THE ESTIMATION OF THE $Z'$ GAUGE BOSON MASS
IN $E_6$ MODELS

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The aim of this study is to estimate the $Z'$ boson mass by using the calculations of the decay width of $Z'\,(\theta)$ boson. So, the decay width of the extra $Z$ boson is calculated numerically in effective rank 5 models for different mixing angles $\theta$ of the model and for different mass values of the extra $Z$ boson. The decay width of $Z'$ boson to the Standard Model (SM) fermions is found to be between 4.42 and 19.36 GeV and the full decay width of $Z'$ boson to all particles is found to be between 20.88 and 37.15 GeV. We calculated the full decay width at the angle $\theta \approx 0$ for $Z'$ and $Z_2 \rightarrow Z'$. The full decay width of $Z'$ boson is written in a single equation according to our calculations. By using these calculations and the previous works the mass of $Z'$ boson and the number of generations of the exotic particles are estimated.

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INTRODUCTION

Although the Standard Model (SM) is consistent with most of the experimental results, there are some discrepancies at high energy experiments [1]. The SM deals with nature at low energies. Extended gauge bosons seem in many extensions of the SM, like left-right symmetric models and GUTs (Grand Unified Theories), etc. Extra gauge bosons have not been discovered experimentally yet. They will be searched for at LHC experiments [2, 3] starting this year. Hence, the decay widths of $Z'$ boson are calculated here, and using the results of these calculations and also the previous works the mass of $Z'$ is estimated.

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The simplest possible extension of the SM gauge group suggested by a gauge group of larger rank involves the introduction of one extra $U(1)$ factor. This produces an extra neutral gauge boson, $Z'$, in the particle spectrum. By the charges and gauge couplings of the extra $U(1)$ factor, the decay widths of the extra neutral gauge boson to the particles under consideration can be calculated in some energy ranges. The low energy phenomenology of $Z'$ bosons has been extensively discussed in the literature [4]. Recently, particularly strong motivation for having the $Z'$ mass below one TeV has been emphasized by Cvetic and Langacker [5, 6].

In the breakdown of the extended gauge groups such as $E_6$ there can be at most two additional gauge bosons in the low energy spectrum. Since the popular examples of the extended gauge theories are based on supersymmetric GUT groups such as $SO(10)$ and $E_6$, it is decided to study the additional $Z'$ bosons originating from $E_6$. GUTs with larger gauge groups than $SO(10)$ predict more than one extra neutral gauge boson and exotic particles. The mass of $Z'$ is estimated to be between electroweak scale and GUT scale. It is hoped that $Z'$ boson can be observed experimentally at LHC experiments. In our calculations we used the particle content of $E_6$ model in the electroweak breaking of $U(1)$ symmetry [7]. However, for simplicity we will consider an effective rank 5 low energy theory with only one additional gauge boson associated with an extra $U(1)$ and parameterized by

$$Z'(\theta) = Z_\psi \cos \theta - Z_\chi \sin \theta,$$

where $\theta$ is the mixing angle in the $E_6$ group [4], and

(i) $Z_\psi$ occurs when

$$E_6 \rightarrow SO(10) \times U(1)_\psi,$$

(ii) $Z_\chi$ occurs when

$$SO(10) \rightarrow SU(5) \times U(1)_\chi.$$

The orthogonal combination to $Z'(\theta)$ given in Eq.(1) is assumed to have a mass at the intermediate or Planck scale. When $E_6$ breaks directly to a rank 5 group $[SM \times U(1)_\eta]$ as in superstring inspired models via Wilson line breaking, the extra $Z$ boson is denoted by $Z_\eta \equiv \sqrt{5/8}Z_\psi - \sqrt{3/8}Z_\chi$ [4].

The cross section for $Z'(\theta)$ production at hadron colliders is inversely proportional to the $Z'(\theta)$ decay width. To avoid the cross section singularities at some special energies, the decay widths of neutral vector bosons should be known [8].

