

## Like-sign dilepton signals from a leptophobic $Z'$ boson

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ABSTRACT: A new leptophobic neutral gauge boson  $Z'$  with small mixing to the  $Z$  can have a mass as light as  $M_{Z'} \sim 350$  GeV, and still have escaped detection at LEP and Tevatron. Such a  $Z'$  boson can be derived from  $E_6$  and, if the new heavy neutrino singlets in the **27** representation are lighter than  $M_{Z'}/2$ , the process  $p\bar{p} \rightarrow Z' \rightarrow NN \rightarrow \ell^\pm \ell^\pm X$  is observable. Indeed, this new signal could explain the small excess of like-sign dileptons found at Tevatron. Implications for LHC are also discussed. In particular, the Tevatron excess could be confirmed with less than  $1 \text{ fb}^{-1}$ , and leptophobic  $Z'$  masses up to 2.5 TeV can be probed with  $30 \text{ fb}^{-1}$ .

KEYWORDS: Neutrino Physics, Beyond Standard Model, Hadronic Colliders.

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## 1. Introduction

New neutral gauge bosons, generically denoted as  $Z'$ , arise in a variety of Standard Model (SM) extensions, including well-known grand-unified models as  $E_6$  as well as little Higgs and extra dimensional models [1]. The predicted  $Z'$  bosons typically couple to quarks and charged leptons, thus they can produce a very clean signal at hadron colliders: a pair of opposite charge leptons with very high invariant mass and transverse momenta. Non-observation of this signal at Tevatron has placed limits  $M_{Z'} \gtrsim 600 - 700$  GeV on  $Z'$  bosons appearing in several popular scenarios. Obviously, if a  $Z'$  boson does not couple to charged leptons these constraints do not apply, and one has to look for the new  $Z'$  in other final states. A striking possibility occurs if decays to heavy Majorana neutrinos  $Z' \rightarrow NN$  are kinematically allowed. The subsequent lepton number violating (LNV) decay  $NN \rightarrow \ell^\pm W^\mp \ell^\pm W^\mp$ , with a branching ratio around 12.5% if  $N$  is a SM singlet, produces two energetic like-sign charged leptons (of different flavour in general) plus additional jets or leptons, depending on the  $W^\mp W^\mp$  decay mode. For  $M_{Z'}$  up to several hundreds of GeV and  $Z' \rightarrow NN$  not suppressed by phase space, this process can have a large cross section already at Tevatron energies, while its backgrounds are relatively small, especially at Tevatron [2, 3]. Other interesting final state for leptophobic (that is, not coupling to SM leptons)  $Z'$  bosons is  $Z' \rightarrow t\bar{t}$  [4], in which an excess might be observed if a  $Z'$  boson exists.

In this paper we focus on like-sign dilepton signals, motivated by an apparent excess at Tevatron [2]. In the next section we will show that, unlike many other new physics scenarios,  $Z' \rightarrow NN \rightarrow \ell^\pm W^\mp \ell^\pm W^\mp$  decays could explain this like-sign dilepton excess, reproducing the kinematics as well as any relative number of  $e^\pm e^\pm$ ,  $\mu^\pm \mu^\pm$  and  $e^\pm \mu^\pm$  events. But, even if this excess is not confirmed by additional experimental data, the study of like-sign dilepton signals, in particular from  $Z'$  decays, remains quite interesting for LHC, as we demonstrate in section 3. Their backgrounds have moderate size, arising mainly from: (i) processes with one or two isolated leptons resulting from  $b$  decays, especially  $t\bar{t}n_j$  and  $b\bar{b}n_j$  production (where  $n_j$  stands for  $n$  additional jets at the parton level); (ii) processes where

extra neutrinos and/or charged leptons are produced and missed by the detector (mainly  $WWnj$ ,  $WZnj$  and  $Wt\bar{t}nj$ ). Thus, like-sign dilepton final states are relatively clean, and we will find that they allow to probe leptophobic  $Z'$  masses above 2 TeV, surpassing the sensitivity of other  $Z'$  decay channels such as  $Z' \rightarrow t\bar{t}$ . The last section is devoted to summarise our results.

## 2. Like-sign dileptons at Tevatron

The small dilepton excess (44 events for  $33.2 \pm 4.7$  expected) found by CDF [2] might be a statistical fluctuation, or an uncontrolled systematic error. But, if we put aside these two hypotheses, it is quite demanding to explain the excess invoking to new physics. This is because:

- (i) The simplest new physics scenarios giving this signal also lead to other much larger effects, which have not been found.
- (ii) Even predicting a like-sign dilepton excess, the kinematics must match the one observed, which is non-trivial. The transverse momenta distribution of the leading charged lepton exhibits a rather flat excess distributed from low to high  $p_T$  values, in contrast with most common processes which sharply concentrate at low  $p_T$ . Likewise, the  $\ell\ell$  invariant mass distribution shows an excess up to relatively large values  $m_{\ell\ell} \sim 160$  GeV.

