PHYSICAL REVIEW D **71,** 035014 (2005)

Z' discovery limits for supersymmetric E_6 models

Junhai Kang and Paul Langacker

Department of Physics and Astronomy, University of Pennsylvania, Philadelphia , Pennsylvania 19104-6396, USA

(Received 24 December 2004; published 25 February 2005)

We study how the exotic particles and supersymmetric partners would affect the discovery limit at the Tevatron and LHC for neutral gauge bosons in generic E_6 models. We examine the Z' decay in the extreme case that all of the particles are massless, then consider how the masses of nonstandard model particles will affect the discovery limit. We also calculate the discovery limit for a supersymmetric E_6 model with a secluded sector as a concrete example of a model with a definite set of exotic particles. Its discovery limit is small compared with other E_6 models due to the $U'(1)$ charge assignment.

DOI: 10.1103/PhysRevD.71.035014 PACS numbers: 12.60.Cn

I. INTRODUCTION

While the standard model (SM) has been precisely tested by experiments, it is believed to be only a low energy effective description of nature. Extended gauge symmetries and/or extra gauge bosons appear in many extensions of the standard model, such as left-right symmetric models [1], superstring motivated models [2], GUT (grand unification theory) [3], little Higgs models [4], large extra dimensions [5], and dynamical symmetry breaking [6]. They are good candidates for new physics at future colliders. To date, extra gauge bosons have not been observed, setting constraints on various models.

In this paper, we focus on extra neutral gauge bosons [7]. The direct search for Z' requires the collider energy to be high enough to produce the Z' and the signal to be distinguished from the standard model background. The discovery limit for the Z' mass is model dependent, but it is convenient to give it for some representative models, such as the SSM (sequential standard model), LRM (left-right symmetric model), and E_6 models. The CDF and DO collaborations [8] give direct Z' search limits ranging from 560 GeV to 690 GeV for different specific models from their Run I data from the nonobservation of $\bar{p}p \to e^+e^-, \mu^+\mu^-$. These should be improved to $O(800\ \mathrm{GeV})$ from these and other decay modes in Run II, and to several TeV at the LHC. The discovery reach for various models at future hadron and lepton colliders was studied in [9–15]. There are also stringent indirect limits, especially on $Z - Z'$ mixing, from low energy, Z-pole, and LEP2 experiments [16–20].

The model dependence arises in part because of the $U(1)'$ gauge couplings and quark and lepton charges. However, $U(1)'$ models necessarily imply new exotic fermions needed for anomaly cancellations [21]. If some of these and/or some of the superpartners in supersymmetric versions are light enough to be produced in Z' decays, the leptonic branching ratios and discovery limits will be affected. Some earlier discussions of the implications of exotics and superpartners on the discovery limits are found in [22–31]. In this paper, we study these effects in detail for the example of generic E_6-motivated Z' models. The E_6 gauge group can be broken as

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi. \quad (1)$$

The $U(1)_\psi$ and $U(1)_\chi$ charges for the E_6 fundamental representation **27** are given in Table I. Each **27** includes one SM family, an exotic charge $-1/3$ D quark and its conjugate; two SM singlets $\overline{N}$ and S_L; and one pair of Higgs-like doublets $H'_{u,d}$. One pair can be associated with the MSSM Higgs doublets, and the other two as exotics[1]. As described below, we will also add some additional doublets and singlets from $\mathbf{27} + \overline{\mathbf{27}}$ pairs.

The $U(1)'$ in consideration is one linear combination of the $U(1)_\chi$ and $U(1)_\psi$

$$Q' = \cos\theta Q_\chi + \sin\theta Q_\psi, \quad (2)$$

parametrized by angle θ. For simplicity, we assume that the other $U(1)$ gauge symmetry from the orthogonal linear combination of the $U(1)_\chi$ and $U(1)_\psi$ is absent or broken at a high scale[2]. $U(1)_\eta$ is a particular combination of $U(1)_\chi$ and $U(1)_\psi$, i.e., $\theta = 2\pi - \tan^{-1}\sqrt{\frac{5}{3}} = 1.71\pi$. It occurs in Calabi-Yau compactifications of the heterotic string model if E_6 leads directly to a rank five group via the Wilson line (Hosotani) mechanism. $U(1)_N$ is a special model used in [33,34], in which the right-handed neutrino decouples from the low energy $U(1)$, avoiding big bang nucleosynthesis constraints. It corresponds to $\theta = \tan^{-1}\sqrt{15} \sim 0.42\pi$.

Besides the general discussion of E_6 models, we are interested in a secluded sector model proposed in [35,36], with $\theta = \tan^{-1}(\sqrt{15}/9) \sim 0.13\pi$. This model makes use of three **27**'s of E_6 and some particle pairs

[1]It is sometimes convenient, depending on the symmetries of the superpotential, to interpret the exotic Higgs fields as exotic lepton doublets, which have the same gauge quantum numbers.

[2]We are not considering a full E_6 grand unified theory, because a light Z' would prevent a large doublet-triplet splitting and lead to rapid proton decay. Rather, it is convenient and conventional to simply consider the $U(1)'$ charge assignment and exotic particle content of E_6 as an example of an anomaly free construction. Other examples, such as superstring motivated models, typically have more complicated exotic structures [32].

 © 2005 The American Physical Society

TABLE I. Decomposition of the E_6 fundamental representation **27** under $SO(10)$ and $SU(5)$, and their $U(1)_\chi$, $U(1)_\psi$, $U(1)_\eta$, secluded sector $U(1)'_s$, and neutral-N model $U(1)_N$ charges.

$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$	$2\sqrt{15}Q_\eta$	$2\sqrt{15}Q_s$	$2\sqrt{10}Q_N$
16	$10(u, d, \bar{u}, \bar{e})$	-1	1	-2	$-1/2$	1
	$\bar{5}(\bar{d}, \nu, e)$	3	1	1	4	2
	$1\bar{N}$	-5	1	-5	-5	0
10	$5(D, H'_u)$	2	-2	4	1	-2
	$\bar{5}(\bar{D}, H'_d)$	-2	-2	1	$-7/2$	-3
1	$1S_L$	0	4	-5	5/2	5

from $\mathbf{27} + \overline{\mathbf{27}}$. It is anomaly free, can solve the MSSM μ problem, can give a natural explanation of the $Z - Z'$ mass hierarchy, and allows an enhanced possibility for electroweak baryogenesis.

We focus on the direct search for Z' at hadron colliders such as the Tevatron and LHC by their decay into e^-e^+ and $\mu^-\mu^+$. We discuss the effect of exotic particles as well as supersymmetric partners on the discovery limits. Our concern is not so much the precise discovery limits themselves. These will be obtained much better by the experimenters in their own analysis. Rather, we want to quantitatively show the sensitivity of the discovery limit to the exotic particle spectrum.

The paper is organized as follows. In the next two sections, we give the general discussion of Z' physics and the necessary formulas for the decay width and couplings for mass eigenstates. In Sec. IV we study the branching ratios and the total decay widths for different θ, and consider how the discovery limits will be affected by the masses of the non-SM particles. In Sec. V we review the secluded sector E_6 model and calculate the discovery limits for Z' only decaying into SM particles and for decays including the exotics and supersymmetric partners.

II. GENERAL DISCUSSION OF THE Z' DECAY WIDTH

The Born cross section $\sigma^f[pp(p\bar{p}) \to (\gamma, Z, Z')X \to f\bar{f}X]$ is [7]

$$\sigma^f = \Sigma_q \int_0^1 dx_1 \int_0^1 dx_2 \sigma(sx_1x_2; q\bar{q} \to f\bar{f}) G_A^q(x_1, x_2, M_{Z'}^2)\theta(x_1x_2s - M_\Sigma^2) \tag{3}$$

where M_Σ is the sum of the masses of the final particles, $x_{1,2} = \sqrt{\frac{Q^2}{s}}\exp(+y)$ and y is the rapidity. The function $G_A^q(x_1, x_2, M_{Z'}^2)$ depends on the structure functions of the quarks. In an approximation adequate for our purposes, σ^f is given by [37,38]

$$\sigma_T^f \equiv \frac{N_Z'}{L} = \frac{1}{s} c_{Z'} C \exp\left(-A\frac{M_{Z'}}{\sqrt{s}}\right) \tag{4}$$

where $C = 600(300)$ and $A = 32(20)$ for $pp(p\bar{p})$ collisions. s is the center of mass energy square of the collision, N_Z' is the number of events, L is the luminosity, and the subscript T means it is a tree level result. QCD corrections (K factors) increase the lowest order cross section by 20–30%. We take $K \sim 1.3$ in our numerical calculation [12]. From (4), we see that the predicted cross section falls exponentially as a function of $M_{Z'}$. The details of the Z' model are collected in a quantity c'_Z that depends on $M_{Z'}$, the Z' couplings, and the masses of the particle the Z' can decay into:

$$c_{Z'} = \frac{4\pi^2}{3}\frac{\Gamma_{Z'}}{M_{Z'}} Br_2^f\left[Br_2^u + \frac{1}{C_{ud}} Br_2^d\right], \tag{5}$$

where $C_{ud} = 2(25)$, $\Gamma_{Z'}$ is the total Z' width, and Br_2^f is the branching ratio into $f\bar{f}$.

