

3-3-1 exotic quark search at CERN LEP-II-LHC

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The 3-3-1 electroweak model is the simplest chiral extension of the standard model which predicts single and double charged bileptons and exotic quarks carrying $-4/3$ and $5/3$ units of the positron charge. In this paper we study the possibilities of the production and decay of one of these exotic quarks at CERN LEP-II-LHC collider. For typical vector bilepton, exotic quark masses and mixing angles we obtained between 20 and 750 events per year. Angular distributions are also presented.

I. INTRODUCTION

It is a celebrated fact that the standard model of the electroweak interactions accommodates all the present experimental results. However, since it is not able to give response to some fundamental questions in particle physics, the building of extensions and alternative models are well motivated. One of these questions is the family replication problem, which can have an elegant solution in the simplest chiral extension of the standard model [1,2]. We are referring on a chiral model which is based on the $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ (3-3-1 for short) semi simple symmetry group which breakdown to the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ in some energy scale higher than the Fermi one.

One peculiar feature of the model is that the anomaly cancelation occurs only when the three fermion generations are considered together. This implies that the number of families must be multiple of the color number and, as a consequence, the 3-3-1 model suggests a route towards the response of the flavor question.

There is a high interest in the bilepton phenomenology (see Ref. [3] and references cited therein). Usually bileptons ($L = 2$) are vector gauge or scalar bosons which couple two leptons. In 3-3-1 model they couple also an ordinary to an exotic quark. Some works on 3-3-1 phenomenology can be found in Refs. [4–13]. The presence of the vector bileptons in the model has two phenomenologically interesting possibilities. First there is a hope that this kind of gauge bosons can be detected in a relatively low mass scale and second they contribute to processes which violate lepton number, *i.e.*, it is free of standard model background. Since a new generation of colliders will be working in the next years, we think that this kind of model deserves more detailed phenomenological treatment.

In this paper we are interested in 3-3-1 exotic quark production and decay, particularly one carrying $5/3$ units of positron charge. This exotic quark, if detected, would be also a signature for a double charged bilepton present in the model. Double charged vector bilepton masses are bounded from below from muonium to antimuonium

conversion to a value ~ 850 GeV [14].

Here a comment is in order. All the constraints on the 3-3-1 parameters coming from experiments evolving leptonic interaction should be seen with care. In 3-3-1 model the leptons mix by a Cabibbo-Kobayashi-Maskawa like mixing matrix whose elements do not yet measured [10]. Usually these experiments apply only when the leptonic mixing matrix is diagonal [14]. Also, in models with extended Higgs sector some not unrealistic situations could exist in which scalar bosons contribution to muonium to antimuonium conversion is not negligible [15]. Therefore, in this work we assume a more interesting lower limit on the double charged bilepton mass, ~ 350 GeV, which is accessible to next generation of accelerators and is compatible with others low energy bounds [9,16].

Recently, lower bounds on exotic supersymmetric particles were translated to a lower bound on 3-3-1 exotic quark masses ~ 250 GeV [4]. Upper bound on bilepton masses can be ~ 3.5 TeV [6] and the exotic quark masses have no upper bound.

We examine here the possibility for the observation of the reaction $e^- p \rightarrow e^+ X l^- l^-$ at CERN LEP-II-LHC center of mass energy, where X is a quark jet and $l = e, \mu, \tau$. The 3-3-1 exotic quark production *via* double charged bilepton exchange was already studied [8]. However, our results differ from the previous one since we considered also the decay of the exotic quark and mixing angles.

This paper is organized as follows. In Sec. II we discuss the relevant features of the 3-3-1 model, in Sec. III we present the total cross sections and some distributions and finally in Sec. IV our conclusions.

