

DO-TH-95/05
NIIG-DP-95-1
April, 1995

Baryon and Lepton Number Assignment in E_6 Models

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Abstract

In E_6 models there are new particles whose baryon number is not uniquely assigned. We point out that the baryon and lepton number assignment to these particles can change the baryogenesis scenario significantly. We consider left-right symmetric extension of the standard model in which $(B - L)$ quantum number is gauged. The identification of $(B - L)$ with a generator of E_6 is used to define the baryon and lepton numbers for the exotic particles in a way that the electroweak baryon and lepton number anomaly corresponding to the $SU(2)_L$ group vanishes, *i.e.*, there is no non-perturbative baryon or lepton number violation during the electroweak phase transition. We study some consequences of the new assignment.

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In the standard model and its generalizations to Grand Unified Theories (GUTs) the quantum number $(B - L)$ is conserved [1]. In fact, it has been proven that the gauge bosons of GUTs can not decay to light fermions, which are classified in $SU(3)_c \times SU(2)_L \times U(1)_Y [\equiv G_{std}]$ group, by violating the $(B - L)$ quantum number [2]. In addition, it is known that the contributions of the $SU(2)_L$ anomaly to the baryon and lepton current satisfies [3],

$$\begin{aligned}\partial j_B &\sim N_g(3B_q + B_l)\text{Tr}F\tilde{F} \\ \partial j_L &\sim N_g(3L_q + L_l)\text{Tr}F\tilde{F}\end{aligned}$$

where, $B_q = 1/3$ and $B_l = 0$ are baryon numbers and $L_q = 0$ and $L_l = 1$ are lepton numbers for quarks and leptons, respectively and N_g the number of generations. This implies,

$$\partial(j_B - j_L) = \partial(j_{(B-L)}) = 0 \tag{1}$$

The aim of this paper is to investigate the assignment of quantum numbers of the new (exotic) fermions, which appear in the group E_6 [1, 4, 5, 6] and study the anomalies generated for the B and L currents. We are interested to produce at a high energy scale (cosmological) B and L asymmetries and investigate their development to low temperature, that is the present epoch of the universe. For the sake of clarity, we present a general discussion on the origin and conservation of the B and L quantum numbers.

We begin discussing the origin of the $(B - L)$ quantum number. The B and L quantum numbers are globally conserved in the Standard Model and they prevent proton decay. This follows from the internal symmetry and Lorentz invariance of the theory. B and L are not conserved locally because ψ_L and ψ_R transform differently. In higher groups like $SU(2)_L \times SU(2)_R \times U(1)_{B-L} [\equiv G_{LR}]$ [7] or $SO(10)$ [1], we can treat left- and right-handed particles on equal footing and there is a new generator of the enlarged group corresponding to $(B - L)$.

This points to ways of breaking B and L . In the standard model we can break the global symmetries or a linear combination of them spontaneously, which implies a Goldstone boson. This is unphysical. The second method is breaking the local symmetry spontaneously.

In extensions of the standard model G_{std} or the left-right symmetric model G_{LR} , $(B + L)$ is explicitly broken. The breaking manifests itself as four-fermion operators composed of quarks and leptons which have dimension six. An enumeration of the operators reveals [2] that all dimension -6 B -violating operators which can be constructed from the known quarks and leptons conserving G_{std} and Lorentz invariance have $B - L = 0$ and $B + L = 2$. Operators with $(B - L) \neq 0$ have higher dimension and are suppressed by factors (M_W/M_{GUT}) .

A second contribution to the violation of baryon number is through $SU(2)_L$ anomalies, discussed at the beginning of this paper. The anomalies break $(B + L)$ and again preserve $(B - L)$. Thus the anomalies can wash out any $(B + L)$ asymmetry discussed [8] but will preserve a $(B - L)$ asymmetry with the possible transformation of $\Delta(B - L) \rightarrow \Delta B$ [9].

The above discussions indicates that it is difficult to create a $(B - L)$ asymmetry through couplings of the standard fermions, because

1. there are no lowest dimension operators with $B - L \neq 0$ and higher order operators are suppressed by M_W/M_{GUT}
2. there is no $(B - L)$ anomaly which will generate or wash out a $(B - L)$ asymmetry.