Here firstly the calculation of the decay width for $E_6$ boson $Z'(\theta)$ to the SM fermions is done for different mixing angles $\theta$ and masses. After that the gauge eigenstates $Z'$ and $Z_0$ are written as a mixture of the mass eigenstates $Z_1$, $Z_2$ and the decay widths of $Z'$ boson to $SU(2)$ bosons $W^+W^-$ and $Z_1H_0^0$ are calculated. The full decay width for $Z'$ boson to the SM particles and to their supersymmetric partners is calculated at the small mixing angle $\theta \approx 0$. By using these calculations and the previous works, the mass of $Z'$ boson and the number of generations of the exotic fermions are estimated.

**CALCULATION**

In the extension of the SM the relevant neutral current (NC) Lagrangian is given as [9]

$$-L_{NC} = g_1 J_{0\mu} Z_0^\mu + g_2 J_{\theta\mu} Z'(\theta),$$

where $\theta$ is the mixing angle in the $E_6$ group [4], and

(i) $Z_\psi$ occurs when

$$E_6 \rightarrow SO(10) \times U(1)_\psi,$$

(ii) $Z_\chi$ occurs when

$$SO(10) \rightarrow SU(5) \times U(1)_\chi.$$
where

\[ J_{0\mu} = \sum_f \bar{f} \gamma_\mu (g_V - g_A \gamma_5) f, \quad J_{0\mu} = \sum_f \bar{f} \gamma_\mu (g'_V - g'_A \gamma_5) f \] (5)

and

\[ g_1 = (g^2 + g'^2)^{1/2} = \frac{e}{2 \sin \theta_W \cos \theta_W} = (\sqrt{2} G_\mu M^2_{Z_0})^{1/2}, \] (6)

\[ g_2 = g_0 = g_1 \sqrt{\frac{5}{3}} \sin \theta_W = (\sqrt{2} G_\mu M^2_{Z_0})^{1/2} \frac{5}{3} \sin \theta_W, \] (7)

here \( \theta_W \) is the Weinberg angle.

The Feynman diagrams for \( Z_0 \rightarrow f\bar{f} \) and \( Z'(\theta) \rightarrow f\bar{f} \) are similar and given in Fig.1. The matrix elements and the cross sections for \( Z_0 \rightarrow f\bar{f} \) and \( Z'(\theta) \rightarrow f\bar{f} \) are also the same formally. Firstly, the equations of \( \Gamma_{Z_0} \) are derived and after that \( \Gamma_{Z'(\theta)} \) is found by using the same formalism. Here we take \( f = \nu, e^- \), and \( \nu = \nu_e, \nu_\mu, \nu_\tau \); \( e = e, \mu, \tau \) leptons; \( u = u, c, t \); \( d = d, s, b \) quarks.

The matrix element for the process \( Z_0(p) \rightarrow f(p_2)\bar{f}(p_1) \) can be written as \([10, 11]\)

\[ M = \bar{u}(p_2) \gamma_\mu (g_V - g_A \gamma_5) v(p_1) Z^\mu_{0}. \] (8)

Multiplying \( M \) with its hermitian conjugate \( M^\dagger \) we obtain

\[ |M|^2 = g^2_1 [\bar{v}(p_1) \gamma_\mu (g_V - g_A \gamma_5) u(p_2)] \times [\bar{u}(p_2) \gamma_\nu (g_V - g_A \gamma_5) v(p_1)] \varepsilon^\mu \varepsilon^\nu = g^2_1 \left( -g_{\mu\nu} + \frac{p_\mu p_\nu}{M^2_{Z_0}} \right) \times \text{Trace} [p_1 \gamma_\mu p_2 \gamma_\nu (g^2_V + g^2_A - 2 g_V g_A \gamma_5)]. \] (9)

After trace calculations and averaging over 3 spin states of \( Z_0 \) boson

\[ |M|^2 = \frac{g^2_1 M^2_{Z_0} C}{3} (g^2_V + g^2_A) \] (10)

is obtained. Here \( C \) is the color factor and \( C = 1 \) for leptons and \( C = 3(1 + \alpha_s(M_{Z_0})/\pi + 1.409(\alpha_s(M_{Z_0})/\pi)^2 - 12.77(\alpha_s(M_{Z_0})/\pi)^3) \) for quarks [12], \( \alpha_s(M_{Z_0}) \) is the strong coupling constant. For two-body decay, in the rest frame of the decaying particle \( |p_1| = |p_2| \), the differential decay width is given by

\[ d\Gamma = \frac{|p_1|}{32 \pi^2 M^2_{Z_0}} |M|^2 d\Omega, \] (11)

where the solid angle is

\[ d\Omega = d\phi_1 d(\cos \theta_1). \] (12)