In the limit that the fermion masses are small compared with $M_{Z'}$, the Z' decay width into fermions is,

$$\Gamma_{Z' \to f\bar{f}} = \frac{g'^2 M_{Z'}}{24\pi}(Q_l^2 + Q_r^2), \tag{6}$$

where Q_l, Q_r are the $U(1)'$ charges for the left (right) chiral fermions. g' denotes the tree level $U(1)'$ coupling. We use $g' = \sqrt{\frac{5}{3}} g_Y$ throughout this paper. From (5), the dependence on $M_{Z'}$ cancels out in this limit, and c'_Z is a constant depending only on the particle charge assignments. Then (4) can be inverted to obtain the Z' discovery limit,

$$M_{Z'}^{\lim} \sim \frac{\sqrt{s}}{A}\ln\left(\frac{L}{s}\frac{c_{Z'}C}{N_{Z'}}\right) \sim \sqrt{s} \times \left[0.386(0.583) + \frac{1}{32(20)}\ln\left(\frac{1000L \cdot c_{Z'}}{N_{Z'} \cdot s}\right)\right], \tag{7}$$

where on the right hand side, L is expressed in fb^{-1} and s in TeV. For $M_{Z'} < M_{Z'}^{lim}$, more than $N_{Z'}$ events are expected. If the Z' decays only into the SM fermions, (7) gives a good estimate. The result is changed only a small amount for the models and mass ranges we are considering if we include the effect of the top quark mass of 175 GeV.

However, to study the effects of light exotic particle and/or light supersymmetric partners on the Z' discovery limits, we need to deal with particles with masses comparable to the Z' mass. In that case, the Z' decay width will depend on

the particle masses, and $c_{z'}$ is not a constant, implying the need for a numerical study. The width for Z' decays into boson pairs with nonzero masses is [39,40]

$$\Gamma_{Z'\to b_1 b_2^*} = \frac{g'^2 f_{zb_1b_2^*}^2 M_{Z'}}{48\pi}\left(1+\frac{m_1^4}{M_{Z'}^4}+\frac{m_2^4}{M_{Z'}^4}-2\frac{m_1^2}{M_{Z'}^2} - 2\frac{m_2^2}{M_{Z'}^2}-2\frac{m_1^2m_2^2}{M_{Z'}^4}\right)^{3/2} \tag{8}$$

where $f_{zb_1b_2^*}$ is the Z' couplings to b_1, b_2^*. It is a product of $U(1)'$ charges and a matrix connecting the mass eigenstates and weak eigenstates and will be given in the next section. The width for Z' decays into fermions is more complicated because the formulae for Z' decay into Majorana spinors (for example, neutralinos) and Dirac spinors (quarks and leptons) are different. The decay width for Z' decays into Majorana spinors is [40]

$$\Gamma_{Z'\to f_i f_j} = \frac{g'^2 M_{Z'}}{24\pi}\left(1+\frac{m_i^4}{M_{Z'}^4}+\frac{m_j^4}{M_{Z'}^4}-2\frac{m_i^2}{M_{Z'}^2}-2\frac{m_j^2}{M_{Z'}^2} - 2\frac{m_i^2m_j^2}{M_{Z'}^4}\right)^{1/2}\left[\left(1-\frac{m_i^2+m_j^2}{2M_{Z'}^2}-\frac{(m_i^2-m_j^2)^2}{2M_{Z'}^4}\right)\times(C_{l(i,j)}^2+C_{r(i,j)}^2)+3\frac{m_1m_2}{M_{Z'}^2}(C_{l(i,j)}C_{r(i,j)}^* + C_{r(i,j)}C_{l(i,j)}^*)\right]\frac{1}{1+\delta_{ij}} \tag{9}$$

where C_l and C_r are the product of $U(1)'$ charges and the matrix connecting the mass and weak eigenstates. They will be given in the next section. $m_{1,2}$ are the masses of the two fermions. From the above, we can deduce the decay width for Z' decay into Dirac fermion pairs,

$$\Gamma_{Z'\to f\bar f} = \frac{g'^2 M_{Z'}}{24\pi}\left(1-4\frac{m^2}{M_{Z'}^2}\right)^{1/2}\left[\left(1-\frac{m^2}{M_{Z'}^2}\right)(C_l^2+C_r^2) + 3\frac{m^2}{M_{Z'}^2}(C_lC_r^*+C_rC_l^*)\right]. \tag{10}$$

We now consider the couplings between mass eigenstates.

III. COUPLINGS BETWEEN MASS EIGENSTATES

If the Higgs fields have nonzero $U(1)'$ charge, there will be mixing between the two neutral gauge bosons. The covariant derivative appearing in the Lagrangian of a supersymmetric $U(1)'$ model (we only include neutral gauge bosons) is[3]

$$D_\mu = \partial_\mu - i\frac{g_1g_2}{\sqrt{g_1^2+g_2^2}}A_\mu(T^3+Y) - i\frac{1}{\sqrt{g_1^2+g_2^2}}Z_\mu(g_2^2T^3-g_1^2Y) - ig'Q'Z'_\mu. \tag{11}$$

After the symmetry breaking, $H_{u,d}$ acquire nonzero VEVs $v_{1,2}$ and some SM singlets S_i that are charged under $U(1)'$ will acquire nonzero VEVs to account for the $Z-Z'$ mass hierarchy. The $Z-Z'$ mass squared matrix is

$$M_{ZZ'}^2 = \begin{pmatrix} M_1^2 & \delta M^2 \\ \delta M^2 & M_2^2 \end{pmatrix} \tag{12}$$

where

$$\delta M^2 = \sqrt{g_1^2+g_2^2}g'(Q'_{h_2}v_2^2 - Q'_{h_1}v_1^2) \tag{13}$$

$$M_1^2 = \frac{(g_1^2+g_2^2)(v_1^2+v_2^2)}{2} \tag{14}$$

$$M_2^2 = 2g'^2(Q'^2_{h_1}v_1^2 + Q'^2_{h_2}v_2^2 + Q'^2_{S_i}S_i^2). \tag{15}$$

The mass eigenstates Z_1, Z_2 are related to Z and Z' by

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\theta_z & \sin\theta_z \\ -\sin\theta_z & \cos\theta_z \end{pmatrix}\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} \tag{16}$$

where θ_z is the $Z-Z'$ mixing angle, given by

$$\tan2\theta_z = \frac{2\delta M^2}{M_2^2-M_1^2}. \tag{17}$$

The covariant derivative in terms of Z_1 and Z_2 is

$$D_\mu = \partial_\mu - i\frac{g_1g_2}{\sqrt{g_1^2+g_2^2}}A_\mu(T^3+Y) - i\left[\frac{\cos\theta_z}{\sqrt{g_1^2+g_2^2}}(g_2^2T^3-g_1^2Y) - g'Q'\sin\theta_z\right]Z_{1\mu} - i\left[g'Q'\cos\theta_z + \frac{\sin\theta_z}{\sqrt{g_1^2+g_2^2}}(g_2^2T^3-g_1^2Y)\right]Z'_{2\mu}. \tag{18}$$

The mixing angle, θ_z, is very small by the LEP and SLD Z-pole data and other precise constraints [16–20], so we will neglect it in the following[4].

We also need the Z' couplings to the mass eigenstates. For the standard model and other Dirac fermions, the C_l and C_r in (10) are just the $U(1)'$ charges for the left-handed and right-handed components. For squarks and sleptons, the Lagrangian is

[3]We neglect the possibility of kinetic mixing [41].

