Discovery and Identification of $W'$ Bosons in $e\gamma \rightarrow \nu q + X$

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Abstract

We examine the sensitivity of the process $e\gamma \rightarrow \nu q + X$ to $W'$ bosons which arise in various extensions of the standard model. We consider photon spectra from both the Weizsäcker-Williams process and from a backscattered laser. The process is found to be sensitive to $W'$ masses up to several TeV, depending on the model, the center of mass energy, the integrated luminosity, and assumptions regarding systematic errors. If extra gauge bosons were discovered first in other experiments, the process could also be used to measure $W'$ couplings. This measurement would provide information that could be used to unravel the underlying theory, complementary to measurements at
the Large Hadron Collider.

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I. INTRODUCTION

Extra gauge bosons, both charged ($W'$) and/or neutral ($Z'$), arise in many models of physics beyond the Standard Model (SM) \[1\]–\[3\]. Examples include extended gauge theories such as grand unified theories \[4\] and Left-Right symmetric models \[5\] along with the corresponding supersymmetric models, and other models such as those with finite size extra dimensions \[6\]. To elucidate what physics lies beyond the Standard Model it is necessary to search for manifestations of that new physics with respect to the predicted particle content. Such searches are a feature of ongoing collider experiments and the focus of future experiments. The discovery of new particles would provide definitive evidence for physics beyond the Standard Model and, in particular, the discovery of new gauge bosons would indicate that the standard model gauge group was in need of extension. There is a considerable literature on $Z'$ searches. In this paper we concentrate on $W'$ searches, for which less work has been done.

Limits have been placed on the existence of new gauge bosons through indirect searches based on the deviations from the SM they would produce in precision electroweak measurements. For instance, indirect limits from $\mu$-decay constrain the left-right model $W'$ to $M_{WR} \gtrsim 550$ GeV \[7\]. A more severe constraint arises from $K_L - K_S$ mass-splitting which gives $M_{WR} \gtrsim 1.6$ TeV \[8\], assuming equal coupling constants for the two $SU(2)$ gauge groups.

New gauge boson searches at hadron colliders consider their direct production via the Drell-Yan process and their subsequent decay to lepton pairs. For $W'$ bosons, decays to hadronic jets are sometimes also considered. The present bounds on $W'$ bosons from the CDF and D0 collaborations at the Tevatron $p\bar{p}$ collider at Fermilab are $M_{W'} \gtrsim 720$ GeV \[8\]. The search reach is expected to increase by $\sim 300$ GeV with 1 fb$^{-1}$ of luminosity \[9\]. The Large Hadron Collider is expected to be able to discover $W'$s up to masses of $\sim 5.9$ TeV \[9\]. These $W'$ limits assume SM strength couplings and decay into a light stable neutrino which is registered in the detector as missing $E_T$. They can be seriously degraded by loosening the
model assumptions.

There are few studies of indirect searches for $W'$ bosons at $e^+e^-$ colliders. In a recent paper we examined the sensitivity of the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ to $W'$ and $Z'$ bosons [10] (see also [11]). We found it was sensitive to $W'$'s up to several TeV in mass, depending on the model, the centre of mass energy, and the integrated luminosity.

Clearly, if deviations from the standard model are observed, it will take many different measurements to disentangle the nature of the new physics responsible. In this paper we present the results of a study of the sensitivity of the process $e\gamma \rightarrow \nu q + X$ to $W'$ bosons. We find that this process is sensitive to $W'$ masses up to several TeV, in many cases more sensitive than the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. In particular, we find that it is far more sensitive to the Un-Unified model (UUM) [12]. The process $e\gamma \rightarrow \nu q + X$ is sensitive to both the quark and lepton couplings to the $W'$, and, furthermore, does not have the complication of contributions from $Z'$ bosons. It can therefore contribute information that complements that obtained from $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, helping to build a picture of the underlying physics.

We consider various extended electroweak models. The first is the Left-Right symmetric model [5] based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ which has right-handed charged currents. The second is the Un-Unified model [12] which is 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 $SU(2)$. The final type of model, denoted as the KK model, contains the Kaluza-Klein excitations of the SM gauge bosons which are a possible consequence of theories with large extra dimensions [6]. We give the relevant couplings for those models in Section II but refer the reader to the literature for more details. Additionally, we study discovery limits for a $W'$ boson with SM couplings. Although it is not a realistic model, this so-called Sequential Standard Model (SSM) has been adopted as a benchmark to compare the discovery reach of different processes.

