

Bilepton production at hadron colliders

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We examine, as model-independently as possible, the production of bileptons at hadron colliders. When a particular model is necessary or useful, we choose the 3-3-1 model. We consider a variety of processes: $q\bar{q} \rightarrow Y^{++}Y^{--}$, $u\bar{d} \rightarrow Y^{++}Y^{-}$, $\bar{u}d \rightarrow Y^{+}Y^{--}$, $q\bar{q} \rightarrow Y^{++}e^{-}e^{-}$, $q\bar{q} \rightarrow \phi^{++}\phi^{--}$, $u\bar{d} \rightarrow \phi^{++}\phi^{-}$, and $\bar{u}d \rightarrow \phi^{+}\phi^{--}$, where Y and ϕ are vector and scalar bileptons, respectively. Given the present low-energy constraints, we find that, at the Fermilab Tevatron, vector bileptons are unobservable, while light scalar bileptons ($M_{\phi} \lesssim 300$ GeV) are just barely observable. At the CERN LHC, the reach is extended considerably: vector bileptons of mass $M_Y \lesssim 1$ TeV are observable, as are scalar bileptons of mass $M_{\phi} \lesssim 850$ GeV.

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I. INTRODUCTION

All models of physics beyond the standard model (SM) predict the existence of new particles. One of the more exotic of these is the bilepton [1], a particle of lepton number 2. Bileptons occur in a variety of models of new physics. For example, the gauge bosons of $SU(15)$ grand unified theories [2] include vector bileptons, as do models with an $SU(3)_c \times SU(3)_L \times U(1)$ gauge symmetry (known as the 3-3-1 model) [3]. Scalar bileptons can be found in models with an extended Higgs sector such as left-right symmetric models or models in which Majorana neutrino masses are generated.

Since bileptons couple to a pair of leptons, there are significant constraints on their masses and couplings from low-energy data [1]. The most stringent constraints on doubly charged scalar and vector bileptons come from searches for muonium-antimuonium conversion: $M_L > 1.7-3.3 \lambda$ TeV, where M_L is the mass of the bilepton, and λ its coupling to leptons. The constraints on singly charged bileptons are due to experimental limits on $\mu_R \rightarrow e \nu \nu$ and $\nu_{\mu} \rightarrow \nu_e$ oscillations, and are slightly weaker: $M_L > 1-2 \lambda$ TeV. Thus, for couplings $\lambda \sim 1$, bileptons are generically constrained to have a mass greater than ~ 1 TeV.

There has been considerable work examining the prospects for the detection of bileptons at future colliders. Because bileptons couple principally to leptons, it is only natural that this work has concentrated mainly on colliders involving at least one lepton beam [4]. However, bileptons also couple to the photon and Z , and so could be produced at hadron colliders. Curiously, the possibility of detecting bileptons at future hadron colliders has been little studied in the literature. For a high-energy pp collider, the production

of the vector bileptons of the 3-3-1 model and the scalar bileptons in left-right symmetric models has been calculated in Refs. [5] and [6], respectively. But nobody has attempted to perform a systematic study of bilepton production at hadron colliders. This is the purpose of this paper.

It is clear from the start that $e^{+}e^{-}$ and $e^{-}e^{-}$ colliders potentially have a great advantage over hadron colliders for detecting bileptons. High-energy Bhabha and Møller scattering receive huge corrections from virtual bilepton exchange. If no deviation from the SM is seen, this will constrain the mass of the bilepton to be $M_L \gtrsim 50\sqrt{s} \lambda$ TeV [1]. In other words, depending on the value of the coupling λ , the reach of $e^{+}e^{-}$ and $e^{-}e^{-}$ colliders for bilepton detection potentially extends far beyond their center-of-mass energies. On the other hand, it is equally evident that this reach depends crucially on the value of the λ . The advantage of hadron colliders, in which bilepton production is due mainly to the s -channel exchange of neutral gauge bosons, is that the cross section depends only on gauge couplings, so that the reach is independent of the coupling λ . (The same holds true for direct searches in $e^{+}e^{-}$ colliders.) Thus, even though $e^{+}e^{-}$ and $e^{-}e^{-}$ colliders are potentially better tools for bilepton detection, it is still worthwhile to consider hadron colliders.

Ideally, the study of bilepton production at hadron colliders should be completely model-independent. Unfortunately, this is not possible. Consider the process $q\bar{q} \rightarrow Y^{++}Y^{--}$, where Y^{++} is a doubly charged vector bilepton. If one calculates the cross section for this process using only s -channel γ and Z exchange, one finds that the cross section grows with the center-of-mass energy; i.e., unitarity is violated. This is not surprising. The vector bileptons are the gauge bosons of a larger gauge group, which necessarily contains at least one new neutral Z' boson. It is only through the inclusion of the s -channel Z' exchange that unitarity is restored.¹

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¹This is completely analogous to what happens in the SM. Using only photon exchange the cross section for $e^{+}e^{-} \rightarrow W^{+}W^{-}$ violates unitarity. Unitarity is restored when the contribution of the neutral gauge boson associated with the W —the Z —is also included in the calculation.

Thus, for vector bilepton production at hadron colliders, it is necessary to choose a model in which to perform the calculation. In this paper we choose the 3-3-1 model [3]. Strictly speaking, our results apply only to this model. However, we expect that the order of magnitude of the cross sections will hold in any model containing vector bileptons.

For scalar bileptons, one does not have the same problems with unitarity violation. Thus, the calculations of the cross sections for scalar bilepton production at hadron colliders can be performed without a knowledge of the underlying theory. That is, one can consider only s -channel γ and Z exchange, which is indeed what we do. However, it must be remembered that any particular model may contain Z' bosons, which can affect the cross sections (especially if the Z' can be produced on shell). In this sense, the cross sections for scalar bilepton production presented in this paper should be considered as lower bounds—in a given model, these cross sections may be enhanced due to the exchange of other particles. (It is also conceivable that the cross sections could be decreased, due to cancellations between the Z' and γ/Z contributions. However, in general, this requires fine-tuning.)

We discuss vector bilepton production at both the Fermilab Tevatron and the CERN Large Hadron Collider (LHC) in Sec. II. We consider the production of two real bileptons ($q\bar{q} \rightarrow Y\bar{Y}$), as well as the case where one of the bileptons is virtual ($q\bar{q} \rightarrow Yee$). In Sec. III we turn to scalar bilepton production. We conclude in Sec. IV.

II. VECTOR BILEPTONS

The basic process describing the production of vector bileptons at hadron colliders is $q\bar{q} \rightarrow Y^{++}Y^{--}$, where Y^{++} is a doubly charged vector bilepton. Ideally we would like to study this process model-independently. So, as a first step, we compute the cross section based on the s -channel exchange of the γ and Z only. However, the calculation reveals that this cross section grows as s , where \sqrt{s} is the center-of-mass energy. This signals a violation of unitarity, indicating that there are other important contributions to this process which have not been taken into account.

But it is clear what is happening here. Vector bileptons are the gauge bosons of some larger gauge group, which must necessarily include new neutral Z' gauge bosons. These Z' bosons will also contribute to $q\bar{q} \rightarrow Y^{++}Y^{--}$, and their inclusion must restore unitarity. Thus, it is not possible to perform a model-independent study of vector bilepton production at hadron colliders. It is necessary to choose a particular model, so as to be able to include the Z' (and possibly other) contributions which restore unitarity.

