Four-Lepton Resonance at the Large Hadron Collider

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A spin-1 weakly interacting vector boson, $Z'$, is predicted by many new physics theories. Searches at colliders for such a $Z'$ resonance typically focus on lepton-antilepton or top-antitop events. Here we present a novel channel with a $Z'$ resonance that decays to 4 leptons, but not to 2 leptons, and discuss its possible discovery at the Large Hadron Collider. This baryonic gauge boson is well motivated in a supersymmetry framework.

I. INTRODUCTION

Many models of physics beyond the Standard Model (SM) have an extra Abelian gauge group $U(1)$ [1]. There are many options for this $U(1)$ gauge symmetry and the corresponding $Z'$ from the broken symmetry can enable its identification. The Drell-Yan process, wherein the $Z'$ is produced from quark-antiquark fusion and decays to a lepton-antilepton pair, can give a particularly clear signal at a hadron collider [2, 3].

However, the lepton pair search for a $Z'$ is nullified if the $Z'$ does not couple to the SM leptons. Searches can still be made for dijet decay products of a $Z'$, but the QCD dijet backgrounds are huge and fog such a signal [4, 5]; hence, a $Z'$ resonance may not be discovered in dijets [4, 5], especially if its coupling strength to quarks is not large, although a signal in the top pair channel could be easier to recognize [8, 9].

Our interest here is in a 4-lepton signal from a lepto-phobic $Z'$ that can be produced at the LHC (and the Tevatron) with a large cross section and give a 4-lepton signal comparable to that of the lepton pair signals of generic $Z'$ models. Specifically, we consider a $Z'$ resonance in which the 4-leptons final state is bridged by pair production of a new scalar boson ($\phi$). The $Z'$ couples to quark pairs and $\phi$, but not to lepton pairs, and the new scalar $\phi$ decays into a lepton pair (see Fig. 1). LHC experiments, and possibly Tevatron experiments, can find or reject this distinctive 4-lepton signal.

A lepto-phobic $Z'$ may also appear as a resonance in a 6-lepton final state; a future search for this signal at the LHC requires $\sim 100$ fb$^{-1}$ integrated luminosity at 14 TeV center-of-mass (CM) energy [10].

II. MODEL

We begin by introducing a specific model in which a 4-lepton $Z'$ resonance can be realized without having a corresponding lepton pair signal. We consider a generic supersymmetry (SUSY) framework where scalar fields are abundant. The baryon number ($B$) is not preserved in the SUSY framework and in general the proton is unstable. Thus a gauged $B$ has been sought, but then additional fermions are required to cancel the anomaly effect.

It was pointed out that the a baryonic $Z'$ can be a possible source of the $Wjj$ anomaly recently reported in the Tevatron CDF experiment [13].

One natural way of anomaly cancellation is to add a fourth-generation (4G) of fermions. Then, by requiring all quarks carry $B (= 1/3)$, the 4G lepton charge is uniquely determined to be $−4$ by the anomaly free condition:

$$\begin{align*}
\text{SM quarks: } & 1/3, \quad \text{SM leptons: } 0, \\
\text{4G quarks: } & 1/3, \quad \text{4G leptons: } -4.
\end{align*}$$

This is effectively $U(1)_B$ for the SM fermions: every SM quark has $B$ as a charge, and every SM lepton has 0 charge$^1$.

Although proton stability would not have been guaranteed once the $U(1)_B$ is broken spontaneously, it turned out there exists a residual $Z_4$ discrete symmetry, called baryon tetrality ($B_4$), that forbids proton decay [10]. Under $B_4$, lepton number violating operators can exist (such as $\lambda LLE^c$ and $X^cLQD^c$), but not baryon number violating operators (such as $X^cUeD^c$).

In order to have the $B_4$ residual discrete symmetry, the Higgs boson that spontaneously breaks the $U(1)_B$ gauge symmetry (typically, a new Higgs singlet) should have a $U(1)_B$ charge of 4 or $-4$ [10]. Since it coincides with the $U(1)_B$ charge of the $N'_i$ [4G right-handed neutrino and sneutrino (superpartner of neutrino)], we can adopt the approach of Ref. [20] in which the 4G right-handed sneutrino (let us call it $S$) with a vacuum expectation value (vev) is used to break the $U(1)_B$ without the

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FIG. 1: 4-lepton $Z'$ resonance diagram at a hadron collider.
need for a separate singlet. In general, the 4G sneutrino (left-handed one) can also have a vev through a mixing although we will assume the mixing is very small.

