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BRIEF REPORTS

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Comparison of discovery limits for extra Z bosons at future colliders

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We study and compare the discovery potential for heavy neutral gauge bosons (Z') at various e^+e^- and $p\overset{(-)}{p}$ colliders that are planned or have been proposed. Typical discovery limits are for the Tevatron $\sim$ 1 TeV, Di-Tevatron $\sim$ 2 TeV, LHC $\sim$ 4 TeV, LSGNA (a 60 TeV pp collider) $\sim$ 13 TeV while the e^+e^- discovery limits are $2-10\times\sqrt{s}$ with the large variation reflecting the model dependence of the limits. While both types of colliders have comparable discovery limits the hadron colliders are generally less dependent on the specific Z' model and provide more robust limits since the signal has little background. In contrast, discovery limits for e^+e^- limits are more model dependent and because they are based on indirect inferences of deviations from standard model predictions, they are more sensitive to systematic errors.

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Extended gauge symmetries and the associated heavy neutral gauge bosons, Z', are a feature of many extensions of the standard model such as grand unified theories, left-right symmetric models, and superstring theories. If a Z' were discovered it would have important implications for what lies beyond the standard model. It is therefore a useful exercise to study and compare the discovery reach for extra gauge bosons at the various facilities that will operate during the next decade (Tevatron and LEP200) and future facilities that are being planned or are under consideration for the period beyond (various Tevatron upgrades, LHC, the NLC e^+e^- collider, and LSGNA, a 60 TeV pp collider [1]). Such a comparison was made in earlier papers [2–4] but since those papers were published many new facilities have been proposed making it a useful exercise to update those analysis. In this Brief Report we examine and compare the discovery limits for extra neutral gauge bosons at high energy e^+e^-, and hadron colliders that are being built or have been proposed. The collider parameters are listed in Fig. 1. The goal is to compare the relative strengths and weaknesses of these facilities.

Quite a few models predicting extra gauge bosons exist in the literature. We will present discovery limits for several of these models which, although far from exhaustive, we feel form a representative set for the purposes of comparison. For the benefit of the reader we briefly describe the models we have chosen to study.

(i) Effective rank-5 models [5] originating from E_6 grand unified theories are conveniently labeled in terms of the decay chain $E_6\to \mathrm{SO}(10)\times \mathrm{U}(1)_\psi \to \mathrm{SU}(5)\times \mathrm{U}(1)_\chi\times \mathrm{U}(1)_\psi\to \mathrm{SM}\times \mathrm{U}(1)_{\theta_{E_6}}$. Thus, the Z' charges are given by linear combinations of the $U(1)_\chi$ and $U(1)_\psi$ charges resulting in the Z'-fermion couplings:

$$g_{Z^0}(g_{Z'}/g_{Z^0})(Q_\chi\cos\theta_{E_6}+Q_\psi\sin\theta_{E_6}), \tag{1}$$

where θ_{E_6} is a free parameter which lies in the range $-90^\circ\le\theta_{E_6}\le 90^\circ$, $(g_{Z'}/g_{Z^0})^2\le\frac{5}{3}\sin^2\theta_w$ (here we assume the equality), and $Q_\psi(Q_\chi)=[1,1,1]/2\sqrt{6}$ ($[-1,3,-5]/2\sqrt{10}$) for $[(u,d,u^c,e^c),\ (d^c,\nu,e^-),\ (N^c)]$, the left-handed fermions in the **10**, $\mathbf{\bar{5}}$, and **1** of SU(5) contained in the usual **16** of SO(10). Specific models of interest are model χ ($\theta_{E_6}=0^\circ$) corresponding to the extra Z' of SO(10), model ψ ($\theta_{E_6}=90^\circ$) corresponding to the extra Z' of E_6, and model η ($\theta_{E_6}=\arctan-\sqrt{5/3}$) corresponding to the extra Z' arising in some superstring theories.

(ii) The left-right symmetric model (LRM) extends the standard model gauge group to $\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R\times\mathrm{U}(1)$ [6]. The Z'-fermion coupling is given by

$$g_{Z^0}\frac{1}{\sqrt{\kappa-(1+\kappa)x_W}}[x_W T_{3L}+\kappa(1-x_W)T_{3R}-x_W Q] \tag{2}$$

with $0.55\le\kappa^2\equiv(g_R/g_L)^2\le 1-2$ [7], $T_{3L(R)}$ the isospin assignments of the fermions under $\mathrm{SU}(2)_{L(R)}$, Q the fermion electric charge, and $x_W=\sin\theta_W$. We assume $\kappa=1$ in our analysis which corresponds to strict left-right symmetry. Note that the T_{3L} assignments are the same as in the standard model while the values of T_{3R} for u_R, d_R, e_R, $\nu_R=\frac{1}{2}$, $-\frac{1}{2}$, $-\frac{1}{2}$, $\frac{1}{2}$ and are zero for left-handed doublets.