Then the decay width is obtained as follows:

\[ \Gamma = \frac{1}{16 \pi M_{Z_0}} |M|^2 = \frac{CG_F M^3_{Z_0}}{6\sqrt{2} \pi} (g^2_V + g^2_A). \] (13)
For the SM $Z_0$ boson, the couplings $g_V$ and $g_A$ for $\nu\nu$, $e^+e^-$, $u\bar{u}$, $d\bar{d}$ are calculated as below by using the equations [13]:

$$g_V = T_3^f - 2Q^f \sin^2 \theta_W,$$

and

$$g_A = T_3^f,$$

where $T_3^f$ is the third component of the SM isospin, and $Q^f$ is the charge of fermions in units of the electron charge, i.e., $Q^e = -1$.

In the same manner we can calculate $\Gamma_{Z'(\theta)}$. The matrix element for $Z'(\theta)$ decay and the decay width are given by the following formulas:

$$M = \frac{g_2}{2} \bar{u}(p_2) \gamma_\mu (g'_V - g'_A \gamma_5) u(p_1) Z'(\theta) \mu,$$

$$\Gamma_{Z'(\theta)} = \frac{CM_{Z'(\theta)}}{3 \cdot 16\pi} g_2^2 (g'_V^2 + g'_A^2),$$

where

$$g_2 = g_\theta = \sqrt{\frac{5}{3}} \frac{Q^e}{\cos \theta_W} = \sqrt{\frac{5}{3}} \frac{8M_{Z'(\theta)} G_F \sin^2 \theta_W}{\sqrt{2}}.$$  

By putting Eq. (18) in Eq. (17) we get

$$\Gamma(Z'(\theta) \to f\bar{f}) = \frac{5CM_{Z'(\theta)}M_{Z_0}^2 G_F \sin^2 \theta_W}{18\pi \cdot \sqrt{2}} (g'_V^2 + g'_A^2).$$

For the calculation of $\Gamma_{Z'(\theta)}$, the couplings $g'_V$ and $g'_A$ for $\nu\nu$, $e^+e^-$, $u\bar{u}$, $d\bar{d}$ should be known. These couplings can be calculated by the equations [13]:

$$g'_V = Q'_{fL} + Q'_{fR} + \frac{g_{12}}{g_{22}} (Y_{fL} + Y_{fR}),$$

and

$$g'_A = Q'_{fL} - Q'_{fR} + \frac{g_{12}}{g_{22}} (Y_{fL} - Y_{fR}).$$

In these equations the term with $g_{12}$ can be eliminated because of not requiring any additional symmetry. The breaking of $E_6$ to $SU(5)$ under Eqs. (2) and (3) gives the charge values of $Q_\chi$ and $Q_\psi$ of $U(1)_\chi$ and $U(1)_\psi$ as given in Table 1.

Table 1. The charge values of $Q_\chi$ and $Q_\psi$ of $U(1)_\chi$ and $U(1)_\psi$ from the breaking of $E_6$ under Eqs. (2) and (3)

<table>
<thead>
<tr>
<th>$f$, $\overline{f}$</th>
<th>$2\sqrt{3}Q_\chi$</th>
<th>$2\sqrt{3}Q_\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$, $d$, $\nu$, $\overline{\nu}$</td>
<td>$-1$</td>
<td>$1$</td>
</tr>
<tr>
<td>$\overline{d}$, $\nu$, $e$</td>
<td>$3$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

