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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 $Z \to \gamma\gamma\gamma$ are reproduced (Br($Z \to \gamma\gamma\gamma$) $\sim 10^{-10}$). 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 $SU_L(3)$:

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

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

$$Q_{1,2} = \begin{pmatrix} u \\ d \\ D \end{pmatrix}, \begin{pmatrix} c \\ s \\ S \end{pmatrix} : \ (3, 3, -1/3);$$

$$Q_3 = \begin{pmatrix} b \\ t \\ T \end{pmatrix} : \quad (3, 3^*, 2/3);$$

The right-handed quarks are given as follows:

$$d^c,\ s^c,\ b^c : \quad (3^*, 1, 1/3); \quad D^c,\ S^c : \quad (3^*, 1, 4/3),$$
$$u^c,\ c^c,\ t^c : \quad (3^*, 1, -2/3); \quad T^c : \quad (3^*, 1, -5/3).$$

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 $SU_L(3)$:

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

$$\Phi_2 = \begin{pmatrix} \tilde{\Phi}_2 \\ \rho^{--} \end{pmatrix} : \ (1,3,-1)$$

$$H = \begin{pmatrix} T & \tilde{\Phi}_3/\sqrt{2} \\ \tilde{\Phi}_3^T/\sqrt{2} & \eta'^0 \end{pmatrix} \quad : \quad (1,6,0)\ .$$

The spontaneous symmetry breaking occurs in the following way: $SU_L(3) \otimes U_X(1) \stackrel{\phi_Y}{\longrightarrow} SU_L(2) \otimes U_Y(1) \stackrel{\phi_1,\phi_2,H}{\longrightarrow} U_e(1)$, where ϕ_Y gives masses to the new exotic quarks D , S , T and to the new heavy gauge bosons Z' , $Y^{\pm\pm}$, $Y^{\pm}$.

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

The amplitude of the $\gamma\gamma\gamma V^0$ 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 particles contribution using covariant R_ξ gauges [3], which render finite and gauge invariant contributions

$$\mathcal{M}_{\gamma\gamma\gamma V^0} = \mathcal{M}_{1/2} + \mathcal{M}_1 + \mathcal{M}_0,$$

where $\mathcal{M}_{1/2}$, $\mathcal{M}_1$ and $\mathcal{M}_0$ 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, μ, τ, gauge bosons: W^+, Y^+, Y^{++} auxiliar-pseudo scalar fields: G^+_W, C^+_W, $\bar{C}^+_W$, G^+_Y, C^+_Y, $\bar{C}^+_Y$, G^{++}_Y, C^{++}_Y, $\bar{C}^{++}_Y$ 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:

$$\mathcal{M}^{\mu_1\mu_2\mu_3\mu_4}_{\gamma\gamma\gamma V^0} = \frac{i}{\pi^2}\frac{ge^3}{2c_W}\sum_{i=1}^{18}\left(F^{\frac{1}{2}}_{V^0 i} + F^1_{V^0 i} + F^0_{V^0 i}\right)T^{\mu_1\mu_2\mu_3\mu_4}_i .$$

Bose statistics imposes that the amplitudes must be symmetric under the interchanges of pairs of photons: $(p_1,\mu_1) \leftrightarrow (p_2,\mu_2) \leftrightarrow (p_3,\mu_3)$. Gauge invariance is satisfied: $p_{i\mu_i}\mathcal{M}^{\mu_1\mu_2\mu_3\mu_4}_{\gamma\gamma\gamma V^0} = 0$. There are 18 Lorentz structures:

$$\begin{aligned}
T^{\mu_1\mu_2\mu_3\mu_4}_{V1} &= (p_{12}g^{\mu_1\mu_2} - p_2^{\mu_1}p_1^{\mu_2})(p_{13}g^{\mu_3\mu_4} - p_1^{\mu_3}p_3^{\mu_4}),\\
T^{\mu_1\mu_2\mu_3\mu_4}_{V7} &= (p_{13}p_2^{\mu_1} - p_{12}p_3^{\mu_1})(p_{23}g^{\mu_2\mu_3} - p_3^{\mu_2}p_2^{\mu_3})p_2^{\mu_4},\\
T^{\mu_1\mu_2\mu_3\mu_4}_{V13} &= (p_{13}g^{\mu_1\mu_2} - p_3^{\mu_1}p_1^{\mu_2})(p_{23}g^{\mu_3\mu_4} - p_2^{\mu_3}p_3^{\mu_4})\\
&\quad +(p_{12}p_3^{\mu_1} - p_{13}p_2^{\mu_1})(p_3^{\mu_2}g^{\mu_3\mu_4} - p_3^{\mu_4}g^{\mu_2\mu_3}).
\end{aligned}$$

where $p_{ij} \equiv p_i \cdot p_j$. The rest of structures are obtained from these ones by Bose symmetry. $F_{V^0_i}$ are finite scalar form factors in terms of Passarino-Veltman functions [3].

