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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.

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 a 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 [6, 7], 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 leptophobic 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 (φ). The Z' couples to quark pairs and φ, but not to lepton pairs, and the new scalar φ decays into a lepton pair. (See Fig. 1.) LHC experiments, and possibly Tevatron experiments, can find or reject this distinctive 4-lepton signal.

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

MODEL: We begin by introducing a specific model in which a 4-lepton Z' resonance can be realized without

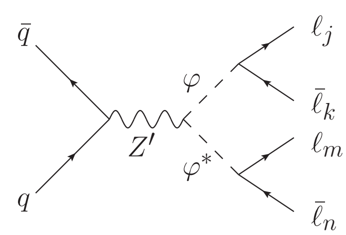

FIG. 1: 4-lepton Z' resonance diagram at a hadron collider.

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 [11–17]. 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.

SM quarks:	1/3	SM leptons:	0
4G quarks:	1/3	4G leptons:	-4

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[32].

Although proton stability would not have been guaranteed once the $U(1)_B$ is broken spontaneously, it turned out there exists a residual $\mathbb{Z}_4$ discrete symmetry, called baryon tetrality ($\mathbb{B}_4$), that forbids proton decay [19]. Under $\mathbb{B}_4$, lepton number violating operators can exist (such as λLLE^c and $\lambda' LQD^c$), but not baryon number violating operators (such as $\lambda'' U^c D^c D^c$).

In order to have the $\mathbb{B}_4$ 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 [19]. Since it coincides with the $U(1)_B$ charge of the N_4^c [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 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 ($\widetilde{\nu}_4$), the spin-0 companion of the 4G neutrino, as a bridging scalar between the Z' and the lepton final states. It has 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 $\widetilde{\nu}_4$ is the Lightest Superpartner (LSP); it can decay into a lepton pair through the lepton number violating interaction $\lambda_{ijk}L_iL_jE^c_k$. (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 $\widetilde{\nu}_4$ 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.

LEPTONIC DECAY OF THE NEW SCALAR PARTICLE: Here, we discuss some characteristic features of the $\widetilde{\nu}_4$ LSP decay exclusively through lepton number violating operators. Renormalizable operators $\lambda_{4jk}L_4L_jE^c_k$ and $\lambda'_{4jk}L_4Q_jD^c_k$ are forbidden by the $U(1)_B$ gauge symmetry. Although operators with two 4G fields such as $\lambda_{4j4}L_4L_jE^c_4$ and $\lambda'_{4j4}L_4Q_jD^c_4$ (or $\lambda'_{44k}L_4Q_4D^c_k$) are allowed at the renormalizable level, $\widetilde{\nu}_4$ decays cannot be mediated by these operators due to kinematics when $\widetilde{\nu}_4$ is the lightest of the 4G states. Thus, nonrenormalizable operators $\lambda_{4jk}\frac{\langle S\rangle}{M}L_4L_jE^c_k$ and $\lambda'_{4jk}\frac{\langle S\rangle}{M}L_4Q_jD^c_k$ with a heavy mass parameter M allow $\widetilde{\nu}_4$ decays since $z[S]=4$. Taking λ_{4jk}, $\lambda'_{4jk}\approx 1$ and $M/\langle S\rangle = 10-1000$, for instance, effective coefficients $\lambda^{\rm eff}_{4jk}\equiv\lambda_{4jk}\frac{\langle S\rangle}{M}$, $\lambda'^{\rm eff}_{4jk}\equiv\lambda'_{4jk}\frac{\langle S\rangle}{M}\approx 0.001-0.1$ are obtained[33].

