Differentiating various extra $Z'$'s at Future Colliders.

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ABSTRACT

We propose a way to differentiate between various extra $U(1)$ models using flavor tagging in the decay modes $Z' \rightarrow q\bar{q}$ once the extra $Z'$ is observed at future colliders in the lepton channel. A generalization of the R parameter, namely, one for charge $\frac{1}{3}$ and one for charge $\frac{2}{3}$ quark gives a two parameter test for the various models. Flavor tagging eliminates the uncertainty because of extra fermions and can reduce the QCD background at SSC/LHC dramatically. For $E_6$ and $SO(10)$ based models the former is always 3. This seems to be a very good way to eliminate certain models.

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Although the standard model of electroweak interaction is in excellent agreement with the present experiments, there are reasons to believe in going beyond the standard model. One of the ways to go beyond the standard model is to extend the gauge group. Any extension of the standard model with a gauge group of rank bigger than four entails one or more extra neutral vector bosons. The lightest of these is generally known as $Z'$ in the literature\(^1\). There are two ways to detect the presence of such a boson. $Z'$ through its mixing with the canonical $Z$ gives rise to various predictable deviations from the standard model results. Most of the effects of the extra neutral boson has been studied in great detail\(^1,2,3\). Many of these studies are exclusively concerned with the effects in high energy experiments\(^2\) and a few deal with atomic parity violation\(^3\). So far all the experimental observations agree very well with the standard model predictions within the limits of experimental and theoretical uncertainties. Hence, at the moment, one can only put limits on the two parameters, the mixing angle of $Z'$ with the canonical $Z$ and the mass of $Z'$. The experimental precision puts a upper bound on the mass upto which the extra neutral gauge bosons effect can be detected. These effects also depend on another parameter, namely the mixing with the canonical $Z$. The limit is very much model dependent. But it will be difficult to detect such an effect if the mass of the extra neutral boson is more than 500 GeV. The other way is to look for direct production and decay at future colliders. Such an extra $Z$ will be produced at future $e^+e^-$ machines NLC/JLC and hadron colliders SSC/LHC if its mass is less than 6 TeV\(^4\). Once it is produced and detected via its leptonic decays we need to know its origin. We need to differentiate between the multitude of such models and possibly rule out many. There have been lot of discussions on this subject. One crucial test is the $A_{FB}$\(^5\). Recently there has been another proposal using rare decays\(^6\) of $Z'$. Because the number of extra $U(1)$ models available are really large it will be helpful if we can find as many test parameters as we can. Here we propose the generalization of the R parameter as a test for the various models.

Most of the studies on $Z'$ decays and differentiating various $Z'$ models have almost exclusively been focussed on the lepton sector. Very little attention has been paid to the decay mode $Z' \rightarrow qar{q}\gamma$. The reason is the understandably large (almost four orders of magnitude larger) QCD background in the hadron colliders. No such disadvantage exist for
the future generation $e^+e^-$ machines, NLC/JLC. Even in the hadron colliders the decay modes $Z' \rightarrow q\bar{q}$ deserve detailed analysis by their own right. The $Z'$ study can’t be complete by only concentrating on the leptonic modes. The question is how to reduce the enormous background? Here we would like to give the proposal of flavor tagging. Instead of looking for $Z' \rightarrow jet + jet$ if we look for two almost back to back jets which originated, let us say, from $b$ and $\bar{b}$ or from $t$ and $\bar{t}$ then we will have more handle on the background. The techniques of identifying a $b$ jet by looking for high $p_T$ leptons already exist and most probably will be improved before the hadron colliders produce their first event. So, we propose to look for flavor tagging in the decay $Z' \rightarrow q\bar{q}$. This will give us better handle on reducing the QCD background in the hadron colliders and will give two new parameters to differentiate the origin of $Z'$. Both these points are discussed in little more detail later on in this letter.