[4]Because we have neglected the mixing angle, we do not consider the decays $Z'\to W^+W^-$ and $Z'\to Z+boson$, since the amplitudes are proportional to the mixing angle [12,25,39,42].

$$L = -ig' Q'_L Z'_\mu \phi_L \partial^\mu \phi_L^* - ig' Q'_R Z'_\mu \phi_R \partial^\mu \phi_R^* \quad (19)$$

For simplicity, we neglect family mixing here. Let ϕ_1, ϕ_2 be the mass eigenstates and θ_s the mixing angle between the left and right fields.

$$\begin{pmatrix} \phi_L \\ \phi_R \end{pmatrix} = \begin{pmatrix} \cos\theta_s & \sin\theta_s \\ -\sin\theta_s & \cos\theta_s \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \quad (20)$$

In terms of the mass eigenstates,

$$\begin{aligned} L = -ig' Z'_\mu [&(Q'_L \cos^2\theta_s + Q'_R \sin^2\theta_s)\phi_1 \partial^\mu \phi_1^* \\ &+ (Q'_L \sin^2\theta_s + Q'_R \cos^2\theta_s)\phi_2 \partial^\mu \phi_2^* + (Q'_L - Q'_R) \\ &\times \sin\theta_s \cos\theta_s (\phi_1 \partial^\mu \phi_2^* + \phi_2 \partial^\mu \phi_1^*)] \end{aligned} \quad (21)$$

from which we can read off the couplings,

$$\begin{aligned} f_{z'11^*} &= (Q'_L \cos^2\theta_s + Q'_R \sin^2\theta_s) f_{z'22^*} \\ &= (Q'_L \sin^2\theta_s + Q'_R \cos^2\theta_s) f_{z'12^*} = f_{z'21^*} \\ &= (Q'_L - Q'_R) \sin\theta_s \cos\theta_s. \end{aligned} \quad (22)$$

It is straightforward to generalize these formulas to include family mixing. In the massless limit, adding all of the possible decay channels, the decay width is,

$$\Gamma_{Z' \to b b^*} = \frac{g'^2 M_{Z'}}{48\pi} (Q_l^2 + Q_r^2). \quad (23)$$

There is a simple relation between the decay width into the standard model fermions and their supersymmetric partners in one chiral supermultiplet in the massless limit, i.e., $\Gamma_{Z' \to b b^*} = \frac{1}{2} \Gamma_{Z' \to f \bar{f}}$.

The couplings between mass eigenstates for other fields can be obtained parallel to the above discussion. There are some subtleties in the extended Higgs and neutralino sectors. Let H_i, A_i be the mass eigenstates for CP even and CP odd Higgs fields and H_{wi}, A_{wi} the weak eigenstates, with

$$H_i = U_{ij} H_{wj}, A_i = V_{ij} A_{wj}, \quad (24)$$

where U_{ij} and V_{ij} are unitary matrices. Then

$$L = ig' H_j U^{-1}_{ji} Q'_i V^{-1}_{ik} \partial A_k. \quad (25)$$

The mass matrix can be derived directly from the superpotential. For the E_6 model with a secluded sector, it is given in the appendix of [36].

For the neutralino sector, since they are Majorana spinors, we need to pay more attention to the details of their couplings (For the chargino sector, we will obtain similar formulae; see [40] for details.). Let N_i be the weak eigenstates and χ_i the 4-component Majorana spinor mass eigenstates, and

$$\psi_i \equiv \begin{pmatrix} N_i \\ \bar{N}_i \end{pmatrix} = N_{ij} \chi_{wj}. \quad (26)$$

Then,

$$\begin{aligned} L &= -ig' Q'_i Z^\mu \bar{N}_i \bar{\sigma}^\mu N_i \\ &= \frac{i}{2} g' Z^\mu \bar{\chi}_i \gamma^\mu (C_{l(i,j)} P_L + C_{r(i,j)} P_R) \chi_j \end{aligned} \quad (27)$$

where $C_{l(i,j)} = Q'_k N_{ik} N^*_{jk}$, $C_{r(i,j)} = -C^*_{l(i,j)}$, and N_{ij} is the matrix that diagonalizes the neutralino mass matrix. $C_{l(i,j)}$ and $C_{r(i,j)}$ are the couplings appearing in (9). One can obtain the matrix from [36] for the E_6 model with a secluded sector. In that model, since there are four Higgs singlet fields, the mass matrices of the Higgs and neutralinos are 6×6 and 9×9, respectively.

IV. Z' DECAY IN DIFFERENT SUPERSYMMETRIC E_6 MODELS

Including more particles will enlarge the total decay width for the Z' and reduce the branching ratio to quark and lepton pairs, reducing the discovery limit. As shown in (8) and (9), the partial decay width depends on the particle mass as well as the couplings to the Z'. If the sum of the particle masses is larger than the Z' mass, the decay will not be kinematically allowed. Also, the Z' couplings will be affected by the mass matrix through mixing, as can be read off from (19) and (21).

For a general E_6 model, the $U(1)'$ is a linear combination of $U(1)_\chi$ and $U(1)_\psi$, as in (2). The angle θ will affect the particle charges and the total decay width (Fig. 1), and branching ratios (Fig. 2). The dashed line in Fig. 1 is the total width for Z' to decay only into SM fermions as a function of θ. In this case, all the particles except for SM particles are heavy or neglected. From (6) and (23), the decay width is proportional to the sum of charge squares of

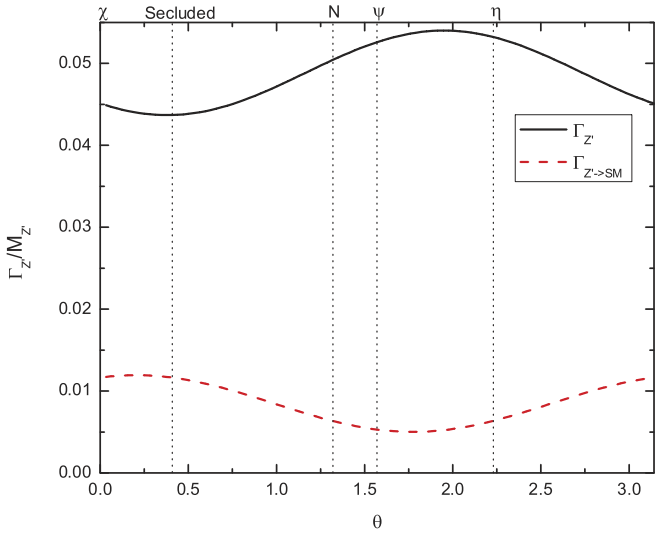

FIG. 1 (color online). The total decay width for E_6 models as a function of the angle θ. The solid (dotted) lines are, respectively, for the case in which all the exotic and supersymmetric partners are massless and for decays into standard model fermions only. m_t is neglected.

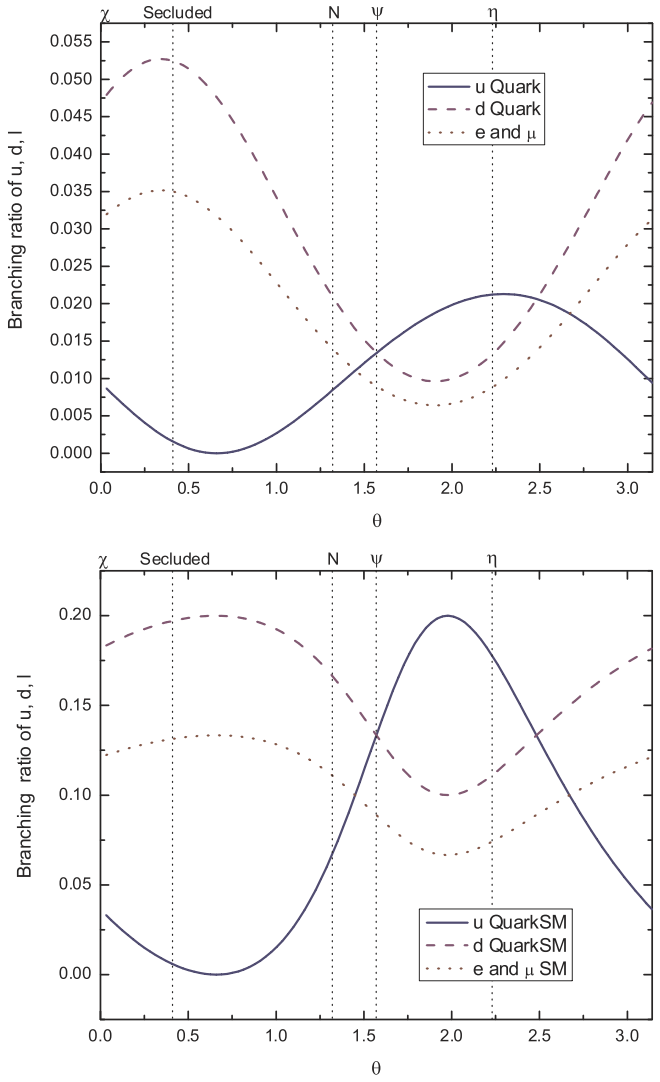

FIG. 2 (color online). The branching ratios into SM particles for E_6 models as a function of θ. The first graph is for the case that Z' only decays into SM fermions, neglecting m_t. The second assumes that Z' can decay into all of the particles and that every particle is massless.

the quarks and leptons. The solid line is a limiting case in which all of the particles are massless. In that case, the decay width will involve the sum of charge squares of all of the particles. If the particle content only included three copies of **27**, the charge square sum would be a constant, independent of the θ. We include an additional H_u, $\overline{H}_u$ from the $\mathbf{27} + \overline{\mathbf{27}}$, as suggested by the gauge coupling unification [35], and three singlet pairs from the $\mathbf{27} + \overline{\mathbf{27}}$ as in the E_6 model with a secluded sector [36]. The charge square sum then depends on θ, due to the charges of H_u, $\overline{H}_u$ and the singlets.