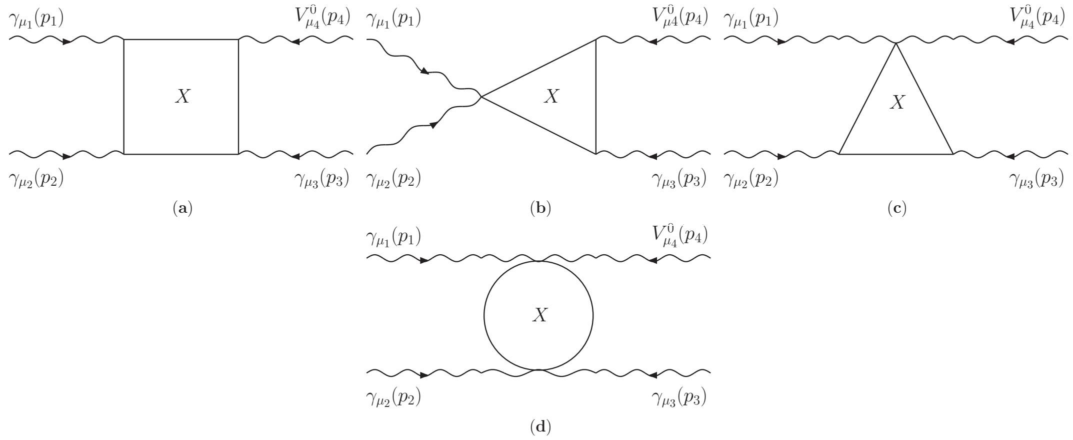

Figure 1. Feynman diagrams contributing to the $V^0 \to \gamma\gamma\gamma$ decay. Fermions only contribute through box diagrams as shown in (a).

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 5.41×10^{-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 5.26×10^{-10}[3].

Sector	Br
Fermions	4.16×10^{-10}
Gauge Bosons	1.03×10^{-11}
Scalar	3.04×10^{-13}
Fermions-Gauge Bosons	9.92×10^{-11}
Fermions-Scalar	-5.90×10^{-14}
Gauge Bosons-Scalar	4.30×10^{-13}
Total	5.26×10^{-10}

Table 1. Contributions by spin of particle to the 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 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 physic 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

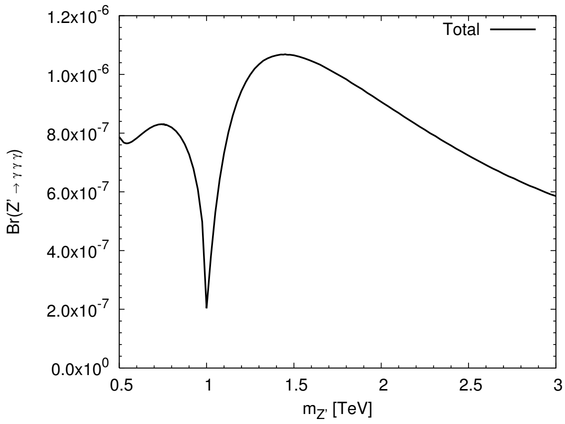

Figure 2. Total contribution to $\mathrm{Br}(Z' \to \gamma\gamma\gamma)$ as a function of $m_{Z'}$.

$\mathrm{Br}(Z \to \gamma\gamma\gamma) \sim 10^{-10}$. For the $Z' \to \gamma\gamma\gamma$ decay, the best signal is $\mathrm{Br}(Z' \to \gamma\gamma\gamma) \sim 1.07 \times 10^{-6}$ when $m_{Z'}$ =1.45 TeV in the scenario $m_Q = 500$ GeV, $m_Y/m_{Z'}$=0.19, m_Y =275.5 GeV and $m_H = 250$ GeV.

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