(iii) The alternative left-right symmetric model (ALRM) [8] originates from E_6 GUT's and is also based on the electroweak gauge group $\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R\times\mathrm{U}(1)$. Here the assignments for $T_{3L(R)}$ differ from that of the usual LRM for $\nu_{L,R}$, e_L, and d_R with $T_{3L(R)}(\nu_L)=\frac{1}{2}(-\frac{1}{2})$, $T_{3L(R)}(e_L)=-\frac{1}{2}(-\frac{1}{2})$, and $T_{3L(R)}(d_R)=0$. The LRM and ALRM have identical u-quark, e_R, and d_L couplings.

(iv) The "sequential" standard model (SSM) consists

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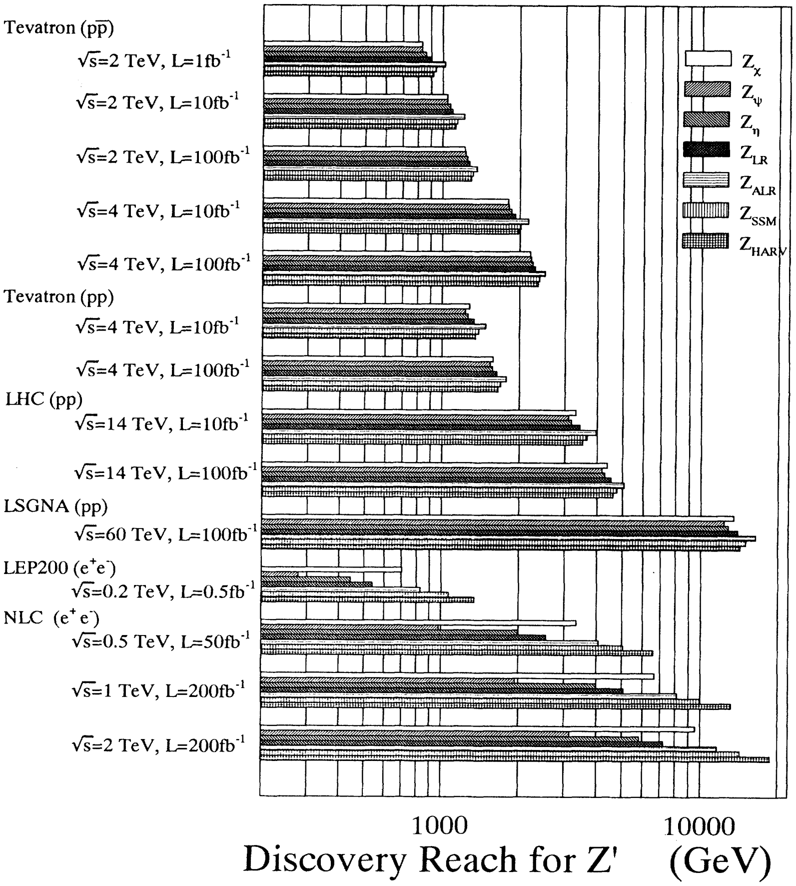

FIG. 1. Discovery limits for extra neutral gauge bosons (Z') for the models described in the text. The discovery limits at hadron colliders are based on ten events in the e^+e^- + $\mu^+\mu^-$ channels while those for e^+e^- colliders are 99% C.L. obtained from a χ^2 based on $\sigma(e^+e^- \to \mu^+\mu^-)$, $R^{\text{had}} = \sigma(e^+e^- \to \text{hadrons})/\sigma_0$, $A_{LR}^{\mu^+\mu^-}$, and A_{LR}^{had}. The integrated luminosities are based on a 10^7 sec year of running.

of a Z' which is just a heavy version of the SM Z^0 boson with identical couplings. Although it is not a realistic model it is often used as a benchmark and for purposes of comparison.

(iv) The Harvard model (HARV) [9] is based on the gauge group $SU(2)_l \times SU(2)_q \times U(1)_Y$, i.e., left-handed leptons (quarks) transform as doublets under $SU(2)_l$ [$SU(2)_q$] and singlets under $SU(2)_q$ [$SU(2)_l$], and right-handed fields are singlets under both groups. The Z'-fermion coupling takes the form

$$g_{Z^0} c_w (T_{3q}/\tan\phi - \tan\phi T_{3l}), \tag{3}$$

where $T_{3q(l)}$ is the third component of the $SU(2)_{q(l)}$ isospin, $c_w = \cos\theta_w$, and ϕ is a mixing parameter which lies in the range $0.22 \leq \sin\phi \leq 0.99$. We take $\sin\phi = 0.5$ in our calculations. The Z' is purely left handed in this model.