These considerations motivated us to investigate the assignment of quantum numbers B and L to fermions in the group E_6 which contains new fermions.

In E_6 GUT, all the chiral fermions belong to the fundamental **27** representation. They are presented in table 1 with the quantum number for

Table 1: Quantum numbers of the fermions in terms of the subgroup $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y_L} \otimes U(1)_{Y_R}$ of E_6

Left-handed fermions		$SU(3)_c$	I_{3L}	I_{3R}	Y_L	Y_R	Q
STANDARD FERMIONS	$Q = \begin{pmatrix} u \\ d \end{pmatrix}$	3	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	0	$\frac{1}{3}$	0	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$
	u^c	$\bar{3}$	0	$-\frac{1}{2}$	0	$-\frac{1}{3}$	$-\frac{2}{3}$
	d^c	$\bar{3}$	0	$\frac{1}{2}$	0	$-\frac{1}{3}$	$\frac{1}{3}$
	$L_1 = \begin{pmatrix} \nu \\ e \end{pmatrix}$	1	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	0	$-\frac{1}{3}$	$-\frac{2}{3}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
	e^c	1	0	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	1
	ν^c	1	0	$-\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0
EXOTIC FERMIONS	D_1	3	0	0	$-\frac{2}{3}$	0	$-\frac{1}{3}$
	D_2	$\bar{3}$	0	0	0	$\frac{2}{3}$	$\frac{1}{3}$
	$L_2 = \begin{pmatrix} N_1 \\ E_1 \end{pmatrix}$	1	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
	$L_3 = \begin{pmatrix} E_2 \\ N_2 \end{pmatrix}$	1	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
	L_s	1	0	0	$\frac{2}{3}$	$-\frac{2}{3}$	0

the diagonal generators. The electric charge is defined in terms of the E_6 generators as,

$$Q = T_{3L} + \frac{Y}{2} = T_{3L} + T_{3R} + \frac{Y_L + Y_R}{2}.$$

For the fermions present in the standard model, the baryon and lepton number assignments are known from experiment. In the notation of table 1:

$$[B = \frac{1}{3}, L = 0] \text{ for } (\mathbf{Q}, \overline{\mathbf{u}}^c, \overline{\mathbf{d}}^c) \text{ and } [B = 0, L = 1] \text{ for } (\mathbf{L}_1, \overline{\mathbf{e}}^c, \overline{\nu}^c).$$

Baryon and lepton numbers are not uniquely defined for the exotic fermions $D_1, D_2, N_1, E_1, N_2, E_2$ and L_s and we shall assign them in a systematic manner. The Yukawa part of the lagrangian invariant under E_6 is,

$$\begin{aligned} \mathcal{L} = & \lambda_{uu} Q^T u^c H_3 + \lambda_{dd} Q^T d^c H_2 + \lambda_{dD} Q^T D_2 H_1 + \lambda_{DD} D_1^T D_2 S_2 \\ & + \lambda_{Dd} D_1^T d^c S_1 + \lambda_{Ee} L_2^T e^c H_1 + \lambda_{ee} L_1^T e^c H_2 + \lambda_{EE} L_3^T L_2 S_2 + \lambda_{eE} L_1^T L_3 S_1 \\ & + \lambda_1 L_2^T L_s H_3 + \lambda_2 L_3^T L_s H_2 + \lambda_3 L_3^T \nu^c H_1 + \lambda_4 L_1^T \nu^c H_3 + h.c. \end{aligned} \quad (2)$$

We used the convention, $\overline{\psi}^c = \psi^T \mathcal{C}$ and have not written the \mathcal{C} operator explicitly.

In writing down this lagrangian we have considered the minimal E_6 model, which might have its origin in the superstring theory. All higgs scalars belong to the fundamental **27**-representation of E_6 . For studying the low energy effective theory for the baryon nonconservation, we write down only the higgs fields which can acquire *vevs*. We list them in table 2. The $SU(2)_L$ doublets are written as H_i , while the singlets as S_i .

