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The $Z, Z' \to \gamma\gamma\gamma$ decays in the minimal 331 model

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Abstract. A complete calculation at one-loop level for the $Z, Z' \to \gamma\gamma\gamma$ decays is presented in the context of the minimal 331 model, which predicts the existence of a new $Z'$ neutral gauge boson, $Y^+, Y^-$ charged gauge bosons, new exotic quarks and charged scalars. Bose symmetry is exploited to write a compact and manifest $SU_C(3)$-invariant vertex function for the $\gamma\gamma\gamma V^0$ coupling. Previous results on the $Z \to \gamma\gamma$ are reproduced ($\text{Br}(Z \to \gamma\gamma) \sim 10^{-10}$). It is found that this decay is insensitive to the effects of new heavy particles. This contrasts with the $Z' \to \gamma\gamma\gamma$ decay where the associated branching ratio is of the order of $10^{-6}$.

1. Introduction

In this work, we will study some properties of the $Z'$ gauge boson predicted by the minimal 331 model [1]. Particularly, we are interested in studying the rare decay of this $Z'$ gauge boson into three photons. This type of decay is naturally suppressed in renormalizable theories, as they first arise at the one-loop level. The analogous decay in the Standard Model (SM) $Z \to \gamma\gamma\gamma$ is very suppressed, with a branching ratio of the order of $10^{-10}$ GeV [2].

2. The minimal 331 model

The minimal 331 model is based on the $SU_C(3) \otimes SU_L(3) \otimes U_X(1)$ gauge group. The $SU_C(3)$ group represents strong interactions and the $SU_L(3) \otimes U_X(1)$ group is the simplest extension of the electroweak gauge group. The minimal 331 model predicts new exotic quarks, new gauge bosons and scalars, among them a new neutral gauge boson $Z'$ is expected at the TeV scale [1]. This model offers a possible solution to the family replication problem: anomalies cancel out when all families are summed over, which suggests that the family number must be 3. The lepton spectrum of the model is accommodated as antitriplets of $SU_L(3)$:

$$L_{1,2,3} = \begin{pmatrix} e \\ \nu_e \\ e^c \\ \mu \\ \nu_\mu \\ \mu^c \\ \tau \\ \nu_\tau \\ \tau^c \end{pmatrix} : (1, 3^*, 0).$$

Two quark generations are arranged as triplets and the other one as an antitriplet:

$$Q_{1,2} = \begin{pmatrix} u \\ d \\ c \\ s \\ D \end{pmatrix} : (3, 3, -1/3);$$
$Q_3 = \begin{pmatrix} b \\ t \\ T \end{pmatrix} : (3,3^*,2/3);$

The right-handed quarks are given as follows:

d', s', b' : (3^*, 1, 1/3); 
D', S' : (3^*, 1, 4/3), 
u', e', t' : (3^*, 1, -2/3); 
T' : (3^*, 1, -5/3).

The $D$, $S$ and $T$ particles are new exotic quarks with charges $-4/3$, $-4/3$ and $+5/3$, respectively. Henceforth, we denote exotic quarks with $Q$. The scalar sector of the minimal 331 model is comprised of three triplets and one sextet of $SU_L(3)$:

$$
\phi = \begin{pmatrix} \Phi_Y \\ \phi^0 \end{pmatrix} : (1, 3, 1), \quad \phi_1 = \begin{pmatrix} \Phi_1 \\ \delta^- \end{pmatrix} : (1, 3, 0), 
\phi_2 = \begin{pmatrix} \tilde{\Phi}_2 \\ \rho^- \end{pmatrix} : (1, 3, -1)
$$

$$
H = \begin{pmatrix} T \\ \Phi_3/\sqrt{2} \\ \eta^0 \end{pmatrix} : (1, 6, 0).
$$

The spontaneous symmetry breaking occurs in the following way: $SU_L(3) \otimes U_Y(1) \phi_Y \rightarrow SU_L(2) \otimes U_Y(1) \phi_V U_{e}(1)$, where $\phi_Y$ gives masses to the new exotic quarks $D, S, T$ and to the new heavy gauge bosons $Z', Y^{\pm}, Y'$. 

3. **Vertex $\gamma\gamma V^0$, with $V \equiv Z, Z'$**

The amplitude of the $\gamma\gamma V^0$ vertex can be written according to the spin of particles circulating in the loops (see Figure 1). This is possible since we calculate the gauge particle contribution using covariant $R_\xi$ gauges [3], which render finite and gauge invariant contributions

$$
M_{\gamma\gamma V^0} = M_{1/2} + M_1 + M_0,
$$

where $M_{1/2}, M_1$ and $M_0$ are, respectively, the spinorial, vectorial and scalar amplitudes.

In Fig. 1, $X$ represents the type of particle circulating in the loops: fermions: $u, d, s, c, b, t, D, S, T, e, \mu, \tau$, gauge bosons: $W^+, Y^+, Y^{++}$ auxiliary-pseudo scalar fields: $G_W^+, C_B^+, C_W^+, G_W^+$, $C_Y^+, G_Y^+, C_Y^+$, $C_Y^{++}$ and scalars: $h_1^+, h_2^+, h_3^+, h_4^+, d_1^+, d_2^+, d_3^+$ [3]. For each fermion: 6 boxes, for each gauge boson and scalar: 6 boxes, 12 triangles and 3 bubbles.