We will find that the process $e\gamma \rightarrow \nu q + X$ can indeed extend the discovery reach for $W'$'s significantly beyond $\sqrt{s}$, with the exact limit depending on the specific model. Additionally, if extra gauge bosons are discovered which are not overly massive, the process considered
here could be used to measure their couplings. This would be crucial for determining the origins of the $W'$. As such, it would play an important complementary role to the LHC studies.

In the next section, we describe the details of our calculations. The resulting $W'$ discovery limits and projected sensitivities for $W'$ couplings are given in Section III. We conclude with some final comments.

II. CALCULATIONS AND RESULTS

We are interested in the process

$$e\gamma \rightarrow \nu q\bar{q}$$

(1)

where the photon arises from either a backscattered laser \[13\] or from Weizsäcker Williams bremsstrahlung \[14\] from the incident $e^+(\sim)$ beam. The relevant Feynman diagrams are given in Fig. 1. In this process it is diagrams 1(a) and 1(b) with the $W'$ exchanged in the t-channel which are most sensitive to the effects of the $W'$. The contribution of these diagrams can be enhanced by imposing the kinematic cut that one of either the $q$ or the $\bar{q}$ 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

$$eq \rightarrow \nu q'$$

(2)

shown in Fig. 2, where the quark is described by the quark parton content of the photon, the so-called resolved photon approximation \[15-17\]. This has been verified numerically by comparing kinematic distributions of the outgoing quark calculated using both process \[1\] and process \[2\] for a given detector acceptance where the outgoing $q$ ($\bar{q}$) is constrained to $|\cos \theta_{q(q)}| \leq \cos \theta_{cut}$ and in addition for process \[1\] $|\cos \theta_{\bar{q}(q)}| \geq \cos \theta_{cut}$ (where $\theta_{cut} \simeq 10^\circ$), i.e. in process 1, one jet is observed while the other is lost down the beam pipe. We use the process $eq \rightarrow \nu q'$ to obtain limits as it is computationally much faster and the discovery
limits obtained using this approximation are in good agreement with those using the full process. The reliability of the limits have been further checked by using different photon distribution functions.

The expression for the unpolarized cross section is given by

$$\sigma = \int dx \int dy f_{\gamma/e}(x, \sqrt{s}/2) f_{q/\gamma}(y, Q^2) \hat{\sigma}(eq \rightarrow \nu q')$$  \hspace{1cm} (3)

where $f_{\gamma/e}(x)$ is the photon distribution, $f_{q/\gamma}(y)$ the distribution for the quark content in the photon, and $\hat{\sigma}(eq \rightarrow \nu q')$ is the cross section for the parton level process given by:

$$\hat{\sigma}(e^- q \rightarrow \nu q') = \int dt \frac{d\hat{\sigma}}{dt}$$  \hspace{1cm} (4)

where

$$\frac{d\hat{\sigma}}{dt} = \frac{\pi \alpha^2}{4 \sin^4 \theta_w} \times f(\hat{s}, \hat{u})$$  \hspace{1cm} (5)

and

$$f(\hat{s}, \hat{u}) = \frac{1}{(t - M^2_W)^2} \left\{ 1 + 2C_L^q C_L^l \left( \frac{\hat{t} - M^2_W}{\hat{t} - M^2_W} \right) \right. \right.$$

$$+ \frac{1}{2} \left( \frac{\hat{t} - M^2_W}{\hat{t} - M^2_W} \right)^2 \left[ (C_L^q)^2 + (C_R^q)^2 (C_L^l)^2 + (C_R^l)^2 (1 + \hat{u}^2/s^2) \right.$$

$$+ (C_L^q - C_R^q) (C_L^l - C_R^l) (1 - \hat{u}^2/s^2) \left. \right\}$$  \hspace{1cm} (6)

and $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the usual Mandelstam variables for the parton level process. We take $Q = \sqrt{s_{eq}}$ in $f_{q/\gamma}$ and the scale $\sqrt{s}/2$ in $f_{\gamma/e}$ is only relevant for photons produced via the Weizsäcker Williams process. The process $e^- \bar{q} \rightarrow \nu q'$ also contributes to the same experimental signature. Its cross section is given by Eq. 3 but with $\hat{s}$ and $\hat{u}$ interchanged in Eq. 3 such that $f(\hat{s}, \hat{u}) \leftrightarrow f(\hat{u}, \hat{s})$. Similarly, for the processes $e^+ \bar{q} \rightarrow \bar{\nu} q'$ and $e^+ q \rightarrow \bar{\nu} q'$, which contribute in the case the of the Weizsäcker Williams process, the cross section is given with $f(\hat{s}, \hat{u})$ and $f(\hat{u}, \hat{s})$ in Eq. 3 respectively. Our conventions for the couplings, $C_L$ and $C_R$, follow from the vertices

