quarks by a,v.) However, there are a number of important differences in the production of E_6 and fourth-generation heavy leptons.

(i) In the E_6 case the Z-boson couplings are different and there are additional Drell-Yan contributions from the Z' boson.

(ii) The gluon-fusion subprocess involves the triangle diagram from heavy quarks. If the t quark has mass[12] $m_t < \frac{1}{2}M_W$, the dominant diagram contribution in E_6 arises from h quarks and in four generations from a and v quarks. No cancellations occur in the h-loop contributions, whereas a and v quarks contribute with opposite signs to the triangle diagram.

(iii) The maximum gluon-subprocess contribution is obtained in the E_6 model for $m_h \gg m_E$, whereas in a four-

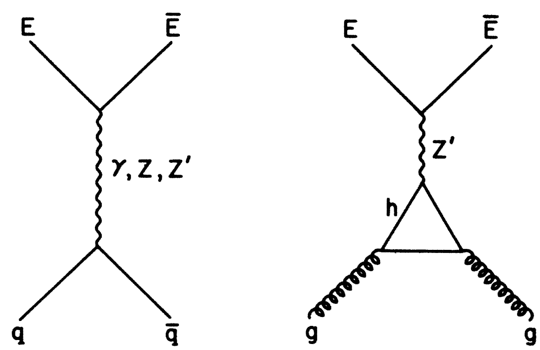

FIG. 1. Drell-Yan and gluon-fusion subprocesses for production of E_6 charged heavy leptons.

generation model the maximum contribution requires[11] $m_v \ll m_E \ll m_a$.

(iv) Only axial-vector Z, Z' couplings contribute to the gluon-fusion subprocess because of Furry's theorem. Since the vectorlike h quark has no axial-vector coupling to the Z boson, only the Z' intermediate state contributes for the E_6 case. This cross-section contribution decreases like $(M_{Z'})^{-4}$ and is thus very sensitive to the Z' mass.

In the E_6 model the couplings[5,6] of the Z and Z' bosons to the fermions f have the form

$$\mathcal{L} = g_Z(G_L Z_\mu + \sqrt{x_W} G'_L Z'_\mu)\bar{f}\gamma^\mu(1-\gamma_5)f + g_Z(G_R Z_\mu + \sqrt{x_W} G'_R Z'_\mu)\bar{f}\gamma^\mu(1+\gamma_5)f \; , \quad (3)$$

where the coefficients G_B and G'_B with $B = R,L$ are given in Table I. Here $g_Z = e[x_W(1-x_W)]^{-1/2}$ and $x_W = \sin^2\theta_W$ as usual. The Z,Z' mixing is known to be small[5] and is neglected here.

The integrated Drell-Yan cross section is given by

$$\hat{\sigma}(q\bar{q} \to \gamma,Z,Z' \to E\bar{E}) = C\beta\frac{\hat{s}}{3\pi}\left[\left(1-\frac{m_E^2}{\hat{s}}\right)(|C_{LL}|^2+|C_{RR}|^2+|C_{LR}|^2+|C_{RL}|^2)+\frac{6m_E^2}{\hat{s}}\mathrm{Re}(C_{LL}^*C_{LR}+C_{RR}^*C_{RL})\right], \quad (4)$$

where $C = \frac{1}{3}$ is the color factor, $\beta = (1-4m_E^2/\hat{s})^{1/2}$ is the heavy-lepton velocity, $\hat{s}$ is the subprocess c.m. energy, and the coefficients C_{BC} are

$$C_{BC} = \frac{Q_q Q_E}{4\hat{s}} + \frac{G_B(q)G_C(E)}{x_W(1-x_W)(\hat{s}-M_Z^2+iM_Z\Gamma_Z)} + \frac{G'_B(q)G'_C(E)}{(1-x_W)(\hat{s}-M_{Z'}^2+iM_{Z'}\Gamma_{Z'})} \; . \quad (5)$$

The gluon-fusion subprocess cross section is determined by the axial-vector couplings

$$A = -G_L + G_R, \; A' = -G'_L + G'_R \quad (6)$$

of the heavy quark and heavy lepton. In the case of a fourth generation the gluon-fusion subprocess cross section, averaged over spin and color, is[11]

$$\hat{\sigma}_Z = \frac{\alpha^2\alpha_s^2}{8\pi}\frac{\beta(A_Q A_L)^2}{x_W^2(1-x_W)^2}\frac{m_L^2}{M_Z^4}|I|^2 \; , \quad (7)$$

where I denotes the integral[13]

$$I = \sum_Q \pm 2\int_{\substack{\alpha+\gamma\le 1\\ \alpha,\gamma>0}} d\alpha\, d\gamma \frac{m_Q^2}{m_Q^2-\alpha\gamma\hat{s}} \; . \quad (8)$$

Charge $\frac{2}{3}$ quarks contribute positively and charge $-\frac{1}{3}$ quarks contribute negatively to I.