We illustrate these difficulties concentrating on new physics processes with genuine lepton number violation.<sup>1</sup> The simplest one is the production of a heavy Majorana neutrino singlet with a charged lepton,  $p\bar{p} \rightarrow W \rightarrow \ell N \rightarrow \ell^\pm \ell^\pm W^\mp \rightarrow \ell^\pm \ell^\pm X$ . (Pair production  $p\bar{p} \rightarrow Z \rightarrow NN$  is much more suppressed by mixing, as well as by phase space, see for example ref. [6].) For the heavy neutrino (singlet) mixings allowed by present constraints [7, 8] the cross section of this process at Tevatron exceeds a handful of events only for  $m_N < M_W$ , when the  $W$  is produced on its mass shell [9]. But for  $m_N < M_W$  the transverse momenta and invariant mass of the two leptons are very small, in contrast with the distributions in ref. [2] which show an excess at larger values. Another process would be  $p\bar{p} \rightarrow W \rightarrow NE \rightarrow \ell^\pm \ell^\pm X$ . In this case  $N$  must transform non-trivially under  $SU(2)_L$  (see for example ref. [10] for  $N, E^\pm$  transforming as a triplet). This process is mainly suppressed by the  $W$   $s$ -channel propagator for large  $N, E$  masses.

In order to have a sizeable  $N$  production cross section for larger neutrino masses, say  $m_N = 150$  GeV, two obvious possibilities are to introduce additional charged ( $W'$ ) [11, 12] or neutral ( $Z'$ ) gauge bosons. (A third possibility would be to produce  $\ell N$  via the exchange of a charged scalar, but in the absence of additional interactions the mixing of the heavy

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<sup>1</sup>New lepton number conserving (LNC) processes, as for example  $W'Z$  and  $WZ'$  production with one charged lepton missed by the detector, can give  $\ell^\pm \ell^\pm$  signals as well. However,  $W'Z$  and  $WZ'$  production are sub-leading with respect to  $W'(\rightarrow \ell\nu)$  and  $Z'(\rightarrow \ell^+ \ell^-)$  production, which have not been observed at Tevatron. A supersymmetric interpretation of these dilepton events is also disfavoured by the absence of trilepton signals [5].

neutrino, mainly a gauge singlet, is very small.) The first one seems difficult to implement while keeping agreement with present constraints on new charged interactions. The new  $W'$  must couple to quarks of the first generation in order to have a sizeable production cross section at hadron colliders, but not to the electron and muon, so that direct production limits do not apply. Besides, the  $W'$  boson must be light enough to be produced, and its coupling cannot be right-handed, otherwise there is a stringent limit  $M_{W'} \gtrsim 2 \text{ TeV}$  from the kaon mass difference [13].

In the following we explore the second possibility. Like-sign dileptons from  $Z'$  decays may be produced in any SM extension with an extra  $Z'$  boson and heavy Majorana neutrinos, provided  $M_{Z'} > 2m_N$ . In particular, if the new boson is leptophobic the lower bound on its mass is rather weak, and sizeable signals are possible already at Tevatron. Early studies on leptophobic  $Z'$  bosons [14–17] were motivated by the initial disagreement between the  $Z \rightarrow b\bar{b}$ ,  $Z \rightarrow c\bar{c}$  decay rates measured at LEP and the SM predictions [18]. Although the differences disappeared with more LEP data, the possibility of such a new gauge boson is still interesting by itself. There is a variety of models with extra leptophobic gauge bosons. For simplicity, we will restrict ourselves to an  $E_6$  model in which heavy Majorana neutrinos appear naturally [19], but our conclusions are more general. The neutral interactions of the standard bosons and the new  $Z'$  are described by the Lagrangian [20]

$$\mathcal{L}_{\text{NC}} = -\bar{\psi}\gamma_\mu \left[ T_3 g W_3^\mu + \sqrt{\frac{5}{3}} Y g_Y B^\mu + Q' g' Z'_\lambda{}^\mu \right] \psi, \quad (2.1)$$

where a sum over the three families of **27** fermions in the fundamental  $E_6$  representation is understood.  $Y$  is the SM hypercharge properly normalised, and the extra charges  $Q'$  of the new boson  $Z'_\lambda$  correspond to the only leptophobic combination within  $E_6$  [21, 22]

$$Q' = 3/\sqrt{10}(Y_\eta + Y/3), \quad (2.2)$$

with  $Y_\eta$  the extra  $U(1)$  defined by flux breaking [23–25]. For left-handed fields,

$$\begin{aligned} 2Q'_u &= 2Q'_{d_1} = Q'_{u^c} = -Q'_{d_2} = -2Q'_{d_{1,2}^c} = -\frac{1}{\sqrt{6}}, \\ Q'_{\nu_{1,2}} &= Q'_{e_{1,2}} = Q'_{e_1^c} = 0, \\ Q'_{e_2^c} &= Q'_{\nu_3} = -Q'_{\nu_{4,5}} = \frac{3}{2\sqrt{6}}. \end{aligned} \quad (2.3)$$

A detailed discussion of the phenomenological constraints on this SM extension can be found in ref. [16], where a nearly-leptophobic model with  $Q' \sim Y_\eta + 0.29Y$  is studied among several other alternatives. This supersymmetric model has the largest field content consistent with perturbative unification of gauge couplings at the GUT scale. The two points relevant here and which any such SM extension must satisfy are:

- (i) The  $Z - Z'_\lambda$  mixing must be small to maintain the good agreement with precision electroweak data. This does not pose a problem in principle, because this mixing can be made as small as experimentally needed invoking a cancellation between the contributions of the vacuum expectation values of the Higgs bosons giving masses to the up and down quarks, respectively.

- (ii) The fermion mass generation mechanism must explain why the extra fermions are heavier than the SM ones. This can be understood due to their vector-like character under the SM gauge group. Still, their masses are protected by the extra gauge interaction and cannot be much heavier than the extra gauge boson.

