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Search for signatures of dilepton gauge bosons in HERA and LEPII-LHC

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Abstract

We examine the prospects of searching for dilepton gauge bosons in e^-p colliders. Specifically we take a $SU(3)_C \times SU(3)_L \times U(1)_X$ model and calculate the cross section for the process, $e^-p \to e^+ + D +$ anything, mediated by doubly-charged dilepton gauge bosons, where D is a new quark predicted by the model. At HERA, with center-of-mass energy $\sqrt{s} = 314$ GeV and the integrated luminosity 100 pb^{-1}, we can obtain the signature of dileptons with mass up to 340 GeV (650 GeV) if D has a mass lighter than 200 GeV (150 GeV). At LEPII-LHC, with center-of-mass energy $\sqrt{s} = 1790$ GeV and an anticipated luminosity 6 $\mathrm{fb}^{-1}\mathrm{yr}^{-1}$, we expect more than 280 events per year provided that both the mass of dileptons and that of the D-quarks is less than 1 TeV.

Although the Standard model (SM) of electroweak and strong interactions has been quite successful in explaining current experimental data, there have been proposed, up to now, a variety of unified models which extend the SM. Among them there is a class of theories [1-6] in which there appear $SU(2)_L$-doublet gauge bosons $(X^{\mp}, X^{\mp\mp})$ carrying lepton number $L = \pm 2$. Hereafter, we refer to these gauge bosons as dileptons. In these models each family of leptons $(l^+, \nu_l, l^-)_L$ transforms as a triplet under the gauge group $SU(3)$ and the total lepton number defined as $L = L_e + L_\mu + L_\tau$ is conserved, while the separate lepton number for each family is not. The gauge group $SU(3)$ will be, for example, an $SU(3)_l$ in the $SU(15)$ grand unification theory model [2] or an $SU(3)_L$ in the $SU(3)_C \times SU(3)_L \times U(1)_X$ model [5].

The dilepton masses are generated when the $SU(3)$ gauge symmetry is spontaneously broken at the scale which could be as low as 250-2000 GeV [2,5,7], and thus they may possibly be in the range accessible to accelerator experiments. The signatures for the existence of dileptons have been studied for future experiments concerning e^+e^-, e^-e^- and e^-p collisions [8-10]. Also, the phenomenology on dileptons has been analyzed in such processes as the low-energy weak neutral current experiments, Bhabha scattering, muon decays [8,11], and the low energy muon related

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processes such as muonium-antimuonium conversion, the second-order corrections to the muon anomalous magnetic moment and exotic decays [12,13]. Furthermore, the dilepton contributions to so-called oblique corrections have been examined [14,15]. The most stringent lower mass bounds at present are $(M_{X^{\pm\pm}}/g_{3l}) > 340$ GeV (95% C.L.) for the doubly-charged dileptons [8] and $(M_{X^{\pm}}/g_{3l}) > 640$ GeV (90% C.L.) for the singly-charged ones [11], and here g_{3l} is the gauge coupling of dileptons to leptons.

In Ref. [10], Agrawal, Frampton and Ng considered a direct search for doubly-charged dilepton $X_{\pm\pm}$ by lepton-number violating processes in e^-p and e^+e^- colliders. They examined the process $e^-p \to e^+\mu^-\mu^-$ + anything, at e^-p collisions and the process $e^+e^- \to 2e^+2\mu^-$ or $2e^-2\mu^+$ at e^+e^- collisions. Both processes are totally free of background from the SM, and thus, once found, they will provide a signature for the existence of dileptons. The production rates, however, are very small. For the case of using the e^-p colliders, it is concluded [10] that at HERA, with center-of-mass energy $\sqrt{s}$ = 314 GeV and the planned luminosity of 1.6×10^{31} cm^{-2}s^{-1}, there will be less than one event per year for $e^-p \to e^+\mu^-\mu^-$ + anything if the doubly-charged dilepton mass M_X ($\equiv M_{X^{\pm\pm}}$) is heavier than 120 GeV. At LEPII-LHC with $\sqrt{s}$ = 1790 GeV and an expected luminosity of 2×10^{32} cm^{-2}s^{-1}, at least 2 events per year are anticipated unless M_X exceeds 650 GeV.