$$W_i f f' = \frac{ig}{\sqrt{2}} \gamma^\mu \left( \frac{1 - \gamma^5}{2} C_L^{W_i} + \frac{1 + \gamma^5}{2} C_R^{W_i} \right).$$  \hspace{1cm} (7)
Thus, in the SM, $C_{W_{L}}^{W_{L}} = 1$, and $C_{W_{R}}^{W_{R}} = 0$. A $W'$ in the SSM also has these SM couplings. In the case of the KK model, the couplings are enhanced by a factor of $\sqrt{2}$ such that $C_{L}^{W_{KK}} = \sqrt{2}$, and $C_{R}^{W_{KK}} = 0$. In the LRM, the extra $W_{R}$ has only right-handed couplings such that $C_{L}^{W_{R}} = 0$, and $C_{R}^{W_{R}} = \kappa$. Here the parameter $\kappa = g_{R}/g_{L}$ is the ratio of the coupling constants of the two $SU(2)$ gauge groups. Since we will ultimately find that the process under consideration here is not as sensitive to a $W_{R}$ as some other processes, we will only consider the LR model for $\kappa = 1$. We also take the CKM matrix elements for right-handed fermions to be equal to those of left-handed fermions. In each of the models mentioned so far, the couplings of the $W'$ to the quarks and the leptons are equal. In the case of the UUM, we have instead $C_{L}^{l} = -\sin \phi/\cos \phi$, $C_{L}^{q} = \cos \phi/\sin \phi$, and $C_{L}^{l} = C_{L}^{q} = 0$. The UUM is parametrized by an angle $\phi$, which represents the mixing of the charged gauge bosons of the two $SU(2)$ groups. The process we consider is actually insensitive to the parameter $\phi$ because $C_{L}^{l}$ and $C_{L}^{q}$ always multiply each other in the expressions for the cross section. The polarized cross sections may be inferred from the coupling structure in Eq. (6).

We begin by showing and discussing the total cross sections and the differential cross sections $d\sigma/dE_{q}$ and $d\sigma/dp_{T,q}$. We do not show the angular distribution as it gives lower limits than do the $E_{q}$ and $p_{T,q}$ distributions. We take the SM inputs $M_{W} = 80.33$ GeV, $\sin^{2} \theta_{W} = 0.23124$, and $\alpha = 1/128$ [8]. Since we work only to leading order, there is some arbitrariness in the above input, in particular $\sin^{2} \theta_{W}$.

To take into account detector acceptance, the angle of the observed jet, $\theta_{q(\bar{q})}$, has been restricted to the range

$$10^{0} \leq \theta_{q(\bar{q})} \leq 170^{0}.$$  \hspace{1cm} (8)

In extracting limits we will also restrict the jet’s transverse momentum to reduce hadronic backgrounds which we discuss below.

The unpolarized cross sections, $\sigma$, for photons coming from the backscattered laser photon distribution and the Weizsäcker Williams distributions are shown in Fig. [3]. We have included $u$, $d$, $s$ and $c$-quark contributions and used the leading order GRV distributions
in calculating these cross sections \[16\]. We will discuss the use of other parametrizations below. For the case of the backscattered photon we included the subprocesses \(e^{-}q \rightarrow \nu q'\) and \(e^{-}\bar{q} \rightarrow \nu \bar{q}'\) where the \(q\) could be either \(u\) or \(c\) and the \(\bar{q}\) could be a \(\bar{d}\) or \(\bar{s}\). For the Weizsäcker Williams case the photon can be radiated from either the \(e^{-}\) or \(e^{+}\) so we must also include the subprocesses \(e^{+}q \rightarrow \bar{\nu} q'\) and \(e^{+}\bar{q} \rightarrow \bar{\nu} \bar{q}'\). The cross section is shown for the SM, LRM (\(\kappa = 1\)), UUM, SSM, and KK model, with \(M_{W'} = 750\) GeV in each case. The mass choice is rather arbitrary, made to illustrate general behaviour. We do not show cross sections for polarized electrons. The cross section for right handed electrons (\(\sigma_R = \sigma(e_R^-)\)) only couples to \(W'\)'s in the LR model. In all other cases considered here, \(\sigma_R\) is zero.