In these models the neutrino sector is rather involved and requires a detailed analysis which will be presented elsewhere. In each family, one of the two extra neutrino singlets  $\nu_{4,5}$  can obtain a large mass (a Majorana mass through a non-renormalisable term, or a heavy Dirac mass if it couples to an additional  $E_6$  singlet). The three resulting heavy neutrinos  $N_i$  (one per family) are the ones we are interested in. The other three neutrino singlets tend to remain massless, and they can combine with the SM neutrinos to form Dirac fermions (in which case the corresponding Yukawa couplings must be very small or zero). In this phenomenological study we will assume for simplicity that these latter neutrinos are heavy enough so that they are not produced in  $Z'_\lambda$  decays. Otherwise, the total  $Z'_\lambda$  width is larger, and in the worst case this would amount to a  $\sim 20\%$  decrease of the like-sign dilepton cross sections presented below.

In summary, the extra vector-like lepton doublets and quark singlets of charge  $-1/3$  are assumed to be heavier than  $M_{Z'_\lambda}/2$ , as three of the heavy neutrinos. Possible supersymmetric partners are taken heavier as well. On the other hand, the three remaining heavy neutrinos  $N$  entering in our discussion are assumed lighter than  $M_{Z'_\lambda}/2$ . Their mixing with the light leptons (see ref. [6] for details and notation) can be made of order  $V \sim O(10^{-6})$ , small enough to avoid too large contributions to light neutrino masses. Even for a mixing of this size heavy neutrinos would decay within the detector.

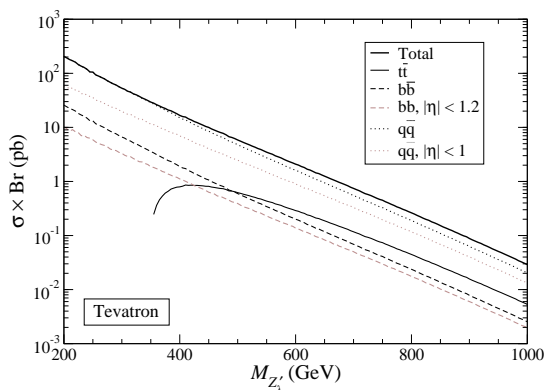
The  $Z'_\lambda$  production cross section at Tevatron (which is obviously independent of the heavy neutrino masses) is plotted in figure 1 as a function of  $M_{Z'_\lambda}$ . We also plot the maximum (i.e. when  $Z'_\lambda$  decays only to SM fermions) cross sections for  $t\bar{t}$ ,  $b\bar{b}$  and  $q\bar{q}$  final states, also including  $q = b$ . The coupling constant of the new  $U(1)'$  has been fixed for reference as  $g' = \sqrt{5/3}g_Y = \sqrt{5/3}g_{SW}/c_W$ , and cross sections are calculated using CTEQ5L parton distribution functions [26]. For easier comparison with Tevatron measurements of the dijet and  $b\bar{b}$  cross sections<sup>2</sup> we also plot the latter two with pseudo-rapidity cuts. A light  $Z'_\lambda$  might be visible in  $b\bar{b}$  final states, but for  $M_{Z'_\lambda} \gtrsim 350$  GeV this seems quite difficult.

If  $Z'_\lambda \rightarrow NN$  decays are kinematically allowed they provide the cleanest signals of the  $Z'_\lambda$  boson. A heavy Majorana neutrino  $N$  can decay to  $W^+\ell^-$ ,  $W^-\ell^+$ ,  $Z\nu_\ell$  and  $H\nu_\ell$ , where  $\ell = e, \mu, \tau$ , with partial widths (see for example ref. [6])

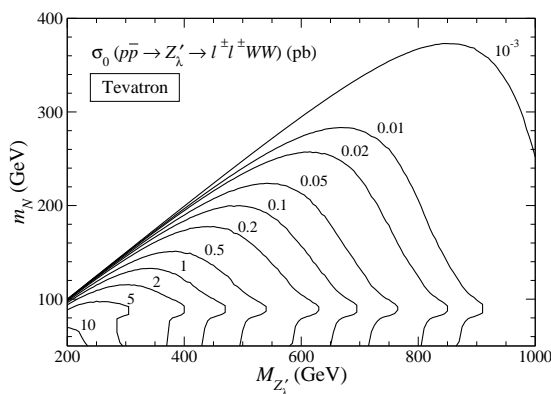
$$\begin{aligned}
 \Gamma(N \rightarrow W^+\ell^-) &= \Gamma(N \rightarrow W^-\ell^+) \\
 &= \frac{g^2}{64\pi} |V_{\ell N}|^2 \frac{m_N^3}{M_W^2} \left(1 - \frac{M_W^2}{m_N^2}\right) \left(1 + \frac{M_W^2}{m_N^2} - 2\frac{M_W^4}{m_N^4}\right), \\
 \Gamma(N \rightarrow Z\nu_\ell) &= \frac{g^2}{64\pi c_W^2} |V_{\ell N}|^2 \frac{m_N^3}{M_Z^2} \left(1 - \frac{M_Z^2}{m_N^2}\right) \left(1 + \frac{M_Z^2}{m_N^2} - 2\frac{M_Z^4}{m_N^4}\right), \\
 \Gamma(N \rightarrow H\nu_\ell) &= \frac{g^2}{64\pi} |V_{\ell N}|^2 \frac{m_N^3}{M_W^2} \left(1 - \frac{M_H^2}{m_N^2}\right)^2.
 \end{aligned} \tag{2.4}$$

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<sup>2</sup>For the latest results see <http://www-cdf.fnal.gov>, <http://www-d0.fnal.gov>



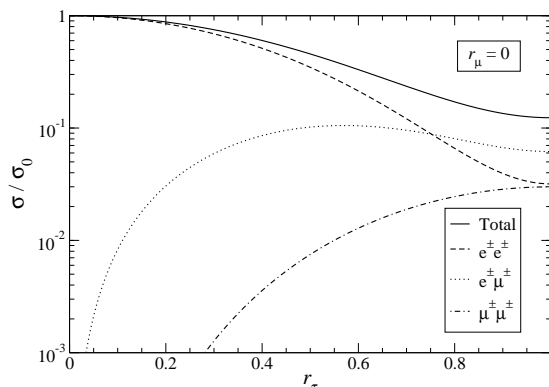
**Figure 1:** Total cross section for  $Z'_\lambda$  production at Tevatron, and cross sections for several SM final states.