For computational purposes, we therefore choose the simplest extension of the SM which contains bileptons, namely the model in which the $SU(2)_L$ gauge group is expanded to $SU(3)_L$, giving an $SU(3)_c \times SU(3)_L \times U(1)$ gauge symmetry (the 3-3-1 model) [3]. Within the minimal 3-3-1 model, the calculation of the cross section for double vector-bilepton production at hadron colliders has been performed in Ref. [5]. In order to be as general as possible, we consider bilepton production in the nonminimal 3-3-1 model. We also examine the possibility of the single production of vector bi-

leptons. Note that, although these calculations are clearly not model-independent, we do expect that the order of magnitude of the cross sections will be the same in any model containing vector bileptons. After all, any model with vector bileptons will have the same types of contributions to $q\bar{q} \rightarrow Y^{++}Y^{--}$ as one finds in the the 3-3-1 model.

We begin this section with a review of the 3-3-1 model.

A. 3-3-1 model

We present here the main features of the 3-3-1 model, concentrating principally on those ingredients which are necessary for our calculation. For more details, we refer the reader to Ref. [7].

In the 3-3-1 model, the gauge group is $SU(3)_c \times SU(3)_L \times U(1)_X$, in which the coupling constants of $SU(3)_L$ and $U(1)_X$ are denoted g and g_X , respectively. The group $SU(3)_L \times U(1)_X$ is broken to $SU(2)_L \times U(1)_Y$ when an $SU(3)_L$ -triplet scalar gets a vacuum expectation value. The matching of the gauge coupling constants at this breaking scale yields the relation

$$\frac{g_X^2}{g^2} = \frac{6 \sin^2 \theta_w}{1 - 4 \sin^2 \theta_w}. \quad (1)$$

When $SU(3)_L \times U(1)_X$ is broken to $SU(2)_L \times U(1)_Y$, there are five exotic gauge bosons which acquire masses. They are the doubly and singly charged bileptons Y^{++} , Y^+ and their antiparticles, along with a new neutral Z' gauge boson. When the minimal Higgs structure is used to break the symmetry, there is a relation between the masses:

$$\frac{M_Y}{M_{Z'}} = \frac{\sqrt{3(1 - 4 \sin^2 \theta_w)}}{2 \cos \theta_w}, \quad (2)$$

where $M_{Y^+} \approx M_{Y^{++}} \equiv M_Y$. In this paper, in order to be as general as possible, we do not assume the minimal Higgs structure. Hence we allow M_Y and $M_{Z'}$ to vary independently of one another.

The fermions transform under the 3-3-1 symmetry as follows:

$$\begin{aligned} \psi_{1,2,3} &= \left(\begin{array}{c} e \\ \nu_e \\ e^c \end{array} \right), \left(\begin{array}{c} \mu \\ \nu_\mu \\ \mu^c \end{array} \right), \left(\begin{array}{c} \tau \\ \nu_\tau \\ \tau^c \end{array} \right) : (1, 3^*, 0), \\ Q_{1,2} &= \left(\begin{array}{c} u \\ d \\ D_1 \end{array} \right), \left(\begin{array}{c} c \\ s \\ D_2 \end{array} \right) : \left(3, 3, -\frac{1}{3} \right), \\ Q_3 &= \left(\begin{array}{c} t \\ b \\ T \end{array} \right) : \left(3, 3^*, \frac{2}{3} \right), \\ d^c, s^c, b^c &: \left(3^*, 1, \frac{1}{3} \right), \\ u^c, c^c, t^c &: \left(3^*, 1, -\frac{2}{3} \right), \end{aligned}$$

TABLE I. Values of the $d_{Z'}^{fL}$ and $d_{Z'}^{fR}$ parameters which define the Z' couplings to fermions.

| | $d_{Z'}^{fL}$ | $d_{Z'}^{fR}$ |
|------------|-----------------------------|-----------------------------|
| u, c | $-(1 - 2 \sin^2 \theta_w)$ | $+4 \sin^2 \theta_w$ |
| d, s | $-(1 - 2 \sin^2 \theta_w)$ | $-2 \sin^2 \theta_w$ |
| l^- | $+(1 - 4 \sin^2 \theta_w)$ | $+2(1 - 4 \sin^2 \theta_w)$ |
| ν_l | $+(1 - 4 \sin^2 \theta_w)$ | |
| t | $+1$ | $+4 \sin^2 \theta_w$ |
| b | $+1$ | $-2 \sin^2 \theta_w$ |
| D_1, D_2 | $+2(1 - 5 \sin^2 \theta_w)$ | $-8 \sin^2 \theta_w$ |
| T | $-2(1 - 6 \sin^2 \theta_w)$ | $+10 \sin^2 \theta_w$ |

$$D_1^c, D_2^c: \left(3^*, 1, \frac{4}{3} \right),$$

$$T^c: \left(3^*, 1, -\frac{5}{3} \right). \quad (3)$$

In this model there are three new, exotic quarks of charge $-\frac{4}{3}(D_{1,2})$ and $\frac{5}{3}(T)$. Here anomaly cancellation takes place among all three generations, in contrast to the SM, where the anomalies are cancelled within each generation.

We write the Feynman rules for the couplings of the neutral gauge bosons and the fermions as

$$ig \left[c_N^{fL} \gamma^\mu \frac{1 - \gamma_5}{2} + c_N^{fR} \gamma^\mu \frac{1 + \gamma_5}{2} \right], \quad (4)$$

where $N = \gamma, Z, Z'$. The couplings of the photon and Z to the fermions are as in the SM, while those of the Z' are

$$c_{Z'}^{fL,R} = \frac{1}{2\sqrt{3} \cos \theta_w \sqrt{1 - 4 \sin^2 \theta_w}} d_{Z'}^{fL,R}, \quad (5)$$

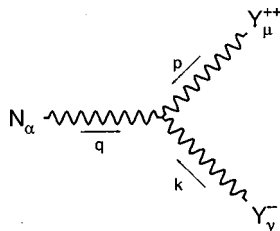
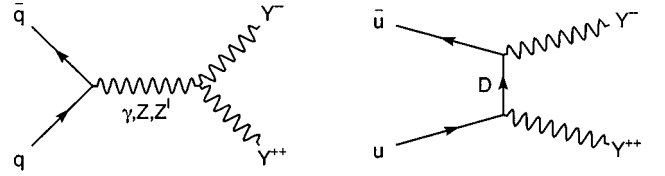
where the $d_{Z'}^{fL,R}$ are given in Table I.

We now turn to the trilinear gauge-boson vertices. The Feynman rule for the N - Y^{++} - Y^{--} vertex (see Fig. 1) is

$$ig c_N^Y [g^{\mu\nu}(k-p)^\alpha + g^{\nu\alpha}(q-k)^\mu + g^{\alpha\mu}(p-q)^\nu], \quad (6)$$

where

$$c_\gamma^Y = 2 \sin \theta_w, \quad c_{Z'}^Y = \frac{1 - 4 \sin^2 \theta_w}{2 \cos \theta_w},$$


 FIG. 1. Momentum and Lorentz-index assignments for the N - Y^{++} - Y^{--} vertex [Eq. (6)].

 FIG. 2. Feynman diagrams contributing to $q\bar{q} \rightarrow Y^{++} Y^{--}$ in the 3-3-1 model.

$$c_{Z'}^Y = -\frac{\sqrt{3}}{2} \sqrt{1 - 3 \tan^2 \theta_w}. \quad (7)$$

Finally, the data on muonium-antimuonium conversion constrain doubly charged vector bileptons to satisfy $M_Y > 1.7\lambda$ TeV [1], where λ is the bilepton coupling to leptons. In the 3-3-1 model, we have $\lambda = g/\sqrt{2}$, which implies that the lower limit on the vector bilepton mass is $M_Y > 740$ GeV. For singly charged vector bileptons, the limits on $\mu_R \rightarrow e \nu \nu$ yield $M_Y > 440$ GeV.