The first term contributes to the up-type quarks mass. The next four terms give the mass matrices for the charge (-1/3) particles, *i.e.*, the down-type quarks and the exotic charge (-1/3) color triplets. The next four terms will contribute to the charged lepton mass matrices, *i.e.*, the usual charged leptons and the exotic charge (-1) color singlet particles. The eight and the ninth terms, along with the rest of the terms will contribute to the mass

Table 2: Quantum numbers of the higgs scalars in terms of the subgroup $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y_L} \otimes U(1)_{Y_R}$ of E_6

Higgs	$SU(3)_c$	I_{3L}	I_{3R}	Y_L	Y_R	Q
H_1	1	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	0	$-\frac{1}{3}$	$-\frac{2}{3}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
H_2	1	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
H_3	1	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
S_1	1	0	$-\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	0
S_2	1	0	0	$\frac{2}{3}$	$-\frac{2}{3}$	0

matrices of the neutral fermions. The baryon and the lepton numbers of the scalars H_2 and H_3 are determined through their Yukawa couplings with the usual fermions to be $B = 0$ and $L = 0$.

We now extend our knowledge of $B-L$ quantum numbers for the standard to the exotic fermions. We demand that $B-L$ is a local symmetry in the left-right extended theory for the exotic fermions of E_6 as well. This is equivalent to saying that $G_{LR} \subset E_6$ or $SO(10) \subset E_6$ (which is usually done). This means that we relate the B and L quantum numbers and the maximal subgroup of E_6 for the exotic fermions in the same way as it is for the standard fermions,

$$(B - L) = Y_L + Y_R. \quad (3)$$

In this case $(B - L)$ is a gauge symmetry and the interesting features of the $SO(10)$ model arising from the gauged $(B - L)$ symmetry directly follow.

The identification of the $(B - L)$ quantum number with the generators of E_6 , eq. (3), does not give unique values for the baryon and lepton numbers of the exotic particles. We exploit this freedom and choose the B and L quantum numbers of the new particles such that the sum total of contributions to $(B + L)$, from standard and exotic particles, add up to zero. Then the extension of the standard model is $SU(2)_L$ anomaly free¹.

D_1 and D_2 are singlets under $SU(2)_L$, they cannot contribute to the anomaly, which does not help us in assigning them B and L number. So we impose one more logical constraint that these particles do not carry lepton number. Similarly, for the singlet particle L_s we impose that it does not carry baryon number.

We now turn to the $SU(2)$ anomaly and find that as long as the sum of the baryon numbers of L_2 and L_3 is -1 , the global B anomaly corresponding to the group $SU(2)_L$ is zero. Similarly for vanishing lepton anomaly the lepton numbers of L_2 and L_3 should add up to -1 . Then demanding the validity of eq. (3), we fix the baryon and lepton numbers of these particles.

The baryon and lepton number anomaly corresponding to the group $SU(2)_L$ can mediate baryon number violation only through non-perturbative effects during the electroweak phase transition, which vanishes for the following choice of baryon and lepton numbers for the exotic particles,

$$\begin{aligned}
 [B = -\frac{2}{3}; L = 0] \text{ for } (\mathbf{D}_1, \overline{\mathbf{D}}_2) & \quad [B = 0; L = 0] \text{ for } (\mathbf{L}_s) \\
 \text{and} \quad [B = -\frac{1}{2}; L = -\frac{1}{2}] \text{ for } (\mathbf{L}_2, \mathbf{L}_3) &
 \end{aligned}$$

In general, the couplings of the gauge bosons to fermions produce change

¹ The absence of the $(B + L)$ anomaly has another consequence that any primordial lepton asymmetry will not be changed into the baryon asymmetry. Hence the bounds on the R-parity violating (L -violating) couplings [11] does not hold.

for ΔB and ΔL at each vertex. For vertices where both standard and exotic fermions couple to the same gauge bosons we may ask if the changes for ΔB and ΔL are the same or different. This question is relevant for the couplings of (X, Y) and (X', Y') bosons in the notation $SO(10)$ or $SU(5)$. Each vertex produces the same $\Delta(B-L)$ for all fermions, since $B-L$ is gauged. However, $\Delta(B+L)$ is different for standard and exotic fermions, because $(B+L)$ is just a global symmetry which can be broken consistently with gauge symmetry, E_6 .