One first notes that the cross sections for the backscattered laser case are somewhat larger than those for the \(e^+e^-\) case with WW photons. This is a direct consequence of the harder photon spectrum in the case of the former. The cross sections are typically of the order of several picobarns. For the luminosities expected at high energy \(e^+e^-\) colliders this results in statistical errors of less than a percent. With systematic errors expected to be of the order of 2\% we therefore expect systematic errors to dominate over statistical errors. From Fig. 3 one also sees that, at least for the example shown, the deviations due to a \(W'\) are significantly larger than the expected measurement error. Thus, it appears that this process will provide a sensitive probe for \(W'\) bosons.

We are interested in reactions in which only the quark (or antiquark) jet is observed. The kinematic observables of interest are therefore, the jet’s energy, \(E_q\), its momentum perpendicular to the beam axis, \(p_{Tq}\), and its angle relative to the incident electron, \(\theta_q\), all defined in the \(e^+e^-\) center-of-mass frame. The differential cross sections, \(d\sigma/dp_{Tq}\) and \(d\sigma/dE_q\), are shown in Fig. 4 for the standard model and the SSM, LRM, UUM, and KK models for the backscattered laser case with \(\sqrt{s} = 500\) GeV and \(M_{W'} = 750\) GeV. We do not show the angular distribution as we found that the \(d\sigma/dp_{Tq}\) and \(d\sigma/dE_q\) distributions were more sensitive to \(W'\)'s. We see that extra \(W\) bosons result in larger relative deviations from the SM in the high \(E_q\) or \(p_{Tq}\) regions but since the lower \(E_q\) or \(p_{Tq}\) regions have higher statistics the result is roughly similar in significance in both kinematic regions although the
high $p_{Tq}$ ($E_q$) region will be less affected by systematic error. To maximize the potential information we divide the distributions into 10 equal sized bins and calculate the $\chi^2$ by summing over the bins.

Before proceeding to our results we must deal with the issue of backgrounds. The dominant backgrounds arise from two jet final states where one of the jets goes down the beam pipe and is not observed. Processes which contribute two jet final states are: $\gamma\gamma \to q\bar{q}$, the once resolved reactions $\gamma g \to q\bar{q}$ and $\gamma q \to gq$, and the twice resolved reactions $gg \to q\bar{q}$, $q\bar{q} \to q\bar{q}$, $qg \to qg$ ... In addition there are backgrounds involving t-channel exchange of massive gauge bosons but these are suppressed relative to the backgrounds already listed. In Fig. 5 we show the $p_{Tq}$ distributions for these backgrounds with only one of the jets observed and the other going down the beam pipe for $\sqrt{s} = 500$ GeV for the backscattered laser case. We use the criteria that, to be seen, the parton must satisfy $170^0 \geq \theta_{q(\bar{q})} \geq 10^0$. It is likely that these cuts would be more stringent in a real detector and with veto detectors close to the beam pipe. However, other issues such as spread of the hadronic jets and the remnants of the photon complicate the analysis and must be carefully considered. In the absence of a detailed detector simulation we feel that the chosen detector cuts will give a reasonable representation of the situation for the purposes of estimating the discovery potential of this process. To extract limits from real data these effects must, of course, be studied in detail. Referring to Fig. 5, the constraint that $p_{Tq} \geq 40$ GeV effectively eliminates these backgrounds. Similarly, for $\sqrt{s} = 1$ TeV we take $p_{Tq} \geq 75$ GeV and for $\sqrt{s} = 1.5$ TeV we take $p_{Tq} \geq 100$ GeV.

**A. Discovery Limits for $W$’s**

The best discovery limits were in general obtained using the observable $d\sigma/dp_{Tq}$ with $d\sigma/dE_q$ being only slightly less sensitive. We found that limits obtained using other observables such as the total cross section, forward backward asymmetry and $d\sigma/d\cos\theta_q$ were less sensitive so the results we present will be based on the $p_{Tq}$ distributions. In addition, for
the backscattered laser case limits were obtained for the LR model using the right-handed polarized cross section, $\sigma_R$ and the left-right asymmetry,

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}. \tag{9}$$

For 100% polarization and only including statistical errors one obtains reasonable limits for the LRM $W'$. However, for more realistic polarizations of 90% these limits are seriously degraded and only slightly greater than those obtained from unpolarized $p_{Tq}$ and $E_q$ distributions. Once systematic errors are included, even though they were only one half those used in the $d\sigma/dp_{Tq}$ calculation (since one expects some cancellation of errors between the numerator and denominator in $A_{LR}$), we find that the sensitivity of $A_{LR}$ is less than those obtained from the $p_{Tq}$ and $E_q$ distributions while the sensitivity of $\sigma_R$ is roughly comparable to the sensitivity of the distributions. We therefore only report limits obtained from the distributions in Tables I and II.