As for the Z' , its couplings to quarks are enhanced relative to its couplings to leptons. Thus, limits on the mass of the Z' come mainly from low-energy experiments such as neutrino-quark scattering and atomic parity violation. These constrain $M_{Z'} \geq 550$ GeV [7].

With this information we can now proceed to the calculation of the cross sections for the production of bileptons.

B. $q\bar{q} \rightarrow Y^{++} Y^{--}$

The process $d\bar{d} \rightarrow Y^{++} Y^{--}$ receives contributions from s -channel γ, Z and Z' exchange (see Fig. 2). The amplitude-squared is

$$\frac{1}{4} \sum_{\text{spins}} |\mathcal{M}|^2$$

$$= \sum_{N, N'} \frac{1}{2} \frac{g^4 c_N^Y c_{N'}^Y (c_N^{dL} c_{N'}^{dL} + c_N^{dR} c_{N'}^{dR})}{(\hat{s} - M_N^2 + i\Gamma_N M_N)(\hat{s} - M_{N'}^2 - i\Gamma_{N'} M_{N'})}$$

$$\times \left[\left(-6M_Y^2 \hat{s} + \frac{\hat{s}^4}{8M_Y^4} \right) (1 - \cos^2 \theta) \right.$$

$$\left. + \frac{\hat{s}^3}{M_Y^2} (1 + \cos^2 \theta) - \frac{9}{2} \hat{s}^2 \left(1 + \frac{7}{9} \cos^2 \theta \right) \right], \quad (8)$$

where $N, N' = \gamma, Z, Z'$, and \hat{s} is the center-of-mass energy of the $q\bar{q}$ system (not to be confused with s , the center-of-mass energy of the collider). It is straightforward to verify that this expression does not violate unitarity. In the limit as $\sqrt{\hat{s}} \rightarrow \infty$, M_N and Γ_N are negligible. But in this limit the cross section vanishes since $\sum_N c_N^Y c_N^{dL,R} = 0$. Thus we see that, as expected, the inclusion of the new contributions (in this case a Z') restores unitarity.

One quantity which appears in the above expression, and which we have not yet discussed, is $\Gamma_{Z'}$. The Z' may decay to the exotic quarks D_i and T , depending on their mass. As in Ref. [5], we assume that $m_Q = 600$ GeV ($Q = D_i, T$). Furthermore, the Z' may decay to the light scalars of the Higgs sector. But since we are considering a general nonminimal 3-3-1 model, we have not specified the Higgs sector. In the minimal model, the partial width of the Z' into light scalars is roughly 10% of its width into the light SM quarks. For simplicity, here we assume that even with a nonminimal

Higgs sector the partial width into scalars is the same as in the minimal model. Note that this assumption does not have strong consequences—the cross sections do not depend much on this partial width.

The process $u\bar{u} \rightarrow Y^{++}Y^{--}$ is a bit more complicated. In addition to the s -channel γ, Z and Z' contributions, there is a diagram in which a D_1 quark is exchanged in the t -channel (see Fig. 2). We denote these two amplitude types as \mathcal{M}_1 and \mathcal{M}_2 , respectively. The amplitude-squared is then the sum of the following three terms:

$$\frac{1}{4} \sum_{\text{spins}} |\mathcal{M}_1|^2 = \sum_{N,N'} \frac{1}{2} \frac{g^4 c_N^Y c_{N'}^Y (c_N^{uL} c_{N'}^{uL} + c_N^{uR} c_{N'}^{uR})}{(\hat{s} - M_N^2 + i\Gamma_N M_N)(\hat{s} - M_{N'}^2 - i\Gamma_{N'} M_{N'})} \left[\left(-6M_Y^2 \hat{s} + \frac{\hat{s}^4}{8M_Y^4} \right) (1 - \cos^2 \theta) + \frac{\hat{s}^3}{M_Y^2} (1 + \cos^2 \theta) - \frac{9}{2} \hat{s}^2 \left(1 + \frac{7}{9} \cos^2 \theta \right) \right], \quad (9)$$

$$\frac{1}{4} \sum_{\text{spins}} |\mathcal{M}_2|^2 = \frac{g^4}{16} \frac{1}{(\hat{t} - M_D^2)^2} \left\{ -\hat{s}(1 - 5 \cos^2 \theta) M_Y^2 - \hat{s}^2 \left(\frac{7}{4} + \frac{21}{4} \cos^2 \theta + \cos^4 \theta \right) + \frac{\hat{s}^3}{2M_Y^2} (1 + \cos^2 \theta)^2 + \frac{\hat{s}^4}{16M_Y^4} (1 - \cos^4 \theta) - \hat{s}^2 \beta (3 \cos \theta + \cos^3 \theta) + \frac{\hat{s}^3}{4M_Y^2} \beta (5 \cos \theta + 3 \cos^3 \theta) + \frac{\hat{s}^4}{8M_Y^4} \beta \cos \theta \sin^2 \theta \right\}, \quad (10)$$

and

$$\frac{1}{4} \sum_{\text{spins}} \mathcal{M}_1 \mathcal{M}_2^* + \text{H.c.} = \sum_N g^4 \frac{c_N^Y c_N^{uL} (\hat{s} - M_N^2)}{[(\hat{s} - M_N^2)^2 + (\Gamma_N M_N)^2] (\hat{t} - M_D^2)} \left\{ -\frac{3}{2} \hat{s} M_Y^2 \sin^2 \theta - \frac{\hat{s}^2}{8} (9 + 7 \cos^2 \theta) + \frac{\hat{s}^3}{4M_Y^2} (1 + \cos^2 \theta) - \frac{1}{4} \hat{s}^2 \beta \cos \theta (3 + \cos^2 \theta) + \frac{\hat{s}^4}{32M_Y^4} \sin^2 \theta + \frac{\hat{s}^3}{16M_Y^2} \beta (5 \cos \theta + 3 \cos^3 \theta) + \frac{\hat{s}^4}{32M_Y^4} \beta \cos \theta \sin^2 \theta \right\}, \quad (11)$$

where $\beta \equiv \sqrt{1 - 4M_Y^2/\hat{s}}$.

We obtain the cross section for bilepton production at hadron colliders by convoluting the above expressions with the CTEQ3M structure functions [8]. We consider both the Tevatron ($\sqrt{s} = 1.8$ TeV) and the LHC ($\sqrt{s} = 14$ TeV). The present luminosity at the Tevatron is $100 \text{ pb}^{-1}/\text{yr}$ (run 1), and this is expected to be increased to at least $2 \text{ fb}^{-1}/\text{yr}$ in 2002 (run 2).² The design luminosity at the LHC is $10 \text{ fb}^{-1}/\text{yr}$. Since we have not included a rapidity cut on the produced

particles taken into account the detection efficiency, as a figure of merit we therefore (conservatively) require 25 events for discovery. This corresponds to a cross section of 0.25 pb (run 1) or 12.5 fb (run 2) at the Tevatron, and 2.5 fb at the LHC.

The results for $Y^{++}Y^{--}$ production are shown in Fig. 3, where the cross sections are plotted as a function of M_Y for various Z' masses. [In Ref. [5], the production cross section is calculated within the minimal 3-3-1 model, in which the condition of Eq. (2) between M_Y and $M_{Z'}$ is assumed. When we impose this condition, we find that we do indeed reproduce the results of Ref. [5].] For the Tevatron (run 1), we see that only bileptons of mass $M_Y \lesssim 250$ GeV are observable if $M_{Z'} \geq 600$ GeV. This increases modestly to $M_Y \lesssim 320$ GeV in run 2 (for $\sqrt{s} = 2$ TeV, this upper limit becomes 360 GeV). However, as explained above, in all cases this bilepton mass range has already been ruled out. We therefore conclude that, given the present constraints on M_Y from low-energy data, vector bileptons cannot be observed at experiments at the Tevatron.