There are numerous other models predicting Z''s in the literature [10] but the subset described above has properties reasonably representative of the broad class of models, at least for the purposes of comparing discovery limits of high energy colliders.

Before proceeding to future colliders it is useful to list existing bounds as a benchmark against which to measure future experiments. Constraints can be placed on the existence of Z''s either indirectly from fits to high precision electroweak data [11, 12] or from direct searches at operating collider facilities [14].

There have been a number of fits to precision data [11, 12]. We list results from the Particle Data Group [13] in Table I. These results contain no assumptions on the Higgs sector.

The highest mass limits come from direct searches by the CDF experiment at the Tevatron [14]. The CDF limits are obtained by looking for high invariant mass lepton pairs that would result from a Z' being produced via the Drell-Yan mechanism [15] and subsequently decay to lepton pairs, $p\bar{p} \to Z' \to \ell^+\ell^-$. The most recent CDF 95% confidence level results based on $\mathcal{L}_{\text{int}} = 19.6\ \text{pb}^{-1}$ are listed in Table I.

Bounds on extra gauge bosons attainable from low energy neutral current precision measurements, measurements at the TRISTAN, LEP, and SLC e^+e^- colliders, as well as at the HERA ep collider have been surpassed by direct limits obtained at the Tevatron $p\bar{p}$ collider or

TABLE I. Current constraints on $M_{Z'}$ (in GeV) for typical models from direct production at the Tevatron ($\mathcal{L}_{\text{int}} = 19.6\ \text{pb}^{-1}$) [14], as well as indirect limits from a global electroweak analysis [13]. Both sets of limits are at 95% confidence level.

Model	Direct	Indirect
χ	425	321
ψ	415	160
η	440	182
LR	445	389
SSM	505	779

will be from future Tevatron upgrades. Thus, we will restrict our results to LEP200, proposed Tevatron upgrades, the LHC and LSGNA *pp* colliders, and the NLC high luminosity e^+e^- colliders.

A. Hadron colliders. The signal for a Z' at a hadron collider consists of Drell-Yan production of lepton pairs [15] with high invariant mass via $p\overset{(-)}{p} \to Z' \to l^+l^-$. The expressions for this process are given in Ref. [2]. We obtain the discovery limits for this process based on ten events in the $e^+e^- + \mu^+\mu^-$ channels using the EHLQ structure functions set I [16], taking $\alpha = 1/128.5$, $\sin^2\theta_w = 0.23$, and including a one-loop K-factor in the Z' production. We include a t quark of mass 174 GeV in the Z' decay width, and two-loop QCD radiative corrections, and one-loop QED radiative corrections in calculating the Z' width. Using different quark distribution functions results in a roughly 10% variation in the Z' cross sections [17] with the subsequent change in discovery limits. We note that including realistic detector efficiencies would lower these limits.

In our calculations we assumed that the Z' only decays into the three conventional fermion families. If other decay channels were possible, such as to exotic fermions filling out larger fermion representations or supersymmetric partners, the Z' width would be larger, lowering the discovery limits. On the other hand, if decays to exotic fermions were kinematically allowed, the discovery of exotic fermions would be an important discovery in itself. In addition, the $Z - Z'$ mixing is tightly constrained by electroweak precision measurements so we set it to zero without affecting our conclusions.

The discovery limits for various models at the colliders under discussion are summarized in Fig. 1. An important conclusion for these discovery limits is that these bounds are relatively insensitive to specific models. In addition, since they are based on a distinct signal with little background they are relatively robust limits. For the case of the Di-Tevatron ($\sqrt{s} = 4$ TeV), the $p\bar{p}$ option has a 50% higher discovery reach than the pp option for a given luminosity indicating that valence quark contributions to the Drell-Yan production process are still important at these energies.

B. e^+e^- colliders. At e^+e^- colliders discovery limits are indirect, being inferred from deviations from the standard model predictions due to interference between the Z' propagator and the γ and Z^0 propagators [18]. This is similar to PEP/PETRA seeing the standard model Z^0 as deviations from the predictions of QED. The basic process is $e^+e^- \to f\bar{f}$ where f could be leptons (e, μ, τ) or quarks (u, d, c, s, b). From the basic reactions a number of observables can be used to search for the effects of Z''s: The leptonic cross section, $\sigma(e^+e^- \to \mu^+\mu^-)$, the ratio of the hadronic to the QED point cross section, $R^{\rm had} = \sigma^{\rm had}/\sigma_0$, the leptonic forward-backward asymmetry, A^{ℓ}_{FB}, the leptonic longitudinal asymmetry, A^{ℓ}_{LR}, the hadronic longitudinal asymmetry, $A^{\rm had}_{LR}$, the forward-backward asymmetry for specific quark or lepton flavors, A^f_{FB}, the τ polarization asymmetry, $A^{\tau}_{\rm pol}$, and the polarized forward-backward asymmetry for specific fermion flavors, $A^f_{FB}({\rm pol})$. The indices $f = \ell,\ q,\ \ell = (e, \mu, \tau)$, $q = (c,\ b)$, and had = "sum over all hadrons" indicate the final state fermions. The expressions for these observables are given in Ref. [2].