The neutral current interaction for any fermion is given by

$$\mathcal{L}_{NC} = -i\bar{\psi}\gamma^\mu \{eQA_\mu \sin^2 \theta_W Z_{\mu}(I_3 - Q \sin^2 \theta_W \cos \chi + \frac{\cos \theta_W g_2}{g} X \sin \chi)$$

$$- \sin \theta_W \cos \theta_W Z'_{\mu}(- (I_3 - Q \sin^2 \theta_W \sin \chi + \frac{\cos \theta_W g_2}{g} X \cos \chi)\psi, \quad (1)$$

where $g$ and $g_2$ are the coupling constants for $SU(2)_L$ and the extra $U(1)$ respectively; $X$ is the extra-$U(1)$ charge of $\psi$.

Here the X-charges of the various fermions and the coupling constant of the extra $U(1)$, $g_2$, are model dependent. For any given model the X-charges are exactly determined, upto a constant multiplicative factor which can be absorbed into the coupling constant. In models based on bigger unification group the coupling constant $g_2$ is related to $g$ and the relation depends on the details of the model such as the original gauge structure and the representations of Higgs bosons responsible for symmetry breaking. We have tabulated the X-charges of the fifteen standard fermions in each family for the eleven models we have chosen for our analysis in Table 1. We can safely assume the mixing angle to be very small and hence the interaction of the fermions with $Z'$ is given by
\[ \mathcal{L}_{NC} = ig_2X \bar{\psi} \gamma^\mu Z'_\mu \psi. \]  

(2)

The partial decay width of \( Z' \to \bar{f}f \) for any fermion is given by

\[ \Gamma(Z' \to \bar{f}f) \propto C_f (v_f^2 + a_f^2), \]  

(3)

where \( v_f \) and \( a_f \) are the vector and the axial vector couplings and are respectively proportional to \( X_L + X_R \) and \( X_L - X_R \) and \( C_f \) is the color factor which is 3 for quarks and 1 for leptons. Although the absolute branching fraction is uncertain by a factor of 2 because of the uncertainty of the spectrum of the exotic fermions in a model, the relative branching fractions between the known fermions are very precisely known theoretically for any particular model. So if we can distinguish between the various exclusive decay modes involving leptons and charge \( \frac{1}{3} \) and charge \( \frac{2}{3} \) quarks that will give us two very precise ratios. Flavor tagging is possible in \( e^+e^- \) machines and are relatively clean. The signature for \( Z' \to jet + jet \) in the hadron colliders will be difficult because of the huge QCD background. The rough analysis shows that this is in the borderline of being barely accessible. Our hope is that by flavor tagging we can reduce the signal to background ratio dramatically. A systematic study of this question has not been done yet. The Monte-Carlo simulation of such events with appropriate cuts and the relevant background using PYTHIA are in progress. Preliminary results show that by putting appropriate cuts on \( p_T \) and invariant mass we have been able to reduce the background to signal ratio from a number \( \sim 10,000 \) to \( 40 \sim 50 \).

Here we assume that such identification is possible and propose the following two ratios of the branching fractions as a way to differentiate between the various extra \( U(1) \) models and possibly eliminate certain models.

\[ R_1 = \frac{\Gamma(Z' \to \bar{b}b)}{\Gamma(Z' \to l^+l^-)} \]  

(4)

and

\[ R_2 = \frac{\Gamma(Z' \to \bar{c}c \text{ or } \bar{t}t)}{\Gamma(Z' \to l^+l^-)} \]  

(5)

