W + γ + jet production as a test of the electromagnetic couplings of W at LHC and SSC

F.K. Diakonos\textsuperscript{a}, O. Korakianitis\textsuperscript{a, b}, C.G. Papadopoulos\textsuperscript{c}
C. Philippides\textsuperscript{a, d}, W.J. Stirling\textsuperscript{e}

Abstract

The reaction $pp \rightarrow W + \gamma + jet + X$ is considered at centre-of-mass energies $\sqrt{s} = 16$ and 40 TeV, including anomalous three-gauge-boson couplings $\kappa$ and $\lambda$. The possibility of obtaining limits on these quantities by comparison with the standard model is investigated. The radiation zero properties of the subprocess matrix elements are studied.
One of the main features of the non-abelian character of the $SU(2)_L \otimes U(1)_Y$ standard model (SM), is the existence of trilinear and quadrilinear gauge boson couplings with definite properties. The precise form of these vertices, as specified in the SM, has not yet been verified experimentally. It is therefore important to measure these couplings and look for possible deviations from the SM, which would provide hints for new physics such as compositeness of the intermediate vector bosons.

The most general C,P,T and $U(1)$ gauge invariant effective Lagrangian describing three- and four-gauge-boson interactions can be written as follows:

$$\mathcal{L}_{int} = \mathcal{L}^{(3)}_{SM} + \mathcal{L}^{(4)}_{SM} + \mathcal{L}^{(3)}_{\kappa} + \mathcal{L}_{\lambda}$$

where the first two terms are the familiar SM three- and four-gauge-boson interactions and their deviations are described by the last two

$$\mathcal{L}^{(3)}_{\kappa} = -ie(\kappa - 1)W_\mu W_\nu F^{\mu\nu}$$
$$\mathcal{L}_{\lambda} = -ie\frac{\lambda}{M_W^2}G_{\mu\nu}G^{\mu\nu}F_\rho$$

where

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$$
$$G_{\mu\nu} = W_{\mu\nu} - ie(A_\mu W_\nu - A_\nu W_\mu)$$

with $W_\mu$ the $W$ field and $A_\mu$ the photon field. The parameters $\kappa$ and $\lambda$, which enter both in the three- and four-gauge-boson couplings, are related to the anomalous magnetic dipole and electric quadropole moments of $W$ by

$$\mu = \frac{e}{2M_W}(1 + \kappa + \lambda), \quad Q = \frac{e}{M_W^2}(\lambda - \kappa)$$

The SM has at tree order: $\kappa = 1$ and $\lambda = 0$. The three- and four-gauge-boson vertices $W^+W^-\gamma$ and $W^+W^-\gamma\gamma$, respectively, implied by the Lagrangian of eq.(1) are given in ref. [1].

The phenomenology of anomalous couplings in $W$ production at future pp colliders

$$LHC : \sqrt{s} = 16 \text{ TeV}, \quad \mathcal{L} = 100 \text{ fb}^{-1}/\text{year},$$
$$SSC : \sqrt{s} = 40 \text{ TeV}, \quad \mathcal{L} = 10 \text{ fb}^{-1}/\text{year}.$$
has already been studied extensively in refs. [1, 2, 3]. The main purpose has been to limit the values of the parameters $\kappa$ and $\lambda$, which describe the deviation from the SM predictions. Since these parameters also receive contributions from higher-order corrections to the SM, it is of great importance to approach phenomenologically the limit set by higher-order corrections. The large number of events expected in the strong process $pp \to W^\pm + \gamma + jet + X$ offers large statistics and therefore gives a better perspective to obtain more stringent bounds on the parameters $\kappa$, $\lambda$ than the previously examined process $pp \to W^\pm + \gamma + \gamma + X$ [1], through the three-gauge-boson vertex entering the Feynman diagrams (see Fig. ??).

From the three-gauge-boson vertex given in eq.(3) of ref. [4], we see that $\lambda$ is multiplied by factors of the form $p^2 / M^2_W$, which are equal to 1 for on-shell $W$'s but large for processes involving virtual $W$'s. This motivates us to consider $W\gamma jet$ production at $pp$ colliders, since in this process off-shell $W$'s enter into several Feynman diagrams and thus we expect this reaction to be very sensitive to the parameter $\lambda$. This is actually the case and as we will show below, this reaction provides us with more stringent limits on $\lambda$ than $\kappa$, of the order $5 \times 10^{-2}$, which is of the order of the 1-loop SM values [5].

Specifically, we consider the process: $pp \to W^\pm \gamma jet + X$. The cross section in the parton model is given by the usual convolution of a subprocess cross section with parton distributions:

$$\sigma(pp \to W^\pm \gamma jet + X) = \sum_{a,b,c=q,g} \int_0^1 dx_a dx_b f_{a/p}(x_a, Q^2) f_{b/p}(x_b, Q^2) \times \hat{\sigma}(a(p_1)b(p_2) \to W(p_3)\gamma(p_3)c(p_4))$$

(10)

For the parton distributions we use the KMRS(B0) set [3], with $\Lambda^{(4)}_{\overline{MS}} = 190$ MeV and $Q^2 = \hat{s} = x_a x_b s$. For the electroweak parameters we use $\sin^2 \theta_W = 0.23$, $M_W = 80$ GeV and $\alpha^{-1}_{em} = 128$.

