Simulation of photon-photon interactions in hadron collisions with SHERPA

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We describe the capabilities of the SHERPA Monte Carlo event generator in simulating two-photon induced processes. We focus especially on the description of these processes at hadron colliders such as the LHC.

1. Introduction

Photon collisions have been used as an excellent testbed to study QCD-induced phenomena. This is due to the fact that the photon structure, in a simple approximation, can be understood on purely perturbative grounds. At future colliders such collisions additionally provide an excellent opportunity to study interactions both within and beyond the Standard Model. A prime example is the coupling of the Standard Model Higgs boson to photons via heavy particle loops. In the context of studying new physics phenomena, this coupling, if measured, may provide indirect information about energy scales much higher than the ones that could be tested directly through the experiment. In principle, this process offers the opportunity for comparably straightforward experimental analyses. In practise, however, there may be a plethora of interesting signals (and corresponding backgrounds) that necessitate more involved techniques. To connect theory and experiment in such cases, precise predictions for multi-particle final states are mandatory. Such predictions must respect, among others, exact kinematics and interferences of different contributions and therefore correctly describe multi-particle correlations. In such situations, Monte Carlo event generators have been an indispensable tool in the last decades. Their major strength is that within their framework, experimental requirements and cuts can be implemented easily and in an intuitive manner.

1.1. Trends in modern event generators

Besides the well-established multi-purpose generators \cite{1, 2} and their modern versions \cite{3, 4}, new codes have emerged which put special emphasis on the correct description of multi-particle production through the corresponding exact tree-level matrix elements \cite{5, 6, 7, 8}. In the case of QCD and QCD-associated final states, techniques are available to combine higher order real corrections with resummation described by parton shower programs. Such techniques are implemented for example in the generators ALPGEN \cite{5}, HELAC \cite{6}, MADEVENT \cite{9} and SHERPA \cite{8}. Given the decreasing accuracy of resummation with increasing hardness of radiation, it is important at current and future colliders to have at hand tech-

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Techniques to predict and reliably describe signals of, and backgrounds to, new physics. Multi-particle observables in general also obtain significant corrections from higher-order real emission matrix elements due to spin and colour correlations between the final states that are not fully taken into account in the parton shower approximation. A prime example here is the production and decay of a Higgs boson at a photon collider. Assuming a light Higgs boson, the dominant decay channel is into two $b$-quarks, which obviously must be in a spin-0 state. The corresponding background is suppressed by powers of $m_b/E$, leading to a potentially clean signal. However, taking into account higher-order corrections due to a hard gluon emitted into the final state changes this picture drastically, since the kinematic suppression is not present anymore. This effect and the dominance of Mercedes star-like signatures has been discussed also in [10]. This effect would be completely missed in a parton shower Monte Carlo based on lowest-order matrix elements only.

In view of the startup of the LHC later this year the further development and validation of the new tools is a major task for phenomenologists. Careful studies of their systematics are under way and have been presented for example in Refs. [11,12]. The experimental significance of the procedure has been exemplified in a recent DØ study [13].

A further important aspect of Monte Carlo event generation at hadron colliders is the description of possibly-occurring secondary hard and soft interactions of hadron remnants. Idem applies in photon collisions if the resolved component of the photon is concerned. At present no theory exists based on first principles to describe multi-particle scattering or re-scattering. Instead, there are a number of models [14, 15], which are based on some kind of “eikonal picture” of multiple, rather independent, parton scattering. These models are capable of describing all present data satisfactorily. New developments in this area aim at a more inclusive description of the underlying QCD activity, and include effects such as interleaving [16], aim at a description based on the BFKL evolution equation, like, e.g. [17], or try to include diffractive processes into the picture [18]. Eventually, this will lead to an improved modelling of this effect. Again, photon collisions could provide a wonderful and valuable testbed for this kind of effect, since, due to their comparably simple QCD structure, a source of systematic uncertainties would be widely absent. In addition, the distribution of virtual masses of such photons may add a further set of observables critical to this phenomenon. The dedicated forward proton detector at the LHC will allow to use this machine as a photon-photon collider, with a unique coverage of up to 1 TeV c.m. energy [19]. It should be mentioned here that in $pp$ collisions at the LHC photon-induced processes will carry a sizable fraction of events in or around the percent-range. Many of these events, however, will be comparably soft, with signatures that are quite similar to diffractive events. At larger energies, however, the $\gamma\gamma$ collisions tend to dominate over the diffractive ones.