It is still necessary to make the assignment consistent with the lifetime of proton and produce realistic fermion masses. This is achieved by introducing discrete symmetries. We introduce a \mathcal{Z}_2 symmetry, under which,

$$\{D_1, D_2, L_2, L_3\} \rightarrow -\{D_1, D_2, L_2, L_3\} \quad (4)$$

and all other particles remaining unchanged. The lagrangian will then be given by,

$$\begin{aligned} \mathcal{L} = & \lambda_{uu} Q^T u^c H_3 + \lambda_{dd} Q^T d^c H_2 + \lambda_{DD} D_1^T D_2 S_2 + \lambda_{ee} L_1^T e^c H_2 \\ & + \lambda_{EE} L_3^T L_2 S_2 + \lambda_4 L_1^T \nu^c H_3 + h.c. \end{aligned} \quad (5)$$

The down quark mass matrix as well as the charged lepton mass matrix are now diagonal. We assume the mass of the exotic particles are in the range of 100 GeV, so that this provides a rich E_6 phenomenology [4]. In addition, these particles contribute to the diagrams which produce the $SU(2)_L$ anomaly during the electroweak phase transition. The field H_1 now carries $(B-L)$ quantum number but does not contribute to the mass of any particle and hence need not acquire vev . S_1 carries $(B-L)$ quantum number and its vev breaks the group $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ at a scale close to the GUT scale or at an intermediate scale.

There is still a problem with the neutrino masses, as it is the case in most superstring inspired E_6 -models. It can be solved with one additional **351**

scalar representation, which gives large majorana mass to the fields ν^c and L_s , which in turn induce the see-saw mechanism. Another possibility is for gravity to induce an effective term, which is similar to the coupling of the fields in **351** [6].

The fields H_2 and H_3 carry zero baryon and lepton numbers. The coupling of the scalar S_2 with coefficient λ_{DD} requires this field to have $B = L = 0$, but the coupling with coefficient λ_{EE} requires $B = L = 1$. These two couplings together will give rise to baryon and lepton number violation, which has to be prevented. However, since these fields do not couple to the ordinary particles directly, there is no danger of proton decay. But their interactions can wash out any baryon asymmetry of the universe, which must be suppressed.

These couplings can give rise to baryon number violation through decays of S_2 , shown in fig. 1, and through scattering processes,

$$D_1 + D_2 \rightarrow L_2 + L_3$$

shown in fig. 2. These processes must be slow enough so that they are not in equilibrium during the electroweak phase transition and destroy the baryon asymmetry of the universe. In other words, the decay rates of the field $S_2 \rightarrow L_2+L_3$ and D_1+D_2 , as well as the scattering rates for $L_2+L_3 \rightarrow D_1+D_2$ at temperature $T = M_S$ must be slower than the expansion rate of the universe,

$$\left\{ \frac{\lambda_{EE}^2}{16\pi} M_S, \frac{\lambda_{DD}^2}{16\pi} M_S, \lambda_{EE}\lambda_{DD} \frac{T^5}{(T^2 + M_S^2)^2} \right\} \leq 1.7\sqrt{g_*} \frac{T^2}{M_{Pl}} \quad (6)$$

All these conditions can be satisfied provided,

$$\lambda_{EE} \leq 10^{-5} \quad \text{and} \quad \lambda_{DD} \leq 10^{-5}, \quad (7)$$

which implies an intermediate symmetry breaking scale, $M_S \sim \langle S_2 \rangle \geq 10^7$ GeV. So far we assigned B and L quantum numbers to the exotic particles

and discussed the conditions under which the model is not ruled out by experiments. The above conditions guarantee the consistency of the model but they are not unique; alternative conditions consistent with our B and L assignment are also possible.

As mentioned at the beginning of this article, in standard GUTs (without any extra fermions beyond the standard model), the operator analysis [2], reveals that all baryon number violating lowest dimensional operators, invariant under the standard model gauge group, can be written in the forms $\mathbf{q}_L^T \mathbf{q}_L \mathbf{q}_L^T \mathbf{l}_L$; $\mathbf{q}_L^T \mathbf{q}_L \mathbf{q}_R^T \mathbf{l}_R$; $\mathbf{q}_R^T \mathbf{q}_R \mathbf{q}_L^T \mathbf{l}_L$ and $\mathbf{q}_R^T \mathbf{q}_R \mathbf{l}_R^T \mathbf{l}_R$. This implies that there are no $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant operators with non-zero $(B - L)$. For this reason most of the GUTs articles discuss only $(B - L)$ conserving proton decays. $(B - L)$ violating proton decays are allowed only in some complicated scenarios with higher dimensional operators [10]. This restriction is not present in the E_6 model discussed. In the rest of the paper we classify the new operators which violate $(B - L)$ and a new scenario for baryogenesis.