²Strictly speaking, run 2 involves not only a luminosity increase, but also an increase in energy from 1.8 TeV to 2.0 TeV. For simplicity, in the figures we continue to take $\sqrt{s} = 1.8$ TeV at the Tevatron for both runs. However, we have also performed the calculations for 2.0 TeV. Although the cross sections are increased by a factor of 1.5 to 2, this does not affect our conclusions significantly. For the various processes, we indicate in the text the effects of using $\sqrt{s} = 2.0$ TeV instead of 1.8 TeV for run 2.

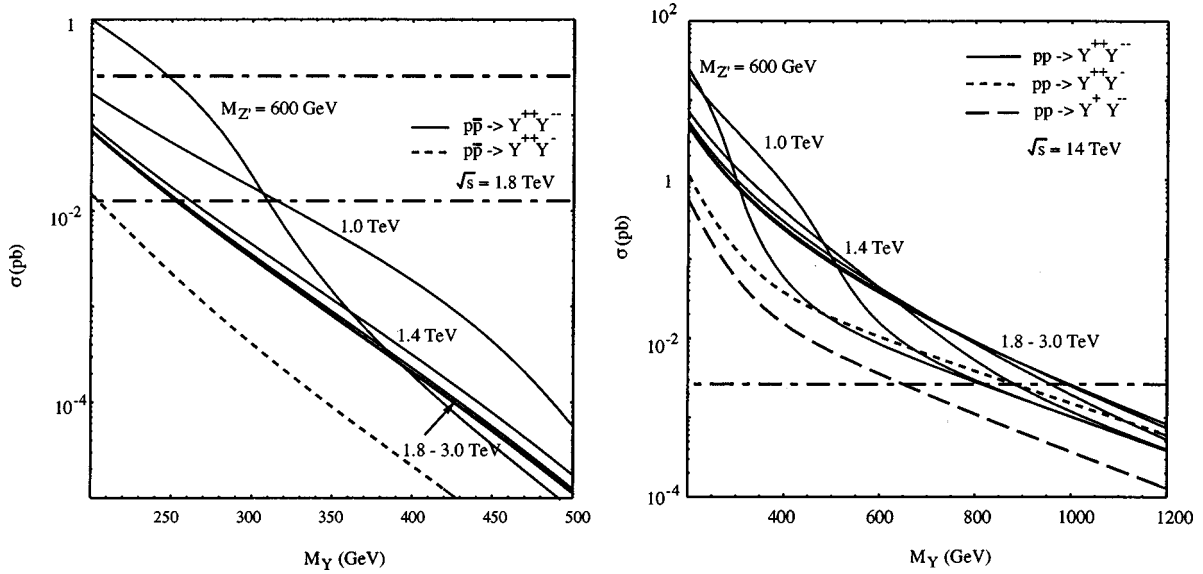


FIG. 3. Cross sections for $Y^{++}Y^{--}$, $Y^{++}Y^{-}$ and $Y^{--}Y^{+}$ production at the Tevatron ($\sqrt{s} = 1.8$ TeV) and at the LHC ($\sqrt{s} = 14$ TeV) as a function of M_Y , for various values of $M_{Z'}$. The horizontal lines indicate the cross sections required for discovery: 0.25 pb (Tevatron, run 1), 12.5 fb (Tevatron, run 2), and 2.5 fb (LHC).

At the LHC, on the other hand, bileptons of mass $M_Y \lesssim 1$ TeV are observable. Since the vector bilepton mass is presently constrained to be $M_Y > 740$ GeV, this means that there is a window of observability.

It is instructive to separate out the contribution of an on-shell Z' to the vector bilepton production cross section from that of the γ and Z . In Fig. 4, for various values of $M_{Z'}$, we present the cross section for $pp \rightarrow Y^{++}Y^{--}$ at the LHC due to the real Z' alone. By comparing Figs. 3 and 4, we can see for which values of $M_{Z'}$ the on-shell Z' dominates the process and for which values it is negligible.

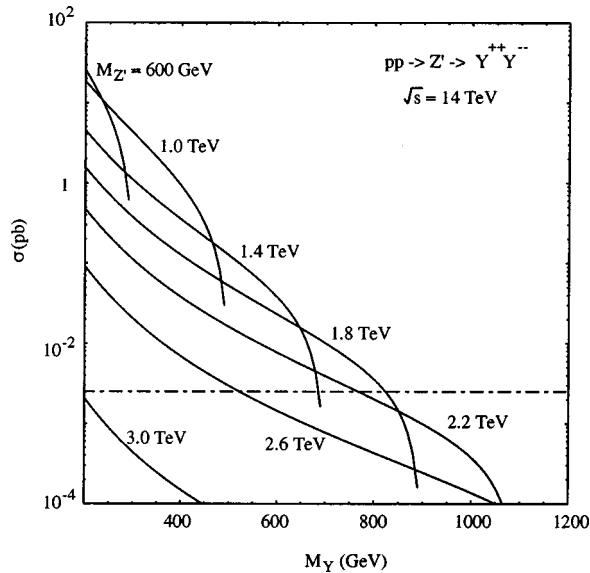


FIG. 4. Real Z' contribution to $Y^{++}Y^{--}$ production at the LHC ($\sqrt{s} = 14$ TeV) as a function of M_Y , for various values of $M_{Z'}$. The horizontal line indicates the cross section required for discovery: 2.5 fb.

In particular, we note that real Z' exchange is dominant only for $M_{Z'} \lesssim 1.0$ TeV. Thus, for such values of $M_{Z'}$, the production of bileptons of mass $M_Y \lesssim 500$ GeV is due principally to the exchange of an on-shell Z' . On the other hand, the real Z' contribution is basically negligible for $M_{Z'} \gtrsim 1.8$ TeV, so that bileptons of mass $M_Y \gtrsim 900$ GeV are produced mainly via γ or Z exchange. For $1.0 \text{ TeV} \lesssim M_{Z'} \lesssim 1.8 \text{ TeV}$, the Z' and γ, Z contributions are similar in size.

We can therefore conclude that, for the entire range of M_Y for which bileptons are observable at the LHC, namely $740 \text{ GeV} \lesssim M_Y \lesssim 1 \text{ TeV}$, the cross section is never dominated by the exchange of an on-shell Z' . Indeed, the γ - and Z -exchange contributions dominate the cross section for the larger values of M_Y . Thus, although we have performed the calculations within the 3-3-1 model, the details of this model are largely unimportant to the conclusions. In other words, the result that vector bileptons of mass $M_Y \lesssim 1$ TeV are observable at the LHC is basically model-independent.

The production of two doubly charged bileptons will result in an unmistakable signature. Each of the bileptons will decay to two same-sign leptons, not necessarily of the same flavor, leading to an $l_1^+ l_1^+ l_2^- l_2^-$ signal, in which each pair of same-sign leptons has the same invariant mass. The SM background to this process is tiny. Should bileptons be produced at the LHC, there should be no difficulty in detecting them.

