Z' Decays into Four Fermions *

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Abstract

If a new Z' is discovered with a mass ~ 1 TeV at LHC/SSC, its (rare) decays into two charged leptons plus missing transverse energy will probe the Z' coupling to the lepton doublet \( \left( \nu_e \right)_L \) and to \( W^+W^- \), allowing further discrimination among extended electroweak models.

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Many approaches to extending the standard model lead to a larger gauge group which implies a new heavier $Z'$ boson which some day will be discovered. Then it will be important to learn experimental techniques to use the $Z'$ decays to determine what the new gauge group is. In this letter we extend the analysis of this question.

Large hadron colliders offer the best chance to observe (in contrast with indirect evidence) a new heavy $\sim 1 \, TeV$ gauge boson, $Z'$ [1, 2, 3]. If it couples to quarks and leptons with a sizeable strength ($g \sim 0.1$) it should be discovered in the two lepton final states, $e^+e^-$ and $\mu^+\mu^-$. The subsequent measurement of the forward-backward asymmetry should constrain the ratio of the axial to the vector charged lepton ($Z'$) couplings, discriminating among possible extended electroweak models. Recently it has been pointed out that the $Z'$ decays into two fermions and a $W$ or a $Z$ would further distinguish among models [4]. These processes, however, appear in detectors as four fermion final states and then require a definite strategy for their identification. As a matter of fact, the $Z'$ decays into $W^+W^-$ also contribute to this signal. We argue that for the popular ($E_6$) models the most interesting decays are those involving two charged leptons and two neutrinos, although the cross section is small [5]. These decays constrain the $Z'$ coupling to the lepton doublets $\left( \begin{array}{c} \nu \\ e \end{array} \right)_{L}$ and $\left( \begin{array}{c} \nu \\ \mu \end{array} \right)_{L}$ as well as the $Z'W^+W^-$ coupling, and then do discriminate among models. Two samples can be distinguished, one containing the events with two charged leptons of different flavor, $e^-\mu^+\not{p}$ and $e^+\mu^-\not{p}$, and other the events with two charged leptons of the same flavor, $e^-e^+\not{p}$ and $\mu^-\mu^+\not{p}$. These are final products of $Z'$ decays into $f\bar{f}W$, $f\bar{f}Z$ and $WW$, where $f$ can be $e, \mu$ or $\nu$. Both samples are of the same size and give similar information but the first one is cleaner (and simpler to evaluate). Elsewhere we discuss the sample with two charged leptons of the same flavor and the other four fermion channels. The latter, however, have too small a cross section (four charged leptons) or too large a background (non leptonic final states).

Let us present first the numerical results (plots) and postpone the discussion to the end. We assume that a new $Z'$ with a mass, for instance, of $1 \, TeV$ is known to exist. And we are interested in events with one electron and one muon ($e^-\mu^+$ or $e^+\mu^-$) plus missing transverse energy ($\not{p}_T$). The two main backgrounds result from the $WW$ continuum and from heavy quark
(t) production. Whereas the first is irreducible (and after cuts small), the second is difficult to estimate. We assume that the latter will be controlled once large transverse momenta for $p$ and/or $e, \mu$ are required and a good understanding of the heavy quark (t) production is obtained, using criteria of isolation and multiplicity \[3\]. We concentrate on the four fermion $Z'$ signal and the standard model (continuum) WW background. The former gets contributions from five diagrams: four corresponding to $Z' \rightarrow f \bar{f}$ followed by $W$ emission from one of the two (charged or neutral) fermions leaving the $Z'$ vertex and one including the $Z'$ decay into $W^+W^-$. In Fig. 1 we show for the $Z' \rightarrow e^-\mu^+\bar{p}$ events and for the continuum $WW \rightarrow e^-\mu^+\bar{p}$ background the $e^-, \mu^+$ (which are equal) and $\bar{p}$ transverse momentum distributions. For definiteness we use the $Z_\chi$ model with $\Gamma_{Z'} = 0.012 M_{Z'}$ (assuming that the open channels are those involving only known particles, including the top quark) and with a $Z'Z^0$ mixing angle $\sin\theta_3 = -\frac{0.0034}{M_{Z'}}$. We take, for illustration, the EHLQ (set 1) structure functions \[7\] and $\sqrt{s} = 16$ TeV (LHC). (The numerical results vary significantly for different structure functions but do not change the conclusions. In particular the HMRS structure functions \[8\] give a $\sim 30\%$ larger cross sections.) We have used REDUCE \[9\] and MATHEMATICA \[10\] for calculating the exact amplitudes and RAMBO \[11\] for generating the corresponding events (we work at the parton level). This generator is very convenient for matrix elements which do not fluctuate too much. This is not our case, however, for the matrix elements we are concerned with are very much enhanced when all the internal lines are near on-shell. This means that we have to generate (very) large statistics to obtain a small error. The $Z'$ contributions from $W$ emission and from $W^+W^-$ are comparable, although model dependent. To have a good grip of these events we must note that the contribution of any of the diagrams emitting one $W$ is large if the $W$ is on-shell and the off-shellness of the internal lepton is small. As the fermion propagator $[M_{Z'}(M_{Z'} - 2E)]^{-1}$ is large for large $E$, where $E$ is the energy of the external lepton leaving the $Z'$ vertex in the $Z'$ rest frame, these events have $E \sim M_{Z'}$ \[4\]. Thus, the events we are interested in have at least one fermion ($\bar{p}, e, \mu$) with a very large momentum. The diagram with two $W$'s give a large contribution when both gauge bosons are on-shell.