In obtaining the $\chi^2$ for $d\sigma/dp_{Tq}$, we used 10 equal sized bins in the range $p_{Tq}^{\text{min}} < p_{Tq} < p_{Tq}^{\text{max}}$, where $p_{Tq}^{\text{min}}$ is given by the $p_{Tq}$ cut chosen to reduce the two jet backgrounds and $p_{Tq}^{\text{max}}$ is taken to be the kinematic limit. We have

$$\chi^2 = \sum_{\text{bins}} \left( \frac{d\sigma/dp_{Tq} - d\sigma/dp_{Tq,\text{SM}}}{\delta d\sigma/dp_{Tq}} \right)^2, \tag{10}$$

where $\delta d\sigma/dp_{Tq}$ is the error on the measurement. Analogous formulae hold for other observables. One sided 95% confidence level discovery limits are obtained by requiring $\chi^2 \geq 2.69$ for discovery. Systematic errors, when included, were added in quadrature with the statistical errors.

The discovery limits for all five models are listed in Table I for the backscattered laser case and in Table II for the $e^+e^-$ case with WW photons. Results are presented for $\sqrt{s} = 0.5$, 1.0 and 1.5 TeV, using the same input parameters as for the cross sections presented in the previous section. For each center-of-mass energy, two luminosity scenarios are considered and we present limits obtained with and without systematic errors. Our prescription is to include a 2% systematic error per bin. This number is quite arbitrary but seems reasonable.
In addition to detector systematics, which we expect will dominate, there are uncertainties associated with the beam luminosity and energy, which will be spread over a range. Other systematic errors are associated with background subtraction as well as radiative corrections. Thus, the 2% number should not be taken too seriously except to highlight the fact that a precision measurement is required to take full advantage of the large event rate.

The discovery limits are substantial and compare favourably in most cases to those obtained from the previously studied process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. In all cases, the limits for the WW process are significantly lower than with the backscattered laser. This enhanced reach is an argument in favour of $e\gamma$ colliders. As expected, when systematic errors are not included there is a significant improvement in the limits with the higher luminosity. When 2% systematic errors are included the improvement for the high luminosity scenario is not as dramatic.

In every case for the process considered here, the SSM and UUM yield the same discovery limits. This occurs because the two processes represent positive and negative interferences of equal strength, respectively, with the SM. The limits obtained here for the backscattered laser case for the SSM are similar to those from the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ before a systematic error is included. However, the limits here are downgraded less than for the previous process when a 2% systematic error is included, resulting in a higher discovery reach for this process. The behaviour is similar for the LRM. The limits, for the backscattered laser case, including systematic errors, are similar to those obtained for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$.

For both the KK model and the UUM, this process offers a significant improvement over the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. For the backscattered laser case, the KK $W'$ limits are typically 2 times higher when a systematic error is included than for the previous process. Similarly, the limits obtained for the UUM with the process considered here are a factor of 3 better than for the equivalent case in the previous process.

Beam polarization of 90% does not improve the limits. The only model studied which would benefit from polarization is the LRM for which the $W'$ is right-handed. The process $e\gamma \rightarrow \nu q$ proceeds via t-channel $W$-exchange. The SM contribution is totally left-handed so
that for 100% right-handed polarization a $W_R$ would show up quite dramatically. However, the cross-section for $W_R$'s which are not unrealistically light is orders of magnitude smaller than the left-handed cross section. So even a small pollution of left-handed electrons would largely overwhelm the right-handed cross section. The signal from right-handed $W'$'s is further eroded when systematic errors are included. Quantitatively we found for the backscattered laser case with $\sqrt{s} = 500$ GeV and $L = 50$ fb$^{-1}$ using 100% right-handed electrons a discovery limit of 1.7 TeV. This was degraded to $\sim 700$ GeV when 90% polarization was used and was further degraded to $\sim 600$ GeV when a 2% systematic error on the cross section was included. This is only slightly higher than what is obtained using the $p_T q$ distribution with unpolarized electrons.

The UUM is an interesting case. First, as noted above, the process $e\gamma \rightarrow \nu q$ is considerably more sensitive to a UUM $W'$ than the process studied previously, $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$. In addition, the dependence on the mixing angle between the two $SU(2)$ groups cancels in the process we are studying. The cross section exhibits a straightforward destructive interference of the $W'$ exchange with the SM $W$ exchange, rather than the complicated $\phi$ dependence of the process $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$. This is an example of how the two processes complement each other.