In addition to the operators of the form mentioned above we can write the following operators including the exotic particles which are invariant under the standard model,

$$\begin{array}{lll}
\mathbf{Q} \mathbf{Q} \mathbf{Q} \mathbf{L}_2 & [1] & \mathbf{Q} \mathbf{Q} \mathbf{D}_1 \nu^c & [1] & \mathbf{Q} \mathbf{Q} \mathbf{D}_1 \mathbf{L} & [0] \\
\mathbf{Q} \mathbf{Q} \overline{\mathbf{D}}_2 \overline{\nu^c} & [-1] & \mathbf{Q} \mathbf{Q} \overline{\mathbf{D}}_2 \overline{\mathbf{L}} & [0] & \mathbf{Q} \mathbf{D}_1 \overline{\mathbf{u}^c} \overline{\mathbf{L}}_3 & [0] \\
\mathbf{Q} \overline{\mathbf{D}}_2 \overline{\mathbf{u}^c} \mathbf{L}_2 & [0] & \mathbf{Q} \overline{\mathbf{D}}_2 \overline{\mathbf{u}^c} \mathbf{L}_1 & [0] & \mathbf{Q} \overline{\mathbf{u}^c} \overline{\mathbf{d}^c} \mathbf{L}_2 & [1] \\
\overline{\mathbf{u}^c} \overline{\mathbf{d}^c} \overline{\mathbf{d}^c} \overline{\mathbf{L}} & [1] & \overline{\mathbf{u}^c} \overline{\mathbf{d}^c} \overline{\mathbf{d}^c} \overline{\nu^c} & [0] & \overline{\mathbf{u}^c} \overline{\mathbf{d}^c} \mathbf{D}_1 \nu^c & [1] \\
\overline{\mathbf{u}^c} \overline{\mathbf{d}^c} \mathbf{D}_1 \nu^c & [1] & \overline{\mathbf{u}^c} \overline{\mathbf{d}^c} \overline{\mathbf{D}}_2 \overline{\nu^c} & [-1] & \overline{\mathbf{u}^c} \overline{\mathbf{d}^c} \overline{\mathbf{D}}_2 \overline{\mathbf{L}} & [0] \\
\overline{\mathbf{u}^c} \mathbf{D}_1 \mathbf{D}_1 \overline{\nu^c} & [-2] & \overline{\mathbf{u}^c} \mathbf{D}_1 \mathbf{D}_1 \overline{\mathbf{L}} & [-1] & \overline{\mathbf{u}^c} \overline{\mathbf{D}}_2 \mathbf{D}_1 \nu^c & [0] \\
\overline{\mathbf{u}^c} \overline{\mathbf{D}}_2 \mathbf{D}_1 \mathbf{L} & [-1] & \overline{\mathbf{u}^c} \overline{\mathbf{D}}_2 \overline{\mathbf{D}}_2 \overline{\mathbf{L}} & [-1] & \overline{\mathbf{u}^c} \overline{\mathbf{D}}_2 \overline{\mathbf{D}}_2 \overline{\nu^c} & [-2]
\end{array}$$

with the transportation sign being understood in the first and third fields.

The $(B - L)$ quantum numbers for the various operators are given within the parentheses. It is now obvious that identifying the $(B - L)$ quantum number with the generator of E_6 (as in the $SO(10)$ GUT) we are allowed to have baryon and $(B - L)$ number violating operator with only four fermions.