In Fig. 2, the branching ratios of up quarks, down quarks and the sum of electrons plus muons are shown as a function of θ. These affect the discovery limit as suggested by (5) and (7). The first graph is the branching ratio in the case that the Z' only decays into SM fermions. The second is for the case that the Z' can decay into all of the particles and that every particle is massless.

Including exotic particles and the superpartners of SM particles enlarges the total decay width and reduces the branching ratio for quarks and leptons significantly, i.e., by factors of 5 to 10. The exotic branching ratios are displayed in Fig. 3, assuming that all of the particles are massless. We classify the exotic particles as quark-like, Higgs-like (including the Higgs), and SM singlets, and consider the

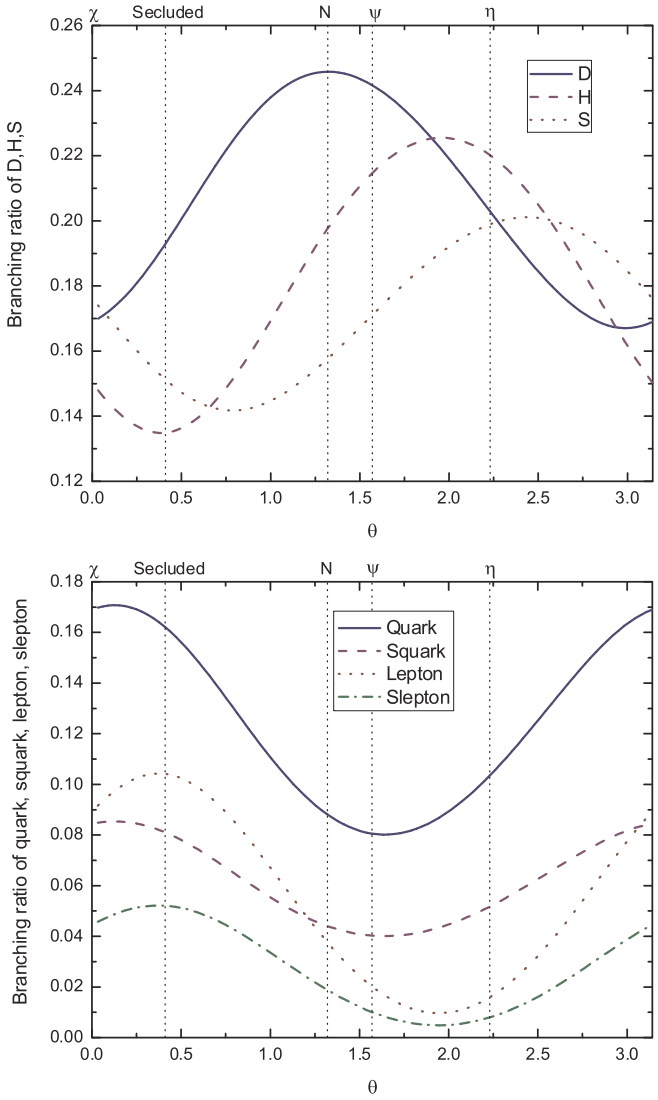

FIG. 3 (color online). Left: the branching ratios into Higgs and exotic particles and their superpartners as a function of θ. D, H, and S are the quark-like, Higgs-like, and singlet particles. Family and color degeneracy have been included. H_u and $\overline{H}_u$ from $\mathbf{27} + \overline{\mathbf{27}}$ have been included in the H, and 3 pairs of singlets from the $\mathbf{27} + \overline{\mathbf{27}}$ have been included in the S. Right: the branching ratios into SM particles and their superpartners. Family and color degeneracy have been included. Lepton includes charged leptons and left-handed neutrinos.

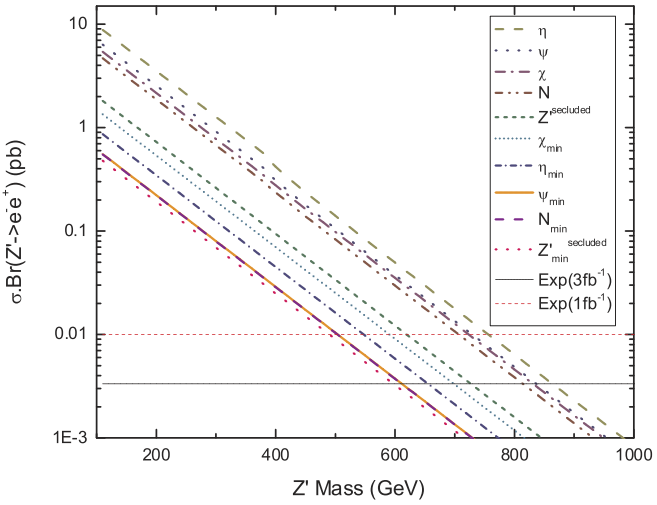

FIG. 4 (color online). The Z' discovery limit (for ten dilepton events) for the E_6 model at the Tevatron ($\sqrt{s} = 1.96$ TeV and $L = 1, 3$ fb^{-1}). Lines with the label min are the limiting case in which all of the particle are massless; lines without are the cases in which the Z' decays only into SM fermions, and the physical top quark mass is included. The intersection point between the experimental line and the theoretical lines are the discovery limits. The particle content is $3 \times \mathbf{27}$; $H_u, \overline{H}_u$ from $\mathbf{27} + \overline{\mathbf{27}}$; and 3 pairs of singlets. The sequence of the curves is same as the sequence in the legend. The lines $N_{\min}$ and $\psi_{\min}$ are almost on top of each other.

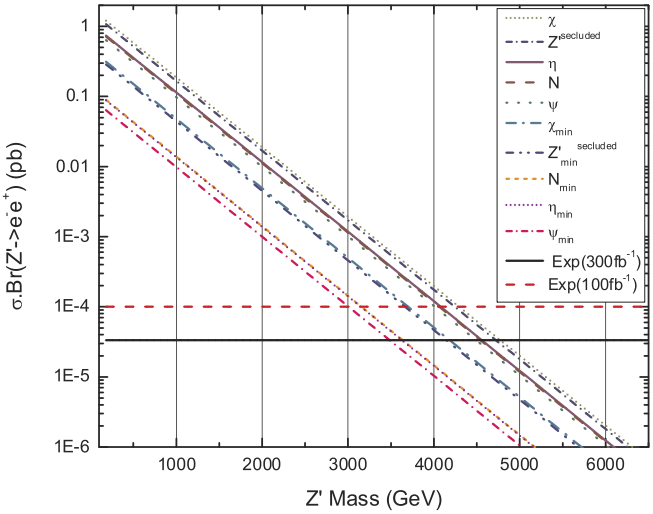

FIG. 5 (color online). The Z' discovery limit (GeV) for the E_6 model at the LHC ($\sqrt{s} = 14$ TeV and $L = 100, 300$ fb^{-1}).The sequence of the curves is same as the sequence in the legend. The lines N and η and the lines $N_{\min}$ and $\eta_{\min}$ are almost on top of each other.

combined contributions of Z' decaying into the exotics and their superpartners. In the second graph in Fig. 3, we display the branching ratios of the superpartners of the quarks (summing the three families), the superpartners of the leptons (charged leptons and left-handed neutrinos), as well as those of the quarks and the leptons.

We now consider the discovery limits for E_6 models at the Tevatron and LHC. The $U(1)'$ charges for specific E_6 models can be found in Table I. We draw two limiting cases in Fig. 4 for the Tevatron ($\sqrt{s} = 1.96$ TeV and $L = 1, 3$ fb^{-1}) and Fig. 5 for the LHC ($\sqrt{s} = 14$ TeV and $L = 100, 300$ fb^{-1}). One is just the Z' decay into SM fermions. The other is a limiting case in which all of the particle are massless.The particle content is $3 \times \mathbf{27}$ and $H_u, \overline{H}_u$ from $\mathbf{27} + \overline{\mathbf{27}}$, which comes from the gauge unification requirement. We also include 3 pairs of singlets for comparison with the secluded sector E_6 model.

