

Extended Gauge Sectors at Multi-TeV e^+e^- Colliders

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We give a brief overview of searches at TeV e^+e^- colliders for new particles that arise in models with extended gauge sectors. We concentrate on some recent developments in W' searches and on leptoquark searches. We also briefly mention Z' searches.

I. INTRODUCTION

There are many models that approximate the standard model (SM) at present collider energies but that have a much richer particle spectrum above 100 GeV. A class of models that extends the SM in a natural way are extended gauge sectors [1–4]. These come in different varieties; Grand Unified Theories (GUTS) such as E_6 and $SO(10)$ (and their Supersymmetric versions) in which the subgroups of the SM are embedded into one larger group, of which an interesting variant is the Left-Right symmetric model embedded in a GUT, $E_6/SO(10) \rightarrow SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$ [4]. There are also numerous non-GUT models of extended gauge sector in the literature; the Un-unified model, horizontal gauge models, and topcolour, to name but a few. The point is that numerous possibilities exist that give rise to rich phenomenologies. To distinguish among the many possibilities and reveal the underlying theory we will need to elucidate the TeV particle spectrum.

There are many new types of particles; Extra Z' 's and W' 's bosons [2, 5–7], New fermions of various types [3] such as mirror fermions which are $SU(2)_R$ doublets and $SU(2)_L$ singlets, vector fermions which are both $SU(2)_R$ and $SU(2)_L$ doublets, and $SU(2)$ singlets like massive neutrinos, and Leptoquarks, Diquarks and Bileptons. Finally, an extended Higgs sector is probably the most obvious extension of the SM. Establishing any extension of the standard will require two steps; Discovery and Identification. For the former it is necessary to identify a signal that can be distinguished from background. For identification there are many tools that can be used — cross sections, angular distributions, decay signatures such as widths and branching ratios, and polarization observables.

It will not be possible to discuss these topics in detail in this brief contribution so I will limit myself to brief comments on W' 's and LQ 's and refer the interested reader to more detailed accounts elsewhere [1–5].

II. EXTRA GAUGE BOSONS

Extra gauge bosons, both charged (W') and/or neutral (Z'), are a feature of many models of physics beyond the Standard Model (SM) [2, 5]. A few models that have received attention recently and that we consider are the Left-Right symmetric model (LRM) based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, which has right-handed charged currents and restores parity at high energy, the Un-Unified model (UUM) based on the gauge group $SU(2)_q \times SU(2)_l \times U(1)_Y$ where the quarks and leptons each transform under their own $SU(2)$, a Third Family Model (3FM) based on the gauge group $SU(2)_h \times SU(2)_l \times U(1)_Y$ where the quarks and leptons of the third (heavy) family transform under a separate group and the KK model (KK) which contains the Kaluza-Klein excitations of the SM gauge bosons that are a possible consequence of theories with large extra dimensions. We also consider a W' with SM couplings (SSM). In studying extra gauge bosons, we are interested in two issues; the sensitivity to Z' and W' discovery and the measurement of their couplings to determine the underlying theory.

A. Z' Search and Identification

In e^+e^- collisions, the Z' contributes to the cross section via an s-channel propagator. For $\sqrt{s} = M_{Z'}$ the resonance cross section is rather large, several orders of magnitude above the SM cross section, and the existence

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TABLE I: W' discovery limits in TeV. For $e\gamma \rightarrow \nu q + X$ the backscattered laser photon spectrum was used.

	$\sqrt{s} = 0.5 \text{ TeV}, L_{int} = 500 \text{ fb}^{-1}$				$\sqrt{s} = 1 \text{ TeV}, L_{int} = 500 \text{ fb}^{-1}$			
	$e^+e^- \rightarrow \nu\bar{\nu}\gamma$		$e\gamma \rightarrow \nu q + X$		$e^+e^- \rightarrow \nu\bar{\nu}\gamma$		$e\gamma \rightarrow \nu q + X$	
Model	no syst.	syst.	no syst.	syst.	no syst.	syst.	no syst.	syst.
SSM W'	4.3	1.7	4.1	2.6	5.3	2.2	5.8	4.2
LRM	1.2	0.6	0.8	0.6	1.6	1.1	1.2	1.1
UUM	2.1	0.6	4.1	2.6	2.5	1.1	5.8	4.2
3FM	2.3	0.8	3.1	1.9	2.7	1.1	4.4	3.1
KK	4.6	1.8	5.7	3.6	5.8	2.2	8.3	6.0