II. THE 3-3-1 MODEL

Let us summarize the most relevant points of the model. In its minimal version the fermion representation content is

$$\psi_{aL} = \begin{pmatrix} \nu_a \\ l'_a \\ l'^c_a \end{pmatrix}_L \sim (\mathbf{3}, 0); \quad (1a)$$

$$Q_{1L} = \begin{pmatrix} u'_1 \\ d'_1 \\ J_1 \end{pmatrix}_L \sim \left(\mathbf{3}, \frac{2}{3} \right), \quad (1b)$$

$$Q_{\alpha L} = \begin{pmatrix} J'_\alpha \\ u'_\alpha \\ d'_\alpha \end{pmatrix}_L \sim \left(\mathbf{3}^*, -\frac{1}{3} \right), \quad (1c)$$

where $l'_\alpha = e', \mu', \tau'$, $\alpha = 2, 3$ [1]. The primed fields are symmetry eigenstates. In Eqs. (1) 0, 2/3 and $-1/3$ are the $U(1)_N$ charges. In this work we are considering massless neutrinos [13]. Each left-handed quark field has its right-handed counterpart transforming as a singlet of the $SU(3)_L$ group. In order to avoid anomalies one of the quark families must transform in a different way with respect to the two others. In fact, the first and the third generation of quarks were arbitrarily singularized by the authors of the Refs. [1] and [2], respectively, but can be showed that we can map one representation to another representation performing a unitary transformation [11,12]. The J_1 exotic quark carries 5/3 units of electric charge while J_2 and J_3 carry $-4/3$ each. The exotic quarks couple to the ordinary ones *via* bileptons which leads to processes where the total lepton number conservation is violated. Should be notice that in the leptonic sector of the model the particle spectrum coincides with the standard model one.

In the gauge sector the single charged (V^\pm) and the double charged ($U^{\pm\pm}$) vector bileptons, together with a new neutral gauge boson $Z^{0\prime}$ complete the particle spectrum with the charged W^\pm and the neutral Z^0 standard gauge bosons.

The charged current interactions for the quarks are given by

$$\begin{aligned} \mathcal{L}_q = & -\frac{g}{2\sqrt{2}} [\bar{U}\gamma^\mu(1-\gamma_5)V_{CKM}DW_\mu^+ + \\ & + \bar{U}\gamma^\mu(1-\gamma_5)\zeta\mathcal{J}\nu_\mu + \bar{D}\gamma^\mu(1-\gamma_5)\xi\mathcal{J}\mathcal{U}_\mu] + \\ & + \text{H. c.}, \end{aligned} \quad (2)$$

where we modified slightly the notation of the reference [1], with

$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \quad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad \mathcal{V}_\mu = \begin{pmatrix} V_\mu^+ \\ U_\mu^{--} \\ U_\mu^{--} \end{pmatrix}, \quad (3a)$$

$$\mathcal{U}_\mu = \begin{pmatrix} U_\mu^{--} \\ V_\mu^+ \\ V_\mu^+ \end{pmatrix}, \quad (3b)$$

and $\mathcal{J} = \text{diag}(J_1 \ J_2 \ J_3)$. The V_{CKM} is the usual Cabibbo-Kobayashi-Maskawa mixing matrix and ξ and ζ are mixing matrices containing new unknown mixing parameters due to the presence of the exotic quarks. In the leptonic sector we have the charged currents

$$\mathcal{L}_l = -\frac{g}{2\sqrt{2}} \sum_l [\bar{\nu}_l\gamma^\mu(1-\gamma_5)lW_\mu^+ +$$

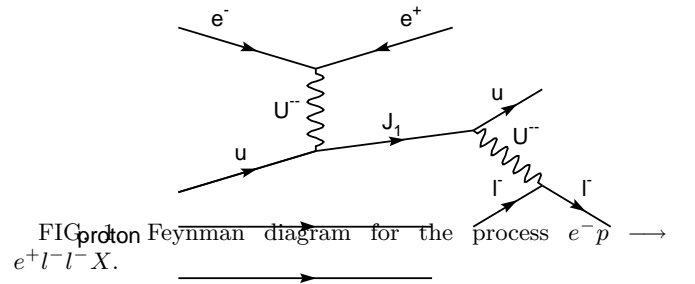
$$\begin{aligned} & + \bar{l}^c\gamma^\mu(1-\gamma_5)\Lambda\nu_lV_\mu^+ + \\ & + \bar{l}^c\gamma^\mu(1-\gamma_5)\Delta lU_\mu^{++}] + \text{H. c.}, \end{aligned} \quad (4)$$

where Λ and Δ are lepton mixing matrices. In Eqs. (2), (3) and (4), unlike Eq. (1), we are working with the mass eigenstates. There are not measurements for matrix elements of ξ , ζ , Λ and Δ mixing matrices. An estimative for $\xi_{J_1 d}^* \xi_{J_1 s}$ was obtained from the neutral kaon system mass difference [5].