TABLE II. The Z' discovery limits (GeV) (for ten dilepton events) for the E_6 model at the Tevatron ($\sqrt{s} = 1.96$ TeV and $L = 1(3)$ fb^{-1}) and LHC ($\sqrt{s} = 14$ TeV and $L = 100(300)$ fb^{-1}), corresponding to Fig. 4 and 5. The particle content is $3 \times \mathbf{27}$; $H_u, \overline{H}_u$ from $\mathbf{27} + \overline{\mathbf{27}}$; and three pairs of singlets.

Tevatron	$Z'^{secluded}$	χ	ψ	η	N
extreme	490(598)	591(699)	505(612)	548(656)	503(611)
$Z' \rightarrow SM$	619(727)	724(832)	730(837)	757(864)	706(814)
LHC	$Z'^{secluded}$	χ	ψ	η	N
extreme	3665(4147)	3703(4184)	3008(3489)	3150(3631)	3157(3638)
$Z' \rightarrow SM$	4243(4725)	4295(4776)	4012(4493)	4079(4561)	4063(4544)

TABLE III. Same as Table II, but without the 3 pairs of singlets.

Tevatron	$Z'^{secluded}$	χ	ψ	η	N
extreme	500(610)	600(710)	520(638)	559(676)	526(634)
$Z' \rightarrow SM$	619(727)	724(832)	730(837)	757(864)	706(814)
LHC	$Z'^{secluded}$	χ	ψ	η	N
extreme	3700(4201)	3718(4230)	3075(3580)	3220(3720)	3260(3741)
$Z' \rightarrow SM$	4243(4725)	4295(4776)	4012(4493)	4079(4561)	4063(4544)

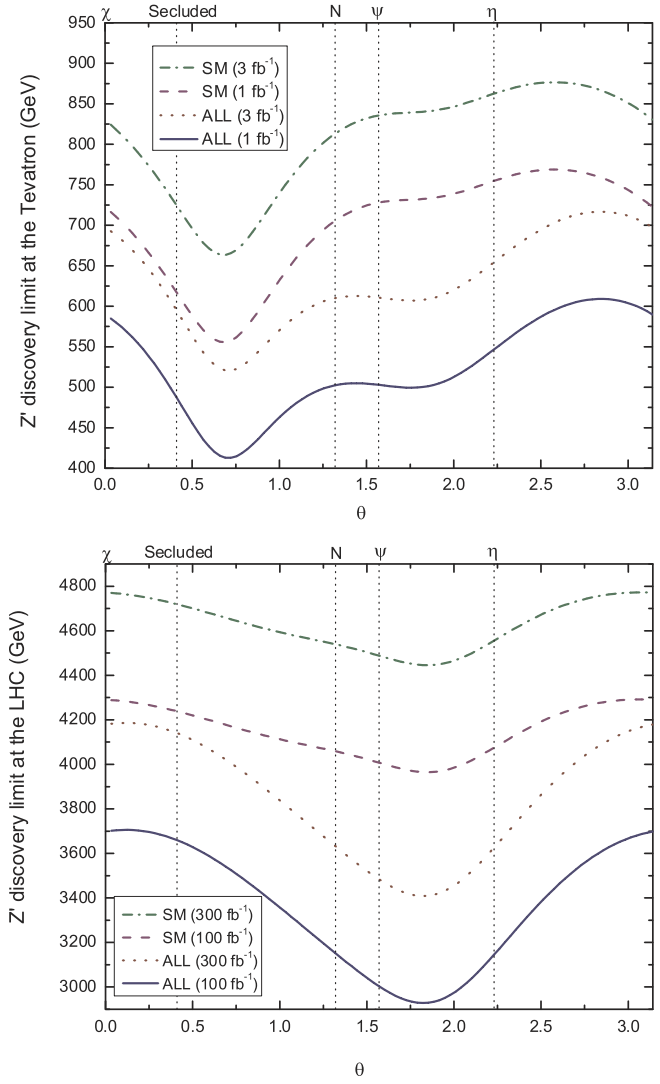

FIG. 6 (color online). The discovery limits for E_6 models as a function of θ at the Tevatron and the LHC. The lower two curves are the discovery limits in the case that Z' decays into all of particles and all are massless (with $L = 1$ fb^{-1} and $L = 3$ fb^{-1} for the Tevatron and $L = 100$ fb^{-1} and $L = 300$ fb^{-1} for the LHC). The upper two curves assume that Z' only decays into SM fermions, with the top quark mass included.

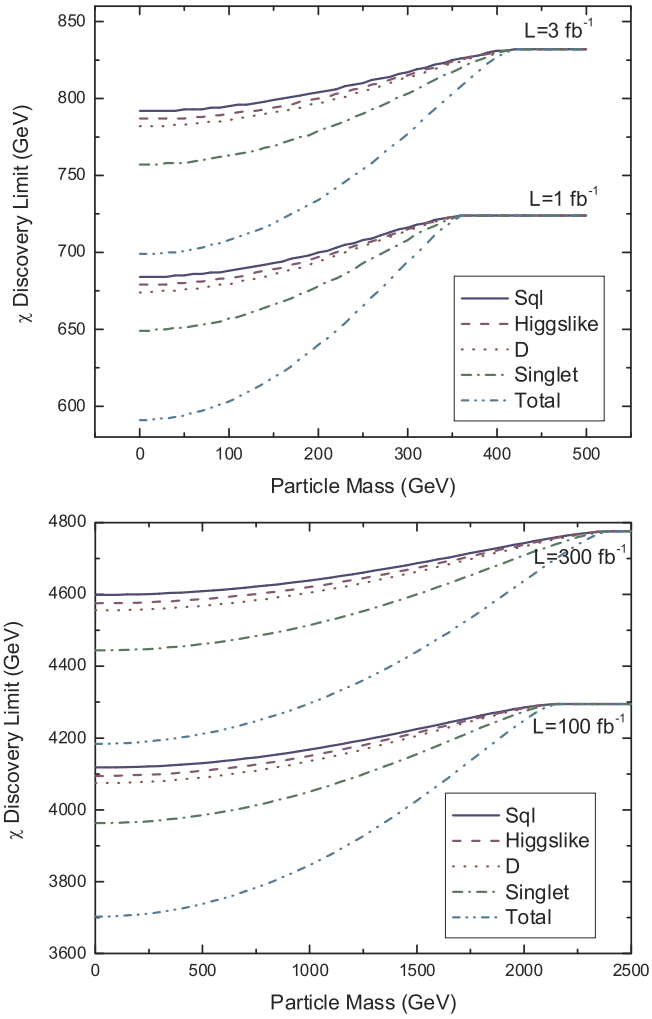

FIG. 7 (color online). The Z' discovery limit for the χ model at the Tevatron ($\sqrt{s} = 1.96$ TeV and $L = 1, 3$ fb^{-1}, left graph) and LHC ($\sqrt{s} = 14$ TeV and $L = 100, 300$ fb^{-1}, right graph) as a function of the mass of the various non-SM particles. The lowest curve, labeled *Total*, assumes that all of the particles have a common mass and the others assume only decays only into the SM fermions and one class of new particle. The sequence of the curves is same as the sequence in the legend.

We have included the top quark mass effect in the SM figures. We use (4) as an estimate of the cross section; it is not accurate for small $M_{Z'}$ but gives a good approximation for the large $M_{Z'}$ that we are mainly concerned with. The QCD K factor has been included. The upper limit experimental line is based on a total of ten dilepton events, i.e., including both e^+e^- and $\mu^+\mu^-$. This is meant to be a rough idealization to illustrate the effect of the exotics and sparticles. Of course, the actual experimental analysis leads to an experimental line with more complicated structure than the horizontal line in the figure.

The intersection points between the experimental line and the theoretical lines are the discovery limits, which are shown in Table II. The discovery limits at the Tevatron for the E_6 model with a secluded sector are lower than the other E_6 models because the $U(1)'$ charge of the up quark is smaller. For comparison, we also show the discovery limit for different E_6 models with the particle content $3 \times \mathbf{27}$ and $H_u, \overline{H}_u$ (but without the extra pairs of singlets) in Table III. Since the number of exotic particles is less than that of the previous case, the discovery limits are increased.