For indirect limits, a 99% C.L. corresponds to a 2σ effect of one observable. Since 2σ deviations are not uncommon one must be cautious about how one obtains discovery limits for Z''s. One possibility for obtaining believable limits is to raise the deviation required to indicate the existence of a Z'. A second possibility is to combine several observables to obtain a χ^2 figure of merit. We follow the second approach here by including σ^l, $R^{\rm had}$, A_{LR}, and $A^{\rm had}_{LR}$ to obtain the 99% confidence limits in Fig. 1.[1]

One sees that the discovery limits obtained at e^+e^- colliders are as large or larger than those that can be obtained at hadron colliders. However, the bounds obtained are more model dependent than the bounds obtained at hadron colliders. For example, for model ψ, $C'_L = \pm C'_R$ so that either C'_V or $C'_A = 0$. For $\sqrt{s}$ sufficiently far away from the Z^0 pole deviations are dominated by $Z^0 - Z'$ and $\gamma - Z'$ interference which is proportional to $C_V^2 C'^2_V + 2C_V C_A C'_V C'_A + C_A^2 C'^2_A$. Since for the photon $C_A = 0$, when C'_V is also equal to 0 deviations from the standard model become small.

Because the bounds obtained at e^+e^- colliders are indirect, based on deviations from the standard model in precision measurements, they are sensitive to the experimental errors, both statistical and systematic. For example, reducing the LEP200 integrated luminosity from 500 to 250 pb^{-1} reduces the discovery limits by about 15% and reducing the NLC integrated luminosity from 50 to 10 fb^{-1} (200 to 50 fb^{-1}) for the 500 GeV (1 TeV) case reduces the discovery limit by about 33%. Including a 5% systematic error in cross section measurements and a 2% systematic error in asymmetries where systematic errors partially cancel [19] can lower the discovery limits significantly. The most extreme change is for the sequential standard model Z' which decreases by a factor of 2 at LEP200 and a factor of 3 at the NLC. Clearly, systematic errors will have to be kept under control for high precision measurements.

Finally, we note that we did not include radiative corrections in our results. In general this is an acceptable procedure since we are looking for small deviations from the standard model predictions and radiative corrections to Z' contributions will be a small correction to a small effect. However, QED bremsstrahlung corrections, in particular, initial state radiation, can give large contributions to the observables, altering the statistics we assumed. Since these are dependent on details of the detector we have left them out but note that they can alter the numerical values we show in Fig. 1.

Among the facilities operating in the upcoming decade the Tevatron continues to raise the limits on new heavy gauge bosons with limits up to the 700–900 GeV range for $\mathcal{L}_{\rm int} = 1$ fb^{-1}. Depending on the luminosity, LEP200

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[1] Although it is far from clear whether LEP200 will achieve any significant longitudinal polarization, $A^{\rm had}_{LR}$ only contributes significantly to the limit on Z_χ at LEP200 so that our results are not in general sensitive to the inclusion of this observable in the χ^2 at LEP200.

can achieve comparable limits for some of the models and could even surpass the Tevatron limits for the SSM and HARV models if the systematic errors are controlled.

In the longer term, hadron colliders such as Tevatron upgrades and the LHC as well as the NLC high luminosity e^+e^- collider, would significantly improve limits on the heavy gauge boson masses. For typical models such limits are in the 1–2 TeV region for the Tevatron upgrades, in the 4–5 TeV region for the LHC, and roughly $2 - 10 \times \sqrt{s}$ for the NLC with 50 fb^{-1}. The 60 TeV *pp* LSGNA collider could achieve discovery limits up to 15 TeV or so while a 2 TeV e^+e^- collider could achieve limits ranging from 3 TeV for Z_ψ to 20 TeV for Z_{HARV}. The limits obtained by hadron colliders are much less model dependent than those obtained by e^+e^- colliders.

The LHC and a high luminosity 500 GeV e^+e^- collider have discovery limits for a Z' which are comparable. However, limits obtained from the LHC are robust, in the sense that they are obtained from a direct measurement with little background. On the other hand, the limits obtained for the NLC are indirect, based on statistical deviations from the standard model and are thus more sensitive to having the systematic errors under control.

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