The pattern of symmetry breaking is $SU(3)_L \otimes U(1)_N \rightarrow SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}}$. The bileptons and exotic quarks get masses when the 3-3-1 symmetry breakdown to the standard model one. This breakdown determines the scale for the new physics in the model. At low energy the 3-3-1 model recovers the standard phenomenology [12].

III. CROSS SECTIONS AND DISTRIBUTIONS

In this work we studied the production and decay of exotic quarks from 3-3-1 model in e^-p collision for CERN LEP-II-LHC center of mass energy through the deep inelastic scattering (DIS), represented in diagram of the Fig. 1.



The production and decay of heavy exotic quarks at HERA energy was studied in a different context by one of the authors. In that paper was investigated the signatures for heavy quarks using vector singlet, vector doublet and fermion-mirror-fermion extended models [17]. Here, we study the production and decay of J_1 quark *via* double charged bilepton exchange. We are motivated by the following particular features of the model: (a) the absence of standard model background to $e^-p \rightarrow l^+ X l^- l^-$ reaction (Fig. 1), due to leptonic number violation; (b) the possible low mass scale of bileptons which contributes

to give reasonable rate of events in the next generation of colliders [3]; (c) the production of a charged primary lepton (positron) that can be detected and (d) the existence of quarks with fractionary charge greater than one.

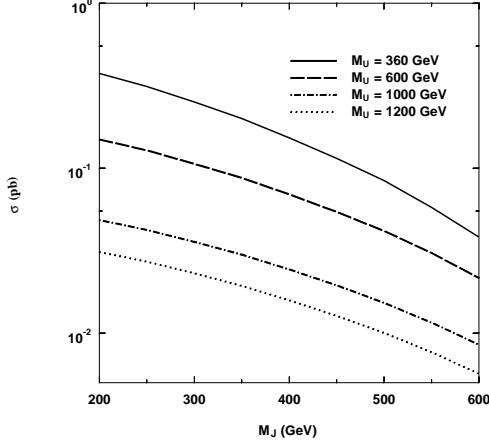


FIG. 2. Cross section as a function of M_J for various values M_U .

The e^-p collision is an interesting place for 3-3-1 model phenomenological study, because presents an unusual vertex were a 3-3-1 bilepton couples an ordinary with an exotic quark [as can see in Eq. (2)].

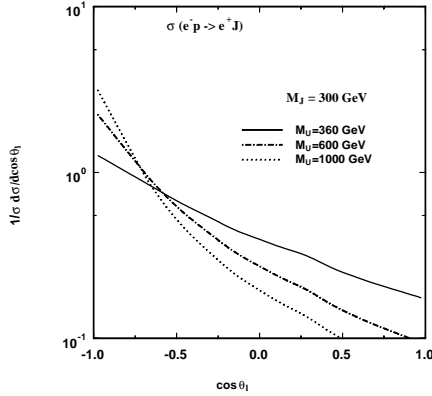


FIG. 3. Normalized angular distribution of the primary lepton with $M_J = 300$ GeV for various M_U .

An exotic J quark can be produced through DIS and vector-boson-gluon-fusion (BGF). The BGF process is suppressed by the mixing parameters when compared with standard model top quark production. In the lack of a more realistic estimate, we can suppose that this

mixing parameter behaves as the one estimate in Ref. [5]. There, under reasonable hypothesis, was showed that numerically the upper bound of the mixing parameter contributing to $K^0 - \bar{K}^0$ transition depends linearly on the bilepton mass as $\xi_{J_1 d}^* \xi_{J_1 s} \simeq 0.1 M_U$, when M_U is the double charged bilepton mass in TeV.