Neglecting the light fermion masses, we obtain the partial widths

$$\Gamma(\widetilde{\nu}_4\to\ell^+_j\ell^-_k)=\frac{1}{16\pi}(\lambda^{\rm eff}_{4jk})^2 m_{\widetilde{\nu}_4}, \quad (1)$$

$$\Gamma(\widetilde{\nu}_4\to\bar{d}_jd_k)=\frac{3}{16\pi}(\lambda'^{\rm eff}_{4jk})^2 m_{\widetilde{\nu}_4}. \quad (2)$$

If we take all $\lambda'=0$, the $\widetilde{\nu}_4$ LSP would decay only through $\lambda^{\rm eff}_{4bc}$ $(b,c=1-3)$ with a total decay width given by

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

It is demanded that $m_{\widetilde{\nu}_4}\gtrsim M_Z/2$ by the result of the LEP Z decay experiment. The $\lambda^{\rm eff}_{4jk}$ can be constrained by various experiments such as $\mu\to e\gamma$, $\mu\to eee$ and similar τ decays. The bounds depend on the final lepton flavor indices (j,k), and currently the most severe bound comes from $\texttt{Br}(\mu\to eee)<1.0\times10^{-12}$, which translates into $|\lambda^*_{i12}\lambda_{i11}|<(6.6\times10^{-7})\times(m_{\widetilde{\nu}_i}/100\text{ GeV})^2$ for $\widetilde{\nu}_i$. In a flavor-blind sense, it corresponds to $|\lambda^{\rm eff}_{4jk}|<0.0008\times(m_{\widetilde{\nu}_4}/100\text{ GeV})$ for the $\widetilde{\nu}_4$ LSP with the other $\widetilde{\nu}$'s sufficiently heavy [24]. That is $|\lambda^{\rm eff}_{4jk}|<0.0004$ (0.0016) for $m_{\widetilde{\nu}_4}=50$ GeV (200 GeV), which falls into the ballpark of the aforementioned $\lambda^{\rm eff}_{4jk}$ value for $M/\langle S\rangle=1000$. Larger $\lambda^{\rm eff}_{4jk}$ may be allowed for a specific choice of (j,k) as the experimental bounds are flavor-dependent. Due to many free parameters in $\Gamma_{\widetilde{\nu}_4}$, a wide range of $\texttt{Br}(\widetilde{\nu}_4\to\ell^+_j\ell^-_k)$ for a given $\ell^+_j\ell^-_k$ can be accommodated.

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][34].

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 $\widetilde{\nu}_4$ LSP is the lightest 4G field, with $m_{\widetilde{\nu}_4}=50$ GeV, and that all new particles, except for the $\widetilde{\nu}_4$ LSP, have masses larger than $M_{Z'}/2$ so that Z' decays only into the SM fermions and the $\widetilde{\nu}_4$ pair. Thus, the total Z' width we take is the minimum value, which is $\Gamma_{Z'}\approx1.6\times10^{-3}M_{Z'}$ for $M_{Z'}\gg m_{\widetilde{\nu}_4}$.

The 4-lepton Z' resonance cross section is

$$\sigma(pp\to4\ell)\simeq\sigma(pp\to Z')\texttt{Br}(Z'\to\widetilde{\nu}_4\widetilde{\nu}^*_4)\texttt{Br}(\widetilde{\nu}_4\to2\ell)^2. \quad (4)$$

The branching fraction is $\texttt{Br}(Z'\to\widetilde{\nu}_4\widetilde{\nu}^*_4)\simeq0.67$ for $M_{Z'}\gg m_{\widetilde{\nu}_4}$. The $\widetilde{\nu}_4$ branching fractions to the light leptons (ee, $e\mu$, $\mu\mu$) are parameter dependent and flavor non-universality is expected. We shall illustrate the case $\texttt{Br}(\widetilde{\nu}_4\to2\ell)=1$, which is indeed possible to arrange.

Figure 2 (a) shows Z' production cross section at the LHC (solid) and Tevatron (dashed), 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 $M_{Z'}\gtrsim1.8-1.9$ TeV [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 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) $|m_{\rm inv}(4\ell)-M_{Z'}|<3\Gamma_{Z'}$ (4-leptons).