As indicated above, we also derived discovery limits using another parametrization of the photon distribution functions, that of Schuler and Sjöstrand [17]. That particular distribution results in lower cross sections than does the GRV parametrization. However, the discovery limits were consistently within 50-100 GeV of those reported in the Tables.

**B. Constraints on Couplings**

In this section, we consider constraints on the couplings of an extra $W'$ from the process $e\gamma \rightarrow \nu q + X$. All constraints are shown for the backscattered laser case. These constraints are significant only in the case where the mass of the corresponding extra gauge boson is considerably lower than its search limit in this process. We assume here that a signal for an
extra gauge boson has been detected by another experiment, such as at the LHC.

Given such a signal, we derive constraints (at 95% C.L.) on the couplings of extra gauge bosons. We present the constraints in terms of couplings $C_L$ and $C_R$ which are normalized as in Eq. 4.

The constraints correspond to

$$\chi^2 = \left(\frac{O_i(SM) - O_i(SM + W')}{\delta O_i}\right)^2 = 5.99,$$

where $O_i(SM)$ is the prediction for the observable $O_i$ in the SM, $O_i(SM + W')$ is the prediction of the extension of the SM and $\delta O_i$ is the expected experimental error. The index $i$ corresponds to different observables such as $\sigma$, $\sigma_R$, $A_{LR}$, or $d\sigma/dp_{Tq}$ where one sums over all bins as in Eq. 10 for the latter.

We examined the sensitivity to polarized beams with the assumption that for single beam ($e^-$) polarization, we have, as in the previous section, equal running in left and right polarization states. We found, as before, that polarized beams with realistic polarization, offer little improvement over the case of unpolarized beams.

In Figs. 6-9 we present our constraints on $W'$ couplings. The SM corresponds to the origin and we vary the $W'$ couplings about it, showing the contours corresponding to a 95% CL deviation. Thus, $W'$ couplings lying within the limits would be indistinguishable from the SM while those outside would indicate statistically significant deviations from the SM. For simplicity we have taken $C_L^e = C_L^q$ and $C_R^e = C_R^q$. This assumption is satisfied for the SSM, the LRM and the KK model. We indicate the couplings corresponding to those three models with a full star, a dot, and an open star, respectively. If one were making simultaneous measurements with different processes one could extract lepton couplings from one measurement and then use those as input to constrain the quark couplings with this process. We also point out that the couplings are normalized differently here than in Ref. 10. For comparison, the limits of our figures correspond to values of approximately $L_f(W)$ and $R_f(W) \approx 0.5$ in Figs. 12-17 of Ref. 10.

In Fig. 6 we show the constraints on the couplings of a 750 GeV $W'$ at a 500 GeV...
collider for different observables and beam polarization. The results are given for the case of an integrated luminosity of 500 fb$^{-1}$, including a 2% systematic error. One sees that one can obtain interesting constraints even though the $W'$ mass is greater than the center of mass energy. The binned differential cross section, $d\sigma/d\rho_Tq$, gives the strongest constraint (solid line). 100% right-handed polarization gives a strong constraint from $\sigma_R$ orthogonal to that obtained from $d\sigma/d\rho_Tq$ (dashed line). However, we see that the constraints from $\sigma_R$ are seriously degraded for 90% polarization (dotted line).

Since we find that $d\sigma/d\rho_Tq$ gives the best limits we will explore variations of machine parameters and $W'$ properties in Figs. 7-9, using that observable only.

In Fig. 7 we show the effect of different luminosities and of including a systematic error. For the case of a 750 GeV $W'$ at a 500 GeV collider illustrated in the figure, the SSM and KK models are distinguishable from the standard model, even for the low luminosity case of 50 fb$^{-1}$, with a 2% systematic error included. On the other hand, the LRM is not distinguishable even for the high luminosity case without any systematic error included. This is consistent with the mass limits quoted for this model in Table I, where $M_{W'} = 750$ GeV is right at the limit of discovery for the most favourable case.

In Fig. 8 we show the constraints on the $W'$ couplings at a 500 GeV collider for three representative $W'$ masses of 0.75 TeV, 1 TeV, and 1.5 TeV. In Fig. 9, for the case of a 1.5 TeV $W'$, the constraints are shown for three different collider energies of 0.5 TeV, 1.0 TeV, and 1.5 TeV. In both Figs. 8 and 9 we have presented the case of an integrated luminosity of 500 fb$^{-1}$ with a 2% systematic error included. In each case shown in the figures, the SSM and KK models are distinguishable from the standard model.