In this paper we consider an indirect search for the existence of doubly-charged dileptons in e^-p colliders. We take a $SU(3)_C \times SU(3)_L \times U(1)_X$ (3-3-1) model [5] for a specific model which accommodate dileptons and study the process, $e^-p \to e^+$ + anything, through the exchange of dileptons. One advantage of considering this process is that a larger event rate is expected than the background-free process $e^-p \to e^+\mu^-\mu^-$ + anything, since the cross section for the former process is of the order of g_{3l}^4 while the latter is of the order of $g_{3l}^4 e^4$, and e is the electric charge. One drawback, however, is that the process is model-dependent. Namely, the cross section for $e^-p \to e^+$ + anything depends not only on dilepton mass, but also on the mass of the exotic quark which the 3-3-1 model predicts. Nonetheless, the process $e^-p \to e^+$ + anything in the 3-3-1 model is worth investigating in the following aspects. Firstly, the 3-3-1 model itself is an interesting model beyond the SM. In this model anomaly cancellation takes place between families and anomaly cancellation requires that the number of families be equal to the number of quark colors [5]. Secondly, a fair magnitude of event rate is expected and, therefore, the 3-3-1 model and the existence of dileptons will rather easily be checked.

In the 3-3-1 model each family of leptons transforms as $(1,3^*,0)$ under $SU(3)_C \times SU(3)_L \times U(1)_X$, and so we have for the first lepton family,

$$\begin{pmatrix} e \\ -\nu_e \\ e^c \end{pmatrix}_L : (1,3^*,0) \tag{1}$$

where $e^c_L \equiv C(\overline{e_R})^T$ and C being the charge-conjugation matrix. The electric charge operator Q for $SU(3)_L$ triplets is defined as

$$Q = \tfrac{1}{2}\lambda^3_L + \tfrac{1}{2}\sqrt{3}\lambda^8_L + X \tag{2}$$

where X is the $U(1)_X$ charge.

The first quark family consists of a left-handed $SU(3)_L$ triplet plus three right-handed singlets:

$$\begin{pmatrix} u \\ d \\ D \end{pmatrix}_L , \quad u^c_L, \quad d^c_L, \quad D^c_L . \tag{3}$$

The $U(1)_X$ charges of the triplet, u^c_L, d^c_L, and D^c_L are $X = -\frac{1}{3}$, $X = -\frac{2}{3}$, $X = +\frac{1}{3}$, and $X = +\frac{4}{3}$, respectively. Thus the new D quark has electric charge $Q_D = -\frac{4}{3}$.

The $SU(3)_L \times U(1)_X$ symmetry breaks spontaneously into $SU(2)_L \times U(1)_Y$. At this breaking five gauge bosons, dileptons ($X^{\pm\pm}$, $X^{\pm}$) and an additional neutral boson, gain masses. Also new quarks, D and the ones belonging to other quark families become massive. From the renormalization group analysis of the gauge coupling constants, the breaking scale is estimated to be 1.7 TeV or lower [6]. We, therefore, expect the masses of dileptons and D quark to be around or less than 1 TeV.

The interaction of dilepton gauge bosons with the first family of leptons and quarks is given by

$$\mathcal{L}_{\rm int} = -\frac{g_{3l}}{2\sqrt{2}}\left[X^{++}_\mu e^T C\gamma^\mu\gamma_5 e + X^{--}_\mu \bar{e}\gamma^\mu\gamma_5 C\bar{e}^T\right] - \frac{g_{3l}}{2\sqrt{2}}\left[X^{+}_\mu \nu^T_e C\gamma^\mu(1+\gamma_5)e + X^{-}_\mu \bar{e}\gamma^\mu(1+\gamma_5)C\overline{\nu_e}^T\right]$$

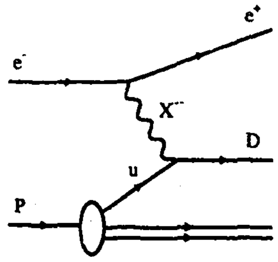

Fig. 1. The process $e^- + p \to e^+ + D +$ anything through doubly-charged dilepton exchange in the quark-parton-model picture.