Once the loop integrals are computed, the amplitudes can be expressed in terms of gauge structures and their associated form factors as follows:

$$
M_{\gamma\gamma V^0} = \frac{i g e^3}{2 c_W} \sum_{i=1}^{18} (F_{V_2}^1 + F_{V_2}^0 + F_{V_2}^1) T_{\gamma\gamma V^0}^{p_i p_j p_k p_l}.
$$

Bose statistics imposes that the amplitudes must be symmetric under the interchanges of pairs of photons: $(p_1, p_2) \leftrightarrow (p_3, p_4)$. Gauge invariance is satisfied: $p_{i\mu} M_{\gamma\gamma V^0}^{\mu \nu \rho \sigma} = 0$.

There are 18 Lorentz structures:

$$
T_{V_{1/2}}^{p_1 p_2 p_3 p_4} = (p_{12} g_{12} - p_{21} g_{21})(p_{13} g_{13} - p_{23} g_{23})(p_{14} g_{14} - p_{24} g_{24}), 
T_{V_{1/2}}^{p_1 p_2 p_3} = (p_{13} p_{21} - p_{12} p_{31})(p_{23} g_{23} - p_{32} g_{32}) g_{24}, 
T_{V_{13}}^{p_1 p_2 p_3} = (p_{13} g_{13} - p_{12} g_{12})(p_{23} g_{23} - p_{32} g_{32}) + (p_{12} g_{12} - p_{13} g_{13}) g_{24} g_{34}.
$$

where $p_{ij} = p_i \cdot p_j$. The rest of structures are obtained from these ones by Bose symmetry. $F_{V_{1/2}}$ are finite scalar form factors in terms of Passarino-Veltman functions [3].


4. The $Z \to \gamma\gamma\gamma$ and $Z' \to \gamma\gamma\gamma$ decays

By using the formula for calculating the decay width [3, 4], we can discuss the impact of new physics on the $Z \to \gamma\gamma\gamma$ decay. To perform this, we consider the scenario: $m_Q = 500$ GeV and $m_Y = m_H = 250$ GeV. The relative importance of each type of contribution is shown in Table 1. The Particle Data Group reports that $\Gamma(Z \to \gamma\gamma\gamma) < 10^{-5}$ GeV [4]. However, the SM prediction states that $\Gamma(Z \to \gamma\gamma\gamma) = 1.35 \times 10^{-9}$ GeV with an associated branching ratio of $5.41 \times 10^{-10}$. In contrast, the minimal 331 model prediction is $\Gamma(Z \to \gamma\gamma\gamma) = 1.31 \times 10^{-9}$ GeV with a respective branching ratio of $5.26 \times 10^{-10}$[3].

| Sector                | Br            |
|-----------------------|---------------|
| Fermions              | $4.16 \times 10^{-10}$ |
| Gauge Bosons          | $1.03 \times 10^{-11}$ |
| Scalar                | $3.04 \times 10^{-13}$ |
| Fermions-Gauge Bosons | $9.92 \times 10^{-11}$ |
| Fermions-Scalar       | $-5.90 \times 10^{-14}$ |
| Total                 | $5.26 \times 10^{-10}$ |

Table 1. Contributions by spin of particle to the $\text{Br}(Z \to \gamma\gamma\gamma)$ in the scenario: $m_Q = 500$ GeV and $m_Y = m_H = 250$ GeV.

As referred to the minimal 331 model, it imposes the theoretical restriction $\frac{m_Y}{m_{Z'}} < 0.26$ [5], whereas lower bounds on $m_Y$ and $m_{Z'}$ obtained from experimental data restrict this ratio to be $0.19 < \frac{m_Y}{m_{Z'}}$ [5]. The most promising scenario occurs when $m_Q = 500$ GeV, $\frac{m_Y}{m_{Z'}} = 0.19$, $m_Y = 275.5$ GeV and $m_H = 250$ GeV. The total contribution to $\text{Br}(Z' \to \gamma\gamma\gamma)$ can be appreciated in Fig. 2. From this figure, we can see that the branching ratio for the $Z' \to \gamma\gamma\gamma$ is mainly of the order of $10^{-6}$. For further details of calculation and analysis see Reference [3].

5. Final remarks

The minimal 331 model predicts new physics at energy relatively near to the Fermi scale and gives a possible solution to the fermion family replication problem. The $Z \to \gamma\gamma\gamma$ decay is insensitive to the presence of the new physics provided by the minimal 331 model. We corroborate that...
Br(Z → γγγ) ∼ 10^{-10}. For the Z' → γγγ decay, the best signal is Br(Z' → γγγ) ∼ 1.07 × 10^{-6} when \( m_{Z'} = 1.45 \text{ TeV} \) in the scenario \( m_Q = 500 \text{ GeV}, m_Y/m_{Z'} = 0.19, \) \( m_Y = 275.5 \text{ GeV} \) and \( m_H = 250 \text{ GeV} \).

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