C. $u\bar{d} \rightarrow Y^{++}Y^{-}$, $\bar{u}d \rightarrow Y^{+}Y^{--}$

In the previous subsection, we noted that the process $q\bar{q} \rightarrow Y^{++}Y^{--}$, in which the bileptons decay to $l_1^+ l_1^+ l_2^- l_2^-$, has virtually no SM background. In fact, even if a single doubly charged bilepton were produced in a reaction, there would be little background, since no SM process will give two same-

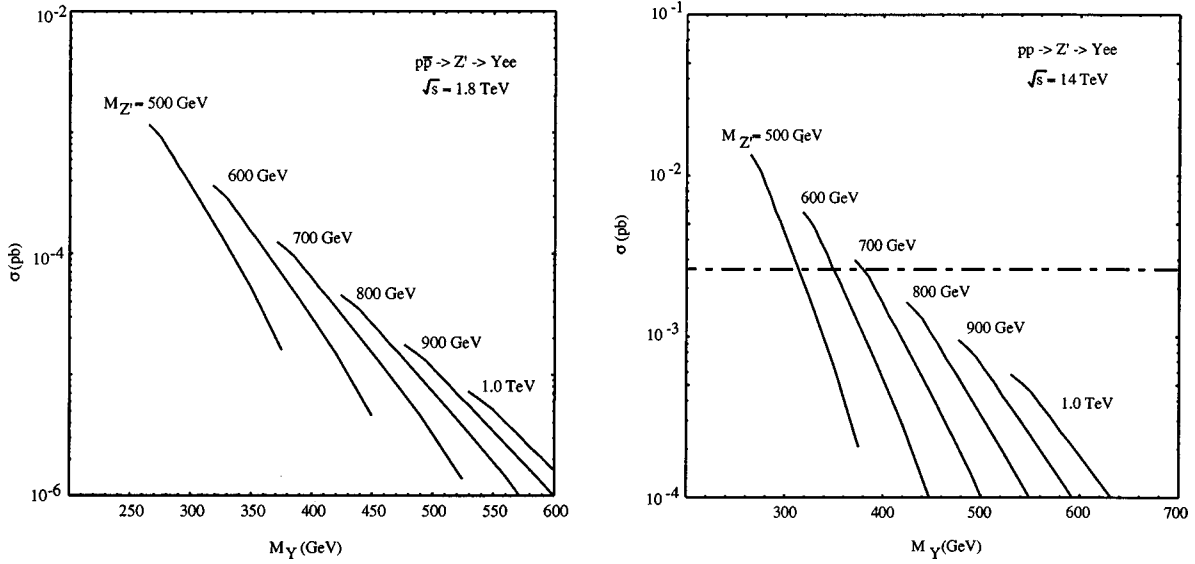


FIG. 5. Z' contribution to $Y^{++}e^-e^-$ production at the Tevatron ($\sqrt{s}=1.8$ TeV) and at the LHC ($\sqrt{s}=14$ TeV) as a function of M_Y , for various values of $M_{Z'}$. The horizontal line indicates the cross section required for discovery at the LHC: 2.5 fb. The process is unobservable at the Tevatron.

sign leptons whose invariant mass has a peak at the bilepton mass. Thus, it is also of interest to examine processes in which one doubly charged bilepton is produced. We therefore consider the reactions $u\bar{d}\rightarrow Y^{++}Y^-$ and $\bar{u}d\rightarrow Y^+Y^{--}$ [9].

The process $u\bar{d}\rightarrow Y^{++}Y^-$ is quite similar to $u\bar{u}\rightarrow Y^{++}Y^{--}$. Indeed, the amplitude-squared for $u\bar{d}\rightarrow Y^{++}Y^-$ is given by the expressions in Eqs. (9)–(11), with the following changes: (i) there is only 1 s -channel diagram, with an internal W , instead of 3 s -channel diagrams ($N, N' = \gamma, Z, Z'$), (ii) $c_N^{uL}\rightarrow c_W=1/\sqrt{2}$, (iii) $c_N^{uR}\rightarrow 0$, (iv) $c_N^Y\rightarrow c_W^Y=1/\sqrt{2}$. The amplitude for $\bar{u}d\rightarrow Y^+Y^{--}$ is identical.

The cross sections for $Y^{++}Y^-$ and Y^-Y^{++} production at hadron colliders are shown in Fig. 3, in which we assume that $M_{Y^+}=M_{Y^{++}}\equiv M_Y$. At the Tevatron, which is a $p\bar{p}$ collider, these two cross sections are equal. However, even with the increased luminosity (and slight increase in energy) of run 2, these processes are unobservable. At the LHC, the cross sections for these two final states are not equal since the LHC is a pp collider, and hence has more u -quarks than d -quarks, thus favoring the $Y^{++}Y^-$ final state. The processes $u\bar{d}\rightarrow Y^{++}Y^-$ and $\bar{u}d\rightarrow Y^+Y^{--}$ are observable for $M_Y\lesssim 900$ GeV and $M_Y\lesssim 660$ GeV, respectively. Given the low-energy constraint of $M_Y>740$ GeV, this implies that there is a small window of observability at the LHC for $Y^{++}Y^-$ production.

D. $q\bar{q}\rightarrow Yee$

The final process involving vector bileptons that we consider is the reaction $q\bar{q}\rightarrow Y^{++}e^-e^-$, in which the e^-e^- pair comes from a virtual bilepton. The advantage of this process over $q\bar{q}\rightarrow Y^{++}Y^{--}$ is clear: it is energetically easier to produce one real bilepton than two. However, there is also a hefty price to pay—the amplitude involves an additional

gauge coupling, and one has to consider 3-body final-state phase space instead of 2-body phase space. The only conceivable way to offset this is if the process is dominated by the decay of a real Z' , with $M_Y>M_{Z'}/2$. (Of course, if $M_Y<M_{Z'}/2$, then pair production of vector bileptons will dominate.) The Z' contribution to the cross section for this process involves a factor

$$\frac{1}{(\hat{s}-M_{Z'}^2)^2+(M_{Z'}\Gamma_{Z'})^2}.$$

In this case, for $\hat{s}=M_{Z'}^2$, it is perhaps possible that the enhancement due to the on-shell Z' might compensate for the above suppressions. This is what we investigate here.

We therefore calculate the cross section for $q\bar{q}\rightarrow Y^{++}e^-e^-$, mediated solely by an on-shell Z' . The results are shown in Fig. 5. It is clear that the reaction $q\bar{q}\rightarrow Y^{++}e^-e^-$ is completely unobservable at the Tevatron. At the LHC, depending on the value of $M_{Z'}$, this process is observable for $M_Y\lesssim 380$ GeV. However, this range of bilepton masses has already been ruled out. And even if such masses were still allowed, the cross section for $q\bar{q}\rightarrow Y^{++}e^-e^-$ due only to intermediate γ and Z exchange is still roughly two orders of magnitude larger. Thus, this process cannot be used to discover the bileptons of the 3-3-1 model.

The problem here is that the Z' in the 3-3-1 model is a relatively broad resonance. For example, the width of a 1 TeV Z' is about 200 GeV. Thus, the hoped-for enhancement due to an on-shell Z' is fairly minimal. However, in a model in which the Z' is quite narrow, say $\Gamma_{Z'}\sim 10^{-2}M_{Z'}$, then the enhancement factor could be substantial, and could well overcome the suppressions mentioned above. Indeed, in such

a model, bileptons would be more easily discovered via $q\bar{q} \rightarrow Z' \rightarrow Y^{++}e^-e^-$ than via $q\bar{q} \rightarrow \gamma, Z \rightarrow Y^{++}Y^{--}$. Thus, we conclude that, although the process $q\bar{q} \rightarrow Y^{++}e^-e^-$ is of little interest within the 3-3-1 model, it might be important in other models containing bileptons. It is therefore worthwhile to search for signals of such a process.

III. SCALAR BILEPTONS

In this section we consider the production of scalar bileptons ϕ at hadron colliders. In contrast to vector bileptons, if one computes the cross section for $q\bar{q} \rightarrow \phi^{++}\phi^{--}$ including only the s -channel contributions from the γ and Z , one finds that unitarity is not violated. Thus, it is not necessary to perform the calculations for scalar bilepton production within a particular model.

However, in a given model, there may be new, exotic contributions to processes such as $q\bar{q} \rightarrow \phi^{++}\phi^{--}$, such as the exchange of a Z' . In fact, as we will see, if one includes these additional contributions, the cross section for scalar bilepton production may be significantly increased relative to the case where only γ and Z exchange are considered.