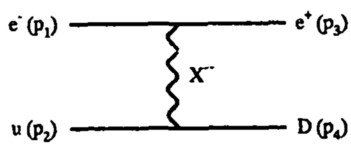

Fig. 2. The Feynman diagram for the process $e^- + u \to e^+ + D$.

$$+\frac{g_{3l}}{2\sqrt{2}}\left[X_\mu^{++}\overline{u}\gamma^\mu(1-\gamma_5)D + X_\mu^{--}\overline{D}\gamma^\mu(1-\gamma_5)u\right]$$
$$+\frac{g_{3l}}{2\sqrt{2}}\left[X_\mu^{+}\overline{d}\gamma^\mu(1-\gamma_5)D + X_\mu^{-}\overline{D}\gamma^\mu(1-\gamma_5)d\right], \qquad (4)$$

where C is the charge-conjugation matrix. The gauge coupling constant g_{3l} is given approximately by $g_{3l} = g_2 = 2.07e$ [5], where g_2 is the $SU(2)_L$ gauge coupling constant. It is noted that the vector parts of the electron coupling to doubly-charged dileptons vanish due to Fermi statistics. The D-quark carries lepton number 2 and decays only through dileptons. From the above interaction Lagrangian (4) we find that D decays as $D \to u + X^{--} \to u + l^- + l^-$ or $D \to d + X^- \to d + l^- + \nu_l$, where $l = e$, μ and τ.

In the quark-parton-model picture, the process $e^-p \to e^+ +$anything is illustrated in Fig. 1. We first consider the subprocess $e^- + u \to e^+ + D$. The corresponding Feynman diagram with momentum assigned to each particle is shown in Fig. 2. The amplitude is given by

$$\mathcal{A} = \left(\frac{g_{3l}}{2\sqrt{2}}\right)^2 \overline{u}(p_4)\gamma_\mu(1-\gamma_5)$$
$$\times u(p_2)\frac{-i}{(p_1-p_3)^2 - M_X^2 + iM_X\Gamma_X}$$
$$\times 2v^T(p_3)C\gamma_\mu\gamma_5 u(p_1) \qquad (5)$$

where a factor of 2 comes out at the e-e-dilepton vertex since two identical electron fields are involved at the vertex. Now taking the spin average for initial e^- and u and the spin sum for the final e^+ and D, we obtain for the differential cross section for $e^- + u \to e^+ + D$,

$$\frac{d\hat{\sigma}}{dQ^2} = \frac{g_{3l}^4}{8\pi}\frac{1}{\hat{s}^2[Q^2+M_X^2]^2}$$
$$\times\left\{2\hat{s}^2 - 2\hat{s}(Q^2+M_D^2) + Q^2(Q^2+M_D^2)\right\} \qquad (6)$$

where M_D is D-quark mass, $\hat{s} = (p_1+p_2)^2$ and $Q^2 = -(p_1-p_3)^2$. Electron, positron and u-quark have been taken to be massless and the width of $X^{\pm\pm}$ in the propagator have been neglected.

Hence the cross section for $e^-p \to e^+ +$ anything is given by

$$\sigma(s, M_X, M_D) = \int_{x_1}^{1} dx$$
$$\times\left[\int_{Q_l^2}^{Q_u^2} dQ^2 f_u(x,Q^2)\frac{d\hat{\sigma}}{dQ^2}(\hat{s} = xs, M_X, M_D)\right] \qquad (7)$$

where $f_u(x,Q^2)$ is the u-quark distribution function in the proton and x is the fractional momentum of the proton carried by the u-quark. Since $s = (p_e + p_p)^2$, with p_e and p_p being the momenta of electron and proton, respectively, we have $\hat{s} = xs$. The upper bound for the Q^2-integration is $Q_u^2 = \hat{s} - M_D^2$ and we take $Q_l^2 = 4\ \mathrm{GeV}^2$ for the lower bound. The lower bound for the x-integration is $x_1 = (M_D^2/s)$, which comes from the constraint $\hat{s} - M_D^2 > 0$. To evaluate the cross section we have adopted the MRSD$'_-$ [16] parton structure functions and used a Monte Carlo method for integration. For the gauge coupling constant g_{3l}, we have used the 3-3-1 model prediction $g_{3l} = 2.07e$.