**Figure 2:** Total cross section for  $\ell^\pm \ell^\pm W^\mp W^\mp$  production at Tevatron, summing final states with any combination of  $\ell = e, \mu, \tau$ .

Within any of these four modes, the branching fractions for individual final states  $\ell = e, \mu, \tau$  are in the ratios  $|V_{eN}|^2 : |V_{\mu N}|^2 : |V_{\tau N}|^2$ . However, as it can be clearly seen from eqs. (2.4), the total branching ratio for each of the four channels above (summing over  $\ell$ ) is independent of the heavy neutrino mixing and determined only by  $m_N$  and the Higgs boson mass, fixed here as  $M_H = 120$  GeV. Then, the total  $\ell^\pm \ell^\pm W^\mp W^\mp$  cross section, shown in figure 2, only depends on  $M_{Z'_\lambda}$  and the three heavy neutrino masses, taken to be equal for simplicity,  $m_{N_i} \equiv m_N$  for  $i = 1, 2, 3$ . The small bump on the right part of the lines is caused by the increase in  $\text{Br}(N \rightarrow W\ell)$  for  $M_W \lesssim m_N \lesssim M_Z$ .

As we have emphasised before, reproducing the correct kinematics of the apparent like-sign dilepton excess at CDF is non-trivial. The presence of events with large missing momentum  $\cancel{p}_T$  requires heavy neutrino mixing with the  $\tau$ , so that decays  $N \rightarrow \tau W$  with  $\tau$  decaying leptonically produce neutrinos in the final state. But the presence of electrons and/or muons with large transverse momentum also suggests heavy neutrino mixing with the electron and/or muon. In this section we do not address the flavour dependence of



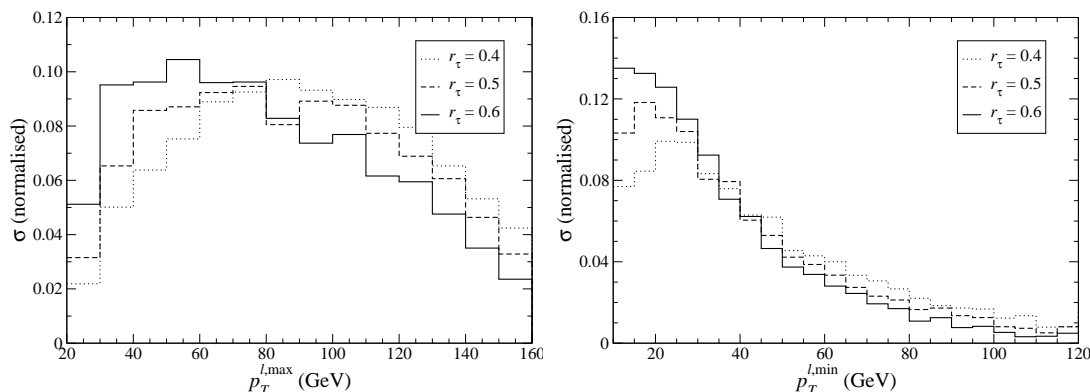
**Figure 3:** Ratio  $\sigma/\sigma_0$  between the dilepton cross section to electron and muon final states and the total one in figure 2. The parameters  $r_\mu, r_\tau$  are defined in eq. (2.5).

the final state (that is, the relative number of  $e^\pm e^\pm$ ,  $\mu^\pm \mu^\pm$  and  $e^\pm \mu^\pm$  events) but our main interest is to reproduce the size and kinematics of the dilepton excess. The reader can easily convince himself that *any* relative rate of dielectron, dimuon and  $e^\pm \mu^\pm$  events can be accommodated by choosing adequate mixings  $V_{eN_i}$ ,  $V_{\mu N_i}$  and  $V_{\tau N_i}$ . Bearing this in mind, one can reduce the number of free parameters in the analysis. We assume equal mixing with the three heavy neutrinos,  $V_{\ell N_i} \equiv V_{\ell N}$ , parameterised as

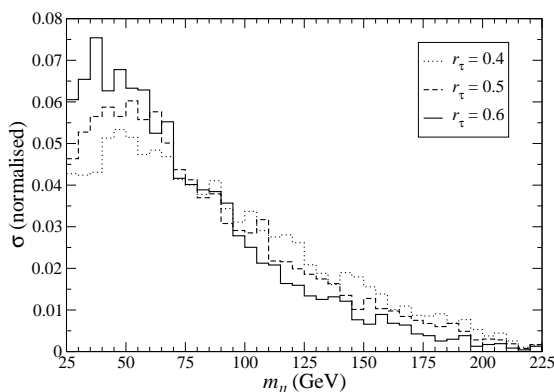
$$\begin{aligned}
 |V_{eN}| &= V \cos \frac{\pi}{2} r_\tau \cos \frac{\pi}{2} r_\mu, \\
 |V_{\mu N}| &= V \cos \frac{\pi}{2} r_\tau \sin \frac{\pi}{2} r_\mu, \\
 |V_{\tau N}| &= V \sin \frac{\pi}{2} r_\tau.
 \end{aligned}
 \tag{2.5}$$