of a Z' would be obvious. In this case detailed studies could be performed and the properties of the Z' could be extracted to high precision. Off resonance, the Z' propagator interferes with that of the γ and SM Z^0 leading to deviations from the SM expectations. By combining the numerous available observables, a sensitivity to Z' 's with masses several times \sqrt{s} can be achieved. Depending on the mass of the Z' one can also constrain its properties, such as its couplings to different fermions. Numerous studies exist in the literature [2, 5–7] and as we have nothing new to add at this point, we will not discuss Z' 's further.

B. W' Search and Identification

Until recently, W' searches in the literature consisted of the W pair production process $e^+e^- \rightarrow W_R^+W_R^-$ and single W production in $e^\pm\gamma \rightarrow W_R^\pm N$. In both cases the search limits are close to the kinematic limit which is $\sim \sqrt{s}/2$ in the former case and $\sqrt{s_{e\gamma}}$ in the latter case. The exact limits will depend on the parameters of the model.

Recently, it has been demonstrated that limits greater than \sqrt{s} can be achieved by considering the interference effects from t-channel W' exchange in the processes $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ and $e\gamma \rightarrow \nu q + X$. Here we give a brief summary of recent work on the subject and refer the interested reader to the more detailed presentations of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in Ref. [8] and of the process $e\gamma \rightarrow \nu q + X$ in Ref. [9].

In the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ [8], the signal is an energetic photon. The kinematic variables of interest are the photon's energy, E_γ , and its angle relative to the incident electron, θ_γ , both defined in the e^+e^- centre-of-mass frame. To take into account finite detector acceptance we imposed the constraints on the kinematic variables: $E_\gamma \geq 10 \text{ GeV}$ and $10^\circ \leq \theta_\gamma \leq 170^\circ$. Several backgrounds should be taken into account. The most dangerous is radiative Bhabba-scatter with the e^+ and e^- go undetected down the beam. This can be eliminated by restricting the photon's transverse momentum to $p_T^\gamma > \sqrt{s} \sin \theta_\gamma \sin \theta_v / (\sin \theta_\gamma + \sin \theta_v)$ where $\theta_v = 25 \text{ mrad}$ and is the minimum angle to which the veto detectors may observe electrons or positrons. There are also higher order backgrounds which cannot be suppressed, such as $e^+e^- \rightarrow \nu\bar{\nu}\nu'\bar{\nu}'\gamma$, which must be included in the SM cross section but are fully calculable. The low E_γ region is most sensitive to the Z' . The best limits are obtained by implementing a kinematic cut on E_γ to eliminate the radiative return to the SM Z^0 -pole. The statistical significance can be increased by binning the E_γ distribution and calculating the χ^2 . The limits obtained by binning the E_γ distribution and calculating the χ^2 with and without a 2% systematic error added in quadrature with the statistical error are given in Table I. The limits were obtained using e_L^- except for the LRM where e_R^- was used. In general, the limits are highly model and machine dependent.

W' couplings can also be constrained using $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. If a W' exists such that $M_{W'}$ is much lower than the search limit, we would expect it to be discovered at the LHC in which case we would want to measure its couplings. In Fig. 1 we show constraints for W' couplings that could be obtained using $e^+e^- \rightarrow \nu\bar{\nu}\gamma$.

The process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ is also sensitive to Z' 's. Although this process is not as sensitive as other final states to Z' 's, it offers a means of measuring the $Z' - \nu\bar{\nu}$ coupling which could be useful in determining the Z' 's origin [8].

The sensitivity of the process $e\gamma \rightarrow \nu q + X$ to W' 's was also studied [9] where the W' 's enter via t-channel exchange. We considered two cases; the backscattered laser case and the Weizacker-Williams photon distribution which applies to $e^+e^- \rightarrow e^+\nu q + X$. Starting with the subprocess $e\gamma \rightarrow \nu q\bar{q}$ the W' contributions can be enhanced by imposing the kinematic cut that either the q or \bar{q} is collinear to the beam axis. In this kinematic region the process $e\gamma \rightarrow \nu q\bar{q}$ is approximated quite well by the simpler process $eq \rightarrow \nu q'$ where the quark is described by the quark parton content of the photon, the so-called resolved photon approximation. The process $eq \rightarrow \nu q'$ was used to obtain limits as it is computationally much faster and free of sensitivity to the quark masses and collinearity cuts.