The SM 4-lepton background to ee and $\mu\mu$ pairs is principally from the $q\bar{q}\to ZZ$ subprocess. As a recent ATLAS analysis shows, with nearly the same p_T and η cuts as ours, the SM background is negligible when the $m_{\widetilde{\nu}_4}$ mass is outside the Z window of $(66-116)$ GeV [28]. Furthermore, some 4-lepton combinations (such as $ee e\mu$, $e\mu\mu\mu$) do not have any significant SM backgrounds. Thus, through all the Z' mass range, we will require a

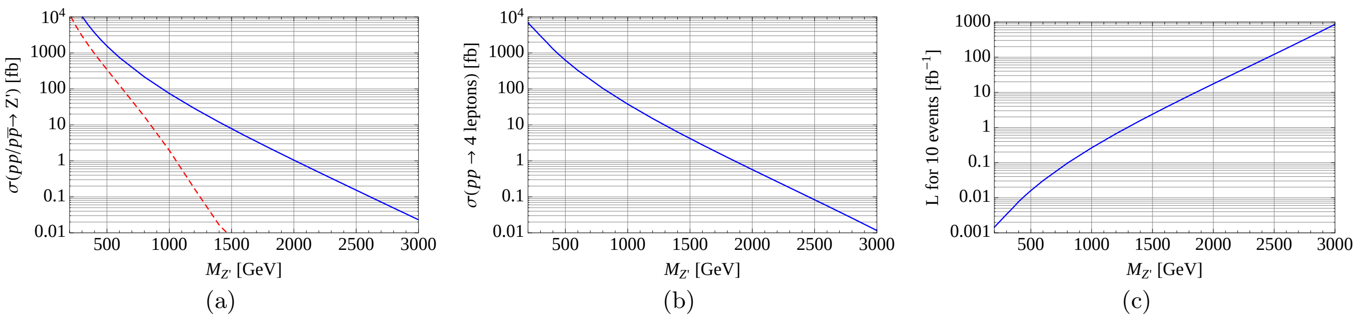

FIG. 2: (a) Z' production cross section at the LHC7 ($E_{\rm CM} = 7$ TeV) (solid curve) and the Tevatron ($E_{\rm CM} = 1.96$ TeV) (dashed curve). (b) Cross section of 4-leptons after cuts at the LHC7. (c) Luminosity for 10 events after cuts at LHC7.

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 $g_{Z'}$[35] 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. [29].

A 4-lepton signal could be confused initially with a possible Higgs signal from $H \to ZZ$ 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 $\widetilde{\nu}_4$ decay, (ii) $\widetilde{\nu}_4$ can decay into different lepton flavors which allows final states like $eee\mu$ and $e\mu\mu\mu$, although these could be switched off by $\lambda^{\rm eff}_{412} = \lambda^{\rm eff}_{421} = 0$, (iii) The angular distribution of leptons in their rest frame is flat for the scalars (Higgs and sneutrino), but θ-dependent for the vectors (Z and Z'), (iv) If the $\widetilde{\nu}_4$ 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, (v) $H \to ZZ$ should be accompanied by $H \to WW$, with 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 [30, 31]. 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 $\lambda^{\rm eff}$ and $\lambda'^{\rm eff}$, such as 4τ, $2\ell + 2b$, $4t$, etc.

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 baryon number for the first 3-generations. The model is made anomaly free by the addition of fourth generation 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 $\widetilde{\nu}_4$ can be discovered or excluded in the near future by the LHC experiments.

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[32] 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 [18].
[33] $\langle S \rangle \lesssim 1$ TeV is expected in SUSY to keep the extra D-term contribution to the sfermion masses small, and $M = 10-1000$ TeV satisfies bounds on the scale of new physics from various constraints such as neutral kaon mixing.
[34] Our model-file is linked at `http://quark.phy.bnl.gov/~hlee/simulation/`.
[35] A direct application of the ATLAS analysis $\sigma_{4\ell} < 4.7$ fb (with 3-events criteria and $L = 1.02$ fb^{-1}) [28] gives $M_{Z'} \gtrsim 1500$ GeV for $g_{Z'} = 0.1$.