The two neutrinos in the final state do not allow for reconstructing the $Z'$ mass, and we are forced to work in the transverse plane. As a consequence and as is apparent in Fig. 1, the strategy for isolating the $Z'$ sample is to
require large transverse momenta. In particular we must demand a large transverse momentum. The $e^- p, \mu^+ p$ or $e^- \mu^+$ transverse angle distributions are of no help. Further cuts reduce the signal without improving the signal to background ratio. For this example 408 $Z' \to e\bar{\mu}p$ events will be produced at LHC ($\int L dt = 10^5 \text{ pb}^{-1}$), where we sum $e^- \mu^+ p$ and $e^+ \mu^- p$ events. (Universality implies equal distributions under the interchange of $e$ and $\mu$ for a given charge assignment.) Requiring $p_t > 200 \text{ GeV}$, $p_t^{e,\mu} > 50 \text{ GeV}$, as suggested by Fig. 1 (not very demanding pseudorapidity cuts make no difference), 151 events are expected for the signal. For the same cuts the expected number of events for the $WW$ continuum background is 23. We are now ready to discuss the significance of these processes.

A new $Z'$ of the usual ($E_6$) type, for instance, $Z_{\chi}$ with a mass $\sim 1 \text{ TeV}$ will produce a sample of 60,000/30,000 $e\bar{e}, \mu\bar{\mu}$ pairs at LHC/SSC (we assume $\int L dt = 10^5/10^4 \text{ pb}^{-1}$ for LHC/SSC). These events should allow for the measurement of $M_{Z'}$. The question is whether four fermion $Z'$ decays are observable at all. $Z'$ decays involving jets, for instance $Z' \to q\bar{q}W, q\bar{q}Z$, may not be observable due to the large, irreducible, QCD background. (However, if the techniques suggested in Ref. [12] can be used to observe $Z' \to W(\to l\bar{\nu})W(\to jj)$, then reconstruction of $M_{Z'}$ can be done for true semileptonic $Z'$ decays and the situation would be much better; we do not consider this analysis here.) The $Z' \to l\bar{l}Z, \nu\bar{\nu}Z \to ll\nu\bar{\nu}$ decays have small cross sections and after cuts it would be difficult to make any definite statement ($l = e, \mu$). This makes the $Z' \to l\bar{l}W, W^+W^- \to l\nu\bar{l}\nu$ decay the most promising leptonic one. However, even this mode seems unobservable for $M_{Z'} > 2 \text{ TeV}$. (Photon emission is of no interest here for it does not make any difference among extended electroweak models.) In Table 1 we give the minimal width, the (largest) $Z'Z^0$ mixing angle $\sin\theta_3$ and the $Z'$ couplings to leptons for the popular models $\chi, LR, \psi, \eta$ [4, 13]. (Note that $g_{Z'\nu_L\nu_R} = g_{Z'\nu_R\nu_L}$ as required by gauge invariance, for both fermions belong to the same ($SU(2)_L$) multiplet.) We also quote the leptonic factors entering into the forward-backward asymmetry, $x = \frac{x^2-1}{x^2+1}$, $x^2 \equiv \frac{\hat{g}_{Z'\nu_L\nu_L}}{\hat{g}_{Z'\nu_R\nu_R}}$, and into the ratio of the $Z' \to e\bar{\mu}p$ to the $Z' \to H$ cross sections, $\frac{x^2}{x^2+1}$. The latter is equal to the former plus 1 and divided by 2. In Table 2 we give for LHC, SSC and for $M_{Z'} = 1$ (upper values), 1.5 (lower values) $\text{ TeV}$ the $pp \to \gamma, Z, Z' \to e\bar{e}, \mu\bar{\mu}$ cross section around the $Z'$ peak (where the contribution of the standard model is at most several per cent the $Z'$ one), the integrated forward-backward
asymmetry and the $Z' \to e\bar{\mu}\bar{\nu}$ cross section after cuts (in parentheses we quote the $Z' \to l\bar{\nu}W$ contribution, corresponding to $\sin \theta_3 = 0$). We demand $p_t > 200$ (250) GeV, $p_t^{e,\mu} > 50$ GeV for $M_{Z'} = 1(1.5)\ TeV$. (We use the EHLQ, set 1, structure functions. The HMRS structure functions give $\sim 20 - 30\%$ larger cross sections and $\sim 10 - 20\%$ smaller asymmetries. All numbers quoted, and in particular $\sigma_{e\bar{\mu}\bar{\nu}}$, have statistical errors which can be as large as 30%, depending on the model and on the $M_{Z'}$ mass. We have generated typically 5 million events per case.) Thus, if a new $Z'$ exists with a mass $\sim 1\ TeV$ some $Z' \to e\bar{\mu}\bar{\nu}$ events should be detected at LHC and SSC. With the same cuts the continuum $WW$ cross sections are $0.23(0.09) / 1.06(0.48)\ fb$ at LHC/SSC, where the numbers in parentheses correspond to $p_t > 250\ GeV$.