Thus, if one wants to study scalar bilepton production at hadron colliders, it is useful to examine both scenarios. In the following subsections we therefore consider two situations concerning the process $q\bar{q} \rightarrow \phi^{++}\phi^{--}$: (i) only the SM γ and Z contributions are present, and (ii) there are additional, exotic contributions. For this latter possibility, we must choose a particular model in which to perform the calculation. As before, in this case we opt for the 3-3-1 model.

We also consider the processes $u\bar{d} \rightarrow \phi^{++}\phi^-$ and $\bar{u}d \rightarrow \phi^{--}\phi^+$, in which a single doubly charged scalar bilepton is produced.

Similar to the case of vector bileptons, the data on muonium-antimuonium conversion constrain doubly charged scalar bileptons to satisfy $M_\phi > 2-3.3\lambda$ TeV [1]. However, there is an important difference between vector and scalar bileptons. For vector bileptons, the coupling λ is a gauge coupling, and is specified within a particular model. But for scalar bileptons, λ is the (unspecified) Yukawa coupling of the bilepton to leptons. In the processes considered below, the coupling λ does not appear, and hence can be taken to be as small as desired. Thus, although we take $M_\phi > 200$ GeV, the only real (λ -independent) constraint on the mass of the scalar bilepton comes from experiments at the CERN e^+e^- collider LEP, namely that it must be greater than $M_{Z/2}$.

A. $q\bar{q} \rightarrow \phi^{++}\phi^{--}$

The process $q\bar{q} \rightarrow \phi^{++}\phi^{--}$ is mediated principally by the exchange of a neutral gauge boson N ($N = \gamma, Z$ and possibly Z'). (In a particular model, there may also be contributions from exotic quarks in the t -channel, which depend on the Yukawa coupling λ . But since we are assuming that this coupling is small, we can ignore these contributions.) The amplitude-squared for this process is

$$\begin{aligned} & \frac{1}{4} \sum_{\text{spins}} |\mathcal{M}_1|^2 \\ &= \sum_{N, N'} \frac{1}{4} \frac{g^4 c_N^\phi c_{N'}^\phi (c_N^{qL} c_{N'}^{qL} + c_N^{qR} c_{N'}^{qR})}{(\hat{s} - M_N^2 + i\Gamma_N M_N)(\hat{s} - M_{N'}^2 - i\Gamma_{N'} M_{N'})} \\ & \quad \times \hat{s}^2 \beta^2 \sin^2 \theta, \end{aligned} \quad (12)$$

where

$$\begin{aligned} c_\gamma^\phi &= Q \sin \theta_w, \\ c_Z^\phi &= \frac{1}{\cos \theta_w} (I_3 - Q \sin^2 \theta_w). \end{aligned} \quad (13)$$

In the above, the scalar dilepton charge Q can be $+2$ or -2 , and its weak isospin I_3 can in principle take any integer or half-integer value. In the 3-3-1 model, there is also a contribution from an s -channel Z' :

$$c_{Z'}^\phi = \frac{1}{\cos \theta_w} \left[-\frac{\sqrt{1-4\sin^2 \theta_w}}{2\sqrt{3}} Y + \frac{1-\sin^2 \theta_w}{\sqrt{3}\sqrt{1-4\sin^2 \theta_w}} X \right], \quad (14)$$

where $Y = 2(Q - I_3)$ is the ordinary SM hypercharge, and X is the $U(1)_X$ charge.

Since the scalar bileptons are defined only by their quantum numbers Q , I_3 and possibly X , there are an infinite number of possible cases one can consider. The minimal 3-3-1 model contains 2 bileptons: (i) η_1^{++} , which has $Q = +2$, $I_3 = +1$, $Y = +2$ and $X = 0$, and (ii) η_2^{--} , which has $Q = -2$, $I_3 = 0$, $Y = -4$ and $X = 0$. For simplicity, in this paper we focus on the η_1 (the results for the η_2 are quite similar).

In Fig. 6 we show the cross sections for $\eta_1^{++}\eta_1^{--}$ production at the Tevatron and LHC. We consider the case where only the SM γ and Z contribute, as well as the case where there is an additional Z' contribution. It is clear from this figure that the effect of the Z' can be considerable. Depending on its mass, the cross section can be increased by up to two orders of magnitude. (Similar behavior was found in Ref. [6], where the production at high-energy colliders of the scalar bilepton of the left-right symmetric model was studied.)

Even with such an enhancement, this process is observable at the Tevatron only if the particles are light: $M_{Z'} \lesssim 600$ GeV and $M_\phi \lesssim 300$ GeV are required to obtain an observable signal. (This holds for both $\sqrt{s} = 1.8$ and 2.0 TeV.) Since the Z' is already constrained to satisfy $M_{Z'} > 550$ GeV, this does not leave much room. On the other hand, $\eta_1^{++}\eta_1^{--}$ production is observable at the LHC for larger masses. But the reach in M_ϕ depends strongly on whether a Z' is present and, if so, what the value of its mass is. If there is no Z' , then such scalar bileptons can be observed for $M_\phi \lesssim 375$ GeV. If a Z' is present, then this reach increases to 800–850 GeV.

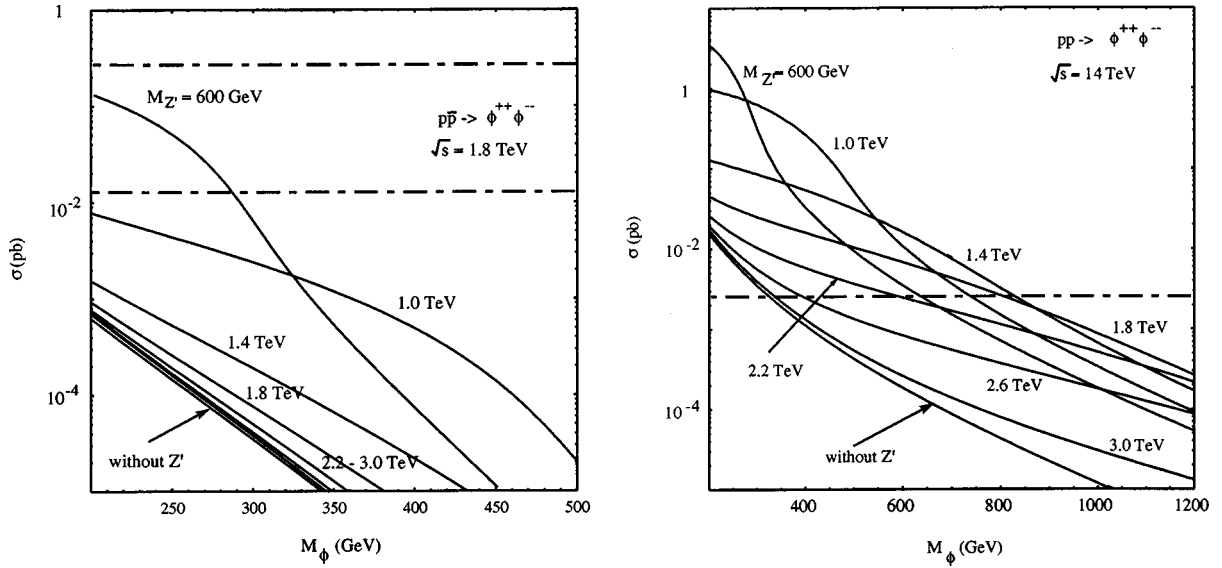


FIG. 6. Cross sections for $\phi^{++}\phi^{--}$ production ($\phi = \eta_1$) at the Tevatron ($\sqrt{s} = 1.8$ TeV) and at the LHC ($\sqrt{s} = 14$ TeV) as a function of M_ϕ , for various values of $M_{Z'}$. The horizontal lines indicate the cross sections required for discovery: 0.25 pb (Tevatron, run 1), 12.5 fb (Tevatron, run 2), and 2.5 fb (LHC).