In the E_6 case, assuming three approximately mass-degenerate h and E lepton generations the cross section for the gluon-fusion subprocess is

$$\hat{\sigma}_{Z'} = 3^3 x_W^2 (M_Z/M_{Z'})^4 \hat{\sigma}_Z \; , \quad (9)$$

with the replacement ($A_Q \to A'_h$, $A_L \to A'_E$, $m_L \to m_E$, and $m_Q \to m_h$) in Eqs. (7) and (8). The gluon distributions cause the subprocess contributions to be peaked near the threshold $\hat{s} = 4m_f^2$; consequently I is essentially unity as long as $m_h \gg 2m_f$. We evaluate the production cross sections numerically under this assumption.

There may, in addition, be contributions from s-channel Higgs-boson exchange to the gluon-fusion subprocess which are incoherent with the Z' contribution. In the standard-model calculation of Ref. 11, the Higgs-boson contribution was found to be comparable to the Z contribution. We do not attempt to estimate the Higgs-boson contribution in the E_6 model because of the complicated nature of the Higgs sector here. Our Z' calculations give a lower bound on the expected heavy-lepton cross section in E_6.

Figure 2 gives predicted integrated cross sections for $E\bar{E}$ production in pp collisions at 40 TeV, corresponding to the energy of the proposed U.S. Superconducting Super Collider (SSC). In these calculations we used the Duke-Owens model 1 gluon distribution[14] with $\Lambda = 0.2$ GeV and $Q^2 = \hat{s}$; essentially identical results were obtained with the distribution from Eichten, Hinchliffe, Lane, and Quigg.[15] The cross sections in Fig. 2 are based on a Z' mass of 150 or 200 GeV. The gg cross-section component scales with $(M_{Z'})^{-4}$; the $q\bar{q}$ component does not vary significantly with the Z' mass.

Figure 3 compares cross sections for $E\bar{E}$ production in pp collisions at SSC energies of $\sqrt{s} = 20$ and 40 TeV with predictions at 10 TeV, appropriate for the proposed Large Hadron Collider at CERN.

Figure 4 compares the $E\bar{E}$ cross section in pp collisions at 40 TeV with corresponding maximal cross sections for production of the fourth-generation heavy lepton L. The Drell-Yan component for $E\bar{E}$ is a factor of 3 larger than for $L\bar{L}$ since we have assumed three mass-degenerate exotic generations.

In E_6 the production of the neutral leptons ν_E, N_E, N,

TABLE I. Left- and right-handed couplings of the Z and Z' bosons in Eq. (3).

Fermion	G_L	G_R	G'_L	G'_R
ν_L	$\frac{1}{4}$	0	$-\frac{1}{12}$	0
L	$-\frac{1}{4}+\frac{1}{2}x_W$	$\frac{1}{2}x_W$	$-\frac{1}{12}$	$-\frac{1}{6}$
a	$\frac{1}{4}-\frac{1}{3}x_W$	$-\frac{1}{3}x_W$	$\frac{1}{6}$	$-\frac{1}{6}$
v	$-\frac{1}{4}+\frac{1}{6}x_W$	$\frac{1}{6}x_W$	$\frac{1}{6}$	$\frac{1}{12}$
h	$\frac{1}{6}x_W$	$\frac{1}{6}x_W$	$-\frac{1}{3}$	$\frac{1}{12}$
ν_E	$\frac{1}{4}$	0	$-\frac{1}{12}$	0
E	$-\frac{1}{4}+\frac{1}{2}x_W$	$-\frac{1}{4}+\frac{1}{2}x_W$	$-\frac{1}{12}$	$\frac{1}{3}$
N	0	0	0	$-\frac{5}{12}$
N_E	0	$\frac{1}{4}$	0	$\frac{1}{3}$
n	0	0	$\frac{5}{12}$	0

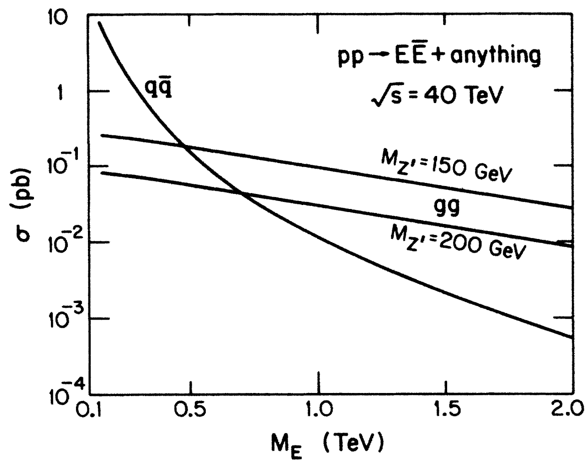

FIG. 2. Cross section vs mass of the E_6 charged heavy lepton in pp collisions at $\sqrt{s} = 40$ TeV, assuming a Z'-boson mass of 150 or 200 GeV. The Drell-Yan ($q\bar{q}$) and the gluon-fusion (gg) subprocess contributions are shown separately. Three approximately mass-degenerate generations of E leptons are assumed with $m_E \ll m_h$.

and n is also of interest. Figure 5 compares the production cross sections of the charged and neutral exotic leptons, assuming that all are heavy and that each neutral heavy lepton is a Majorana particle by itself.

