Wγ and Zγ production at hadron colliders

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Abstract. We present a general purpose Monte Carlo program for the calculation of any infrared safe observable in Wγ and Zγ production at hadron colliders at next-to-leading order in αs. We treat the leptonic decays of the W and Z-boson in the narrow-width approximation, but retain all spin information via decay angle correlations. The effect of anomalous triple gauge boson couplings is investigated and we give the analytical expressions for the corresponding amplitudes. Furthermore, we propose a way to study the effect of anomalous couplings without introducing the ambiguity of form factors.

1 Introduction

The production of Wγ and Zγ in hadronic collisions has been studied extensively since the Born cross sections have been computed [1, 2]. In particular, these processes allow to study the triple gauge boson couplings WWγ, ZZγ and Zγγ. The study of these couplings is mainly motivated by the hope that some new physics may modify them. If the new physics occurs at an energy scale well above that being probed experimentally, it is possible to integrate it out. The result is an effective theory which might result in non standard triple gauge boson couplings.

Both collaborations at the Tevatron have studied the production of Wγ [3] and Zγ [4] pairs. The bounds on the anomalous couplings obtained at the Tevatron tend to be less constraining than those obtained at LEP [5]. However it has to be kept in mind that these analyses are complementary. At the hadron colliders a whole range in the center of mass energy is tested, whereas at LEP the center of mass energy is fixed by the collider. Furthermore, with Run II the expected number of events at the Tevatron increases substantially. Assuming a data sample of 2 fb⁻¹, more than 3000 Wγ → ℓνγ events and 700 Zγ → ℓνγ events are expected for each experiment [6]. Of course, the expected number of events is even bigger for the LHC.

Anomalous triple gauge boson couplings lead to deviations from Standard Model predictions. Obviously, observables for which these deviations are enhanced offer better chances to find new physics or get tighter constraints on anomalous couplings. There are basically two classes of such observables. Either we consider observables which are strongly suppressed in the Standard Model or observables with large transverse momentum (or center of mass energy). In both cases, the inclusion of next-to-leading order (NLO) QCD corrections is mandatory.

A prominent example of an observable that is suppressed in the Standard Model is the so called radiation zero for Wγ production. At leading order (LO) there exist some kinematic configurations for which the amplitude vanishes [1]. This is manifest in some observables as a dip in the rapidity distributions. Since anomalous coupling contributions fill in the dips, there seemed to be excellent prospects to obtain accurate limits for them from experimental data. Unfortunately, next-to-leading order QCD corrections strongly affect the LO analysis. They have the same effect as the anomalous coupling contributions. The dips are filled in, making the extraction of anomalous couplings quite more difficult.

For processes with large transverse momentum or center of mass energy, the NLO corrections are particularly large. This is due to the fact that the cross sections in these cases get large contributions from gluon induced partonic subprocesses, which only enter in a next-to-leading order description of the cross section. Thus, even though the anomalous contributions are enhanced in these regions, a calculation at NLO in αs is required to reliably exclude (or establish) physics beyond the Standard Model.

The relevance of NLO corrections was first shown for the production of real (spin-summed) W and Z bosons with Standard Model couplings and without considering lepton decays and spin correlations [7,8]. These calculations were later extended, in order to include the leptonic decays and anomalous couplings [9–11]. However, the full one-loop amplitudes including leptonic decays became available only very recently [12]. Therefore, [9–11] included decay correlations everywhere except for the finite part of the virtual contributions.

In this paper we present order αs results for the production of Wγ and Zγ in hadronic collisions, including the full leptonic correlations. We work in the narrow-width approximation, where only ‘single-resonant’ Feynman diagrams have to be considered. The simplicity of the helicity method allows to take into account anomalous couplings.
as well and present for the first time analytical expressions for the corresponding amplitudes.

For the case of $WW$, $ZZ$ and $WZ$ production at hadron colliders, some results beyond the narrow-width approximation are known. The narrow-width approximation requires only the calculation of ‘doubly-resonant’ Feynman diagrams. However, for these processes, also the amplitudes including ‘single-resonant’ diagrams have been computed and implemented into a Monte Carlo program [13].

To perform the phase space integration we use the subtraction method discussed in [14]. This allows for a straightforward implementation of the one-loop subtraction method discussed in [14]. The amplitudes, presented in [12] ($V \in \{Z, W\}$). The constructed Monte Carlo code allows the computation of any infrared-safe observable.