1.2. The SHERPA event generator

SHERPA is one of the more recently developed event generators, providing full event simulation at lepton and hadron colliders including single and double photon modes. The generator is designed in a modular fashion, where each module handles the simulation of a certain physical aspect of the collision. This structure reflects the current understanding of high-energy particle reactions, where the time development can be translated into a development in energy scales associated with the respective part of the collision. The central part is formed by the hard interaction, that can be described using perturbative methods. The respective generator for matrix elements and phase space integration is AMEGIC++ [20], which employs the spinor helicity formalism [21, 22] in a fully automated approach to generate processes in a variety of physics models. Besides the Standard Model this includes the Minimal Supersymmetric Standard Model [23], the ADD model of large extra dimensions [24] and an extensive set of operators parametrizing anomalous triple and quartic electroweak gauge boson couplings. The implementation of further interesting interactions is simplified by an easy-to-use interface. AMEGIC++ proves to be competitive to other high-multiplicity generators, like...
e.g. ALPGEN [5], CompHEP [25], HELAC [6] and MADGRAPH [26]. In the near future, SHERPA will also include a new matrix element generator for the production of very large multiplicity final states [27]. At present, this generator is capable of simulating all Standard Model processes and as such can be employed in studies like $pp \rightarrow W + 4 \text{ jets}$, where the correct description of QCD activity from large multiplicity final states plays an essential role for background simulations to, e.g., top quark production or supersymmetric processes.

QCD partons from the hard interaction evolve from the hardest scale down to the hadronization scale. In SHERPA this is simulated by the established shower program APACIC++ [28]. New shower generators have recently been developed in the framework of SHERPA [29, 30]. They account for QCD coherence and kinematics effects in a way consistent with NLO subtraction schemes, which makes them preferred over APACIC++. They will be employed in future versions of SHERPA to construct improved merging prescriptions for matrix elements and showers.

An important aspect of SHERPA is its implementation of a general version of the CKKW algorithm for merging higher order matrix elements and parton showers [31,32]. It has been validated in a variety of processes [33, 34, 35] and proved to yield reliable results in comparison with other generators [11, 12].

SHERPA features an implementation of the model for multiple parton interactions presented in Ref. [14], which was modified to allow for merging with hard processes of arbitrary final state multiplicity and eventually including CKKW merging [36]. The corresponding results again prove to be competitive with those of other generators.

Many other aspects of event generation are also handled by SHERPA. It provides an implementation of a cluster fragmentation model [37], a hadron and tau decay package including the simulation of mixing effects for neutral mesons [38], and an implementation of the YFS formalism to simulate soft photon radiation [39]. Standard interfaces are provided to simplify the usage of the generator and the comparison to similar programs.

2. Photon interactions in SHERPA

Besides the calculation of hard processes initiated by photons the realistic simulation of photon induced events has to take into account the actual formation of the photonic initial state. In the context of leptonic incoming beams, e.g. at a future linear collider, photon beams can be prepared through laser backscattering off the potentially polarized electrons and positrons with very high luminosity [40]. To account for this SHERPA relies on a parametrization that depends on the energy and polarization of the incoming lepton beams as well as on the concrete laser specifications [41]. When considering collisions of hadronic beams, e.g. at the Fermilab Tevatron or the CERN LHC, the two-photon component of the cross section can reasonably be described in the framework of the equivalent-photon approximation (EPA), that relates the hadronic cross section to the interaction cross section of real photons through a two-photon luminosity function [42]. In SHERPA the following parametrization of the energy dependent photon spectra presented ibidem is employed:

$$dn(w) = \frac{\alpha}{\pi} \frac{dw}{w} \left(1 - \frac{w}{E}\right) \times \left[\varphi \left(\frac{q_{\text{max}}^2}{q_0^2}\right) - \varphi \left(\frac{q_{\text{min}}^2}{q_0^2}\right)\right],$$

where $w$ is the photon- and $E$ is the hadron energy and

$$\varphi(x) = \frac{(1 - b) y}{4x \left(1 + x\right)^3} + (1 + ay) \left[-\ln\left(1 + \frac{1}{x}\right) + \frac{1}{k \left(1 + x\right)^k}\right],$$

$$+ c \left(1 + \frac{y}{4}\right) \left[\ln\left(1 + x - b\right) + \frac{b^k}{k \left(1 + x\right)^k}\right],$$

with $y^{-1} = E(E - w)/w^2$. The parameters $a$, $b$
and $c$ are given by
\[ a = \frac{1}{4} \left( 1 + \mu_p^2 \right) + \frac{4m_p^2}{q_0^2} \approx 7.16 , \]
\[ b = 1 - \frac{4m_p^2}{q_0^2} \approx -3.96 , \]
\[ c = \frac{\mu_p^2 - 1}{b^2} \approx 0.028 , \]
where $q_0^2 \approx 0.71 \text{GeV}^2$ and $\mu_p^2 \approx 7.78^{[42]}$.