Very massive leptons would decay to W, Z, and Z' bosons. For example if $m_E > 2M_W$ and $m_{\nu_E} > M_W$ the first-generation charged E lepton could decay dominantly via the decay chain

$$E \rightarrow \nu_E W \rightarrow e W^+ W^- . \tag{10}$$

The pair-produced $E\bar{E}$ state would thus contain four W bosons. If $M_{\nu_E} > m_E > M_W$, the first-generation E lepton would decay by both charged and neutral currents,

$$E \rightarrow \nu_e W, eZ, eZ' , \tag{11}$$

with the proportions determined by mixing angles.[9]

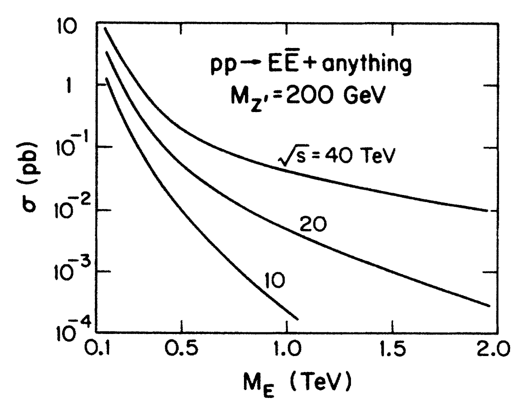

FIG. 3. Comparison of cross sections for $E\bar{E}$ production in pp collisions at $\sqrt{s} = 10$, 20, and 40 TeV, for $M_{Z'} = 200$ GeV.

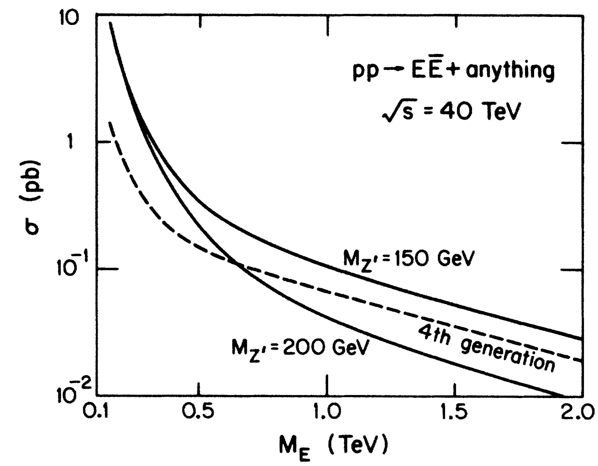

FIG. 4. Comparison of charged-heavy-lepton production cross sections in E_6 and fourth-generation models, in pp collisions at $\sqrt{s} = 40$ TeV vs the lepton mass. The E_6 curves are based on a Z' mass of 150 and 200 GeV.

The Z' boson is coupled strongly to the heavy Majorana neutrinos[6,7] N and n, and these states would be pair produced in pp collisions. These Majorana neutrinos may decay via mixing with an ordinary neutrino. If the Majorana neutrinos are sufficiently heavy, then the following types of decays may be realized for the first generation N if it mixes with ν_e:

$$N \rightarrow e^{\pm} W^{\pm}, \; N \rightarrow \overset{(-)}{\nu} Z, \; N \rightarrow \overset{(-)}{\nu} Z' . \tag{12}$$

The Majorana N decays with the same rate into a particular final state and a state with opposite charges. Thus $N\bar{N}$ production will lead to same-sign W pairs, which would be a dramatic experimental signature.[16]

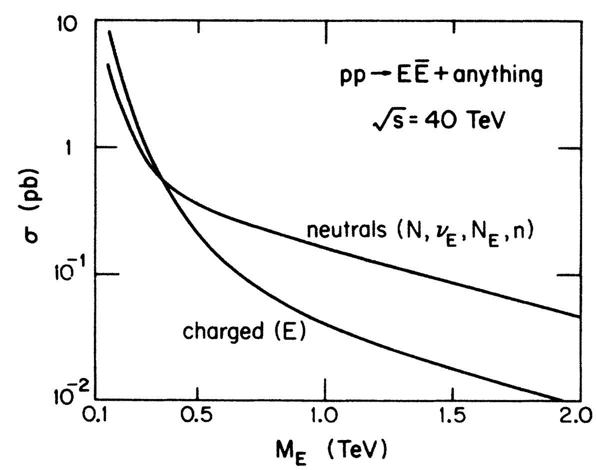

FIG. 5. Cross sections for production of exotic charged and neutral heavy leptons in the E_6 model, in pp collisions at 40 TeV. Three approximately mass-degenerate generations of each lepton type are assumed. The Z' mass is taken to be 200 GeV.

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