The Feynman diagrams contributing to the subprocess $u g \to W^+ \gamma d$ are shown in Fig. ??.
are obtained by crossing. The subprocess matrix elements are evaluated using the E-vector product technique [4] and the explicit expressions for the helicity amplitudes will be given elsewhere [7]. The usual tests of gauge invariance (with respect to the photon as well as the gluon polarization vector) and unitarity have successfully been performed.

In order to identify the final state we have to impose appropriate cuts on the produced photon and jet for two reasons:

(a) To avoid infrared and collinear singularities and
(b) To extract reliably the photon signal, i.e., to reduce significantly the $\pi^0 \rightarrow \gamma\gamma$ background [8].

We therefore use the following cuts

\[
|\eta_\gamma| \leq 1.5, \quad |\eta_{jet}| \leq 2.5,
\]

\[
p_\gamma^T \geq 50 \text{ GeV}, \quad p_{jet}^T \geq 20 \text{ GeV}
\]

\[
\Delta R_{\gamma-jet} = \sqrt{(\phi_\gamma - \phi_{jet})^2 + (\eta_\gamma - \eta_{jet})^2} \geq 0.4.
\]  

We also include a factor of 2/9 for the leptonic branching ratio for the decay of the $W$, in order to avoid the large QCD background. Since at this moment we are interested in examining the sensitivity of the process to $\kappa$ and $\lambda$, rather than extracting precise bounds on these parameters, we do not address several questions concerning the experimental efficiency for the identification of the $W^{\pm} \gamma \text{jet}$ final state. We expect such uncertainties to factor out when we take ratios of differential to total cross sections, as in Fig. ??

We first consider the total cross section, subject to the cuts of eq.(12), as a function of the anomalous couplings, $\sigma(\kappa, \lambda)$. The cross section is a polynomial of degree two in $\kappa - 1$ and $\lambda$,

\[
\sigma(\kappa, \lambda) = \sigma_0 + \sigma_1^\kappa(\kappa - 1) + \sigma_2^\kappa(\kappa - 1)^2 + \sigma_1^\lambda \lambda + \sigma_2^\lambda \lambda^2 + \sigma^{\kappa\lambda}(\kappa - 1)\lambda
\]  

In Tables 1 and 2, we give the coefficients of the total cross sections corresponding to the above expansion.

In Fig. ?? we show contours of equal cross sections in the $\kappa - \lambda$ plane, corresponding to two standard deviations from the SM values. The bounds
| $\sigma_0$ | $\sigma_1^\kappa$ | $\sigma_2^\kappa$ | $\sigma_1^\lambda$ | $\sigma_2^\lambda$ | $\sigma^{\kappa\lambda}$ |
|---------|----------------|----------------|----------------|----------------|----------------|
| 2.1     | 0.42           | 0.87           | 0.31           | 0.55           | 0.29           |

Table 1: Cross-section coefficients in picobarns, for $\sqrt{s} = 16$ TeV.

| $\sigma_0$ | $\sigma_1^\kappa$ | $\sigma_2^\kappa$ | $\sigma_1^\lambda$ | $\sigma_2^\lambda$ | $\sigma^{\kappa\lambda}$ |
|---------|----------------|----------------|----------------|----------------|----------------|
| 6.5     | 1.3            | 2.3            | 0.54           | 2.8            | 1.0            |

Table 2: Cross-section coefficients in picobarns, for $\sqrt{s} = 40$ TeV.

obtained on each of the anomalous couplings, are given for LHC by:

$$0.5 \leq \kappa \leq 0.54, \quad 0.96 \leq \kappa \leq 1.02$$

$$-0.6 \leq \lambda \leq -0.52, \quad -0.04 \leq \lambda \leq 0.04 \quad (14)$$

and for SSC:

$$0.4 \leq \kappa \leq 0.48, \quad 0.96 \leq \kappa \leq 1.04$$

$$-0.2 \leq \lambda \leq 0.05 \quad (15)$$

In order to obtain bounds on the anomalous couplings from the total event rate we have to take into account both experimental (luminosity, acceptance, ...) and theoretical (higher-order corrections, parton distributions, ...) uncertainties on the measured and predicted cross sections. From this point of view, it is more reliable to study deviations from the expected differential cross sections, where the overall normalization can be factored out. Several quantities are likely to be useful in this respect, but the one that is probably the simplest to measure is the distribution of the photon transverse momentum, $p_T^\gamma$. Since this is the momentum entering the three-gauge-boson vertex and it is multiplied by the anomalous couplings $\kappa, \lambda$, we expect this distribution to show the biggest deviation from the SM result in magnitude as well as shape, especially at higher values of the photon transverse momentum and therefore of $\sqrt{s}$, where violation of unitarity becomes more apparent. In Fig. ??, we show the normalized distributions $\frac{1}{\sigma} \frac{d\sigma}{dp_T^\gamma}$ and $\frac{1}{\sigma} \frac{d\sigma}{dp_T^\gamma}$ at $\sqrt{s} = 16$ TeV.
and $\sqrt{s} = 40$ TeV, respectively, for $(\kappa, \lambda) = (1, 0), (1.5, 0)$ and $(1, 0.5)$. We see that the jet distributions are less sensitive to the anomalous couplings. This suggests that the photon transverse momentum is the main tool to analyse the electromagnetic couplings of the $W$.

