Production of Z' associated with photons or jets as a probe of new gauge-boson couplings

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We examine the production of a new Z' gauge boson in association with photons or jets at future hadron supercolliders as a probe of its couplings to fermions. Associated jet production is found to be rather insensitive to these couplings and suffers from large uncertainties as well as substantial backgrounds. On the other hand, the ratio of rates for associated photon Z' production to that of conventional Z' production has a rather clean signature (once appropriate cuts are made), and is found to be quite sensitive to the choice of extended electroweak model, while being simultaneously insensitive to structure-function uncertainties and QCD corrections. Rates at both the Superconducting Super Collider (SSC) and the CERN Large Hadron Collider (LHC) are significant for Z' masses in the 1-TeV range.

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It is by now well known that the production of a new neutral gauge boson Z' in the few TeV mass range should be easily observed at the Superconducting Super Collider (SSC) and the CERN Large Hadron Collider (LHC) [1] via its decay to lepton pairs. If such a particle is observed it will be mandatory to determine its couplings to fermions in order to identify which Z', of the many proposed in the literature, has been discovered. During the past 1–2 years, this subject has received significant attention from several groups of authors [2–6] who have found that Z' identification is a serious problem for realistic detectors if as few as possible theoretical assumptions are made about the Z' decay modes. This problem persists even if such new gauge bosons are relatively light and significant statistics is available. *If* one assumes that the Z' can deacy only to the conventional particles of the standard model (SM) then it has been shown [2] that measurements of its mass (M_2), width (Γ_2), and production cross section (σ_0), together with the corresponding leptonic forward-backward asymmetry ($A^l_{\rm FB}$) can be used to "identify" the Z' for masses up to several TeV. However, we note that many extended electroweak models (EEM) allow for non-SM Z' decays which could dominate the Z' width although the above assumption is not so bad in some specific cases. Of the observables listed above, only $A^l_{\rm FB}$ (other than, of course, M_2) is insensitive to any assumptions about the Z' decay modes and so, by itself, is insufficient to probe the details of the new gauge boson's couplings. It is thus absolutely necessary to find additional observables which are also insensitive to any assumption on how the Z' may decay.

One suggestion [7] is to look for multibody Z' fermionic decay modes and to form various ratios of decay rates and a second is to examine the polarization of τ's resulting from the decay $Z'\to\tau^+\tau^-$ [5]. A third proposal takes advantage of the potential possibility of *polarized pp* scattering [4] to create a sizeable left-right asymmetry. All of these scenarios suffer from either large SM backgrounds which must be subtracted (but are still found to be useful for a relatively light Z' of order 1 TeV in mass) or are hampered by our current lack of knowledge of the polarized parton distributions.

Recently, Cvetič and Langacker [8] have proposed the use of associated Z' production, i.e., $\bar{q}q\to VZ'$, with $V=Z$, $W^{\pm}$, as a new probe of the Z' couplings to fermions. The ratios of the cross sections for these events to that for single Z' production (as measured via the $Z'\to l^+l^-$ channel) are independent of Γ_2, and they were found to be statistically significant in the absence of cuts and quite sensitive to the choice of EEM. Of course, paying the price of applying realistic cuts and allowing for V branching fractions (or V identification efficiencies) will reduce the values of these ratios somewhat resulting in a significant decrease in model sensitivity via a loss is statistical power.

In this paper we will examine both Z' produced together with a single jet or together with an isolated photon; the first process proceeds in lowest order [9] either via $\bar{q}q\to Z'g$ or $gq\to Z'q$ while the second proceeds only via $\bar{q}q\to Z'\gamma$ [10] in lowest order. Although the gq production process was ignored in the brief discussion given by Cvetič and Langacker, we verify their conclusion that Z' production in association with a jet is quite insensitive to the Z' couplings to fermions. $Z'\gamma$ production, on the other hand, will be shown to be very clean and effectively background free when only very mild cuts are applied. Additionally, the efficiency of isolated photon detection is very high for planned collider detectors [11] due to its usefulness in hunting for the intermediate-mass Higgs boson of the SM. We will show below that the ratio of the number of $Z'\gamma$ to Z' events observed at either the SSC or LHC, detected via the leptonic decay of the Z', provides a statistically useful probe of the Z' couplings which is insensitive to variations in the parton densities and higher order QCD corrections. Unlike the situation of $Z'V$ production, in the $Z'\gamma$ case we need not pay any significant price in applying cuts to remove SM backgrounds or for V branching fractions.