By using Eqs. (22) and (23) with the equation

$$Q'f = Q_\psi \cos \theta - Q_\chi \sin \theta$$

(22)
we can get the values of $g'_V$ and $g'_A$ of $Z'$ boson. Thus, the decay widths

$$\Gamma(Z'(\theta) \rightarrow \nu\bar{\nu}) = 0.004570 M_{Z'(\theta)} \left( \frac{\cos \theta}{2 \sqrt{6}} - \frac{3 \sin \theta}{2 \sqrt{10}} \right)^2, \quad (23)$$

$$\Gamma(Z'(\theta) \rightarrow e^+e^-) = 0.002283 M_{Z'(\theta)} \left( \frac{2 \sin^2 \theta}{5} + \left( \frac{\cos \theta}{\sqrt{6}} - \frac{\sin \theta}{\sqrt{10}} \right)^2 \right), \quad (24)$$

$$\Gamma(Z'(\theta) \rightarrow \mu\bar{\mu}) = 0.007125 M_{Z'(\theta)} \left( \frac{\cos \theta}{\sqrt{6}} + \frac{\sin \theta}{\sqrt{10}} \right)^2, \quad (25)$$

$$\Gamma(Z'(\theta) \rightarrow d\bar{d}) = 0.007125 M_{Z'(\theta)} \left( \frac{2 \sin^2 \theta}{5} + \left( \frac{\cos \theta}{\sqrt{6}} - \frac{\sin \theta}{\sqrt{10}} \right)^2 \right) \quad (26)$$

are obtained. The total decay width is

$$\Gamma_{\text{tot}}(Z'(\theta) \rightarrow f\bar{f}) = 0.0214 M_{Z'(\theta)} \left( \frac{\cos \theta}{\sqrt{6}} + \frac{\sin \theta}{\sqrt{10}} \right)^2 + 0.0137 M_{Z'(\theta)} \left( \frac{\cos \theta}{2 \sqrt{6}} - \frac{3 \sin \theta}{2 \sqrt{10}} \right)^2 + 0.0282 M_{Z'(\theta)} \left( \frac{2 \sin^2 \theta}{5} + \left( \frac{\cos \theta}{\sqrt{6}} - \frac{\sin \theta}{\sqrt{10}} \right)^2 \right). \quad (27)$$

Total decay width $\Gamma_{\text{tot}}(Z'(\theta) \rightarrow f\bar{f})$ for certain values of $M_{Z'(\theta)}$ and $\theta$ is obtained numerically and is given in Table 2.

**Table 2. Total decay width $\Gamma_{\text{tot}}(Z'(\theta) \rightarrow f\bar{f})$ for certain values of $M_{Z'(\theta)}$ and $\theta$. $\Gamma$ is used for $\Gamma(Z'(\theta) \rightarrow f\bar{f})$, $\Gamma(Z'(\theta) \rightarrow f\bar{f})$, and $M_{Z'(\theta)}$ are in GeV**

<table>
<thead>
<tr>
<th>$M_{Z'(\theta)}$</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\text{tot}}(\theta = 0)$</td>
<td>4.4217</td>
<td>5.3067</td>
<td>6.1905</td>
<td>7.0752</td>
<td>7.9581</td>
<td>8.8464</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(\theta = 37.8)$</td>
<td>5.7825</td>
<td>6.9387</td>
<td>8.0961</td>
<td>9.2520</td>
<td>10.4088</td>
<td>11.5653</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(\theta = 90)$</td>
<td>9.6768</td>
<td>11.6112</td>
<td>13.5465</td>
<td>15.4824</td>
<td>17.4462</td>
<td>19.3524</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(\theta = 127.8)$</td>
<td>8.7723</td>
<td>10.5312</td>
<td>12.2805</td>
<td>14.0349</td>
<td>15.7896</td>
<td>17.5443</td>
</tr>
</tbody>
</table>

In the case of non-zero mass mixing the $Z$, $Z'$ gauge eigenstates which interact with $SU(2)$ $W$ bosons are written in terms of the $Z_1$, $Z_2$ mass eigenstates as

$$\left[ \begin{array} {c} Z \\ Z' \end{array} \right] = \left[ \begin{array} {cc} \cos \theta_M & -\sin \theta_M \\ \sin \theta_M & \cos \theta_M \end{array} \right] \left[ \begin{array} {c} Z_1 \\ Z_2 \end{array} \right]. \quad (28)$$