This allows new scenarios for baryogenesis. We demonstrate it with a specific example. Any operator of the form $(\overline{\psi}_{iL}^c \psi_{jL})(\overline{\psi}_{kR}^c \psi_{lR})$ can be Fierz transformed to $(\overline{\psi}_{iL}^c \gamma^\mu \psi_{lR})(\overline{\psi}_{kR}^c \gamma^\mu \psi_{jL})$. In E_6 the gauge couplings, $g(\overline{\psi}_{iL}^c \gamma^\mu \psi_{lR})X_1^\mu$ and $g(\overline{\psi}_{kR}^c \gamma^\mu \psi_{jL})X_2^\mu$ are present. The pair $X_1 X_2$ and $\overline{X}_1 \overline{X}_2$ are then singlets under the G_{std} but carry $(B - L) \neq 0$. They can scatter, in general, by coupling to another scalar. The net effect is that the scattering process $X_1 + X_2 \rightarrow \overline{X}_1 + \overline{X}_2$ can generate unequal densities of $X_1 X_2$ and $\overline{X}_1 \overline{X}_2$ scattering states. This occurs provided CP is violated in the couplings of the $X_1 X_2 \rightarrow \text{scalar} \rightarrow \overline{X}_1 \overline{X}_2$, which is not forbidden in these theories. The densities of fermions $(\overline{\psi}_{iL}^c \psi_{jL})(\overline{\psi}_{kR}^c \psi_{lR})$ belongs to the operator classified in the previous paragraph.

In summary, we pointed out that the baryon and lepton numbers of the exotic particles of the E_6 model can have strong implications to the low energy physics. We propose a new assignment of B and L quantum numbers for the exotic particles with the following features,

- (1) baryon and lepton number violating processes do not occur at the electroweak phase transition, because the total $SU(2)_L$ anomaly for the $(B + L)$ quantum number is zero.
- (2) baryon and lepton numbers are no longer global symmetries of the low energy lagrangian.
- (3) there are dimension six operators which violates $(B - L)$ producing new $(B - L)$ violating processes, which suggest a new scenario for the generation of the baryon asymmetry in the universe.

Acknowledgement We would like to thank V. Kiselev, H. Nakano and G. Zoupanos for discussions. U. S. and H. S. would like to acknowledge fellowships from the Alexander von Humboldt Foundation and hospitality from Institut für Physik, Universität Dortmund, during their research stay in Germany. The financial support of DFG is gratefully acknowledged.

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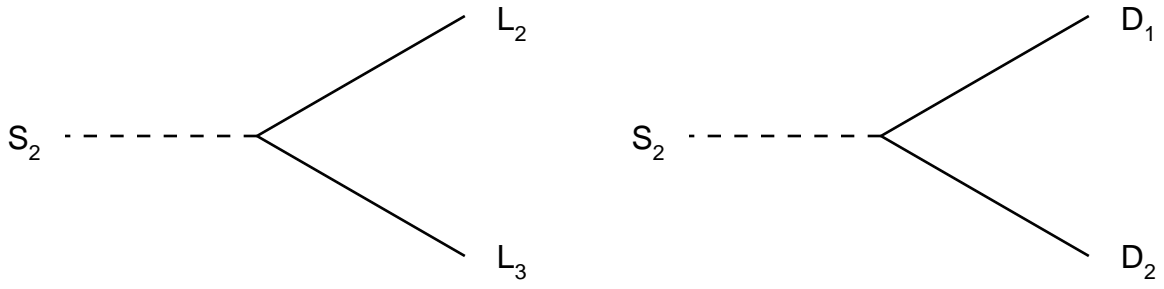


Figure 1: Baryon number violating decays of the scalar S_2 .

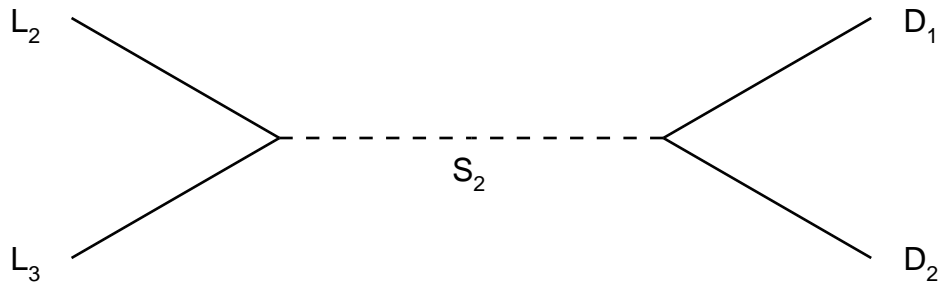


Figure 2: B -violating scattering through the scalar S_2 .