Of course, these results apply specifically to the η_1^{++} bilepton. For a different given bilepton, the observational reach will depend on its quantum numbers. In particular, for bileptons other than the η_1^{++} it is conceivable that this reach can extend to higher masses. Still, the results we have found for the η_1^{++} give one a feel for the order of magnitude of the reach that one can expect for generic scalar bileptons.

We therefore conclude that the process $q\bar{q} \rightarrow \phi^{++}\phi^{--}$ is observable at the Tevatron only if the ϕ^{++} is light and if the mass of the Z' lies just above its present bound. For the LHC, if only the γ and Z contribute to this process, then bileptons are observable if $M_\phi \lesssim 400$ GeV. And if the contributions from non-SM particles such as Z' bosons are significant, then this limit may be pushed up to $M_\phi \lesssim 1$ TeV.

We must also reiterate that these results are independent of λ , the Yukawa coupling of the scalar bilepton to leptons. This is in contrast to Bhabha and Møller scattering at e^+e^- and e^-e^- colliders. Although these lepton colliders are potentially sensitive to much larger scalar bilepton masses, their reach depends directly on the value of the Yukawa coupling. If this coupling is too small, then there will be no measurable effect in e^+e^- and e^-e^- colliders, but the process $q\bar{q} \rightarrow \phi^{++}\phi^{--}$ will still be observable. (Of course, the process $e^+e^- \rightarrow \phi^{++}\phi^{--}$, which is also independent of λ , may be possible, depending on M_ϕ and \sqrt{s} .) Thus, if the Yukawa coupling is small, a hadron collider such as the LHC may in fact be the optimal machine for detecting scalar bileptons.

B. $u\bar{d} \rightarrow \phi^{++}\phi^-$, $\bar{u}d \rightarrow \phi^+\phi^{--}$

We also consider the production of a single doubly charged scalar dilepton via $u\bar{d} \rightarrow \phi^{++}\phi^-$ or $\bar{u}d \rightarrow \phi^+\phi^{--}$. These processes are mediated by the exchange of a W in the s -channel. As in the vector case, this process is similar to

$q\bar{q} \rightarrow \phi^{++}\phi^{--}$, assuming that the masses of the singly charged and doubly charged dileptons are equal. (As a result of constraints from the ρ -parameter, these masses cannot be too different.) The amplitude-squared of these processes is the same as Eq. (12), with the following changes: (i) $q\bar{q}$ becomes $u\bar{d}$, (ii) $c_N^{qL} \rightarrow 1/\sqrt{2}$, (iii) $c_N^{qR} \rightarrow 0$, (iv) $c_N^\phi \rightarrow c_W^\phi$. Therefore, for the process $u\bar{d} \rightarrow \phi^{++}\phi^-$ or $\bar{u}d \rightarrow \phi^+\phi^{--}$, we have

$$\frac{1}{4} \sum_{\text{spins}} |\mathcal{M}|^2 = \frac{1}{8} \frac{g^4 (c_W^\phi)^2}{(\hat{s} - M_W^2)^2 + (\Gamma_W M_W)^2} \hat{s}^2 \beta^2 \sin^2 \theta. \quad (15)$$

The quantity c_W^ϕ parametrizes the $W^- - \phi^{++} - \phi^-$ coupling. Its value depends on the representation that the scalar dileptons are in, as well as how they are defined. For example, for an ordinary $SU(2)_L$ -doublet, $c_W^\phi = 1/\sqrt{2}$. In the minimal 3-3-1 model, only the η_1^{++} couples to the W , with $c_W^\phi = 1$.

In Fig. 7 we present the cross sections for $\phi^{++}\phi^-$ and $\phi^+\phi^{--}$ production at the Tevatron and at the LHC. Specifically, we consider $\phi^{++} = \eta_1^{++}$. [The case of an $SU(2)_L$ -doublet, or indeed any other $SU(2)_L$ representation, can be obtained by simply scaling the results of Fig. 7 by $(c_W^\phi)^2$.] This process is unobservable at the Tevatron, but can be observed at the LHC for scalar bilepton masses $M_\phi \lesssim 400$ GeV ($\phi^+\phi^{--}$) or $M_\phi \lesssim 500$ GeV ($\phi^{++}\phi^-$).

It is also conceivable that, in a particular model, there might be new, exotic contributions to $q\bar{q} \rightarrow \phi^{++}\phi^-$. If these include the exchange of an on-shell particle in the s -channel, then the cross section may be significantly enhanced relative to the results of Fig. 7. As we saw in the case of $q\bar{q} \rightarrow \phi^{++}\phi^{--}$, this enhancement may be large, perhaps as much as several orders of magnitude. Although this does not happen in the 3-3-1 model for $q\bar{q} \rightarrow \phi^{++}\phi^-$, it may occur in other models. So this possibility should be kept in mind.

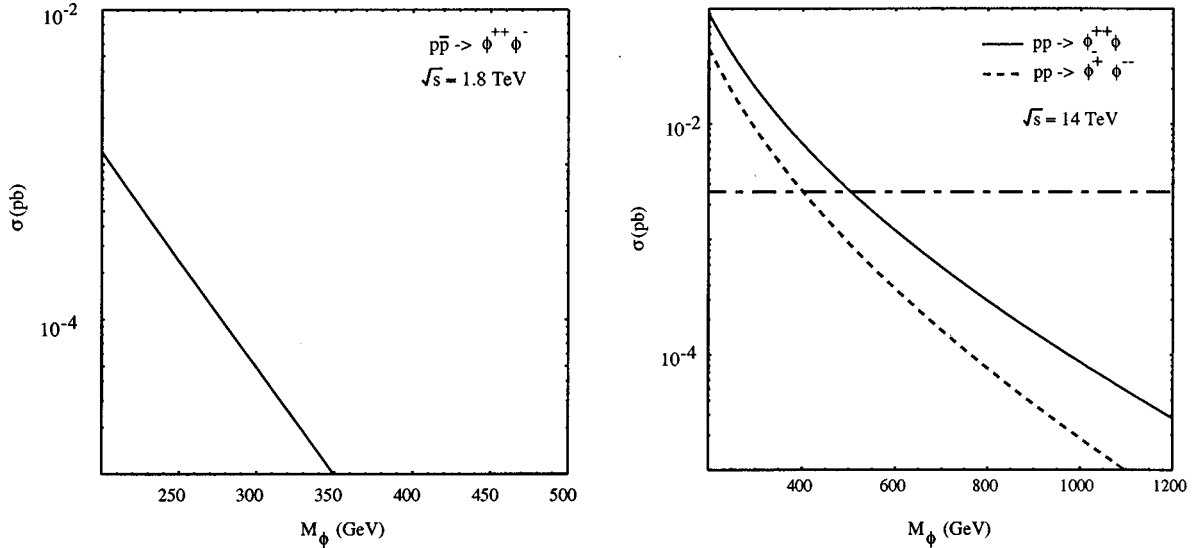


FIG. 7. Cross sections for $\phi^{++}\phi^{-}$ and $\phi^{+}\phi^{-}$ production ($\phi^{++} = \eta_1^{++}$) at the Tevatron ($\sqrt{s} = 1.8$ TeV) and at the LHC ($\sqrt{s} = 14$ TeV) as a function of M_ϕ . The horizontal line indicates the cross section required for discovery at the LHC: 2.5 fb. The process is unobservable at the Tevatron.