The decay width for $Z_2 \rightarrow W^+W^-$ occurs for the small mixing angle $\theta_M \rightarrow 1/M_{Z_2}$. This relation between $\theta_M$ and $M_{Z_2}$ is called mass constraint [13]. For large $M_{Z_2}$ the asymptotic Higgs-structure constraint on $\theta_M$ is that the mixing angle $\theta_M$ is proportional to $1/M_{Z_2}^2 [14]$. In the case $\theta_M \approx 1/M_{Z_2}^2$, $\sin \theta_M \rightarrow 0$ and $\cos \theta_M \rightarrow 1$. Therefore, $Z_1 \rightarrow Z_0$ and $Z_2 \rightarrow Z'$. 
In this limit, the decay width for $Z_2 \to W^+W^-$ can be calculated by the equation [13, 14]:

\[
\Gamma(Z_2 \to W^+W^-) = \frac{g_{ZWW}^2 M_{Z_2}}{192\pi} \sin^2 \theta_M \left( \frac{M_{Z_2}}{M_{Z_0}} \right)^4 \left( 1 - 4 \frac{M_W^2}{M_{Z_2}^2} \right)^{3/2} \times \\
\left( 1 + 20 \frac{M_W^2}{M_{Z_2}^2} + 12 \frac{M_W^4}{M_{Z_2}^4} \right),
\]

where $g_{ZWW} = e \cot \theta_W$ [13], $M_{Z_0} = 91.2$ GeV, $M_W = 80.47$ GeV, and $\alpha = e^2/4\pi = 1/137$ is the fine structure constant. The factor $M_{Z_2}^4$ in Eq. (29) is too large. Therefore, the term $\sin^2 \theta_M$ in this equation is taken as $1/M_{Z_2}^2$ because of the Higgs constraint. Then decay widths can be calculated for different masses.

In the large $M_{Z_2}$ limit, the partial decay widths valid for $SU(2)_L \times U(1)_Y \times U(1)'$ model with two Higgs doublets and one Higgs singlet are given in [14]. When the branching fractions $Z_2 \rightarrow W^+W^-$ and $Z_2 \rightarrow Z_1 H_0'$ are the largest, then the decays $Z_2 \rightarrow H^+H^-$ and $Z_2 \rightarrow P^0H_0'$, where $H^+H^-$ and $P^0$ are the physical charged and the pseudoscalar Higgs bosons, respectively, are suppressed. Therefore, we can take $\Gamma(Z_2 \to Z_1 H_0') = \Gamma(Z_2 \to W^+W^-)$.

Using the relation between the decay width for the fermionic SM particles and bosonic supersymmetric superpartners of them in one chiral supermultiplet in the massless limit given in [15] as

\[
\Gamma(Z' \to bb^*) = \frac{1}{2} \Gamma(Z' \to f\bar{f}) = \Gamma(Z' \to \tilde{f}\tilde{f}),
\]

we can write the relationships between the decay widths for winos, zino and higgsino as

\[
\Gamma(Z_2 \to \tilde{W}^+\tilde{W}^-) = 2\Gamma(Z_2 \to W^+W^-) = \Gamma(Z_2 \to Z_0 H^0). \tag{31}
\]

So, the full decay width for $Z'$ boson at the $\theta_M \approx 0$ is

\[
\Gamma_{\text{full}}(Z', Z_2 \to f\bar{f}, \tilde{f}\bar{f}, W^+W^-, \tilde{W}^+\tilde{W}^-, Z_0 H^0, \bar{Z}_0\bar{H}^0) = \\
= \frac{3}{2} \Gamma_{\text{tot}}(Z' \to f\bar{f}) + 6\Gamma(Z_2 \to W^+W^-). \tag{32}
\]

From the last equation, it is obvious that the full decay width of $Z'$ boson is increased at least by 50% when we consider the supersymmetric partners of the SM particles. The full decay width of $Z'$ for the angle $\theta \approx 0$ is given in Table 3.