Note that for  $V \lesssim 10^{-3}$  constraints from lepton flavour-violating processes [27, 28] and neutrinoless double beta decay [29, 30] are automatically satisfied independently of  $r_\mu$  and  $r_\tau$ . For the remaining of this section we take  $r_\mu = 0$  (no mixing with the muon) for simplicity. Then, the relative mixing with the electron and tau lepton (and thus the branching ratios for  $N \rightarrow eW$  and  $N \rightarrow \tau W$ , which are the relevant quantities for our analysis) depend on a single parameter  $r_\tau$ , ranging from 0 to 1. The values  $r_\tau = 0$  and  $r_\tau = 1$  correspond to  $V_{\tau N} = 0$  and  $V_{eN} = 0$ , respectively, while  $r_\tau = 0.5$  when both couplings are equal. The actual dilepton cross section  $\sigma$  for final states with electrons and/or muons can be straightforwardly obtained in terms of the total cross section  $\sigma_0$  in figure 2, taking into account the branching ratios for  $N \rightarrow eW$  and  $N \rightarrow \tau W$  with subsequent decay  $\tau \rightarrow e/\mu \bar{\nu} \nu$ . The rescaling factor  $\sigma/\sigma_0$  is shown in figure 3. It ranges from unity for  $r_\tau = 0$  (charged current decays only to electrons) to 0.12 for  $r_\tau = 1$  (only to tau leptons).

We select the values  $M_{Z'_\lambda} = 500$  GeV,  $m_N = 150$  GeV to illustrate how the new  $\ell^\pm \ell^\pm X$  signal can account for the small CDF excess. These values are chosen so that decays  $Z'_\lambda \rightarrow NN$  and  $N \rightarrow W\ell$  are not too close to threshold. With these parameters we have  $\text{Br}(Z'_\lambda \rightarrow NN) = 0.20$  (summing over the three neutrinos),  $\text{Br}(N \rightarrow W^+ \ell^-) = \text{Br}(N \rightarrow$



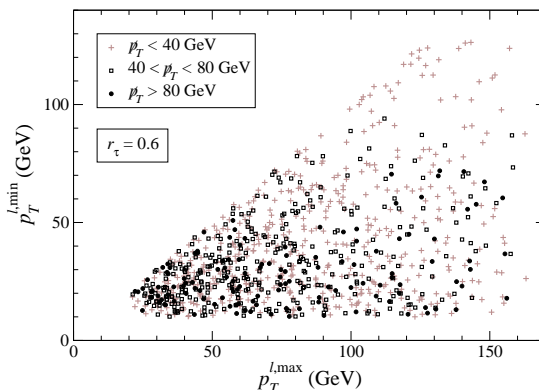
**Figure 4:** Transverse momenta of the leading ( $p_T^{\ell,\max}$ ) and sub-leading ( $p_T^{\ell,\min}$ ) charged leptons.



**Figure 5:** Dilepton invariant mass.

$W^- \ell^+$ ) = 0.33,  $\text{Br}(N \rightarrow Z\nu_\ell) = 0.29$ ,  $\text{Br}(N \rightarrow H\nu_\ell) = 0.05$ . We generate events using the exact matrix element for  $p\bar{p} \rightarrow Z'_\lambda \rightarrow NN \rightarrow \ell^\pm W^\mp \ell^\pm W^\mp \rightarrow \ell^\pm f \bar{f} \ell^\pm f \bar{f}$ , including all finite width and spin effects. Tau leptonic decays are simulated using the tree-level matrix element. In this section we restrict ourselves to hadronic decays of the  $W$  pair, which amount to 44% of the total  $WW$  decay branching ratio. We require the same kinematical cuts on leptons as in ref. [2]: (i) transverse momenta  $p_T^{\ell,\max} \geq 20$  GeV,  $p_T^{\ell,\min} \geq 10$  GeV, where  $p_T^{\ell,\max}$  and  $p_T^{\ell,\min}$  refer to the leading and sub-leading lepton, respectively; (ii) pseudorapidity  $|\eta^\ell| \leq 1$ ; (iii) dilepton invariant mass larger than 25 GeV. Additionally, for charged lepton isolation we require a minimum lego-plot separation  $\Delta R \geq 0.4$  between them and also between them and final state quarks. The parton-level distributions for the transverse momenta of the two leptons are shown in figure 4, for three representative values of the mixing parameter  $r_\tau$ . It is especially remarkable the slow decrease of the  $p_T^{\ell,\max}$  distribution, which is an unusual behaviour (compared for example with  $p_T^{\ell,\min}$ ) and is in good agreement with the  $p_T^{\ell,\max}$  distribution of the dilepton excess in ref. [2]. The dilepton invariant mass is presented in figure 5. Detector effects are not expected to change





**Figure 6:** Transverse momenta of the leading and sub-leading leptons of an arbitrary sample of 1000 unweighted  $\ell^\pm \ell^\pm q\bar{q}q\bar{q}$  events.

drastically the parton-level predictions for charged lepton momenta but, unfortunately, the missing energy of the event cannot be reliably estimated with a parton level analysis. In any case, we find a slowly decreasing  $\cancel{p}_T$  distribution up to  $\sim 120$  GeV. The number of events expected for  $r_\tau = 0.4, 0.5$  and  $0.6$  is 21, 14 and 9, respectively, of the same order of the CDF excess (11 events). An additional signal contribution is expected from the semileptonic (44% of the total branching ratio) and dileptonic (11%) decays of the  $WW$  pair, when the extra leptons are missed by the detector or have small energy. Tripleton signals are also present, but a factor  $\sim 5$  smaller after the selection criteria used in typical analyses [31]. For larger values of  $g'$ , as obtained from renormalisation group evolution [16], cross sections scale accordingly.