There are very many models in the literature which predict the existence of a Z' so that we can hardly perform an exhaustive analysis. Thus, to be specific we will deal with only a small representative set of EEM's which we feel are fairly representative: (i) the "effective rank-5" models (ER5M) arise from string-inspired E_6 [12] and are obtained via the symmetry-breaking chain $E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi \times U(1)_\psi \to SM \times U(1)_\theta$ such that we can identify $Z' = Z_\psi \cos\theta - Z_\chi \sin\theta$ with $-\pi/2 \le \theta \le \pi/2$ being an *a priori* free parameter whose value fixes the Z' couplings to fermions; (ii) the now-classic left-right model (LRM) [13] with $g_L = g_R$; (iii) the "alternative" left-right model (ALRM) [14]; (iv) a toy model wherein the Z' is just a heavier version of the SM Z (SSM). We refer the reader to the original literature for the details on each of these EEM's.

Following Ref. [9], the lowest order Z'+jet or $Z'\gamma$ differential production cross section can be written as

$$\frac{d\sigma}{dp_t dy} = 2p_t \sum_{ij} \int_{x_{\min}}^{1} \frac{\hat{s} f_i(x_1,q^2) f_j(x_2,q^2) \hat{\sigma}_{ij}(\hat{s},\hat{t},\hat{u})}{x_1 s + u - M_2^2} . \tag{1}$$

The kinematics are defined via the relationships

$$\begin{aligned} m_T^2 &= p_t^2 + M_2^2 , \\ \hat{s} &= s x_1 x_2 , \\ t,u &= -\sqrt{s}\, m_T e^{\mp y} + M_2^2 , \\ \hat{t},\hat{u} &= -\sqrt{s}\, m_T x_{1,2} e^{\mp y} + M_2^2 , \\ x_2 &= \frac{-x_1 t - (1-x_1) M_2^2}{x_1 s + u - M_2^2} , \\ x_{\min} &= \frac{-u}{s + t - M_2^2} , \end{aligned} \tag{2}$$

and f_i are the appropriate parton densities. For $\bar{q}q \to Z'g$ we have

$$\hat{\sigma}_{\bar{q}q} = \frac{2\sqrt{2} G_F M_Z^2}{9\hat{s}^2} \left[\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}} + \frac{2\hat{s} M_2^2}{\hat{u}\hat{t}} \right] \alpha_s(q^2)(v_i^2 + a_i^2) , \tag{3}$$

whereas for $\bar{q}q \to Z'\gamma$, we must replace $\alpha_s(q^2)$ by $\frac{3}{4}\alpha(q^2) Q_i^2$ in Eq. (3), where Q_i is the quark electric charge in units of e. It is important to note that it is this additional factor of Q_i^2 that produces the sensitivity to the various possible choices of the Z' couplings. For the $gq \to Z'q$ subprocess one has instead

$$\hat{\sigma}_{gq} = \frac{\sqrt{2} G_F M_Z^2}{12\hat{s}^2} \left[-\frac{\hat{s}}{\hat{u}} - \frac{\hat{u}}{\hat{s}} - \frac{2\hat{t} M_2^2}{\hat{u}\hat{s}} \right] \alpha_s(q^2)(v_i^2 + a_i^2) . \tag{4}$$

In writing these expressions we have normalized the various fermionic couplings to the Z' as in the SM:

$$\mathcal{L} = \frac{g}{2c_w} \bar{q}_i \gamma_\mu (v_i - a_i \gamma_5) q_i Z'_\mu , \tag{5}$$

with $c_w = \cos\theta_w$ and g being the usual weak-coupling constant. For purposes of numerical evaluations we take $q^2 = M_2^2$ and evolve $\alpha_s(q^2)$ via the three-loop renormalization-group equation (taking the appropriate value of the scale Λ associated with the choice of parton distributions); we also take $\alpha^{-1}(q^2) = 127.9$.