Because the 4G Majorana neutrino mass term is forbidden by the $U(1)_B$ symmetry, the 4G neutrino is a Dirac particle on which the seesaw mechanism does not work, and thus can easily satisfy the LEP $Z$ width measurement that is compatible only with 3 light active neutrinos [21].

We take the 4G sneutrino ($\tilde{\nu}_4$), the spin-0 companion of the 4G neutrino, as a bridging scalar between the 4G and lepton final states. It has a nonzero $B$ violating interaction $\lambda_{4jk}L_iL_jE^c_k$. (For instance, see Ref. [22].) A nonzero $U(1)_B$ charge $(-4)$ and can couple to the $Z'$ while the sneutrinos of the first 3 generations have vanishing $U(1)_B$ charge. We assume the $\tilde{\nu}_4$ is the Lightest Superpartner (LSP); it can decay into a lepton pair through the lepton number violating interaction $\lambda_{4jk}L_iL_jE^c_k$. (For instance, see Ref. [22].) A nonzero $U(1)_B$ charge for the 3-generation sneutrinos would inevitably have led to 2-lepton $Z'$ resonance [23].

In the remainder of this paper, we focus on the collider physics consequences of this scenario with the $\tilde{\nu}_4$ LSP. Our analysis does not necessitate this particular supersymmetric model, albeit well motivated. Rather, the model serves as an existence proof of a consistent theory of the 4-lepton $Z'$ resonance without a 2-lepton $Z'$ resonance, and also provides a specific realization of the phenomenology of a new scalar that couples to the $Z'$ and lepton pairs.

### III. leptonic decay of the new scalar particle

Here, we discuss some characteristic features of the $\tilde{\nu}_4$ LSP decay exclusively through lepton number violating operators. Renormalizable operators $\lambda_{4jk}L_iL_jE^c_k$ and $\lambda_{4jk}L_iQ_jD^c_k$ are forbidden by the $U(1)_B$ gauge symmetry. Although operators with two 4G fields such as $\lambda_{4jk}L_iL_jE^c_k$ and $\lambda_{4jk}L_iQ_jD^c_k$ (or $\lambda_{4jk}L_iQ_jD^c_k$) are allowed at the renormalizable level, $\tilde{\nu}_4$ decays cannot be mediated by these operators due to kinematics when $\tilde{\nu}_4$ is the lightest of the 4G states. Thus, nonrenormalizable operators $\lambda_{4jk} \frac{\langle S \rangle}{M} L_iL_jE^c_k$ and $\lambda_{4jk} \frac{\langle S \rangle}{M} L_iQ_jD^c_k$ with a heavy mass parameter $M$ allow $\tilde{\nu}_4$ decays since $\langle S \rangle = 4$. Taking $\lambda_{4jk}$, $\lambda_{4jk} \frac{\langle S \rangle}{M} \approx 1$ and $M/\langle S \rangle = 10 - 1000$, for instance, effective coefficients $\lambda_{4jk} \frac{\langle S \rangle}{M} \approx 0.001 - 0.1$ are obtained.

Neglecting the light fermion masses, we obtain the partial widths

$$
\Gamma(\tilde{\nu}_4 \rightarrow l^+_j l^-_k) = \frac{1}{16\pi} (\lambda_{4jk}^{\text{eff}})^2 m_{\tilde{\nu}_4}, \quad (1)
$$

$$
\Gamma(\tilde{\nu}_4 \rightarrow \tilde{d}_j d_k) = \frac{3}{16\pi} (\lambda_{4jk}^{\text{eff}})^2 m_{\tilde{\nu}_4}. \quad (2)
$$

If we take all $\lambda^i = 0$, the $\tilde{\nu}_4$ LSP would decay only through $\lambda_{4jk}^{\text{eff}}$ ($b,c = 1 - 3$) with a total decay width given by

$$
\Gamma_{\tilde{\nu}_4} = \frac{m_{\tilde{\nu}_4}}{16\pi} \left[(\lambda_{411}^{\text{eff}})^2 + (\lambda_{412}^{\text{eff}})^2 + (\lambda_{413}^{\text{eff}})^2 + (\lambda_{421}^{\text{eff}})^2 + (\lambda_{422}^{\text{eff}})^2 + (\lambda_{423}^{\text{eff}})^2 + (\lambda_{431}^{\text{eff}})^2 + (\lambda_{432}^{\text{eff}})^2 + (\lambda_{433}^{\text{eff}})^2 \right]. \quad (3)
$$