From Figs. 4 and 5, we see that different $U(1)'$ charge assignments affect the discovery limit significantly. The discovery limits at the Tevatron and LHC as a function of θ are shown in Fig. 6. The θ dependences are quite different. This is mainly because the contribution to the Z' produc-

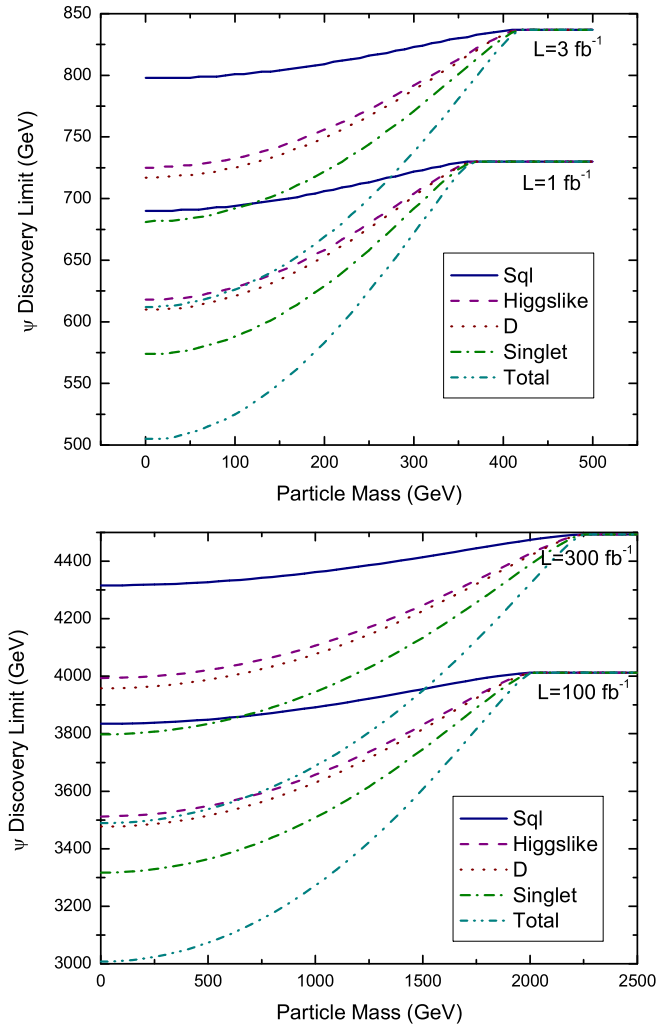

FIG. 8 (color online). The Z' discover limit for the ψ model at the Tevatron and LHC. The sequence of the curves is same as the sequence in the legend.

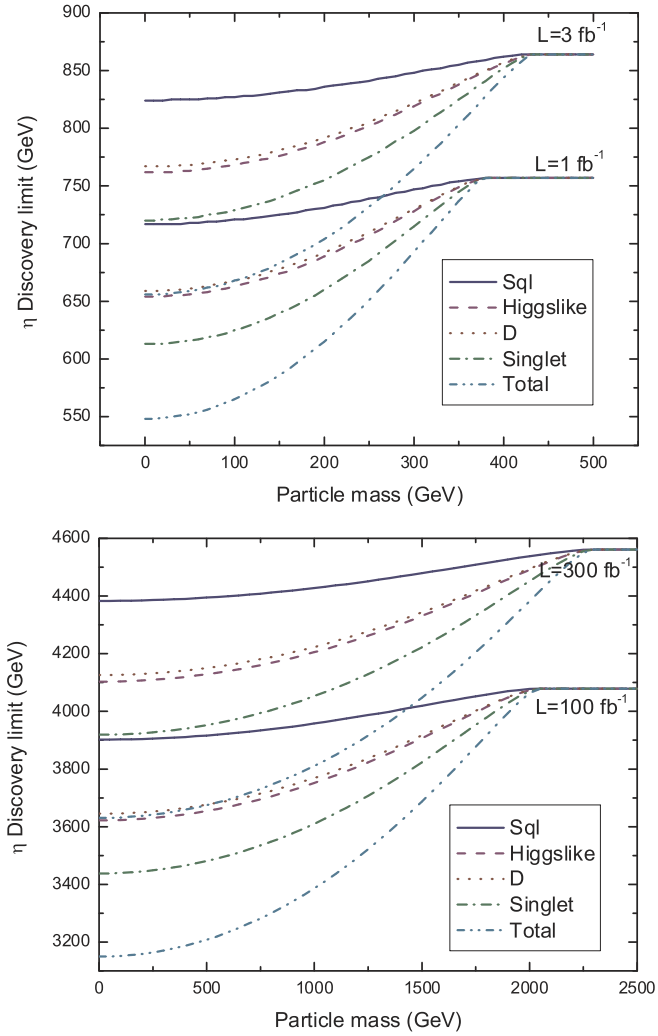

FIG. 9 (color online). The Z' discover limit for the η model at the Tevatron and LHC. The sequence of the curves is same as the sequence in the legend.

tion from the u quark dominates for the Tevatron, while the u and d quark contributions are more comparable for the LHC.

The above analysis assumes that all of the particles are massless for the limiting case. We also consider varying the masses of the non-SM particles. As seen in (8) and (9) the mass enters the discovery limit through the decay width. Since the $c_{Z'}$ in (5) is no longer independent of $M_{Z'}$, we cannot convert it analytically to obtain the discovery limit as in (7), but have to study it numerically.

We classify the non-SM particles as the superpartners of standard model quarks and leptons (sql), the Higgs-like particles, the quark-like exotics (D), and singlets. Both fermions and bosons are included in the last three classes. We take the masses of all the particles and their superpartners in each class to be degenerate for simplicity, except that squarks and sleptons have different masses from the quarks and leptons. We also do not distinguish between the ordinary and exotic Higgs fields.

In Figs. 7–10, we show the discovery limit versus the non-SM particle masses in four typical E_6 models for the Tevatron. For each case only SM particles and the non-SM particles of a given type are included. For example, the curve of sql denotes that the mass of sql is the variable, and other non-SM particles are very heavy. The line labeled *Total* includes every kind of non-SM particle. The minimum value in that line is the extreme case in which all particles are massless. The minimum and maximum of that line correspond to the discovery limits of Figs. 4 and 5.

V. THE Z' DISCOVERY LIMIT IN AN E_6 MODEL WITH A SECLUDED SECTOR

To see the effect of a definite mass spectrum and mass matrix, we consider a concrete model with a definite parameter set.

A supersymmetric E_6 model with a weakly coupled (secluded) sector with a greatly enhanced possibility of

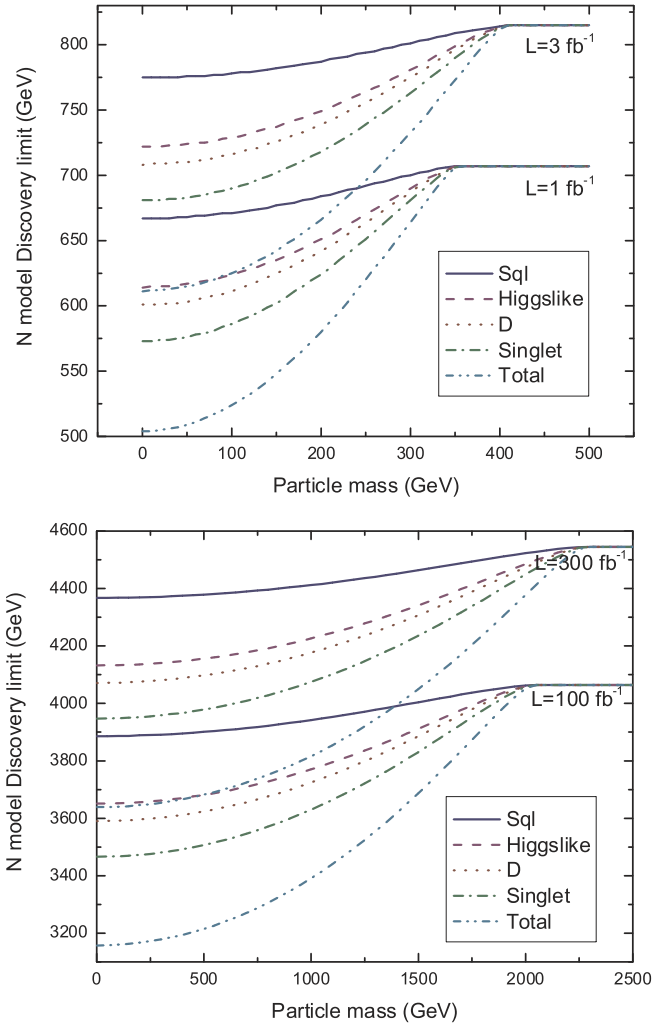

FIG. 10 (color online). The Z' discover limit for the N model at the Tevatron and LHC. The sequence of the curves is same as the sequence in the legend.

TABLE IV. The CP even and CP odd Higgs boson masses in GeV at tree level. The light masses are mainly $SU(2)$ singlets and are consistent with experimental limits [43].

H_1^0	H_2^0	H_3^0	H_4^0	H_5^0	H_6^0	A_1^0	A_2^0	A_3^0	A_4^0
101	150	151	169	229	931	3	62	261	282

TABLE V. The chargino and neutralino masses in GeV at tree level.