IV. CONCLUSIONS

We have investigated the production of vector and scalar bileptons at hadron colliders. Although we would have liked to perform this analysis in a model-independent way, this is unfortunately not possible. To see this, consider, for example, the process $q\bar{q} \rightarrow Y^{++}Y^{--}$, where Y^{++} is a vector bilepton. If one considers only the SM contributions (γ and Z exchange) to this process, one finds that the cross section violates unitarity. In order to avoid unitarity violation, it is therefore necessary that the calculations for vector bilepton production be performed within a specific model.

We have chosen the 3-3-1 model. In this model unitarity is restored by the inclusion of additional contributions to $q\bar{q} \rightarrow Y^{++}Y^{--}$: s -channel Z' exchange and t -channel exotic D -quark exchange. Although, strictly speaking, all our results are model-dependent, we do expect the cross sections to take similar (order-of-magnitude) values in most models. Indeed, for certain values of the Z' and Y masses, we find that some processes are in fact dominated by the SM contributions. The results for these processes are thus essentially model-independent.

Processes involving scalar bileptons ϕ^{++} , such as $q\bar{q} \rightarrow \phi^{++}\phi^{-}$, do not suffer from unitarity violation; so it is not necessary to use a particular model. However, in a given model, there may be new, exotic contributions to scalar bilepton production which may significantly increase the cross sections. It is therefore useful to calculate the cross sections for scalar bilepton production within a chosen model, as well as using only the SM (γ , Z) contributions. For the model-dependent calculations, we have again used the 3-3-1 model, focussing on one of its bileptons, the η_1^{++} .

There are constraints on bileptons from low-energy experiments. The data on muonium-antimuonium conversion imply a lower limit on the mass of the doubly charged vector bileptons of the 3-3-1 model: $M_Y > 740$ GeV. For singly

charged vector bileptons, constraints from $\mu_R \rightarrow e\nu\nu$ yield a somewhat weaker limit: $M_Y > 440$ GeV. For scalar bileptons, the data on muonium-antimuonium conversion require $M_\phi > (2-3.3)\lambda$ TeV, where λ is the Yukawa coupling of the bilepton to leptons. But λ is unknown, and can be taken as small as desired. Thus, the only real constraint on the scalar bilepton mass is $M_\phi > M_Z/2$.

We have examined a variety of processes in which one or two doubly charged bileptons are produced at a hadron collider. We considered both the Tevatron ($\sqrt{s} = 1.8$ TeV) and the LHC ($\sqrt{s} = 14$ TeV). In all cases, as a figure of merit, we required 25 events for observability. This corresponds to a cross section of 0.25 pb (Tevatron, run 1), 12.5 fb (Tevatron, run 2), or 2.5 fb (LHC). (Even with $\sqrt{s} = 2.0$ TeV for run 2 at the Tevatron, our results are little changed.)

Note that if a doubly charged vector or scalar bilepton were produced at a collider, its decay would yield an unmistakable signature. The decay products would be a pair of same-sign leptons, with an invariant mass equal to that of the bilepton. The SM background to such a process is very small. Should bileptons be produced at a hadron collider, there should be no difficulty in detecting them.

Here are our results:

(i) $q\bar{q} \rightarrow Y^{++}Y^{--}$: At the Tevatron, vector bileptons are observable if $M_Y \lesssim 250$ GeV (run 1) or $M_Y \lesssim 320$ GeV (run 2) [$M_Y \lesssim 360$ GeV (run 2, $\sqrt{s} = 2.0$ TeV)]. However, in all cases this mass range has already been ruled out; so we conclude that vector bileptons cannot be observed in this process at experiments at the Tevatron. At the LHC, bileptons of mass $M_Y \lesssim 1$ TeV are observable. In this case there is a window of observability. Note also that bileptons of mass $M_Y \gtrsim 900$ GeV are produced mainly via γ or Z exchange—the Z' of the 3-3-1 contributes little. Thus, the LHC result is largely model-independent.

(ii) $u\bar{d} \rightarrow Y^{++}Y^{-}$, $\bar{u}d \rightarrow Y^{+}Y^{--}$: Given the low-energy

constraint of $M_Y > 740$ GeV, neither of these processes is observable at the Tevatron. At the LHC, only the process $u\bar{d} \rightarrow Y^{++}Y^-$ is observable, for $M_Y \lesssim 900$ GeV.

(iii) $q\bar{q} \rightarrow Yee$: Suppose that the process $q\bar{q} \rightarrow Y^{++}Y^{--}$ were dominated by the exchange of a real Z' (this obviously requires $M_Y < M_{Z'}/2$). Consider now the case where $M_Y > M_{Z'}/2$. Here, it is conceivable that the process $q\bar{q} \rightarrow Y^{++}e^-e^-$ is observable while $q\bar{q} \rightarrow Y^{++}Y^{--}$ is not. We have therefore calculated the cross section for $q\bar{q} \rightarrow Y^{++}e^-e^-$, mediated solely by an on-shell Z' . Unfortunately, given the present low-energy constraints M_Y , we find that this process is unobservable at both the Tevatron and the LHC.

However, this result is highly model-dependent. In the 3-3-1 model, the Z' is a broad resonance, so that its on-shell production yields little enhancement of the cross section. But if the width of the Z' were narrow, say $\Gamma_{Z'} \sim 10^{-2}M_{Z'}$, as could be the case in another model, then the enhancement factor could be substantial. In such a case, bileptons would be more easily discovered via $q\bar{q} \rightarrow Y^{++}e^-e^-$ than via $q\bar{q} \rightarrow Y^{++}Y^{--}$. It is therefore worthwhile to search for signals of $q\bar{q} \rightarrow Yee$.

(iv) $q\bar{q} \rightarrow \phi^{++}\phi^{--}$: We have calculated this cross section for $\phi^{++} = \eta_1^{++}$ (the η_1^{++} has quantum numbers $Q = +2$, $I_3 = +1$, $Y = +2$). We considered (i) the case where only the SM γ and Z contribute, as well as (ii) the case where there is an additional Z' contribution. The effect of the Z' can be considerable: depending on its mass, the cross section can be increased by up to two orders of magnitude.

Even so, this process is barely observable at the Tevatron—an observable signal requires fairly light particles: $M_{Z'} \lesssim 600$ GeV and $M_\phi \lesssim 300$ GeV (and note that $M_{Z'}$

is already constrained to be above 550 GeV). The LHC is considerably more promising, but the reach in M_ϕ depends strongly on whether a Z' is present. If there is no Z' , then such scalar η_1^{++} bileptons can be observed for $M_\phi \lesssim 375$ GeV, while if a Z' is present, then this reach increases to 800–850 GeV.

Note that, although these results have been calculated specifically for the η_1^{++} bilepton, they should also apply, to within factors of order 1, to all scalar bileptons, as long as the bilepton's quantum numbers are not too unconventional. Furthermore, we reiterate that, in contrast to Bhabha and Møller scattering at e^+e^- and e^-e^- colliders, our results are independent of λ , the Yukawa coupling of the scalar bilepton to leptons.

(v) $u\bar{d} \rightarrow \phi^{++}\phi^-$, $\bar{u}d \rightarrow \phi^+\phi^{--}$: We take ϕ^{++} to have $I_3 = +1$. These processes are again unobservable at the Tevatron, but can be observed at the LHC for scalar bilepton masses $M_\phi \lesssim 400$ GeV ($\phi^+\phi^{--}$) or $M_\phi \lesssim 500$ GeV ($\phi^{++}\phi^-$). Note also that this reach can be considerably increased in models in which there is an additional contribution due to the s -channel exchange of an on-shell particle.

To summarize, vector bileptons are unobservable at experiments at the Tevatron, while there is only a small window for detection of scalar bileptons. On the other hand, depending on the process, vector and scalar bileptons of masses up to about 1 TeV may be observable at the LHC.

ACKNOWLEDGMENTS

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