Let us first briefly examine the Z' plus jet production process; we normalize our differential rates by the lowest order $\bar{q}q \to Z'$ production cross section σ_0. Since the $Q = \frac{2}{3}$ and $Q = -\frac{1}{3}$ quarks contribute differently to the two distinct subprocesses one might expect that the Z' plus jets production rate might be sensitive to the fermionic Z' couplings; unfortunately this is not the case. Figure 1(a) shows the normalized differential rate for the SSC as a function of the jet p_t for $y = 0$ assuming the Morfin-Tung set S1 (MT-S1) parton distributions [15] taking $M_2 = 1$ TeV for four different EEM's. Although this is only a Born level calculation, we see the essential feature immediately: all of the predictions lie virtually atop one another over a wide range of p_t. Fixing the p_t at 300 GeV and maintaining $y = 0$, Fig. 1(b) shows the extremely weak θ dependence (about 10%) of the normalized Z' plus jet cross section for the ER5M which again demonstrates the lack of sensitivity of this mechanism to the fermionic Z' couplings anticipated by the discussion given by Cvetič and Langacker [8]. We thus conclude

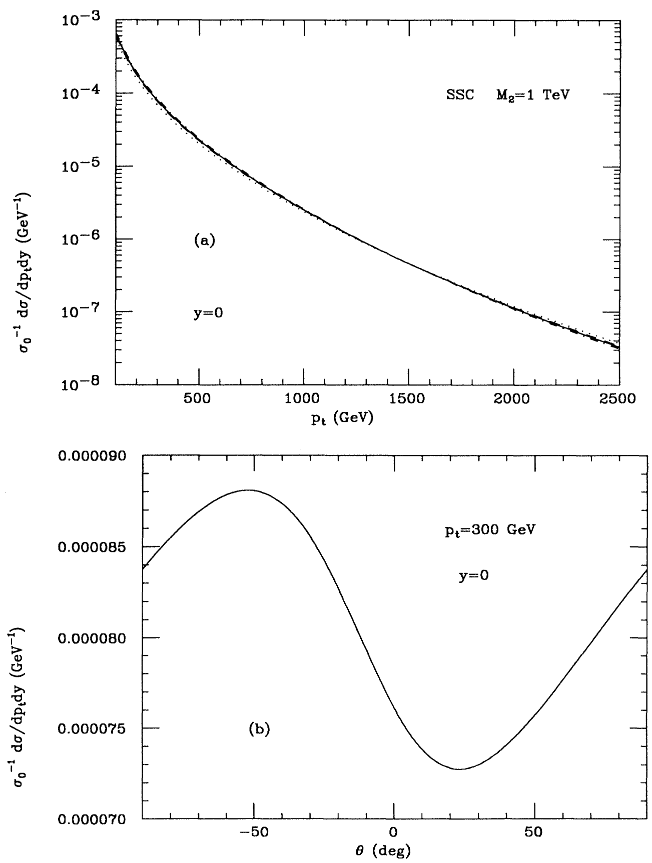

FIG. 1. (a) Normalized Born-level p_t distribution for Z' plus jet production at the SSC with $y = 0$ assuming $M_2 = 1$ TeV and MT-S1 parton distributions. The solid (dash-dotted, dashed, dotted) curve corresponds to the LRM (χ, ψ, ALRM) case. (b) Same as (a) but for the ER5M as a function of θ assuming $p_t = 300$ GeV.

that this reaction is useless as a probe of the Z' couplings. We note, however, that had the color factors been such as to make the gq subprocess occur at an even larger rate then the Z' plus jet mode might have provided a relatively sensitive tool with which to have analyzed the Z' couplings.