We can also extract interesting information about the signal by representing, for each event within a typical sample, the values of  $p_T^{\ell,\max}$  and  $p_T^{\ell,\min}$  in a two-dimensional diagram. This is done in figure 6, using 1000 unweighted  $\ell^\pm \ell^\pm q\bar{q}q\bar{q}$  events at the partonic level and taking  $r_\tau = 0.6$ , for which the distributions in figure 4 resemble most the kinematics of the CDF excess. Events are classified according to their parton-level  $\cancel{p}_T$ , which illustrates to some extent the missing energy expected in a real detector. The point density may be interpreted in terms of probability. We notice that the individual events described in ref. [2] fit well in this distribution. These are:

- (1) Two electrons with  $p_T = 107$  GeV and  $p_T = 103$  GeV,  $\cancel{p}_T = 25$  GeV and an additional non-isolated positron with  $p_T = 5$  GeV. This is the event with largest transverse energy.
- (2) Two positrons with  $p_T = 73$  GeV and  $p_T = 41$  GeV,  $\cancel{p}_T = 96$  GeV. This is the event with second largest transverse energy.
- (3) A  $\mu^+$  with  $p_T = 66$  GeV, an  $e^+$  with  $p_T = 10$  GeV and  $\cancel{p}_T = 37$  GeV.

Finally, we note that like-sign dileptons are not the only signature of a leptophobic  $Z'_\lambda$  boson at Tevatron. Another interesting final state is given by  $Z'_\lambda \rightarrow t\bar{t}$  decays, which would



Let us first consider, for the sake of comparison, the scenario with  $M_{Z'_\lambda} = 500$  GeV,  $m_N = 150$  GeV from the previous section. The larger centre of mass energy and luminosity at LHC will allow to quickly confirm or discard the hypothesis of a  $Z'_\lambda$  boson and heavy neutrinos with these masses. We have performed a fast simulation of this signal for various values of the heavy neutrino mixings, parameterised by  $r_\mu$  and  $r_\tau$ . All decay channels of the  $WW$  pair are included. The SM dilepton backgrounds are taken from ref. [9] (see this reference for further details). We require as pre-selection:

- (i) two like-sign isolated charged leptons with pseudorapidity  $|\eta^\ell| \leq 2.5$  and transverse momentum  $p_T^\ell$  larger than 10 GeV (muons) or 15 GeV (electrons), and no additional isolated charged leptons;
- (ii) no additional non-isolated muons;
- (iii) at least two jets with  $|\eta^j| \leq 2.5$  and  $p_T^j \geq 20$  GeV, and no  $b$ -tagged jets. Although the signal has four jets at the partonic level, for large  $M_{Z'_\lambda}$  and  $m_N$  it is convenient to require only two jets, in order to keep the signal as large as possible.

With these pre-selection criteria the semileptonic and dileptonic  $WW$  decay channels contribute an extra  $\sim 20\%$  to the signal, when the additional charged lepton(s) are missed by the detector.

The signal has different kinematics depending on  $r_\tau$ : for  $r_\tau = 0$  the charged leptons are much more energetic, while for nonzero  $r_\tau$  and specially for  $r_\tau = 1$  the final state has neutrinos from tau decays and large missing energy. Here we do not try to optimise the signal significance in the different channels, but instead we reduce backgrounds using very simple cuts on lepton transverse momenta,

$$p_T^{\ell,\max} > 30 \text{ GeV}, \quad p_T^{\ell,\min} > 20 \text{ GeV}. \quad (3.1)$$

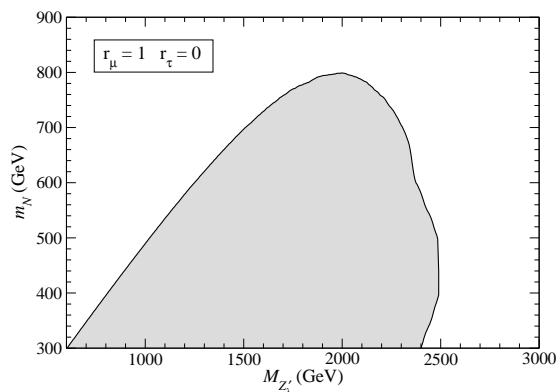
The number of signal and background events for  $1 \text{ fb}^{-1}$  is collected in table 1. Smaller backgrounds are not shown separately but they are included in the figures in the last row. In most cases the signal significance (assuming a 20% background uncertainty) is much larger than  $5\sigma$ . If the heavy neutrinos only couple to tau leptons the luminosity required for the discovery is larger (and cut optimisation is needed).