$\tilde{\chi}_1^{\pm}$	$\tilde{\chi}_2^{\pm}$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_5^0$	$\tilde{\chi}_6^0$	$\tilde{\chi}_7^0$	$\tilde{\chi}_8^0$	$\tilde{\chi}_9^0$
480	105	84	106	159	213	225	228	452	876	990

TABLE VI. Typical squark, slepton and exotic particle (fermion/boson) masses in GeV at tree level.

Squark	Slepton	HiggsExo(f/b)	QuarkExo(f/b)	SingletExo(f/b)
336	336	180/358	180/358	180/358

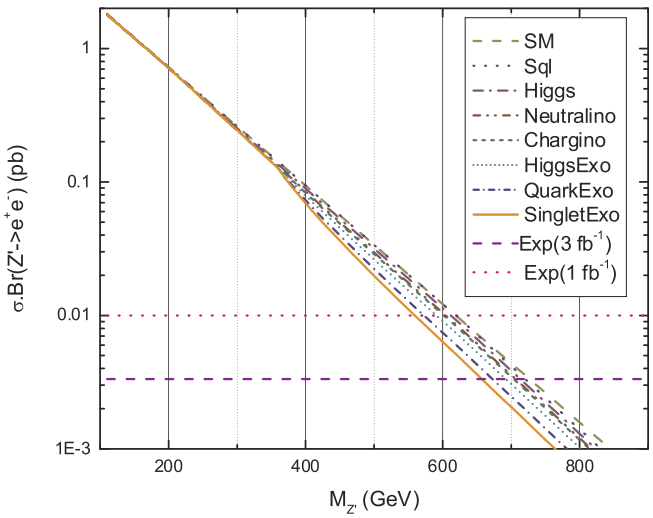

FIG. 11 (color online). The Z' Discovery limit for the secluded sector model at the Tevatron. Different classes of particles are added one after the other. The final theoretical line includes all particles. Lines *Neutrino* and *Chargino* are almost on top of each other.

electroweak baryogenesis was proposed in [36]. We will calculate the Z' discovery limit for that model for the parameters in [36]. We first give a short review of that model.

A. Review of the Model

There is one pair of Higgs doublets H_u and H_d, and four SM singlets, S, S_1, S_2, and S_3. The $U(1)'$ charges for the Higgs fields satisfy

$$Q_S = -Q_{S_1} = -Q_{S_2} = \frac{1}{2}Q_{S_3}, Q_{H_d} + Q_{H_u} + Q_S = 0. \tag{28}$$

The superpotential for the Higgs is

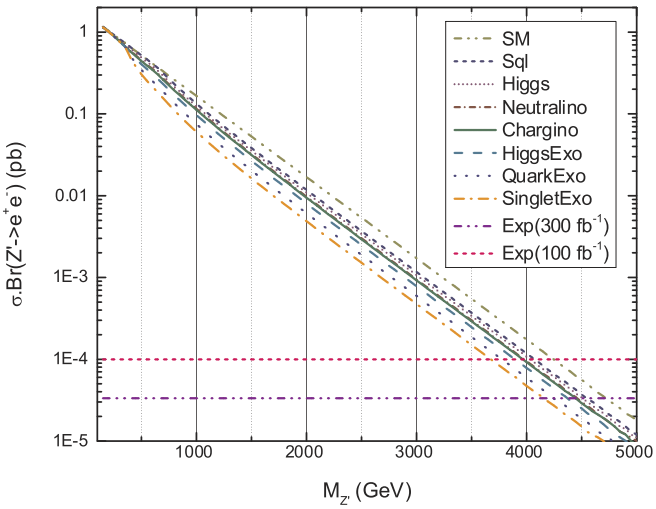

FIG. 12 (color online). The Z' Discovery limit for the secluded sector model at the LHC. Lines *Neutrino* and *Chargino* are almost on top of each other.

TABLE VII. The Z' Discovery limit (GeV) for the secluded sector model at the Tevatron. In each column an additional type of decay channel in included.

Fields	SM	Sql	Higgs	Neutralino	Chargino	HiggsExo	QuarkExo	SingletExo
$L = 1\ \text{fb}^{-1}$	619	620	612	605	602	591	573	560
$L = 3\ \text{fb}^{-1}$	727	721	714	707	704	693	674	658

TABLE VIII. Same as Table VII, for the LHC.

Fields	SM	Sql	Higgs	Neutralino	Chargino	HiggsExo	QuarkExo	SingletExo
$L = 100\ \text{fb}^{-1}$	4244	4072	4032	3977	3965	3894	3774	3676
$L = 300\ \text{fb}^{-1}$	4725	4551	4511	4456	4444	4372	4252	4154

$$W_H = hSH_dH_u + \lambda S_1S_2S_3, \tag{29}$$

where the Yukawa couplings h and λ are, respectively, associated with the effective μ term and with the secluded sector. The existence of a number of SM singlets and the nondiagonal nature of the superpotential are in part motivated by explicit superstring constructions. There is an almost F and D flat direction involving the S_i, with the flatness lifted by a small Yukawa coupling λ. For a sufficiently small value of λ, the Z' mass can be arbitrarily large. For example, if $h \sim 10\lambda$, one can generate a $Z - Z'$ mass hierarchy in which the Z' mass is of order 1 TeV.

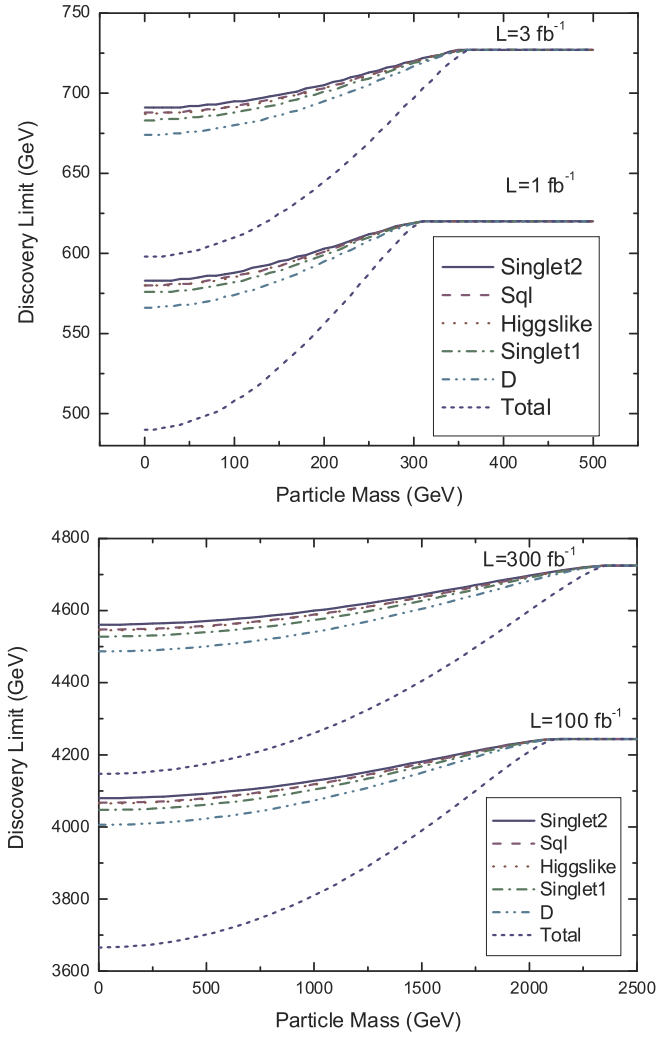

FIG. 13 (color online). The Z' discover limit for the secluded sector E_6 model at the Tevatron and LHC.

Because the representations of E_6 are anomaly free, we consider the three families of SM fermions, one pair of the Higgs doublets (H_u and H_d) from three **27**s, and a number of SM singlets, exotics, and additional Higgs-like doublets. The embedding of the SM fermions is obvious, and we assume that the Higgs doublets (H_u and H_d) are the doublets in **10** (or **5** and $\bar{\mathbf{5}}$) in the third **27**. In addition, we assume that the four SM singlets S, S_1, S_2, S_3 are the S_L, S_L^*, S_L^* and $\overline{N}^*$ respectively in two pairs of **27** and $\overline{\mathbf{27}}$. We include the extra S_L and $\overline{N}$ so that there are three complete pairs from $\mathbf{27} + \overline{\mathbf{27}}$ to avoid anomalies. An H_u and $\overline{H}_u$ pair from $\mathbf{27} + \overline{\mathbf{27}}$ is also introduced for gauge unification. For simplicity, we assume that the other particles in the two pairs of **27** and $\overline{\mathbf{27}}$ are absent or very heavy.

From $Q_S = \frac{1}{2}Q_{S3}$, we obtain

$$\tan\theta = \frac{\sqrt{15}}{9}. \tag{30}$$

The $U(1)'$ charges for the standard model fermions and exotic particles are given in Table I. The general superpotential and soft terms are given in [35,36].