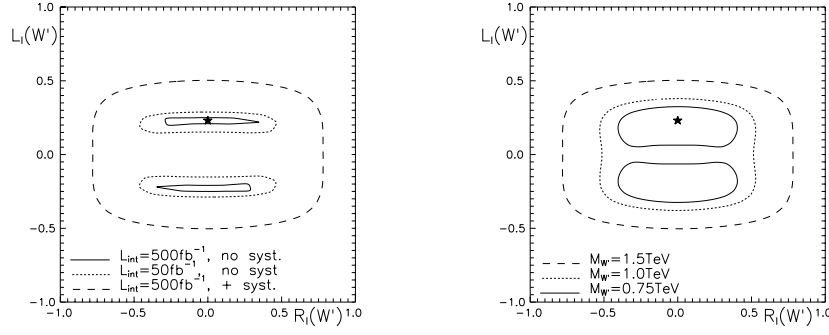


FIG. 1: 95% C.L. constraints on $L_f(W) = C_L^{W_i} g / (2\sqrt{2})$ and similarly for $R_f(W)$ based on σ and A_{LR} for $\sqrt{s} = 0.5$ TeV. We take 90% electron and, where indicated, 60% positron polarization. The couplings of the assumed model, SSM W' , is indicated with a star. (a) $M_{W'} = 1.5$ TeV for integrated luminosities of $L_{\text{int}} = 50$ and 500 fb^{-1} with and without a 2% systematic error added in quadrature with the statistical error. (b) Limits for $M_{W'} = 0.75, 1.0$, and 1.5 TeV taking $L_{\text{int}} = 500 \text{ fb}^{-1}$. A systematic error of 2% (1%) is included for σ (A_{LR}).

As usual, kinematic cuts were included to reflect finite detector acceptance; the angle of the outgoing $q(\bar{q})$ was restricted to the range $10^\circ \leq \theta_{q(\bar{q})} \leq 170^\circ$. We included u, d, s , and c -quark contributions and used the leading order GRV distributions[10]. The search limits are fairly insensitive to the specific choice of distribution. The kinematic variable most sensitive to W' is the p_{T_q} distribution. σ_R was only found to be sensitive to the LR model but even small e_L pollution swamps σ_R .

As always, it is necessary to consider and eliminate serious backgrounds. The dominant backgrounds are two jet final states comprised of $\gamma\gamma \rightarrow q\bar{q}$, the once resolved reactions $\gamma g \rightarrow q\bar{q}$ and $\gamma q \rightarrow gq$, and the twice resolved reactions $gg \rightarrow q\bar{q}$, $q\bar{q} \rightarrow q\bar{q}$, $qg \rightarrow qg$, $gg \rightarrow gg$, $qq \rightarrow qq$..., where one of the jets goes down the beam pipe and is not observed. These backgrounds can be effectively eliminated by imposing the constraint $p_{T_q} > 40, 75, 100$ GeV for $\sqrt{s} = 0.5, 1.0$, and 1.5 TeV, respectively. Discovery limits were obtained by binning the p_{T_q} distribution and calculating the χ^2 for an assumed integrated luminosity. As before, a 2% systematic error was included in quadrature with the statistical error. The discovery limits using the backscattered laser spectrum are given in Table I. In all cases, the limits from the backscattered laser are better than those from the Weizsacker Williams process due to the harder photon spectrum of the former. Again, the limits are given for unpolarized beams. Electron beam polarization was not found to yield significantly improved results for this process.

The limits from the process $e\gamma \rightarrow \nu q + X$ compare favourably with those from $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in all models other than the LRM. In that case, the limits are comparable for the two processes. The LHC is expected to detect W' 's up to a mass of about 5.9 TeV [11], although that number is also highly model dependent. Hence the process $e\gamma \rightarrow \nu q + X$ shows promise even compared with the reach of the LHC. Therefore, a more detailed consideration of the exact process, rather than the resolved photon approximation given here, and including radiative corrections, is motivated.