Several remarks regarding these results are in order. Backgrounds with charged leptons from  $b$  decays are large, especially in  $e^\pm e^\pm jj$  and  $e^\pm \mu^\pm jj$  final states [9], and with the loose cuts in eqs. (3.1) they remain dominant in these two channels. The number of  $\mu^\pm \mu^\pm jj$  events from  $WZnj$  production is smaller than the number of  $e^\pm e^\pm jj$  events due to the requirement of no non-isolated muons. Therefore, the highest sensitivity is achieved if heavy neutrinos only couple to the muon, so that decays  $NN \rightarrow \mu^\pm \mu^\pm W^\mp W^\mp$  have the largest branching ratio possible, around 12.5%.

For larger  $Z'_\lambda$  masses the charged leptons produced in its decay are more energetic. This fact can be exploited by requiring large transverse momenta (e.g. 200 GeV for the leading and 50 GeV for the sub-leading lepton) and dilepton invariant mass to reduce backgrounds significantly. In particular, processes in which one or two charged leptons come from  $b$

	$e^\pm e^\pm$	$\mu^\pm \mu^\pm$	$e^\pm \mu^\pm$		$e^\pm e^\pm$	$\mu^\pm \mu^\pm$	$e^\pm \mu^\pm$
$Z'_\lambda (0,0)$	923.8	—	—	$t\bar{t}nj$	44.4	1.2	40.7
$Z'_\lambda (1,0)$	—	664.1	—	$b\bar{b}nj$	27	1	9
$Z'_\lambda (0,1)$	6.1	4.4	10.3	$tj$	1.0	0.0	1.1
$Z'_\lambda (0.5,0)$	230.0	166.9	388.0	$Wb\bar{b}nj$	1.6	0.0	1.4
$Z'_\lambda (0,0.5)$	161.4	4.4	52.0	$Wt\bar{t}nj$	0.7	0.4	1.1
$Z'_\lambda (1,0.5)$	5.9	117.5	50.5	$WWnj$	2.3	2.0	4.3
				$WZnj$	6.3	3.5	9.5
				$WWWnj$	0.8	0.8	1.6
				Total Bkg.	84.8	9.1	69.6

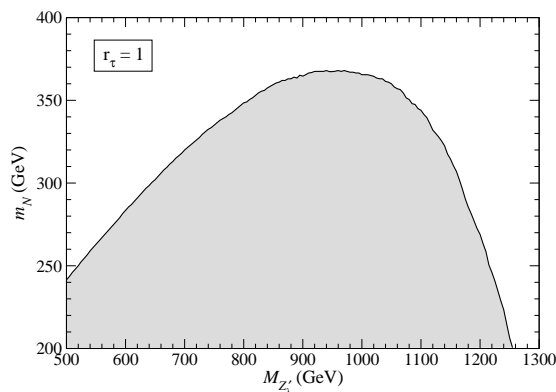
**Table 1:** Number of  $\ell^\pm \ell^\pm jj$  events at LHC for  $1\text{fb}^{-1}$ , after the cuts in eqs. (3.1). The signal is evaluated assuming  $M_{Z'_\lambda} = 500\text{ GeV}$ ,  $m_N = 150\text{ GeV}$ , with the parameters between parentheses standing for  $r_\mu$  and  $r_\tau$ , respectively.



**Figure 8:**  $5\sigma$  discovery limit for  $pp \rightarrow Z'_\lambda \rightarrow NN$  giving  $\mu^\pm \mu^\pm X$  final states at LHC, for a luminosity of  $30\text{fb}^{-1}$ . Heavy neutrinos are assumed to couple only to the muon.

decays ( $t\bar{t}nj$ ,  $b\bar{b}nj$ , etc.) can be practically removed so that the numbers of  $e^\pm e^\pm jj$  and  $\mu^\pm \mu^\pm jj$  background events are practically equal. Therefore, for larger  $Z'_\lambda$  masses the sensitivities in the  $e^\pm e^\pm jj$  and  $\mu^\pm \mu^\pm jj$  channels become very similar. In figure 8 we plot the  $5\sigma$  discovery limits in the case that the heavy neutrinos only couple to the muon,  $r_\mu = 1$ ,  $r_\tau = 0$ , for a luminosity of  $30\text{fb}^{-1}$ . The shaded area corresponds to masses  $(M_{Z'_\lambda}, m_N)$  for which the statistical significance is larger than  $5\sigma$ . It has been obtained generating samples for several points  $(M_{Z'_\lambda}, m_N)$  close to the boundary. Performing the corresponding analyses the number of signal events after selection cuts can be obtained for each point, and interpolation or extrapolation is used for the remaining points in the boundary. Notice that this boundary has not the same shape as the lines of constant cross section in figure 7 (right), because the efficiency after cuts varies with the  $Z'_\lambda$  and heavy neutrino masses. For  $M_{Z'_\lambda} \gg m_N$  the efficiency significantly decreases because the  $N$  decay products are very collinear.

For heavy neutrinos coupling only to the electron the discovery limits are very similar



**Figure 9:** 90% exclusion region (shaded area) on  $M_{Z'_\lambda}$  and  $m_N$  if like-sign dilepton signals are not observed at LHC with a luminosity of  $30 \text{ fb}^{-1}$ . Heavy neutrinos are conservatively assumed to couple only to the tau.

to those in figure 8. For large  $M_{Z'_\lambda}$  (upper-right part of the boundary) this is because  $e^\pm e^\pm jj$  and  $\mu^\pm \mu^\pm jj$  backgrounds have similar size after cuts. For smaller  $M_{Z'_\lambda}$  (left part of the boundary) the discovery limit is determined by the kinematical limit for  $Z'_\lambda \rightarrow NN$ , and, even though  $e^\pm e^\pm jj$  backgrounds are larger in this region, the signal cross section varies rapidly with  $m_N$  and the curves for both final states lie very close.