Turning now to the $Z'\gamma$ mode we see in Fig. 2(a) the normalized differential rate for this process as a function of the photon's E_t for the same situation as in Fig. 1(a). Unlike the $Z'g$ final state, the production cross section for the $Z'\gamma$ is weighted by the square of the electric charges of the initial-state quarks Q_i^2 and leads to a significant sensitivity to the Z' couplings. Instead of lying atop one another, we see here that the predictions of the four different EEM's yield somewhat different results giving us some hope of the usefulness of this channel. Of course, since the rates are small and differential distributions are more sensitive to QCD corrections than are integrated quantities, we integrate our distribution over the photon $E_t > 50$ GeV and the rapidity interval

$$|y| \leq \min \left[2.5, \cosh^{-1} \left[\frac{s+M_2^2}{2\sqrt{s}\, m_T} \right] \right] . \tag{6}$$

Here the former value represents the typical γ rapidity coverage of the SSC and LHC detectors [11] while the latter is purely kinematic. (A similar rapidity cut can be applied to the leptons from the decay of the Z'.) Backgrounds from decays such as $Z' \to l^+ l^- \gamma$ can be completely removed by demanding that the lepton pair mass satisfy $M_{ll} > 0.95 M_2$ coupled with the photon's E_t cut for a Z' with a mass of 1 TeV. Note that the typical supercollider detector will have a dilepton pair mass resolution of order 1% or better [11]. As long as the probability of misidentifying a jet as a photon is less than about 10^{-3}, there are no significant backgrounds from QCD sources which are not removed by the above cuts. This level of jet rejection should be obtainable for most of the SSC and LHC detectors [11].

The ratio of $Z'\gamma$ to Z' events, R_γ, is shown for the SSC assuming $M_2 = 1$ TeV for the ER5M case as a function of the parameter θ in Fig. 2(b) for several different choices of the parton densities: MT-S1 and MT-S2 [15], Harriman-Martin-Roberts-Stirling set B (HMRS-B) [16], and Kwiecinski-Martin-Stirling-Roberts sets B0 and B2 (KMRS-B0, KMRS-B2) [17]. Here we see that (i) the results are insensitive to the choice of parton densities with