In Fig. 2 we show the constraints on W' couplings that can be obtained from the process $e\gamma \rightarrow \nu q + X$. We assume that a W' has been discovered elsewhere and its mass is known. The contours are based on the p_{T_q} distribution.

III. LEPTOQUARKS

Leptoquarks appear in many theories, from GUTS to technicolour to composite models. Leptoquarks are colour triplets or antitriplets that carry both baryon and lepton quantum numbers and can have either spin 0 or 1. According to the Buchmuller-Ruckl-Wyler classification there are 10 distinct types of LQ's. At the LHC, with $L_{\text{int}} = 100 \text{ fb}^{-1}$, LQ's can be discovered up to $M_{LQ} = 1.4$ TeV and 2.2 TeV for scalar and vector LQ's respectively.

We consider LQ production via the quark content of the photon in $e\gamma$ collisions [12]. The quark fuses with the electron to produce a LQ and the $\sigma(eq \rightarrow LQ)$ cross section is convoluted with the quark distribution inside the photon which is subsequently convoluted with the photon distribution function. Cross sections for LQ production for the $e\gamma$ case using a backscattered laser and for the e^+e^- case with Weizsacker-Williams photons are shown in Fig. 3. In addition to direct production one can also obtain indirect limits via t-channel LQ exchange in $e^+e^- \rightarrow q\bar{q}$ [13].

For the luminosities envisaged at future e^+e^- colliders such as the LC and CLIC, LQ's can be discovered

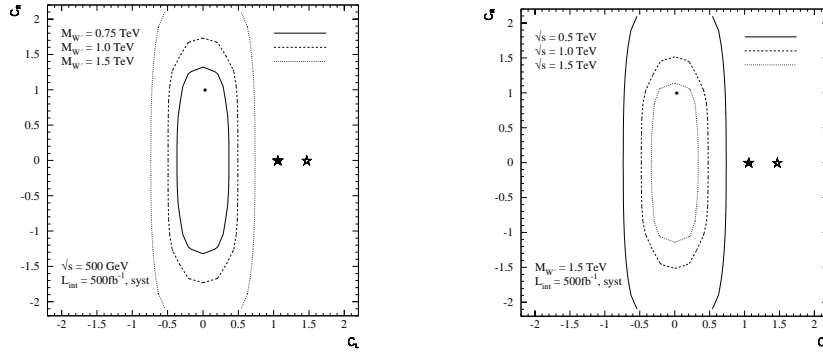


FIG. 2: 95% C.L. constraints on W' couplings from the process $e\gamma \rightarrow \nu q + X$ with a backscattered laser spectrum assuming the SM and using the $d\sigma/dp_{T_q}$ with a 2% systematic error. We have taken $C_{L(R)}^e = C_{L(R)}^q$ which is satisfied in many models. The SSM, LRM and the KK model are indicated by a full star, a dot and an open star, respectively. (a) For different values of $M_{W'}$ with $\sqrt{s} = 500$ GeV. (b) For different values of \sqrt{s} with $M_{W'} = 1.5$ TeV.