In addition, if the photons themselves are resolved, their quark and gluon content may be parametrized by a photon PDF, see for example Refs. [43, 44]. In this context the event generation is essentially equivalent to the procedure for hadronic initial states, although with varying c.m. energy. This can easily be understood, since on the perturbative side of the simulation all that matters is that there is a PDF – no further information about the incoming beam being a photon is explicitly needed. This then allows for a consistent incorporation of initial- and final-state parton showers, possibly corrected for hard emissions through exact higher order real emission matrix elements according to the CKKW formalism.

3. Example results

We present here some examples for the performance of SHERPA in photon-photon interactions at the LHC. They should not be understood as a thorough analysis, but merely as an introduction to what studies are possible with the help of this generator.

3.1. Leptonic final states

We consider in this section processes of the type $\gamma\gamma \rightarrow W^+W^- \rightarrow l\ell' + E_T$ at the CERN LHC with $\sqrt{s} = 14\text{ TeV}$, either in the continuum or mediated by an intermediate Standard Model Higgs boson of mass $m_H = 160\text{ GeV}$. An analysis of the respective decay mode of the Higgs boson is preferred for Higgs boson masses around the $2m_W$ threshold due to the large branching ratio $H \rightarrow W^+W^-$. However, as it has been found in Ref. [45], in the vector boson fusion channel, even for a relatively light Higgs boson, this decay mode yields a signal that is sufficiently different from the main backgrounds to allow a discovery.

We employ SHERPA’s built-in matrix element generator AMEGIC++ to provide the full decay chain, i.e. all spin correlations are described appropriately. The coupling of the Higgs boson to photons via an intermediate top-quark loop is described by an effective Lagrangian for $m_t \rightarrow \infty$. We employ the following lepton identification cuts
\[ p_{T,l} \geq 10\text{ GeV}, \quad |\eta_l| < 2.5, \quad \Delta R_{W} \geq 0.2. \]

Using SHERPA’s decay package to simulate tau decays, we find that these do not have a significant effect on the kinematical distributions of the identified leptons. This is because the kinematics of the decay products is essentially determined by the initial direction of the decaying tau lepton and the high energy of the taus when emerging from the hard interaction.

Figure 1 shows the respective spectra for the azimuthal separation of all possible lepton combinations emerging from the $W$-decays. This observable provides an excellent handle on the irre-
Figure 2. Transverse mass $m_{T,WW}$ in $\gamma\gamma \rightarrow W^+ W^- \rightarrow l'^+ E_T$ with and without an intermediate Standard Model Higgs boson of $m_H = 160\,\text{GeV}$

The above process constitutes an irreducible background to Higgs boson production in large rapidity gap events and is thus of particular importance for future analyses at the LHC. In the context of this work we focus on resolved incoming photons. Their parton content is described by an appropriate PDF [44]. Figure 3 shows, for this setup, the dijet invariant mass $m_{jj}$ in $\gamma\gamma \rightarrow b\bar{b}$ with (CKKW) and without (APACIC++) the simulation of an additional hard jet described by the appropriate NLO real emission matrix element. Coloured (thin) lines display the contributions from 2- and 3-jet final states in the hard matrix element. Note that the distributions are normalized to unity.

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3.2. Hadronic final states with resolved photons

We consider the process $\gamma\gamma \rightarrow b\bar{b}(g)$ to exemplify the capabilities of SHERPA in merging NLO real emission matrix elements and parton showers. A corresponding study for a linear collider environment has recently been presented in Ref. [46]. The above process constitutes an irreducible background to Higgs boson production in large rapidity gap events and is thus of particular importance for future analyses at the LHC. In the context of this work we focus on resolved incoming photons. Their parton content is described by an appropriate PDF [44]. Figure 3 shows, for this setup, the dijet invariant mass of the leading jets reconstructed with the CDF Run II $k_T$ algorithm [47], a D-parameter of 0.4 and a minimum transverse momentum of 20 GeV. Note that the distributions are normalized to unity allowing an easy comparison of their shape. The sample generated by CKKW merging shows on average a considerably larger mass than the prediction from pure parton showering. This is the effect of hard initial state radiation off the incoming
parton lines being described appropriately by the respective NLO real emission matrix elements.

4. Conclusions

Essential features of the recently established event generator SHERPA have been described. The concept of simulating photon initial states in a hadron collider environment has been exemplified for the case of Higgs boson production and decay into leptons via $W$ bosons. The effect of higher order real QCD corrections on hadronic final states of a photon-photon annihilation has been exemplified for $b\bar{b}$ production using the CKKW merging prescription. We find that SHERPA is well capable of simulating the associated multi-particle final states and can be considered ready-to-use for corresponding analyses at the LHC.

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