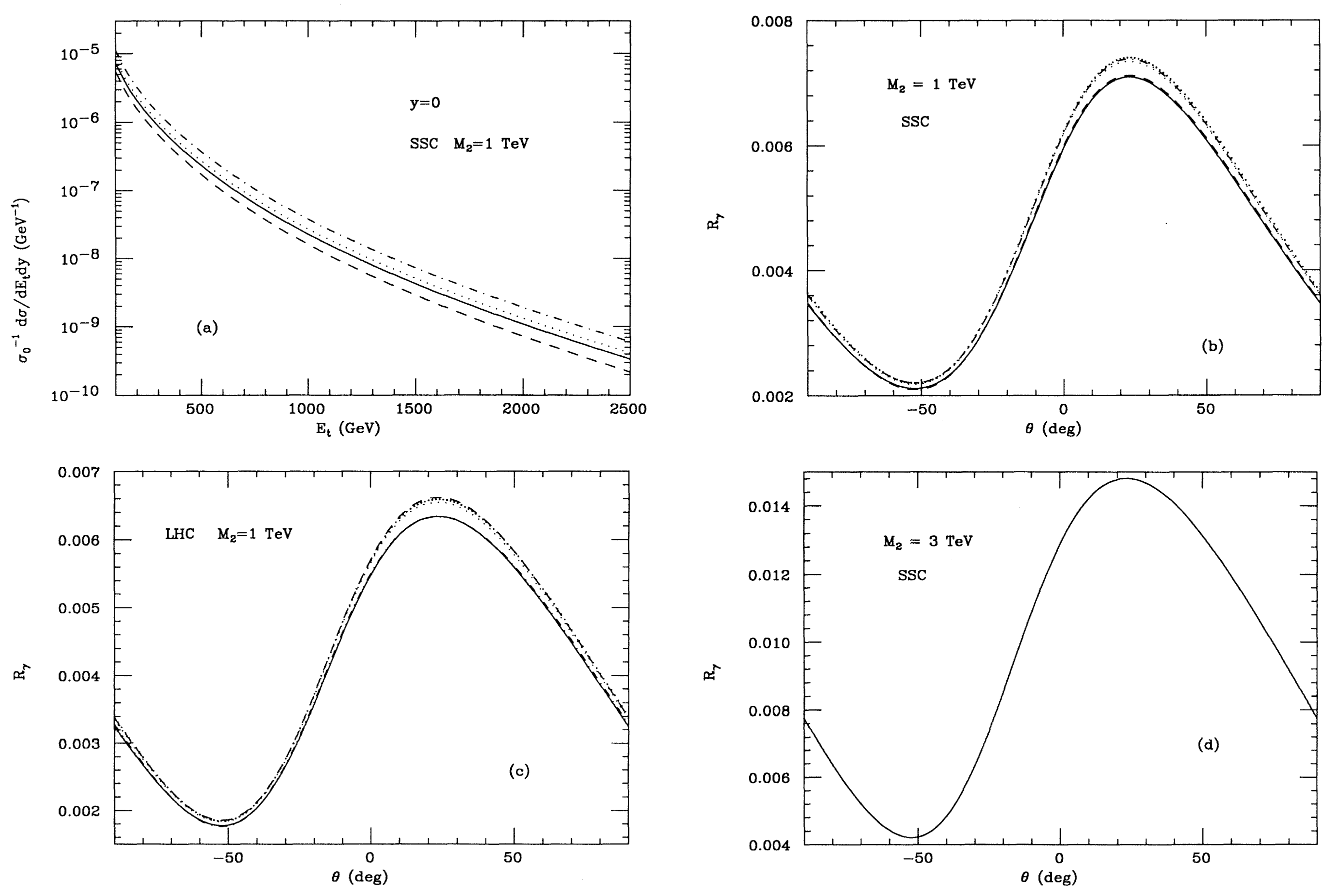

FIG. 2. (a) Normalized Born-level E_t distribution for $Z'\gamma$ production at the SSC with $y=0$ assuming $M_2 = 1$ TeV and MT-S1 parton distributions. The solid (dash-dotted, dashed, dotted) curve corresponds to the LRM (ALRM, ψ, χ) case. (b) The ratio R_γ assuming a 1 TeV Z' at the SSC after cuts for the ER5M as a function of θ. The solid (dash-dotted, dashed, dotted, square dotted) curve corresponds to the choice of MT-S1 (HMRS-B, MT-S2, KMRS-B0, KMRS-B2) parton densities. (c) Same as (b) but for the LHC assuming the same sets of parton distributions. (d) Same as (b) but for a 3 TeV Z' at the SSC.

a variation of at most 5% for the models we've examined; (ii) R_γ lies in the range 0.2–0.9 %; and (iii) R_γ is quite sensitive to the value of θ as we would hope. Assuming MT-S1 distributions we also find that $R_\gamma=(4.95,\ 8.46,\ 5.50)10^{-3}$ corresponding to the (LRM, ALRM, SSM) cases, respectively. For the LHC, under identical assumptions for the same models we find instead that $R_\gamma=(4.65,\ 7.26,\ 5.11)10^{-3}$, numerically comparable to their corresponding values at the SSC. For the ER5M case, the predicted value of R_γ at the LHC is shown in Fig. 2(c) as a function of θ assuming the same sets of structure functions as in Fig. 2(b).

For larger Z' masses, e.g., $M_2=3$ TeV, the ratio R_γ is somewhat increased as shown in Fig. 2(d) and has a comparable sensitivity to variations in the Z' couplings. In fact, R_γ is found to approximately scale with the Z' mass and choice of minimum photon E_t as $\ln^2(M_2/E_t^{\min})$. However, since the *number* of Z' events is drastically smaller for the larger Z' mass we lose the statistical power of R_γ as will be apparent from the number of events that we present below in the case of $M_2=1$ TeV.