**III. CONCLUSIONS**

In this paper, we studied the sensitivity of the process $e\gamma \rightarrow \nu q$ to $W'$ bosons. We used this process to find $W'$ mass discovery limits and to see how well one could measure the couplings of the $W'$ bosons expected in various extensions of the standard model.
For the discovery limits the highest reach was obtained by binning the \( d\sigma/dp_T q \) distribution. For most models, the discovery reach of the backscattered laser process is typically in the 2-10 TeV range depending on the center of mass energy, the integrated luminosity, and the assumptions regarding systematic errors. These limits compare very favourably with other processes, including measurements at the LHC. For the \( e^+ e^- \) process with WW photons, the reach is typically in the 1-6 TeV range.

For the \( W_R \) boson of the LRM, for which LHC discovery limits are available, the discovery limits are significantly lower. For \( g_R = g_L, M_{W'} = 0.75, 1.2, \) and 1.6 TeV for \( \sqrt{s} = 500, 1000, \) and 1500 GeV respectively assuming \( L_{\text{int}} = 500 \text{ fb}^{-1} \) relative to a reach of 5.9 TeV at the LHC.

Even for cases where the discovery reach for \( W' \)’s with this process is not competitive with the reach of the LHC, precision measurements can give information on extra gauge boson couplings which complements that from the LHC. In particular, if the LHC were to discover a \( W' \) the process \( e\gamma \to \nu q \) could be used to constrain \( W' \) couplings.

We have demonstrated that this process has a great deal of potential in searching for the effects of extra gauge bosons. As we stated at the outset the resolved photon approach was a useful approximation adequate for estimating the discovery potential. However, when considering real data one must of course have exact calculations including radiative corrections. With the knowledge that this process may be a good probe for new physics the motivation to perform more detailed calculations now exists.

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FIG. 1. The Feynman diagrams contributing to the process $e\gamma \to \nu q\bar{q}$.

FIG. 2. The Feynman diagram contributing to the process $eq \to \nu q'$. 
FIG. 3. The cross section $\sigma(e^-\gamma\rightarrow\nu q + X)$ as a function of $\sqrt{s}$ for the SM (solid line), and with a $W'$ of mass 750 GeV for the SSM (dotted line), UUM (dash-dot-dot line), and the KK model (dashed line). The LR model cross section overlaps the SM cross section. (a) uses the backscattered laser photon spectrum and (b) uses the Weizsäcker-Williams photon spectrum.
FIG. 4. The differential cross sections (a) $d\sigma/dp_{Tq}$ and (b) $d\sigma/dE_q$. They are shown for the backscattered laser case with $\sqrt{s} = 500$ GeV and for $M_{W'} = 750$ GeV. The SM is given by solid line, the SSM by the dotted line, UUM by the dash-dot-dot line, and the KK model by the dashed line.
FIG. 5. The differential cross section $d\sigma/dp_T$ for the SM and the various backgrounds. They are shown for the backscattered laser case with $\sqrt{s} = 500$ GeV. The process $e\gamma \rightarrow \nu q + X$ is given by the solid line, the subprocess $\gamma\gamma \rightarrow q\bar{q}$ by the dotted line, the singly resolved backgrounds by the dash-dot-dot line, and the doubly resolved backgrounds by the dashed line. For the backgrounds we impose the cuts that one jet is observed with $|\cos \theta_q| < \cos 10^\circ$ while the other jet is lost down the beampipe with $|\cos \theta_q| > \cos 10^\circ$. 
FIG. 6. 95% C.L. constraints on $W'$ couplings arising from $d\sigma/dp_T$ (solid line) and $\sigma_R$ with 100% (dashed line) and 90% (dotted line) polarization. The results are for $\sqrt{s} = 500$ GeV with the backscattered laser spectrum, $M'_{W} = 750$ GeV, and $L_{int} = 500$ fb$^{-1}$ with a 2% systematic error. The couplings corresponding to the SSM, LRM and the KK model are indicated by a full star, a dot and an open star, respectively.
FIG. 7. 95% C.L. constraints on $W'$ couplings for $\sqrt{s} = 500$ GeV with the backscattered laser spectrum and $M_{W'} = 750$ GeV. The integrated luminosity and systematic error is varied.
FIG. 8. 95% C.L. constraints on $W'$ couplings for $\sqrt{s} = 500$ GeV with the backscattered laser spectrum and $L_{int} = 500 \, fb^{-1}$ with a 2% systematic error. The three $W'$ masses of 0.75 TeV (solid line), 1.0 TeV (dashed line) and 1.5 TeV (dotted line) are presented.
FIG. 9. 95% C.L. constraints on $W'$ couplings for $M_W' = 1.5$ TeV and $L_{int} = 500 \text{ fb}^{-1}$ with a 2% systematic error. The three collider energies of 0.5 TeV (solid line), 1.0 TeV (dashed line) and 1.5 TeV (dotted line) with the backscattered laser spectrum are presented.
TABLE I. $W'$ 95% C.L. discovery limits, in TeV, for the backscattered laser case obtained in the SSM, LRM ($\kappa = 1$), UUM, and the KK model using $d\sigma/dp_T^q$ as the observable. Results are presented for $\sqrt{s} = 500, 1000, \text{and} 1500 \text{ GeV}$ and for two luminosity scenarios, with and without a 2% systematic error included.