It is demanded that $m_{\tilde{\nu}_4} \gtrsim M_{Z'}/2$ by the result of the LEP $Z$ decay experiment. The $\lambda_{44k}^{\text{eff}}$ can be constrained by various experiments such as $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ and similar $\tau$ decays. The bounds depend on the final lepton flavor indices $(j,k)$, and currently the most severe bound comes from $\text{Br}(\mu \rightarrow e\gamma) < 1 \times 10^{-12}$, which translates into $|\lambda_{41j}^{\text{eff}}| < (6.6 \times 10^{-7}) \times (m_{\tilde{\nu}_4}/100 \text{ GeV})^2$ for $\tilde{\nu}_4$. In a flavor-blind sense, it corresponds to $|\lambda_{4jk}^{\text{eff}}| < 0.0008 \times (m_{\tilde{\nu}_4}/100 \text{ GeV})$ for the $\tilde{\nu}_4$ LSP with the other $\tilde{\nu}_4$ sufficiently heavy [24]. That is, $|\lambda_{4jk}^{\text{eff}}| < 0.0004$ (0.0016) for $m_{\tilde{\nu}_4} = 50 \text{ GeV}$ (200 GeV), which falls into the ballpark of the aforementioned $\lambda_{4jk}^{\text{eff}}$ for $M/\langle S \rangle = 1000$. Larger $\lambda_{4jk}^{\text{eff}}$ may be allowed for a specific choice of $(j,k)$ as the experimental bounds are flavor-dependent. Because of many free parameters in $\Gamma_{\tilde{\nu}_4}$, a wide range of $\text{Br}(\tilde{\nu}_4 \rightarrow l^+_j l^-_k)$ for a given $l^+_j l^-_k$ can be accommodated.

### IV. collider phenomenology

In this section we present quantitative cross section predictions of the 4-leptons channel for the LHC7 (LHC with 7 TeV CM energy) experiments. For the calculations we use Comphep/Calchep [25, 26], with some modifications, and the parton distribution function of CTEQ6L [27, 28].

For definiteness, we take the $Z'$ gauge coupling constant to be $g_{Z'} = 0.1$; the $Z'$ production cross section and $Z'$ width can be simply scaled by $(g_{Z'}/0.1)^2$ for other $g_{Z'}$ values. We assume that the $\tilde{\nu}_4$ LSP is the lightest 4G field, with $m_{\tilde{\nu}_4} = 50 \text{ GeV}$, and that all new particles, except for the $\tilde{\nu}_4$ LSP, have masses larger than $M_{Z'}/2$ so that $Z'$ decays only into the SM fermions and the $\tilde{\nu}_4$ pair. Thus, the total $Z'$ width we take is the minimum value, which is $\Gamma_{Z'} \approx 1.6 \times 10^{-3} M_{Z'}$ for $M_{Z'} \gg m_{\tilde{\nu}_4}$.

The 4-lepton $Z'$ resonance cross section is

$$
\sigma(pp \rightarrow 4l) \approx \sigma(pp \rightarrow Z') \text{Br}(Z' \rightarrow \tilde{\nu}_4\tilde{\nu}_4) \text{Br}(\tilde{\nu}_4 \rightarrow 2l)^2.
$$

(4)

The branching fraction is $\text{Br}(Z' \rightarrow \tilde{\nu}_4\tilde{\nu}_4) \approx 0.67$ for $M_{Z'} \gg m_{\tilde{\nu}_4}$. The $\tilde{\nu}_4$ branching fractions to the light leptons ($ee, \mu\mu, \tau\tau$) are parameter dependent and flavor nonuniversality is expected. We shall illustrate the case $\text{Br}(\tilde{\nu}_4 \rightarrow 2l) = 1$, which is indeed possible to arrange.
Figure 2 (a) shows the $Z'$ production cross section at the LHC (solid curve) and Tevatron (dashed curve), for the $Z'$ mass range $M_{Z'} = 200 - 3000$ GeV. The low mass region would have been excluded by the dilepton $Z'$ resonance searches at the LHC had a $Z'$ coupled to the light leptons. For instance, the current bound on the sequential $Z'$ model is already $M_{Z'} \gtrsim 1.8 - 1.9$ TeV \cite{2,3} though its couplings are larger than our benchmark coupling. The ratio of the Tevatron to LHC $Z'$ production cross sections is about 0.2 for $M_{Z'} = 500$ GeV, and it drops rapidly at higher $M_{Z'}$. Though it might be possible to have an observable 4-lepton resonance at the Tevatron, especially for the low $Z'$ mass region, we will focus on the LHC experiments in our analysis.