A brief overview of the calculation is given in Sect. 2. were we summarize the input parameters used and the cuts implemented to obtain our phenomenological results. In Sect. 3 we present some benchmark cross section numbers for both $W\gamma$ and $Z\gamma$ production at the LHC and study the typical scale dependence of some observables at NLO in the Standard Model. Since many distributions have been studied in the past, we refrain from doing a detailed analysis. However, as soon as more precise data becomes available such an analysis can easily be done.

In Sect. 4 we concentrate on anomalous triple gauge boson couplings. We describe the parameterization of the triple gauge boson vertex in terms of anomalous coupling parameters and search for the kinematical region where its effect is amplified, namely at large transverse momentum of the photon and leptons. We also analyze the possibility of seeing the effect of approximate radiation zeros in the $W\gamma$ process, i.e. by looking for ‘dips’ in rapidity distributions. In order to avoid the arbitrariness introduced by form factors, we propose to analyze the anomalous couplings as a function of the squared partonic center of mass energy $\hat{s}$. This has been suggested previously for the $Z\gamma$ case [15], where such an analysis is straightforward. We extend this idea to the $W\gamma$ production. This case is more involved, since a complete reconstruction of $\hat{s}$ is impossible, due to the appearance of a non observed neutrino in the $W$ decay. Particularly, we present an observable quantity which is highly correlated to $\hat{s}$ and, therefore, allows such an analysis even for $W\gamma$ production. Finally, in Sect. 5 we give our conclusions and in the appendix we present analytical expressions for the amplitudes relevant for the inclusion of anomalous couplings are presented in the appendix. In order to cancel analytically the soft and collinear singularities coming from the bremsstrahlung and one loop parts, we have used the version of the subtraction method presented in [14]. The amplitudes are therefore implemented into a numerical Monte Carlo style program, which allows to calculate any infrared-safe physical quantity with arbitrary cuts.

Obviously, the Monte Carlo program can be used for the Tevatron and the LHC. However, in this paper we will mainly concentrate on results for the LHC collider, which corresponds to $pp$ scattering at $\sqrt{s} = 14$ TeV. Unless otherwise stated, the results are obtained using the following cuts: we make a transverse momentum cut of $p_T > 25$ GeV for the charged leptons and the rapidity is limited to $|y| < 2.4$ for all detected particles. The photon transverse momentum cut is $p_T > 50(100)$ GeV for $W\gamma$ production. For the $W\gamma$ case we require a minimum missing transverse momentum carried by the neutrinos $p_T^{\text{miss}} > 50$ GeV. Additionally, charged leptons and the photons must be separated in the rapidity-azimuthal angle by $\Delta R_{\ell\gamma} = |y_\ell - y_\gamma|^2 + (\phi_\ell - \phi_\gamma|^2 > 0.7$. Moreover, since our calculation is done in the narrow-width approximation and, therefore, ignores the radiation of photons from the final state leptons, we apply an additional cut to suppress the contribution from the off-resonant diagrams. For that purpose, we require the transverse mass $M_T > 90$ GeV for $W\gamma$ production and the invariant mass of the $\ell\ell$ system $M_{\ell\ell} > 100$ GeV for the $Z\gamma$ case.

Finally, photons can also be significantly produced at LHC from the fragmentation of a final state parton. Unfortunately, fragmentation functions of partons into photons are not very well determined and the NLO calculation for such a contribution is not available yet. In principle, a full NLO calculation should include it however, since only the sum of the ‘direct’ plus ‘fragmentation’ components is physically well defined at NLO (only in the sum all collinear singularities cancel out). In order to circumvent this problem, we include the LO component of the fragmentation part but using NLO fragmentation distributions, where we can factorize the final state $q\gamma$ collinear singularities. Since the ‘fragmentation’ component can be further suppressed implementing certain cuts (see below) the lack of its NLO calculation is not expected to affect the final result beyond the few percent level.

The fragmentation contribution constitutes a background to the search of anomalous couplings, since it does not involve any triple gauge boson coupling. Fortunately, there is a way to suppress its contribution by requiring the photons to be isolated from hadrons. In this paper we require the transverse hadronic momentum in a cone of size $R_0 = 0.7$ around the photon to be smaller than a small fraction of the transverse momentum of the photon

$$\sum_{\Delta R < R_0} p_T^{\text{had}} < 0.15 p_T^\gamma$$

This completes the definition of our ‘standard’ cuts.

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1. The corresponding Fortran codes are available upon request.

2. This contribution is also known in the literature as ‘bremsstrahlung’.