| $\sqrt{s}$ (GeV) | Model | Lum. (fb$^{-1}$): | 500 | 500 | 50 | 500 |
|------------------|-------|------------------|-----|-----|----|-----|
|                  | SSM   | 2.3              | 4.1 | 1.9 | 2.6 |
|                  | LRM   | 0.53             | 0.75| 0.51| 0.63|
|                  | UUM   | 2.3              | 4.1 | 1.9 | 2.6 |
|                  | KK    | 3.2              | 5.7 | 2.7 | 3.6 |
| 1000             | SSM   | 4.6              | 5.8 | 3.7 | 4.2 |
|                  | LRM   | 1.0              | 1.2 | 0.98| 1.1 |
|                  | UUM   | 4.6              | 5.8 | 3.7 | 4.2 |
|                  | KK    | 6.6              | 8.3 | 5.2 | 6.0 |
| 1500             | SSM   | 5.7              | 7.2 | 4.8 | 5.6 |
|                  | LRM   | 1.4              | 1.6 | 1.3 | 1.5 |
|                  | UUM   | 5.7              | 7.2 | 4.9 | 5.7 |
|                  | KK    | 8.1              | 10. | 6.8 | 8.0 |
TABLE II. $W'$ 95\% C.L. discovery limits, in TeV, for the $e^+e^-$ case with WW photons obtained in the SSM, LRM ($\kappa = 1$), UUM, and the KK model using $d\sigma/dp_{T_q}$ as the observable. Results are presented for $\sqrt{s} = 500$, 1000, and 1500 GeV and for two luminosity scenarios, with and without a 2\% systematic error included.

| $\sqrt{s}$ (GeV) | Model | Lum. (fb$^{-1}$): 50 | 500 | 50 | 500 | 200 | 500 | 200 | 500 | 200 | 500 |
|------------------|-------|-----------------------|-----|----|-----|-----|-----|----|-----|-----|-----|
| 500              | SSM   | 1.4                   | 2.5 | 1.3 | 1.9 | 2.9 | 3.6 | 2.5 | 3.0 | 3.6 | 4.5 |
|                  | LRM   | 0.38                  | 0.54| 0.37| 0.51| 0.74| 0.85| 0.72| 0.82| 0.95| 1.1 |
|                  | UUM   | 1.4                   | 2.5 | 1.3 | 1.9 | 2.9 | 3.6 | 2.5 | 3.0 | 3.6 | 4.5 |
|                  | KK    | 2.0                   | 3.5 | 1.8 | 2.7 | 4.1 | 5.1 | 3.5 | 4.2 | 5.1 | 6.4 |
| 1000             | Lum. (fb$^{-1}$): 200 | 500 | 200 | 500 | 200 | 500 | 200 | 500 | 200 | 500 |
|                  | SSM   | 2.9                   | 3.6 | 2.5 | 3.0 | 3.6 | 4.5 | 3.2 | 3.8 | 3.6 | 4.5 |
|                  | LRM   | 0.74                  | 0.85| 0.72| 0.82| 0.95| 1.1 | 0.93| 1.1 | 0.95| 1.1 |
|                  | UUM   | 2.9                   | 3.6 | 2.5 | 3.0 | 3.6 | 4.5 | 3.2 | 3.9 | 3.6 | 4.5 |
|                  | KK    | 4.1                   | 5.1 | 3.5 | 4.2 | 5.1 | 6.4 | 4.5 | 5.4 | 5.1 | 6.4 |