As can be seen in Table 2 the $Z' \to l\bar{\nu}W, W^+W^- \to e\bar{\mu}\bar{\nu}$ ($Z' \to l\bar{\nu}W \to e\bar{\mu}\bar{\nu}$) cross sections are model dependent. The $Z' \to e\bar{\mu}\bar{\nu}$ cross sections with no cuts are, for instance for $M_{Z'} = 1\ TeV$ and for LHC, $\chi : 4.08(3.22)\ fb; LR : 5.34(1.48)\ fb; \psi : 2.55(0.90)\ fb; \eta : 3.47(0.42)\ fb$ (the numbers in parentheses correspond to $\sin \theta_3 = 0$). By comparing these cross sections to those in Table 2 we observe that the cut on $p_t$ increases the ratio of $W$ emission to $W^+W^-$ cross sections. At any rate, the contributions of the $W$ emission and of $W^+W^-$ are comparable and indistinguishable after cuts. The $e\bar{\mu}\bar{\nu}$ sample constrains the model although it does not allow for an independent measurement of the $W$ emission and the $W^+W^-$ contributions. The former is proportional to the $Z'$ coupling to left-handed leptons, $g_{Z'\nu L\nu L} = g_{Z'u_Lu_L}$ (as required by $SU(2)_L$ invariance); and the latter to the $Z'Z^0$ mixing angle $\sin \theta_3$ so it will be important to eventually separate them. The $W$ emission cross section (in parentheses in Table 2) normalized to the $Z' \to l\bar{l}$ cross section (in the first columns in Table 2) is proportional to $\frac{x^2}{x^2 + 1}$ in Table 1. Whereas the $Z' \to W^+W^-$ cross section is proportional to $\sin^2 \theta_3$ in the same Table. $\sin \theta_3$ can be only measured in this process. $x^2$, however, is also related to the forward-backward asymmetry. This forward-backward asymmetry, which will be measured with a higher precision, has a more involved model dependence as can be seen comparing the $\frac{x^2 - 1}{x^2 + 1}$ column in Table 1 with the $A_{FB}$ columns in Table 2. $A_{FB}$ is also proportional to a similar factor involving the $Z'$ couplings to quarks. Besides, up and down quark contributions must be summed up and the rapidity dependence integrated. At any rate, if a new $Z'$ exists with a mass $\sim 1\ TeV$, the $Z' \to e\bar{\mu}\bar{\nu}$ decays...
can help to distinguish among different models in a way complementary to the information coming from the forward-backward asymmetry.