The results for the dependence of $\sigma(s, M_X, M_D)$ on M_X and M_D are shown in Fig. 3 for the center-of-mass energy $\sqrt{s} = 314$ GeV (HERA) and in Fig. 4 for $\sqrt{s} = 1790$ GeV (LEPII-LHC). The present mass bound for the doubly-charged dileptons is $(M_{X^{\pm\pm}}/g_{3l}) > 340$ GeV (95% C.L.) which was obtained from the analysis of dilepton contributions to Bhabha scatterings [8]. For $g_{3l} = 2.07e$, we obtain $M_X > 210$

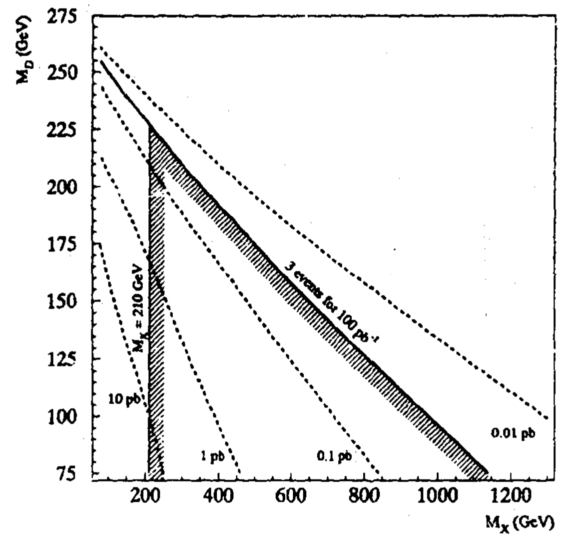

Fig. 3. The cross sections for the process $e^- + p \rightarrow e^+ + D +$ anything with $Q^2 > 4$ GeV at the center-of-mass energy $\sqrt{s} = 314$ GeV and its dependence on M_X and M_D. The shaded area shows the domain for M_X and M_D in which we expect at least 3 events per year with luminosity 100 $\text{pb}^{-1}\text{yr}^{-1}$. Also shown is the present mass bound for doubly-charged dileptons $M_X > 210$ GeV.

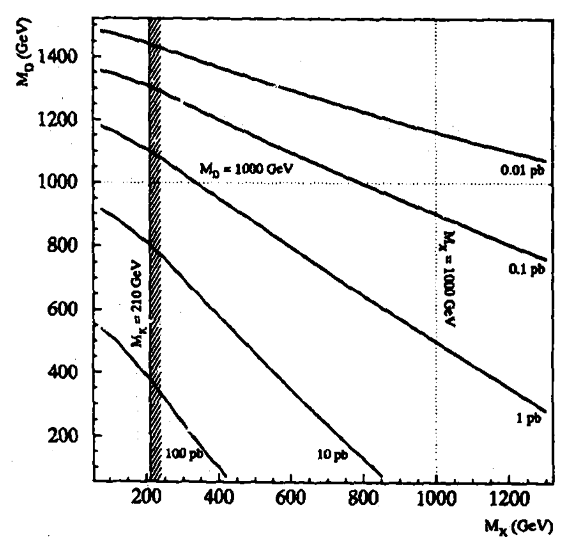

Fig. 4. The cross sections for the process $e^- + p \rightarrow e^+ + D +$ anything with $Q^2 > 4$ GeV at the center-of-mass energy $\sqrt{s} = 1790$ GeV and its dependence on M_X and M_D. Also shown is the present mass bound for doubly-charged dileptons $M_X > 210$ GeV.

GeV. The luminosity of HERA is expected to be 100 $\text{pb}^{-1}\text{yr}^{-1}$. Then the shaded area in Fig. 3 shows the domain for M_X and M_D in which we expect at least 3 events per year for $e^-p \rightarrow e^+ +$ anything at HERA. For example, we can obtain signatures of the 3-3-1-model dileptons with mass up to 340 GeV (650 GeV) if M_D is lighter than 200 GeV (150 GeV).

LEPII-LHC, with its center-of-mass energy $\sqrt{s} = 1790$ GeV, has a far extended prospect for dilepton search. In fact, we expect at least 0.048 pb for the cross section of the process, $e^-p \rightarrow e^+ +$ anything, if both M_X and M_D are lighter than 1 TeV. In other words, provided that an annual luminosity of 6 $\text{fb}^{-1}\text{yr}^{-1}$ is attained, we anticipate at least 280 events unless both M_X and M_D are heavier than 1 TeV.

Several comments are in order. Firstly, it is almost hopeless to search for the doubly-charged dileptons with a positron beam through the process, $e^+p \rightarrow e^- +$ anything, because in this case the subprocess is $e^+ + \bar{u} \rightarrow e^- + \overline{D}$ and $\bar{u}$-quark distribution function gives only a negligible contribution to the cross section.