In order to compare with the previous calculations on $W\gamma\gamma$ production, we show in Fig. ?? the ratio $\frac{\sigma(\kappa, \lambda)}{\sigma_0}$ as a function of $\Delta\kappa = \kappa - 1$ and $\lambda$, where $\sigma_0 = \sigma(\kappa = 1, \lambda = 0)$. We see that the sensitivity of the process $pp\to W\gamma\gamma$ is much larger than that of the process $pp\to W\gamma jet$. This is due to the fact that the cross section for the former process is a quartic polynomial in $\Delta\kappa$ and $\lambda$ whereas for the latter we have at most quadratic dependence. Nevertheless, the process under consideration gives a cross section which is orders of magnitude larger than the $W\gamma\gamma$ one and thus offers a large statistics channel for the study of anomalous $W$ couplings.

A final point that we wish to study is the impact of the presence of a radiation zero in the $q_i\bar{q}_j\to W\gamma g$ matrix element. It is well known that the leading order $u\bar{d}\to W^+\gamma$ amplitude vanishes when the centre-of-mass scattering angle of the photon satisfies $\cos\theta_{\gamma} = 1 + 2Q_d = 1/3$. Less well known is the fact that this zero is unchanged when additional neutral particles are emitted in the same direction as the photon. In both cases, the zero disappears when additional anomalous three- and four-gauge-boson couplings are included in the Lagrangian. In the present context this means that the amplitudes such as $u\bar{d}\to W^+\gamma g$ vanish when (a) the photon and the gluon are collinear ($M_{\gamma g} = 0$), (b) $\cos\theta_{\gamma g} = 1/3$ in the $u\bar{d}$ centre-of-mass, and (c) $\kappa = 1, \lambda = 0$. There are two issues here. First, the existence of a zero under these conditions is a powerful check on the matrix element calculation and, secondly, can the zero be observed, and if so can it provide more stringent limits on the anomalous couplings than the total cross section and $p_T$ distribution measurements described above? Fig. ?? shows the matrix element squared $|M(u\bar{d}\to W^+\gamma g)|^2$ for $\sqrt{s} = 1$ TeV and equal photon and gluon momenta in the final state ($p^\mu_{\gamma} = p^\mu_{g}$), as a function of the common photon-gluon centre-of-mass scattering angle $\theta_{\gamma g}$ for different choices of the anomalous couplings $\kappa$ and $\lambda$, $(\kappa, \lambda) = (1, 0), (1.1, 0)(1, 0.1), (1, 1)$. The zero in the Standard Model case is immediately apparent, and the anomalous couplings are seen to fill in the dip caused by the radiation zero. In the region of the zero there is evidently a high-sensitivity to these couplings.

Unfortunately it is in practice very difficult to identify the $W\gamma$ radiation zero in high-energy hadron-hadron collisions. The main problems...
are that (a) the zero occurs in the subprocess centre-of-mass frame which is different event by event from the laboratory frame, (b) the centre-of-mass frame is difficult to construct from the final state momenta because there is an undetected neutrino in the leptonic decay of the $W$, and (c) at high energy proton-proton colliders, the $u\bar{d}$ process is overwhelmed by processes involving an initial state gluon, e.g. $ug\rightarrow W^+\gamma d$. (Explicit computation shows that $qg$ scattering processes represent 88% (92%) of the total $W + \gamma + jet$ cross section at LHC (SSC) energies.) Not only do these latter processes have no radiation zero but they are also singular when the final state photon and jet are collinear! These singularities are only regulated when a proper next-to-leading order definition of a jet is implemented (for example, as energy inside a cone). In other words, it seems impossible either theoretically or experimentally to identify a parallel photon and gluon in the final state.

In conclusion, we have shown that the study of the $pp \rightarrow W^+\gamma jet + X$ reaction will provide at future high energy proton-proton colliders many events to test the electroweak three- and four-gauge-boson couplings of the standard model, which are a direct consequence of the $SU(2)_L \otimes U(1)_Y$ gauge symmetry. Furthermore, the radiation zero of the amplitudes is still there for a particular phase space configuration and is very sensitive to the anomalous couplings $\kappa, \lambda$. In an ideal experimental situation where the subprocesses $u\bar{d}\rightarrow W^+\gamma g$ and $d\bar{u}\rightarrow W^-\gamma g$ could be isolated and their cross sections measured in the partonic centre-of-mass frame, this zero would provide us with arbitrarily high sensitivity to measure the anomalous couplings.

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