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Table Captions

Table 1. Minimal width, (largest) $Z'Z^0$ mixing angle, and leptonic $Z'$ couplings for $Z_{\chi,LR,\psi,\eta}$. The leptonic factors entering into the forward-backward asymmetry and into the ratio $\frac{\sigma(Z'\rightarrow e\bar{\mu})}{\sigma(Z'\rightarrow n)}$ are also given. ($x^2 \equiv \frac{g^{2\mu}_{Z'LL}}{g^{2\mu}_{Z'LR}}.)$

Table 2. Total cross section for $Z'$ decay into lepton ($e\bar{e}, \mu\bar{\mu}$) pairs, integrated forward-backward asymmetry and the $Z' \rightarrow e\bar{\mu}\phi$ cross section after cuts, $p_t > 200(250)$ GeV, $p_t^{e/\mu} > 50$ GeV for $M_{Z'} = 1(1.5)$ TeV, for LHC and SSC. The upper (lower) values correspond to $M_{Z'} = 1(1.5)$ TeV. The numbers in parentheses correspond to the $Z' \rightarrow l\bar{\nu}W \rightarrow e\bar{\mu}\phi$ contribution, corresponding to $\sin\theta_3 = 0$.

Figure Captions

Fig. 1. Transverse momentum distributions for $Z' \rightarrow e^-\mu^+\phi$ (solid curves) and the continuum $WW$ background (dashed curves). The charged lepton distributions are the same for $e^-$ and $\mu^+$. 

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\[
\frac{1}{M^2_{\mu}} \sin \theta_3 M^2_Z (TeV^2) \quad g_{\bar{\nu} \nu \ell} \frac{c_w}{c_e} \quad g_{\bar{\nu} \nu \ell} \frac{c_w}{c_e} \quad \frac{x^2 - 1}{x^2 + 1} \quad \frac{x^2}{x^2 + 1}
\]

|       |       | $\frac{1}{M^2_{\mu}} \sin \theta_3 M^2_Z (TeV^2)$ | $g_{\bar{\nu} \nu \ell} \frac{c_w}{c_e}$ | $g_{\bar{\nu} \nu \ell} \frac{c_w}{c_e}$ | $\frac{x^2 - 1}{x^2 + 1}$ | $\frac{x^2}{x^2 + 1}$ |
|-------|-------|-------------------------------------|-------------------------------|-------------------------------|-------------------|------------------|
| $\chi$ | 0.012 | -0.0034 | $\frac{1}{6} \sqrt{\frac{3}{2}}$ | $\frac{1}{2} \sqrt{\frac{1}{6}}$ | $\frac{8}{10}$ | $\frac{9}{10}$ |
| $LR$   | 0.021 | -0.0063 | $\frac{1}{2} \frac{s_W}{\sqrt{1 - 2 s_W^2}}$ | $\frac{1}{2} \frac{s_W}{\sqrt{1 - 2 s_W^2}}$ | $\frac{8}{10}$ | $\frac{9}{10}$ |
| $\psi$ | 0.006 | -0.0043 | $-\frac{1}{6} \sqrt{\frac{3}{2}}$ | $\frac{1}{6} \sqrt{\frac{1}{2}}$ | 0 | $\frac{1}{2}$ |
| $\eta$ | 0.007 | -0.0055 | $\frac{1}{6} \sqrt{\frac{3}{2}}$ | $\frac{1}{6} \sqrt{\frac{1}{2}}$ | $-\frac{3}{5}$ | $\frac{1}{5}$ |

Table 1

|       | LHC | $\sigma_{eff}(pb)$ | $A_{FB}$ | $\sigma_{eff}(fb)$ | $\sigma_{eff}(pb)$ | $A_{FB}$ | $\sigma_{eff}(fb)$ |
|-------|-----|-------------------|---------|-------------------|-------------------|---------|-------------------|
| $\chi$ | 0.63 | -0.12 | 1.51(1.36) | 2.82 | -0.10 | 6.75(6.08) |
| $LR$   | 0.74 | 0.10 | 1.11(0.62) | 3.11 | 0.09 | 5.83(2.62) |
| $\psi$ | 0.29 | 0.11 | 0.44(0.22) | 0.78 | 0.10 | 2.60(1.26) |
| $\eta$ | 0.06 | 0.01 | 0.26(0.14) | 0.30 | 0.01 | 1.35(0.72) |

Table 2