If a positive signal is not found at LHC, limits on  $M_{Z'_\lambda}$  and  $m_N$  can be set. The most conservative limits are obtained assuming that heavy neutrinos only couple to the tau lepton. If no excess is observed in the like-sign dilepton channels, the shaded region shown in figure 9 can be excluded at 90% CL. This region is obtained by simulating several signal samples and optimising the kinematical cuts for each point. The relevant variables are the jet multiplicity (for  $M_{Z'_\lambda}, m_N$  masses not very large it is convenient to require four jets in event selection), the charged lepton momenta  $p_T^{\ell, \max}$  and  $p_T^{\ell, \min}$ , their invariant mass  $m_{\ell\ell}$ , the rapidity and azimuthal angle differences,  $\Delta\eta_{\ell\ell}$  and  $\Delta\phi_{\ell\ell}$  respectively, the momentum of the most energetic jet  $p_T^{\max}$  and the missing energy  $\cancel{p}_T$ .

#### 4. Summary

Like-sign dileptons are interesting final states in which to look for new physics at hadron colliders. Their backgrounds, mainly from  $t\bar{t}nj$  and  $b\bar{b}nj$  production, have moderate size in contrast with other LNC final states [9]. Like-sign dilepton signals are characteristic of Majorana fermions (such as new heavy neutrinos) and of doubly charged scalars, both mediating LNV interactions. They can also appear from LNC processes when additional leptons are missed by the detector.

Motivated by an apparent like-sign dilepton excess at Tevatron, we have studied a model in which heavy neutrino pairs can be produced at hadron colliders via the exchange of an  $s$ -channel leptophobic  $Z'_\lambda$  boson. Constraints on the latter are rather loose, and if  $Z - Z'_\lambda$  mixing is negligible the new boson could be as light as  $M_{Z'_\lambda} \sim 350 \text{ GeV}$ , with very

large production cross sections at hadron colliders and, in particular, leading to potentially large like-sign dilepton signals. In case that the Tevatron excess is confirmed with more statistics, a possible explanation might be the one proposed here: a new  $Z'_\lambda$  boson decaying to heavy neutrino pairs,  $p\bar{p} \rightarrow Z'_\lambda \rightarrow NN \rightarrow \ell^\pm \ell^\pm W^\mp W^\mp$ . We have shown that not only the size of the excess but also its kinematics can be explained with an additional  $Z'_\lambda$  boson. Taking, for example, masses  $M_{Z'_\lambda} = 500$  GeV,  $m_N = 150$  GeV, the  $p_T$  distribution of the leading and sub-leading charged leptons and the dilepton invariant mass can be well accommodated.

As we have already noted, like-sign dilepton signals at hadron colliders are also predicted in several other SM extensions involving heavy neutrinos. It is worth comparing the  $Z'_\lambda$  model studied here with some of them. The most popular ones are:

- (i) Models with heavy neutrino singlets (as those appearing in type-I seesaw<sup>3</sup>) without extra interactions, that is, without  $W'$  or  $Z'$  bosons. In this case the main production process is  $p\bar{p}^{(-)} \rightarrow W \rightarrow \ell N$  and dilepton cross sections are much smaller because they are proportional to the square of the heavy neutrino mixing with the SM fermions, which is experimentally constrained to be very small [7, 8]. If  $m_N > M_W$  the cross section is also suppressed by the off-shell  $W$  propagator.
- (ii) Models with heavy neutrinos in  $SU(2)_L$  lepton triplets, as those appearing in type-III seesaw. In this case heavy lepton pairs can be produced through  $s$ -channel  $W$  boson exchange,  $p\bar{p}^{(-)} \rightarrow W \rightarrow NE$ , giving the same final state studied in this work [10]. The  $WNE$  coupling has gauge strength with mixing  $O(1)$  but the cross section is still suppressed by the off-shell  $W$  propagator.
- (iii) Left-right models or, more generally, models with an extra  $W'$  and heavy neutrinos. The latter can be produced in association with a charged lepton,  $p\bar{p}^{(-)} \rightarrow W' \rightarrow \ell N$  [11, 12], with interactions of gauge strength. The cross section is only suppressed by present lower bounds on the  $W'$  mass resulting from direct searches and indirect limits.

In these three cases the allowed like-sign dilepton cross sections are generically smaller than for a leptophobic  $Z'_\lambda$  boson. Hence, producing large signals at Tevatron, so as to explain the apparent CDF excess, seems difficult in these models.

Finally, even if the Tevatron excess is diluted with additional data, like-sign dilepton signals, either from a leptophobic  $Z'_\lambda$  boson or within the models (i-iii) listed above, will remain quite interesting for LHC [9, 37, 38]. In the SM extension studied in this work, leptophobic  $Z'_\lambda$  bosons will be probed up to masses  $M_{Z'_\lambda} \simeq 2.5$  TeV and  $m_N \simeq 800$  GeV for a luminosity of  $30 \text{ fb}^{-1}$ , in the most favourable case that heavy neutrinos do not couple to the tau lepton. This  $M_{Z'_\lambda}$  scale is much higher than the one which can be probed in the hadronic final states, approximately 700 GeV in  $Z'_\lambda \rightarrow t\bar{t}$ . On the other hand, if a dilepton excess is not found at LHC, useful limits could be set on the mass of such a new  $Z'_\lambda$  boson, which is, as we have emphasised before, loosely constrained at present.

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<sup>3</sup>For a recent review on seesaw models of neutrino masses and their low energy effects see ref. [36].

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