Secondly, if doubly-charged Higgs bosons exist, they may also give rise to the process $e^-p \rightarrow e^+ +$ anything. Currently there are two popular models which incorporate such doubly-charged Higgs bosons. One is the Gelmini–Roncadelli model [17,18] which is a straightforward extension of the SM to include a Majorana mass for the left-handed neutrino. Besides the usual $SU(2)_L$ doublet Higgs, the model has a triplet Higgs $\boldsymbol{H} = (H^0, H^-, H^{--})$ and $H^{\pm\pm}$ couples to a left-handed charged-lepton pair as

$$\mathcal{L}_{H^{\pm\pm}} = -g_{ll}(\bar{l}_L l_L^c H^{--} + \bar{l}_L^c l_L H^{++}), \qquad (8)$$

where g_{ll} is a dimensionless coupling constant. However, $H^{\pm\pm}$ does not couple to quarks since it has $Y = \pm 2$. The other model is the left-right symmetric extension [19] of the SM. The gauge group of this model is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The minimal Higgs sector consists of a bidoublet Φ, and two triplets $\boldsymbol{H}_L$ and $\boldsymbol{H}_R$ whose quantum numbers are $(\frac{1}{2}, \frac{1}{2}, 0)$, $(1, 0, -2)$ and $(0, 1, -2)$, respectively. Both triplet Higgs, $\boldsymbol{H}_L$ and $\boldsymbol{H}_R$, have doubly-charged Higgs bosons $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ which couple to charged lepton-pairs by a similar Lagrangian as Eq. (8). Again these doubly-charged Higgs do not couple to quarks.

The 3-3-1 model also incorporate the doubly-charged Higgs bosons. Indeed Frampton introduced [5] three $SU(3)_L$ triplet and one sextet Higgs bosons. However, we can show that those Higgs multiplets which accommodate the doubly-charged ones do not couple to both leptons and quarks at the same time. Thus we may safely neglect the possibility of the process $e^- p \to e^+ +$ anything through the exchange of doubly-charged Higgs bosons.

Thirdly, in Figs. 3 and 4 we have assumed that the D-quark mass is heavier than 100 GeV. D-quarks do not couple to the W-boson but to the Z-boson and the photon. Then one would think that there would be an effect of D-quarks on the low-energy phenomena through radiative corrections and that we could say something about the D-quark mass just as in the case of t-quarks. But this is not the case for D-quarks. First note that heavy fermions decouple from the photon [20]. In fact the D-quark contribution to the (renormalized) photon vacuum polarization behaves like $\Pi_D^\gamma(k^2) \propto \alpha Q_D^2(k^2/M_D^2)$. Next it was shown in Ref. [6] that if the mixing of the two neutral gauge bosons which appear in the 3–3–1 model besides the photon is neglected, then the coupling of the D-quark to the Z-boson is vector-like. From the severe experimental restrictions on the flavor-changing neutral currents, we expect that the mixing of the two neutral gauge bosons should be small and thus the D-quark coupling to the Z-boson is mostly vector-like. Hence the D-quark contribution to the Z-boson vacuum polarization is expected to behave in a similar way as $\Pi_D^\gamma(k^2)$ and we conclude that the D-quark also decouples from the Z-boson.

Finally, $D(\overline{D})$-quarks may also be produced in powerful pp colliders such as LHC, through the process gluon + gluon $\to D + \overline{D}$. The signal for a produced D-quark is characterized by 1 jet + 2 leptons, since the D quark decays as $D \to u + l^- + l^-$ through X^{--} exchange or as $D \to d + l^- + \nu_l$ through X^- exchange, where $l = e,\ \mu$ and τ.

In conclusion, we have considered the prospects of searching for dilepton gauge bosons predicted by the 3–3–1 model in $e^- p$ colliders. We have calculated the cross section for the process $e^- p \to e^+ +$ anything mediated by doubly-charged dileptons. At HERA, with center-of-mass energy $\sqrt{s} = 314$ GeV and an integrated luminosity 100 pb^{-1}, we can obtain the signature of dileptons with mass up to 340 GeV (650 GeV) if the new D quark has a mass lighter than 200 GeV (150 GeV). At LEPII-LHC, with center-of-mass energy $\sqrt{s} = 1790$ GeV and an anticipated annual luminosity 6 fb^{-1}yr^{-1}, we can expect at least 280 events per year unless both the mass of dileptons and that of the D-quarks is heavier than 1 TeV.

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