2.8 New Gauge Bosons and Exotic Particles

In many extensions to the Standard Model, in particular those involving an enlargement of the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group or compositeness, new particles are expected to exist beyond those associated with either supersymmetry or technicolor. The properties and signatures of exotic particles have recently been reviewed in [93] In almost all cases, these particles can be directly produced and have their properties analyzed in e^+e^- collisions given a sufficiently large center-of-mass energy. If such energies are not available, the indirect influence of the existence of many kinds of exotic particles can also be examined through precision measurements at the NLC.

Perhaps the most well-studied of all exotic particles is the new neutral gauge boson, Z', which is a basic ingredient of all theories with extended gauge sectors. (When the additional group factor is non-abelian, new charged gauge bosons, W', may also be present.) If such a particle exists and is accessible at the TeV scale, it is possible that it may first be directly produced via the Drell-Yan process at the LHC, provided the Z' couples to *both* quarks and leptons as it does in most models. If the Z' does not couple to leptons it cannot be produced at the NLC; in this case, searches at the LHC would also be difficult, since the effects of the Z' would have to be observed as perturbations of di-jet mass distributions. If the Z' couples only to leptons, then the NLC provides the unique means to study it.

It is possible that a Z', though it exists, may not be seen at the LHC due to its mass and/or the nature of its couplings to fermions. In this case the NLC can extend the search reach for some models; in addition the NLC may be able to determine both the mass and couplings of the Z'. A 'lucky' scenario would be one where the mass of the Z' is less than the NLC center-of-mass energy; in this case, by sitting on-resonance and repeating the LEP/SLC experimental program, we can determine all of the Z''s couplings to fermions. A much more likely scenario is that $M_{Z'} > \sqrt{s}$ so that deviations in the cross section and associated asymmetries for various flavors could be used to look for *indirect* Z' effects in a manner similar to the observation of the Z at PEP, PETRA, and TRISTAN below the resonance. In some cases, this indirect 'reach' can be as large as $M_{Z'} \simeq 10\sqrt{s}$. Figure 2.45 shows a comparison of the indirect Z' search capability at LEP and the NLC as well as the direct production reach at the Tevatron and LHC for several extended models.

If a Z' exists, we would like to know how it couples to the various flavors so that we can identify the correct extended gauge structure. If the Z' is seen at the LHC and its mass is not much larger than about 1 TeV, several analyses have shown [93] that the LHC and a $\sqrt{s} = 500$ GeV NLC will nicely complement each other in extracting fermion coupling information. If the Z' is more massive, then LHC cannot perform coupling analyses using any of the presently available techniques either due to backgrounds or statistical limitations. However, if the mass of the Z' is less than about 2 TeV, then the NLC running in the $\sqrt{s} = 0.5 - 1$ TeV range can obtain significant coupling information even if the Z' is missed by the LHC and its mass is *a priori* unknown. (This value goes up to $M_{Z'} \simeq 3$ TeV if $\sqrt{s} = 1.5$ TeV energies are available.) A representative example of such an analysis is shown in Fig. 2.46 [94]. Similar results can be obtained for different values of the input parameters as well