We have analyzed eleven models for this report. \( S^{(0)} \) is the model recently proposed by Mahanthappa and the author in which the X-charges are exactly proportional to the weak...
hypercharges ($Y$) for the fifteen standard fermions. $S^{(i)} (i=1,2,3)$ come from $E_6$. They are respectively called $\chi$, $I$ and $\eta$ in the literature (see, for example, the review by Hewett and Rizzo$^1$). $S^{(i)} (i=4,5)$ come from the flipped $SU(5) \otimes U(1)$ broken to the standard model with the Higgs fields residing in $(27 + \bar{27})$- and 78-dimensional representations of $E_6$ respectively. $S^{(6)}$ is the doubly flipped $SU(5) \otimes U(1) \otimes U(1)$ with the Higgs fields residing in $(27 + 27)$-dimensional representations of $E_6$. $S^{(7)}$ has its origin in the Pati-Salam group. $S^{(i)} (i=8,9,10)$ refer to the $SU(3) \otimes U(1)$ models in which the extra third quark has electric charge $\frac{2}{3}$, $\frac{1}{3}$ and $-\frac{1}{3}$ respectively$^{10}$. The models $S^{i} (i=1..7)$ have been studied by Brahm and Hall$^{11}$ in connection with dark matter. For the models $S^{(i)} (i=0..7)$ $g_2 = 0.8 \, c \, g$ with the factor $c$ being close to unity and for the models $S^{(i)} (i=8,9,10)$ $g_2 = \frac{g}{\cos \theta_W}$.

The $R_1$ and $R_2$ for the models discussed above are given in Table 2 and are plotted in Fig. 1. One remarkable fact that emerges is that $R_1$ is 3 for all the $E_6$ and thereby $SO(10)$ based models. So any model with significant departure from this value will be ruled out. Combining this analysis with those involving $A_{F,B}$ and rare decays would further restrict the allowed models.

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Table 1: X-charges of the fermions for the various extra $U(1)$ models. $N$ is the normalization factor.

| Model  | $q_L$ | $u_R$ | $d_R$ | $l_L$ | $e_R$ | $\nu_R$ | $1/N$ |
|--------|-------|-------|-------|-------|-------|---------|-------|
| $S^{(0)}$ | 1     | 4     | -2    | -3    | -6    | 0       | 6     |
| $S^{(1)}$ | 1     | -1    | 3     | -3    | -1    | -5      | $\sqrt{40}$ |
| $S^{(2)}$ | 2     | -2    | -4    | 4     | -2    | 0       | $\sqrt{160}$ |
| $S^{(3)}$ | 4     | -4    | 2     | -2    | -4    | -10     | $\sqrt{240}$ |
| $S^{(4)}$ | 0     | -2    | 0     | 2     | 2     | 0       | 4     |
| $S^{(5)}$ | 2     | 4     | -2    | -4    | -8    | -2      | $\sqrt{96}$ |
| $S^{(6)}$ | 0     | -1    | 1     | 0     | 1     | -1      | 2     |
| $S^{(7)}$ | 1     | 1     | 1     | -3    | -3    | -3      | $\sqrt{24}$ |
| $S^{(8)}$ | 0.29  | 0.11  | -0.05 | 0.19  | -0.16 | 0       | 1     |
| $S^{(9)}$ | 0.25  | 0     | 0     | 0.25  | 0     | 0       | 1     |
| $S^{(10)}$ | 0.24  | -0.11 | 0.053 | 0.35  | 0.16  | 0       | 1     |

Table 2: Comparision of the branching ratios of the $Z'$ in the various models.

| Model  | $r_1$ | $r_2$ |
|--------|-------|-------|
| $S^{(0)}$ | 0.33  | 1.13  |
| $S^{(1)}$ | 3.00  | 0.60  |
| $S^{(2)}$ | 3.00  | 1.20  |
| $S^{(3)}$ | 3.00  | 4.80  |
| $S^{(4)}$ | 0.00  | 1.50  |
| $S^{(5)}$ | 0.30  | 0.75  |
| $S^{(6)}$ | 3.00  | 3.00  |
| $S^{(7)}$ | 0.30  | 0.30  |
| $S^{(8)}$ | 4.41  | 4.83  |
| $S^{(9)}$ | 3.00  | 3.00  |
| $S^{(10)}$ | 1.24  | 1.42  |
$R_1$ and $R_2$ for the various models discussed in the text.