Since we have so far presented only a Born-level calculation, we must worry about how R_γ would be modified by QCD corrections; such corrections have been considered in the literature for the production of $Z\gamma$ and $W^\pm\gamma$ [18]. One possibly sizeable correction at SSC and LHC energies arises from the box diagram-mediated process $gg\to Z'\gamma$. In the SM case, this represents an approximate 30% effect due to the high gg luminosity at small x values. In the $Z'\gamma$ case this contribution will be much smaller as significantly larger x values are being probed since the Z' is so massive. Additionally, this contribution is *model dependent* as it is sensitive to the existence of all color nonsinglet fields in the model which couple to the Z' and the photon. Full next-to-leading (NLL) order calculations of $Z\gamma$ production in pp collisions have only recently been completed by Ohnemus [18]; we note that the choice of kinematic cuts selected by that author is quoting his results is identical to the choice we have made above. Thus we can estimate that the corrections to the integrated $Z'\gamma$ cross sections at both the SSC and LHC will be almost identical to the size of the "K-factor" correction to the total Z' production rate as given, e.g., by the analysis of Hamberg and co-workers [19] which we have used in our earlier work [2]. This being the case, we estimate that the numerical values of R_γ presented above are relatively insensitive to large higher-order QCD corrections at the level of more than a few percent. In quoting the numbers of events below, we will take all such "K-factor" effects into account.

How well can R_γ be determined? Since there is little background and many of the various systematic uncertainties cancel in forming the ratio of cross sections, the dominant error in R_γ is expected to be statistical so that it will scale approximately inversely proportional to the square root of the number of $l^+l^-\gamma$ events (N_γ) which pass our cuts. We will assume that the isolated lepton identification efficiency is 0.85 separately for *both* e's and μ's and will sum over both leptonic flavors below. Table I shows the resulting values of N_γ for both the SSC ($L=10$ fb^{-1}) and LHC ($L=100$ fb^{-1}) with $M_2=1$ TeV and assuming MT-S1 parton distributions for several different EEM. The table also shows the anticipated size of the relative error on a R_γ measurement for each of the EEM at both colliders. With the integrated luminosities that we have assumed, it is clear that R_γ can be relatively well determined at either supercollider for a 1 TeV Z' although the anticipated errors for the LHC are somewhat smaller due to the approximate factor of 2 larger event rate. It is important to note that the assumed fact of 10 larger luminosity of the LHC *only* translates into an approximate factor of 2 larger rate due to the LHC's smaller center of mass energy. It is clear from the numbers in the table that this method will fail for Z' masses significantly larger than 1 TeV since the event rates will fall off quite rapidly with increasing Z' mass. Thus this technique is seen to be limited to the case of a relatively light Z'.

TABLE I. The number of $Z'\gamma$ events (N_γ) and the relative error in R_γ in percent for several EEM's at both the SSC and LHC assuming MT-S1 parton distributions.

EEM	N_γ	$\delta R_\gamma/R_\gamma$ (%)
	SSC (10 fb^{-1})	
LRM	65.4	12.4
ALRM	180.7	7.4
SSM	109.6	9.6
ψ	26.8	19.3
χ	40.0	15.8
η	39.0	16.0
	LHC (100 fb^{-1})	
LRM	125.2	8.9
ALRM	393.6	5.0
SSM	207.5	6.9
ψ	63.4	12.6
χ	74.6	11.6
η	81.7	11.0

In this paper we have obtained the following results:

(i) By explicit calculation, we demonstrated that the associated production of Z' plus jets is insensitive to the fermionic couplings of the Z' even though two distinct subprocesses contribute to the full cross section.

(ii) We have shown that the ratio of the cross sections for $Z'\gamma$ and Z' production, R_γ, is a sensitive probe of the Z' couplings, and is insensitive to structure function uncertainties and QCD corrections when suitable "K-factor" contributions are accounted for. We note again that it is the additional factor of Q_i^2 in the expression for the production cross section for the $Z'\gamma$ final state that produces the sensitivity in R_γ to various Z' couplings.

(iii) With suitably soft cuts which do not modify the signal rate, $Z'\gamma$ production is found to be essentially free of QCD and radiative Z' decay backgrounds with a final state that can be easily identified with high efficiency without paying the price of small branching fractions.

(iv) Although sufficient statistics can be accumulated at both the SSC and LHC to make R_γ a useful tool for a 1 TeV Z', the event rate falls off quite quickly with increasing mass rendering it useless if the Z' is significantly heavier.

Hopefully a new Z' will exist in the mass range of interest and provide us with further clues to new physics beyond the SM.

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