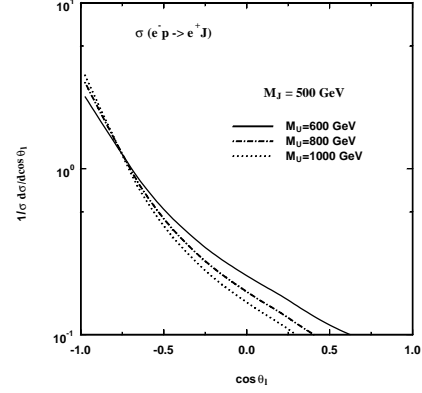


FIG. 4. The same as Fig. 3 but for $M_J = 500$ GeV.

However, since this parameter appears in the cross section formula as a multiplicative factor, our results can be immediately adapted for other values of the mixing angles (should be notice that this observation apply also to the leptonic mixing parameters).

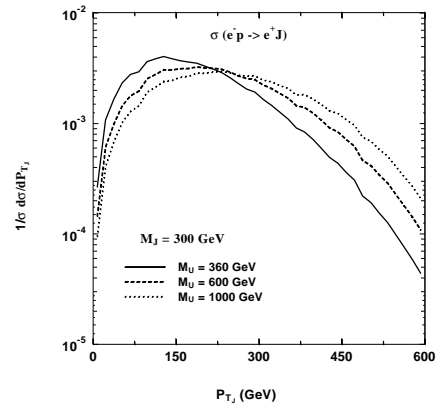


FIG. 5. Normalized P_{TJ} distribution with $M_J = 300$ GeV for various M_U .

On the other hand, in DIS process a J quark production dominates the top quark production in the standard model, since we are using the aforementioned upper bound for the 3-3-1 quark mixing parameter which is greater than the analogous V_{CKM} one. In the same

way as we comment in the Sec. I that we do not know as the 3-3-1 Higgs scalars contribute to the muonium to antimuonium conversion, we also do not can predict how would be its contribution to the quark production in DIS.

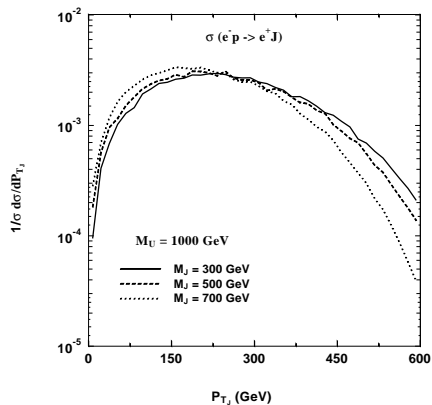


FIG. 6. Normalized P_{TJ} distribution with $M_U = 1000$ GeV for various M_J .

For sake of simplicity we is assuming here that the gauge boson contributions dominate in this process.

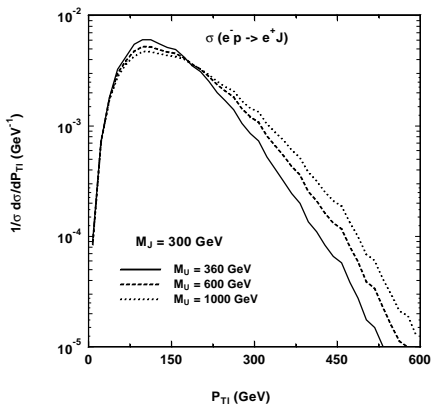


FIG. 7. Normalized P_{Tl} distribution of the more energetic secondary lepton with $M_J = 300$ GeV for various values of M_U .

The Fig. 2 shows the total cross section for heavy quark production as a function of quark mass (M_J) for some values of double charged bilepton mass. For CERN LEP-II-LHC center of mass energies (1.8 TeV) and an integrated luminosity of $\mathcal{L} = 6 \text{ fb}^{-1}\text{yr}^{-1}$, we obtain for $M_J = 300$ GeV between 70 and 750 events/year for M_U running from 1200 GeV to 360 GeV. For $M_J = 600$ GeV between 20 and 120 events/year are expected for

the same range of M_U . Would be notice that the limits of these ranges of events correspond to the particular case when the leptonic mixing parameter is diagonal (see comment in Sec. I). We observed that the cross section decreases as M_J and M_U increase.