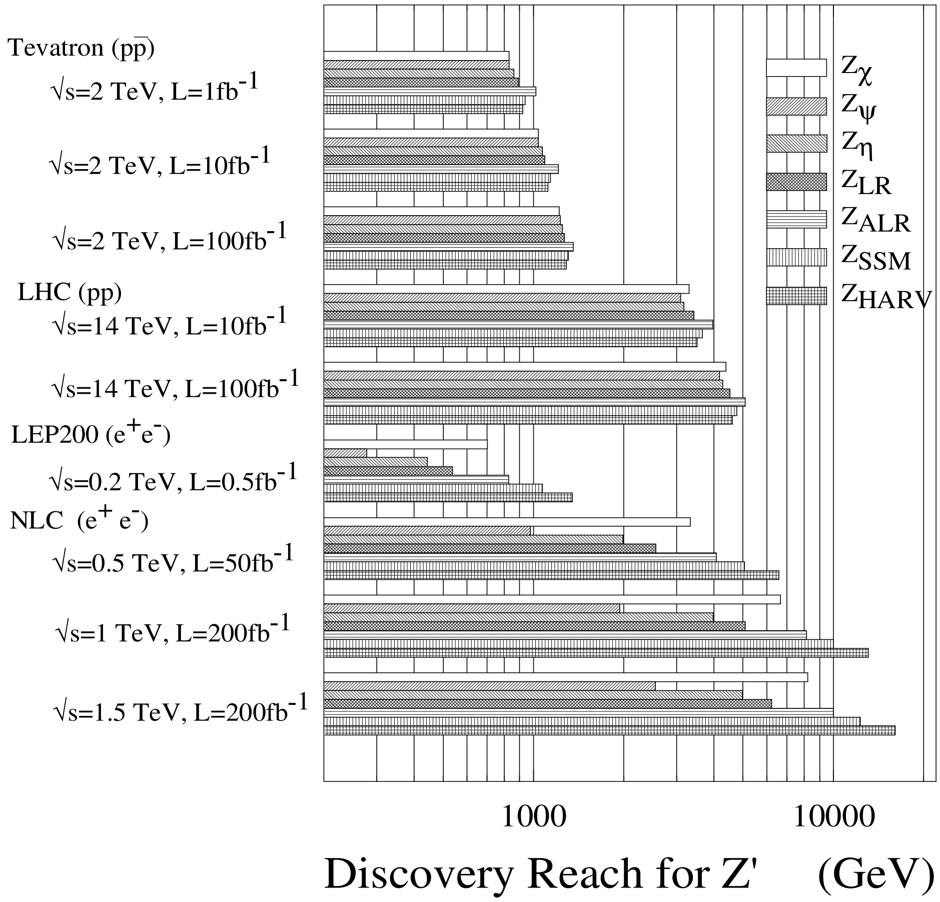

Figure 2.45: Tevatron and LHC bounds are based on 10 events in the $e^+e^- + \mu^+\mu^-$ channels; decays to SM final states only is assumed. LEP and NLC bounds are 99% CL using the observables σ_l, $R^{\rm had}$, A^l_{LR} and $A^{\rm had}_{LR}$.

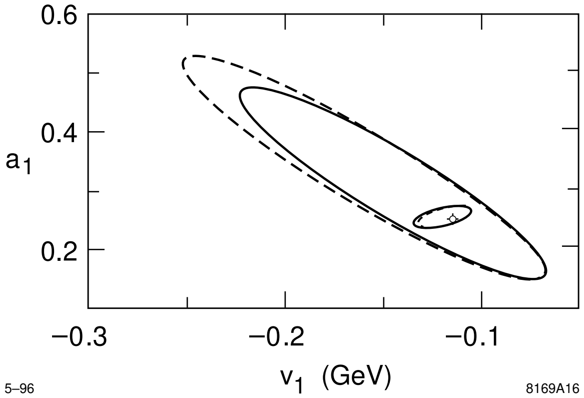

Figure 2.46: Extracted leptonic couplings of a 1.53 TeV Z' at the NLC, at 95% CL, using data at 0.5(70 fb^{-1}), 0.75(100 fb^{-1}), and 1 TeV(150 fb^{-1}). All leptonic observables were used and generation independence was assumed. The large ovals are applicable when $M_{Z'}$ is unknown a priori and must be obtained from the fit; the solid (dashed) curve corresponds to electron beam polarization $P = 90(80)\%$. The small ovals correspond to the scenario in which $M_{Z'}$ is known (for example, from the LHC); the two curves represent the same two cases. The dot represents the input values of the couplings.

as for the other fermion flavors (although fewer observables are available), thus allowing the structure of the extended gauge model to be determined by comparing the extracted values of these couplings with specific model predictions.

In generic Standard Model extensions, the new gauge bosons are usually accompanied by additional fermionic and/or bosonic degrees of freedom the most common of which are either vector-like or singlets with respect to the Standard Model electroweak group. In addition to new quarks and leptons, some of these particles, such as leptoquarks (LQs) and diquarks, may have atypical B and L number assignments. The production and decay of both spin-0 and spin-1 LQs at ep, e^+e^-, and $pp/p\overline{p}$ colliders has been studied by many groups [93, 94]. Allowing for both helicities in their interactions with ordinary quarks and leptons there are 14 possible species of LQs with reasonably strict constraints applicable to their intergenerational couplings. (Low energy constraints also force LQ couplings to be chiral.) At ep colliders, LQ production rates are proportional to the squares of unknown Yukawa couplings so they may easily be missed. By contrast, at hadron colliders, the cross section is the same for all LQ types of a given spin but the signal depends upon how the LQ decays. Thus it will not be possible at hadron colliders to uniquely determine which LQ type is being produced. On the other hand, at e^+e^- machines, the production cross sections and asymmetries are determined solely by the LQ electroweak quantum numbers and spin. Several studies have shown [93] that the LQ species can found and identified in both e^+e^- and γe collisions. In the first case the 'ID reach' is $\simeq 0.45\sqrt{s}$; this improves to $\simeq 0.8\sqrt{s}$ in the γe mode if the Yukawa couplings are of order electromagnetic strength. In a manner similar to the Z' searches discussed above, t and u channel LQ exchange can be probed for indirectly via the process $e^+e^- \to q\overline{q}$ provided the Yukawa couplings are sufficiently large. For Yukawa couplings of electromagnetic strength, the reach can exceed 6 TeV at the NLC.