Figure 2 (b) shows the 4-lepton $Z'$ resonance cross section at the LHC after the following typical acceptance cuts and $Z'$ invariant mass cut:

(i) $p_T > 15$ GeV (each lepton),
(ii) $|\eta| < 2.5$ (each lepton),
(iii) $m_{4\ell} - M_{Z'} < 3 M_{Z'}$ (4-leptons).

The SM 4-lepton background to $ee$ and $\mu\mu$ pairs is principally from the $q\bar{q} \rightarrow ZZ$ subprocess. As a recent ATLAS analysis shows, with nearly the same $p_T$ and $\eta$ cuts as ours, the SM background is negligible when the $m_{4\ell}$ mass is outside the $Z$ window of $(66 - 116)$ GeV \cite{29}. Furthermore, some 4-lepton combinations (such as $ee\mu\mu$, $e\mu\mu\mu$) do not have any significant SM backgrounds. Thus, through all the $Z'$ mass range, we will require a small number of 4-lepton events (10 events) after the acceptance cuts, in order to estimate the discovery reach.

Figure 2 (c) shows the required luminosity at LHC7 to realize a signal of 10 events at a 4-lepton resonance as read from Fig. 2 (b). For $g_{Z'} = 0.1$, an integrated luminosity at LHC7 of $L \simeq 17$ fb$^{-1}$ is needed for discovery (10 events) of $M_{Z'} = 2$ TeV. The existence of a 4-lepton $Z'$ resonance is already being probed at LHC7 in terms of the $M_{Z'}$ and $g_{Z'}$\cite{3}; and an integrated luminosity of 5 fb$^{-1}$ in each detector is expected before the end of 2011. The current LHC dijet search results (with $L \sim 1$ fb$^{-1}$) do not constrain the model for $g_{Z'} = 0.1 - 0.3$, as can be deduced from the estimates in Ref. \cite{30}.

A 4-lepton signal could be confused initially with a possible Higgs signal from $H \rightarrow ZZ$ with each $Z$ decaying to lepton pairs. There are several distinguishing characteristics of the signals: (i) $Z$ decay includes neutrino decay modes that are absent in $\tau_4$ decay; (ii) $\tilde{\nu}_4$ can decay into different lepton flavors which allows final states like $ee\mu\mu$ and $e\mu\mu\mu$, although these could be switched off by $\lambda_{312}^e = \lambda_{221}^e = 0$; (iii) The angular distribution of leptons in their rest frame is flat for the scalars (Higgs and sneutrino), but $\theta$-dependent for the vectors ($Z$ and $Z'$); (iv) If the $\tilde{\nu}_4$ mass differs from the $Z$ boson mass, the lepton pair invariant mass distributions from the sneutrino decays would peak at a value different from $M_{Z'}$, either lower or higher; and (v) $H \rightarrow ZZ$ should be accompanied by $H \rightarrow WW$, with a ratio of about 1 to 2.

Another exotic possibility for 4-lepton events is that a Higgs-like boson is produced via gluon-gluon fusion and it decays to a pair of hidden sector fields (vectors or scalars), each of which then decay to two leptons \cite{31,32}. The production cross section for a Higgs boson via gluon-gluon fusion would be much larger at LHC7 than at the Tevatron.

Though we have limited ourselves to only 4-lepton events, it is straightforward to extend the idea to other 4-fermion resonances depending on the values of $\lambda_{eff}$ and $\lambda'_{eff}$, such as $4\tau$, $2\ell + 2b$, $4t$, etc.

V. SUMMARY

We have discussed a novel $Z'$ search channel in which a 4-lepton $Z'$ resonance can be produced at the LHC without an accompanying 2-lepton $Z'$ resonance signal. We have shown that it is possible to construct a consistent supersymmetric model which has a $Z'$ particle with this property. The $U(1)$ symmetry of the model respects the baryon number for the first three generations. The model is made anomaly free by the addition of a fourth gener-
ation of fermions. Then the $Z'$ can decay to the fourth generation sneutrino pair, which in turn decay into lepton pairs, thus giving the 4-lepton resonance signal. The $Z'$ and the $\tilde{\nu}_4$ can be discovered or excluded in the near future by the LHC experiments.

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