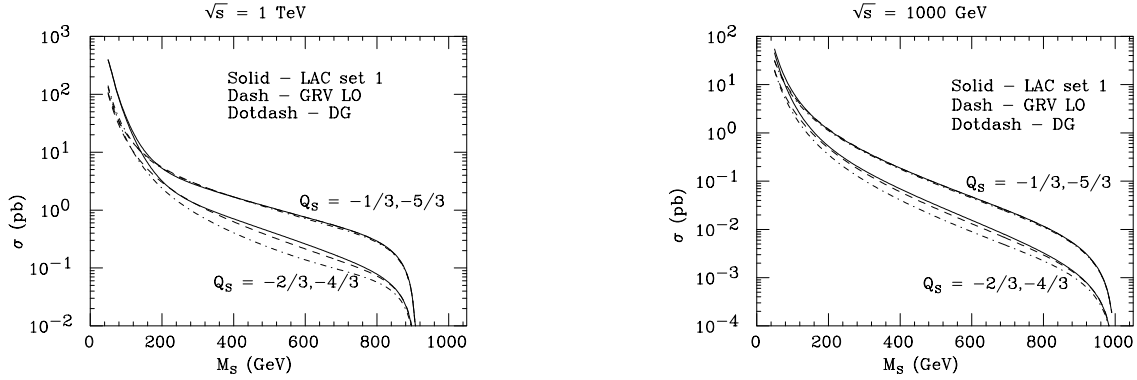


FIG. 3: The cross sections for leptoquark production due to resolved photon contributions in $e\gamma$ collisions from a $\sqrt{s} = 1$ TeV e^+e^- collider. (a) The photon beam is due to laser backscattering in the e^+e^- collider. (b) The photon distribution is given by the Weizsäcker-Williams effective photon distribution.

almost up to the kinematic limit. Discovery limits are given in Table II. The limits for $q = -1/3$ and $-5/3$ LQ's are slightly larger than for $q = -4/3$ and $-2/3$ LQ's because of the higher u-type quark content of the photon compared to the d-type quark content. The vector LQ's have slightly higher limits compared to scalar LQ's because of vector vs scalar couplings to fermions. Finally, it turns out that for some cases e^+e^- colliders yield higher limits than $e\gamma$ colliders because for $e\gamma$ colliders the maximum $\sqrt{s_{e\gamma}}$ is less than that of an e^+e^- collider and the high luminosities more than compensate for the softer photon spectrum. It should be noted that this search strategy has been employed by the OPAL [14] and DELPHI [15] collaborations to obtain LQ limits.

If leptoquarks were discovered their production in $e\gamma$ collisions could be used to identify them which would be crucial for determining their theoretical origin. Their decay distributions can be used to determine whether

TABLE II: Leptoquark discovery limits for e^+e^- and $e\gamma$ colliders. The discovery limits are based on the production of 100 LQ's for the centre of mass energies and integrated luminosities given in columns one and two. The results were obtained using the GRV distribution functions.

		e^+e^- Colliders				$e\gamma$ Colliders			
\sqrt{s}	L	Scalar		Vector		Scalar		Vector	
(TeV)	(fb $^{-1}$)	(-1/3, -5/3)	(-4/3, -2/3)	(-1/3, -5/3)	(-4/3, -2/3)	(-1/3, -5/3)	(-4/3, -2/3)	(-1/3, -5/3)	(-4/3, -2/3)
0.5	50	490	470	490	480	450	450	450	440
1.0	200	980	940	980	970	900	900	910	910
1.5	200	1440	1340	1470	1410	1360	1360	1360	1360
5.0	1000	4700	4200	4800	4500	4500	4400	4500	4500

they are scalar or vector and electron polarization asymmetries can be used to determine the chirality of their couplings to fermions. Finally, the cross sections of the different LQ's are different enough that they can be separated on this basis to relatively high masses.

IV. SUMMARY AND OUTLOOK

Extended gauge sectors give rise to a very rich phenomenology. In this brief report we only touched the surface, neglecting many important topics such as extra fermions, bileptons and diquarks.

A considerable body of work exists on Z' 's and a large effort continues to be applied to the topic. The exclusion limits that can be obtained at TeV linear colliders are similar to, or exceed, the discovery limits of the LHC. If a Z' is discovered at the LHC, the LC would be an important tool for its identification. Recently, indirect effects of W' 's in e^+e^- and $e\gamma$ collisions have also been studied and it was found that measurements at e^+e^- colliders are sensitive to W' bosons considerably higher in mass than their centre-of-mass energy. For some models, the reach that can be obtained at a LC is competitive with that of the LHC, particularly in the case of the process $e\gamma \rightarrow \nu q + X$. If a W' were discovered at the LHC the LC would be an important tool in measuring their properties. However, there have only been a few such studies and there is room for new ideas. The studies of both Z' 's and W' 's need to be updated to include the energies relevant to CLIC and to take into account the higher luminosities now envisaged. Leptoquarks could be discovered for masses up to almost \sqrt{s} . If LQ's are discovered, $e\gamma$ could make significant contributions to their understanding.

To conclude, high energy e^+e^- colliders have considerable potential for the discovery of the particles expected in extended gauge theories. But more than that, they could play a crucial role in measuring the properties of new particles, and hence unravel the underlying theory.

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