<table>
<thead>
<tr>
<th>$M_{Z_2}$ (GeV)</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\text{full}}(\theta \approx 0)$</td>
<td>20.8706</td>
<td>24.0341</td>
<td>27.2438</td>
<td>30.4968</td>
<td>32.0972</td>
<td>37.1436</td>
</tr>
</tbody>
</table>
Fig. 2. The plot of decay width for $\Gamma(Z_2 \rightarrow W^+W^-, \tilde{W}^+\tilde{W}^-, Z_0 H^0, \tilde{Z}_0 \tilde{H}^0)$ defined by the line $g(x,0)$ as a function of different values of $M_{Z^{'}}(\theta)$. The other five lines defined by $n_{g1}(x,0), n_{g2}(x,0), n_{g3}(x,0), n_{g4}(x,0)$ and $n_{g5}(x,0)$ in the figure are for the number of generations of exotic fermions with values 1, 2, 3, 4 and 5, respectively, as seen in Eq. (33)

![Image 1](image1.png)

Fig. 3. The plot of $\Gamma_{\text{full}}(Z', Z_2 \rightarrow f\bar{f}, \tilde{f}\bar{f}, W^+W^-, \tilde{W}^+\tilde{W}^-, Z_0 H^0, \tilde{Z}_0 \tilde{H}^0)$ decay widths defined by the line $g2(x,0)$ and $\Gamma(Z_2 \rightarrow W^+W^-, \tilde{W}^+\tilde{W}^-, Z_0 H^0, \tilde{Z}_0 \tilde{H}^0)$ defined by the line $g(x,0)$ as a function of different values of $M_{Z^{'}}(\theta)$. The other five lines defined by $n_{g1}(x,0), n_{g2}(x,0), n_{g3}(x,0), n_{g4}(x,0)$ and $n_{g5}(x,0)$ in the figure are for the number of generations of exotic fermions with values 1, 2, 3, 4 and 5, respectively, as seen in Eq. (33)

![Image 2](image2.png)

By using the equation [14]

$$\Gamma_{Z_2}(\text{GeV}) = (0.6 + 0.6n_g)(M_{Z^{'}} - M_{Z_0}), \quad (33)$$

where $n_g$ is the number of generations of exotic fermions, and Eq. (32) both in the full form and taking only the second term on the right of this equation, we plotted Figs. 2 and 3 for trying to guess the $Z'$ mass at the intersections of the lines of these equations.

**DISCUSSION AND CONCLUSION**

As seen from the calculations, the $Z'$ decays to the $SU(2)$ bosons are considered and the decay width for $W^+W^-, Z_0 H^0$ and for the supersymmetric partners of these bosons
is calculated numerically at the small mixing angle $\theta_M$ which is defined by Higgs mass constraint as well as the calculation of the $Z'$ decays to the SM fermions and to the sparticles of the SM particles. The full decay width of $Z'$ boson is written by Eq. (32) according to our calculations. By using the calculations of $Z'$ boson decay widths, we drew Figs. 2 and 3. From Fig. 2, the mass of $Z'$ boson can be decided to be about 630 GeV when we plot only the second term on the right of Eq. (32) with Eq. (33) for different values of $n_g$ as a function of decay width versus different masses of $Z'$ boson. The intersection occurs first for $n_g = 3$. Since the decaying particle is the same, it must have the same mass estimated by Fig. 2 when we plot a figure including the full decay of $Z'$ boson to all particles. Therefore, in Fig. 3, we plotted Eq. (32) in the full form together with the second term on the right of this equation as we drew in Fig. 2. In this case, again the intersection occurs with the mass of $Z'$ about 630 GeV for $n_g = 5$. Therefore, it is estimated that the mass of $Z'$ boson is about 630 GeV and the number of generations of the exotic fermions is to be 3 or 5. The collider LHC is designed to collide the protons with a center-of-mass energy 14 TeV. Since the center-of-mass energy of proton–proton collisions at LHC is 14 TeV, the particle cascades coming from the collisions might contain $Z'$ if the mass is below 1 TeV as calculated in this work. Therefore, we conclude that $Z'$ boson can be discovered at LHC.

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