B. The Z' Discovery Limit With A Definite Parameter Set

To discuss the effect of non-SM particles on the Z' discovery limit, we need to specify their mass matrices. We use a specific set of typical Yukawa couplings and soft terms. These were an example of a set which leads to a strong enough first order phase transition for electroweak baryogenesis[5]. The mass spectrum for the various particles are listed in Tables IV, V, and VI.

[5]The parameters we use are slightly different from those used in [36], since here we only use the tree level mass matrix, while in [36] the spectrum is obtained through the full one-loop effective potential. However, the basic features of the strong first order phase transition will not be affected.

We classify the nonstandard model particles into 7 classes. The superpartners of standard model quarks and leptons, the Higgs fields, the neutralinos, the charginos, the Higgs-like exotics, the quark-like exotics, and the singlet exotics. To show their contribution to the discovery limit, we include them one by one into the Z' decay width, in Fig. 11 for the Tevatron and Fig. 12 for the LHC. The line labeled *Sql* corresponds to including the Z' decay into SM fermions and their supersymmetric partners, while other non-SM particles remain too massive to be kinematically allowed. The other lines correspond to adding other non-SM particles one after another. The more particles included, the lower the discovery limit, which can become as small as 560(658) GeV at the Tevatron for $L = 1(3)\ \mathrm{fb}^{-1}$ and 3676(4154) GeV at the LHC for $L = 100(300)\ \mathrm{fb}^{-1}$. The intersection points are given in Tables VII and VIII.

As in the generic discussion of E_6 models, we can vary the non-SM particle masses to see how they affect the discovery limit, as shown in Fig. 13. The only difference is that in this model, we separate the singlets into two groups, *Singlet1* represents the singlets from $3 \times \mathbf{27}$, and *Singlet2* is for the singlets belonging to $\mathbf{27} + \overline{\mathbf{27}}$.

VI. CONCLUSIONS AND DISCUSSIONS

In this paper, we discussed how the Higgs, exotic particles, and supersymmetric partners would affect the Z' discovery limit in E_6 models. We first considered two limiting cases, Z' decays only into standard model particles and Z' decays into all particles with all particles massless. We showed how the total decay width and branching ratios into fermions would differ in these two limiting case, typically by a factor of 5 to 10. We then studied the discovery limits of different E_6 models at the Tevatron and LHC. We showed how the discovery limits would be affected in the two limiting cases and as we varied the masses of the exotic particles and sparticles. From Tables II and III, for example, we see that the discovery limits at the Tevatron (LHC) are typically lowered by as much as 200 GeV (1 TeV) when the Z' can decay into the non-SM particles than for the case of decaying to SM fermions only. As a concrete example, we considered the mass spectrum for a typical set of parameters for the exotics and sparticles for an E_6 model with a secluded sector.

ACKNOWLEDGMENTS

This research was supported in part by the U. S. Department of Energy under Grant No. DOE-EY-76-02-3071.

[1] See M. Cvetič, P. Langacker, and B. Kayser, Phys. Rev. Lett. **68**, 2871 (1992), and references therein.
[2] M. Cvetič and P. Langacker, Phys. Rev. D **54**, 3570 (1996); Mod. Phys. Lett. A **11**, 1247 (1996).
[3] For a review, see, M. Cvetič and P. Langacker, in *Perspectives on supersymmetry*, edited by G. L. Kane (World Scientific, Singapore, 1998), p. 312.
[4] N. Arkani-Hamed, A. G. Cohen, and H. Georgi, Phys. Lett. B **513**, 232 (2001); N. Arkani-Hamed, A. G. Cohen, E. Katz, and A. E. Nelson, J. High Energy Phys. 07 (2002) 034; T. Han, H. E. Logan, B. McElrath, and L. T. Wang, Phys. Rev. D **67**, 095004 (2003).
[5] M. Masip and A. Pomarol, Phys. Rev. D **60**, 096005 (1999).
[6] For a review, see C. T. Hill and E. H. Simmons, Phys. Rep. **381**, 235 (2003); [**390**, 553(E) (2004)].
[7] For reviews, see J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193 (1989); P. Langacker, M. x. Luo, and A. K. Mann, Rev. Mod. Phys. **64**, 87 (1992); A. Leike, Phys. Rep. **317**, 143 (1999); K. S. Babu and C. Kolda, S. Ê Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
[8] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 2192 (1997); D0 Collaboration, V. M. Abazov *et al.*, Phys. Rev. Lett. **87**, 061802 (2001).
[9] S. Capstick and S. Godfrey, Phys. Rev. D **37**, 2466 (1988).
[10] F. Del Aguila, Acta Phys. Pol. B **25**, 1317 (1994).
[11] M. Cvetič and S. Godfrey, hep-ph/9504216.
[12] A. Leike, Ref. [7], and references therein.
[13] S. Godfrey, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics, Snowmass, 2001)* edited by N. Graf, econf C010630, P344 (2001).
[14] M. Dittmar, A. S. Nicollerat, and A. Djouadi, Phys. Lett. B **583**, 111 (2004).
[15] M. Carena, A. Daleo, B. A. Dobrescu, and T. M. P. Tait, Phys. Rev. D **70**, 093009 (2004).
[16] ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. C **12**, 183 (2000); L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. B **479**, 101 (2000); DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. B **485**, 45 (2000); OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. C **33**, 173 (2004); LEP Collaboration, hep-ex/0312023.
[17] P. Langacker and M. x. Luo, Phys. Rev. D **45**, 278 (1992).
[18] J. Erler and P. Langacker, Phys. Lett. B **456**, 68 (1999); Phys. Rev. Lett. **84**, 212 (2000).
[19] G. C. Cho, Mod. Phys. Lett. A **15**, 311 (2000).
[20] K. m. Cheung, Phys. Lett. B **517**, 167 (2001).
[21] See, for example, J. Erler, Nucl. Phys. **B586**, 73 (2000), and reference therein.

[22] L. S. Durkin and P. Langacker, Phys. Lett. B **166**, 436 (1986).
[23] D. London and J. L. Rosner, Phys. Rev. D **34**, 1530 (1986).
[24] M. J. Duncan and P. Langacker, Nucl. Phys. **B277**, 285 (1986).
[25] F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. **B284**, 530 (1987); Nucl. Phys. **B287**, 419 (1987).
[26] V. D. Barger, N. G. Deshpande, J. L. Rosner, and K. Whisnant, Phys. Rev. D **35**, 2893 (1987).
[27] J. R. Ellis, P. J. Franzini, and F. Zwirner, Phys. Lett. B **202**, 417 (1988).
[28] F. del Aguila, J. M. Moreno, and M. Quiros, Phys. Rev. D **41**, 134 (1990); [**42**, 262(E) (1990)].
[29] P. Langacker and M. x. Luo, in Ref. [17].
[30] F. Abe *et al.*, in Ref. [8].
[31] T. Gherghetta, T. A. Kaeding, and G. L. Kane, Phys. Rev. D **57**, 3178 (1998).
[32] See, for example, G. Cleaver, M. Cvetic, J. R. Espinosa, L. L. Everett, P. Langacker, and J. Wang, Phys. Rev. D **59**, 055005 (1999).
[33] T. Hambye, E. Ma, M. Raidal, and U. Sarkar, Phys. Lett. B **512**, 373 (2001).
[34] J. Kang, P. Langacker, and T. Li, Phys. Rev. D **71**, 015012 (2005).
[35] J. Erler, P. Langacker, and T. Li, Phys. Rev. D **66**, 015002 (2002).
[36] J. Kang, P. Langacker, T. j. Li, and T. Liu, Phys. Rev. Lett. **94**, 061801 (2005).
[37] A. Leike, Phys. Lett. B **402**, 374 (1997).
[38] F. del Aguila, J. M. Moreno, and M. Quiros, Phys. Rev. D **40**, 2481 (1989).
[39] V. D. Barger and K. Whisnant, Phys. Rev. D **36**, 3429 (1987).
[40] H. E. Haber and G. L. Kane, Phys. Rep. **117**, 75 (1985).
[41] B. Holdom, Phys. Lett. B **166**, 196 (1986); F. Del Aguila, M. Cvetic, and P. Langacker, Phys. Rev. D **52**, 37 (1995); F. del Aguila, M. Masip, and M. Perez-Victoria, Acta Phys. Pol. B **27**, 1469 (1996); K. S. Babu, C. Kolda, and J. March-Russell, Phys. Rev. D **54**, 4635 (1996).
[42] J. F. Gunion, L. Roszkowski, and H. E. Haber, Phys. Lett. B **189**, 409 (1987); Phys. Rev. D **38**, 105 (1988).
[43] T. Han, P. Langacker, and B. McElrath, Phys. Rev. D **70**, 115006 (2004).