Table 2.11 shows a comparison of the search capabilities of LEPII, the Tevatron, the LHC and NLC for a number of different exotic particles. As is clear from the above, great care should be exercised when comparing the capabilities of different machines to find and explore the properties of exotics. The results in the table for e^+e^- colliders are indirect bounds for Z''s but represent direct production limits at hadron colliders. Limits on all other particles in the case of e^+e^- colliders are for direct production except where noted. It is important to remember that in many other cases e^+e^- colliders provide important indirect bounds as in both the Z' and LQ examples. For a W' in the Left-Right Symmetric Model (W_R), a number of additional assumptions are required before search reaches can be quoted for hadron colliders; these are: (i) equal left- and right-handed gauge couplings and CKM matrices, (ii) right-handed neutrinos appear only as missing p_t, (iii) only Standard Model final states are accessible in decays. The possibility of surrendering any or all of these assumptions has been analyzed and was found to lead to downward, potentially drastic, alterations in search expectations via the Drell-Yan process. Searches for new quarks at hadron colliders are also subject to decay mode assumptions and are species dependent. In some cases, for example, flavor changing neutral current decays are at least as important as the more conventional charged current ones.

Table 2.11: Limits on various exotic particles, in GeV. Run II is 2 fb^{-1} at 2 TeV; NLC is 200 fb^{-1}; LHC is 14 TeV and 100 fb^{-1}. Z' limits at hadron colliders assume only SM final states are accessible. Z' limits at e^+e^- colliders are indirect. * is the Tevatron limit assuming the standard W' search assumptions. † limit applies when none of the conditions in text are fulfilled; †† result using Z' bound and LR model relationships. $^+$ is from single production. The limit is for first generation spin-0,1 LQs at HERA and the Tevatron including Run 1b estimate; similar numbers will hold for the 2nd generation case at hadron colliders. In the dilepton, diquark and LQ cases, EM strength Yukawas are assumed. $^{++}$ are indirect limits from $e^+e^- \to q\bar{q}$ with these EM strength Yukawas. ** combines several search modes. ‡ is from $e^+e^- \to 2\gamma$. * implies the limit is highly decay mode dependent. The value of '60' as the present limit for the last four entries reflect approximate LEP1.4 null searches. New lepton limits are for both charged and neutral cases. Many entries are estimates.

Particle	Present	LEPII	TeV(Run II)	LHC	NLC(1 TeV)
Z'_{SM}	650	1070	1020	4760	10000
Z'_χ	425	703	910	4380	6670
Z'_ψ	415	278	910	4180	1940
Z'_η	440	443	940	4280	3980
$Z'_{LR}(\kappa=1)$	445	538	970	4520	5090
Z'_{ALRM}	420	820	1100	5080	8150
W_R	$720^*,300^\dagger$	90	$990,400^\dagger$	$5310,1500^{\dagger\dagger}$	800^+
LQ(spin-0)	180	$90,160^+,700^{++}$	$300,400^{++}$	$1400,1700^{++}$	$500,900^+,6000^{++}$
LQ(spin-1)	300	$90,160^+$	$440,500^{++}$	$2200,2500^{++}$	$500,900^+,?^{++}$
Axigluon	200-930	150?	1160	5000?	800
E_6 diquark	280-350	90	200-570	5000	500
q^*	$90\text{-}750^{**}$	$90,180^+$	820	5000-6000?	$500,900^+$
e^*	$60,127^\ddagger$	$90,180?^+$	500?	4000	$500,900^+$
new leptons	60	90	??	1000	500
new quarks	60	90	*	*	500
dileptons	60	90	–	–	900^+