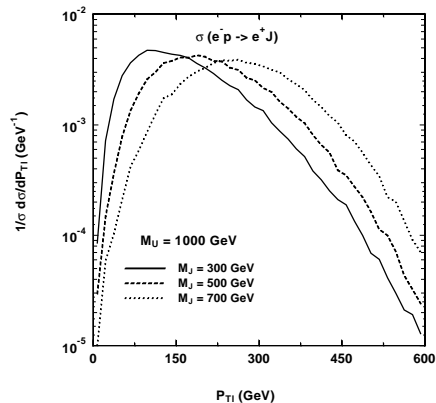


FIG. 8. Normalized P_{Tl} distribution of the more energetic secondary lepton with $M_U = 1000$ GeV for various M_J .

The primary lepton normalized angular distribution can be seen in Figs. 3 and 4. In the former one we fixed $M_J = 300$ GeV and studied the distributions for some values of M_U . In the latter same as done for $M_J = 500$ GeV.

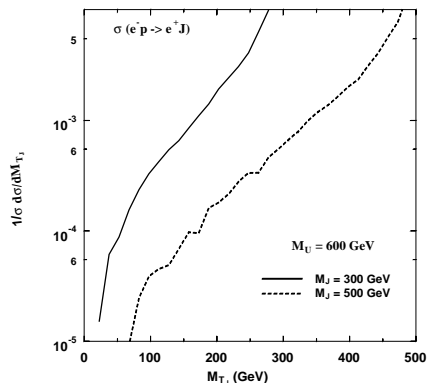


FIG. 9. Normalized cluster transverse mass spectrum of the exotic heavy quark.

We observed that these distributions dominate the backward region, the increase of quark mass difficulties to distinguish the plots for different bilepton masses.

The transverse quark momentum distribution can be seen in Fig. 5 for fixed $M_J = 300$ GeV and for some values of M_U . We observed that the maximum value is

for $p_T \simeq 150$ GeV, for an expressive range of bilepton masses. The same behavior is observed to other values of M_J which was not showed. In Fig. 6 we fixed $M_U = 1000$ GeV and we can see that the shapes of the curves are very similar among them.

We continue our analysis, by using the same values as the Figs. 5 and 6, now studying the transverse momentum of the most energetic secondary lepton produced in the J_1 quark decay (see Fig. 1). As the Fig. 5, the Fig. 7 does not allow to distinguish the plots. On the other hand, Fig. 8 shows distributions whose maxima values in p_T are shifted to right as M_U increases. For other values of M_J the plots present similar behavior.

Finally we present in Fig. 9 the transverse quark mass which gives information about the recoiling u quark jet and has a sharp peak at the exotic quark mass.

IV. CONCLUSIONS

We have investigated the production and decay of one of the exotic quark predicted by 3-3-1 electroweak model at CERN LEP-II-LHC center of mass energy. Employing a Monte Carlo simulation we studied the process $e^-p \rightarrow e^+Xl^-l^-$ depicted in Fig. 1. We analyzed the total cross section as a function of exotic quark mass and several kinematical distributions of the final state particles in order to identify the masses of the new particles of the model. We stress that we have an exclusive semileptonic channel of heavy quark decay in the model, which is free of the standard model background and can give a reasonable rate of events in the CERN LEP-II-LHC center of mass energy. In the range of typical values of mass parameters we have between 20 and 750 events/year.

We can see that the p_T distribution of the more energetic secondary lepton is more sensitive to M_J variation (see Fig. 8). It shows clearly a distinction between the exotic quark masses for a fixed double charged bilepton mass. One should also notice that the Fig. 8 is a transverse momentum distribution of the most energetic secondary lepton which is directly observed in the experiment.

We conclude so that the 3-3-1 model is a promising option for searching new physics in the next generation of accelerators and the deep inelastic scattering could give spectacular signatures.

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